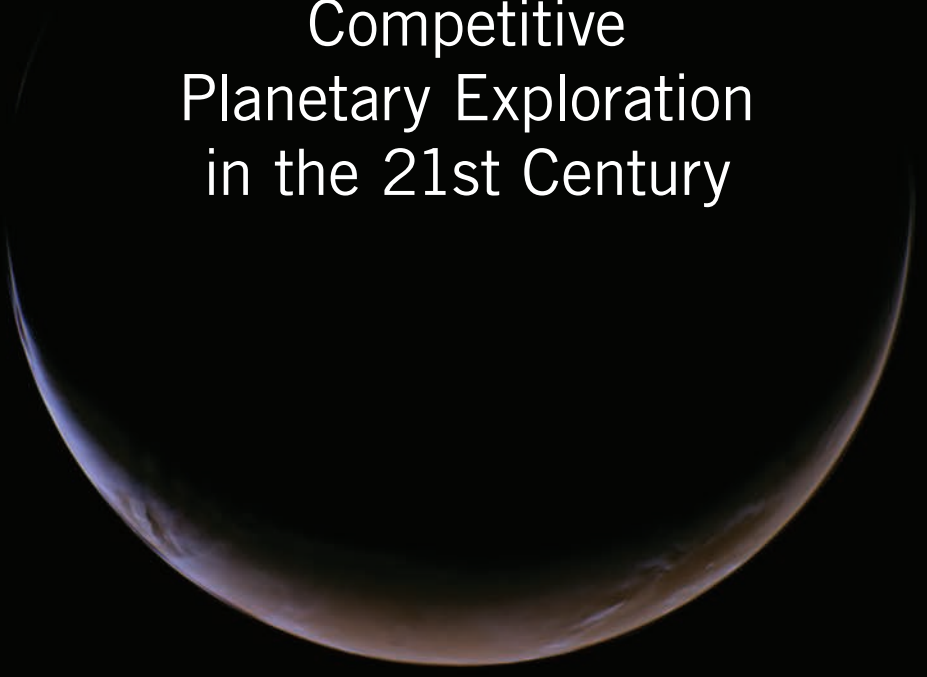
NASA's DISCOVERY PROGRAM

Competitive Planetary Exploration in the 21st Century



DAVID W. BROWN

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by

DAVID W. BROWN



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CONTENTS

Foreword		v
Introduction		ix
Chapter 1	**2011**	1
Chapter 2	**2012**	27
Chapter 3	**2013**	49
Chapter 4	**2014**	57
Chapter 5	**2015**	67
Chapter 6	**2016**	81
Chapter 7	**2017**	91
Chapter 8	**2018**	103
Chapter 9	**2019**	109
Chapter 10	**2020**	121
Chapter 11	**2021**	131
Chapter 12	**2022**	145
Chapter 13	**2023**	155
Chapter 14	**2024**	163
Chapter 15	**2025 and Beyond**	169
Endnotes		179
Acknowledgments		239
Acronyms and Abbreviations		241
About the Author		245
The NASA History Series		247
Index		261

FOREWORD

Although I never planned it this way, the Discovery Program has turned out to be the constant companion of my career. Fresh out of graduate school, I worked as a postdoctoral researcher on the Imaging Team for NEAR (the first mission launched under Discovery). Continuing my career, I became an Instrument Scientist, then Deputy Project Scientist and Co-Investigator on MESSENGER, the first mission to orbit Mercury and the seventh mission in the Discovery Program. Later, I led the concept study for Trident—a flyby mission to Neptune's largest moon, Triton—which was down-selected to Phase A of the 2019 Discovery Announcement of Opportunity (AO). Now, in my role as the Planetary Science Division (PSD) Director at NASA Headquarters, I am responsible for the full planetary science portfolio of which the Discovery Program is a critical part. The first major mission milestone I enjoyed as PSD Director, just weeks after starting in the role, was the flyby of the main-belt asteroid Donaldjohanson by our Lucy spacecraft (the 13th Discovery mission) in April 2025 while en route to tour the Jupiter Trojan asteroids later this decade. Psyche (the 14th Discovery mission) is also on its journey to orbit the metal-rich asteroid of the same name, starting in 2029. The latest selected Discovery missions, DAVINCI and VERITAS, despite facing some challenges, are in development and headed to Venus with planned launches in the early 2030s.

More than a companion, the Discovery Program has provided me with direction, support, inspiration, and the opportunity to grow as a planetary scientist. This book (along with the first volume), wonderfully highlights three overarching lessons I have learned through my involvement with the Discovery Program. Moreover, I believe these lessons are applicable to our field and community as a whole.

First, science is always the foundation. The grounding as a planetary scientist I received during my years working on NEAR and MESSENGER provided a hugely

valuable basis on which to root the rest of my career. Likewise, the early pioneers of the Discovery Program recognized the potential that could be achieved if science were the driver for our missions and our exploration. They understood that small, yet ambitious, missions would have the power to corral our scientific community to ask—and answer—bold questions, but also to galvanize congressional stakeholders and inspire and involve the general public. The power of our science to inspire has never wavered.

Second, great leaders and great teams stimulate creativity. As Principal Investigator (PI) of the Trident team, I had the privilege of leading an incredible and passionate team. I saw, firsthand, scientists and engineers learning to "speak each other's language" as they were focused on a singular goal. I've learned, and this book illustrates, that the immense effort and creativity required for a successful mission can only be nurtured in a safe and trusting environment.

Third, perspective and patience—always. As part of a mission team, single-mindedness and relative myopia are understandable. However, none of our missions exist in a vacuum. Since becoming PSD Director, I have gained a new appreciation for the perspectives of NASA Headquarters, and the agency as a whole, which can sometimes seem to be at odds with those of specific missions or the planetary science community. As described in this book, "Discovery competitions are inseparable from politics." No decision is made in isolation, and the full arc of missions and the program as a whole can only be fully understood with the benefit of time and hindsight.

This book, together with the preceding volume, serves as a valuable resource for understanding the full history of the Discovery Program. I'm positive it will be especially useful to current, and future, mission PIs and teams, as well as students of the space sciences and NASA history. Together, the two volumes provide a comprehensive look at the twists and turns, and myriad internal and external pressures the Program has endured. This book provides an important reminder of how this Program, despite the many challenges, helped change the paradigm of NASA's robotic exploration and its incredible scientific achievements. Discovery has truly bred discovery. The view we now have of our solar system (and other solar systems) would not be nearly as vivid without the progress that has been driven by Discovery. In Chapter 5, MESSENGER's great achievement is described as "narrowing the distance" between Earth and Mercury. I think that sentiment also captures the overall purpose and success of Discovery—making space more accessible, in both a literal and figurative sense.

I am delighted to see this NASA History Office project, ably steered by NASA's Chief Historian Dr. Brian Odom, completed with the publication of this volume. It has been a long-road—starting back in 2010 as the late Dr. Susan Niebur's

brainchild. I am proud to have called Susan a colleague and friend; her contributions to planetary science were bold and inspirational, and she is greatly missed. I am also incredibly grateful to David Brown for taking up the mantle and lending his narrative prowess and NASA insights to telling, and bringing up to date, the story of Discovery and for fully realizing this part of Susan's legacy.

The Discovery Program of today is by no means the Discovery Program first envisaged in the 1990s. The original cadence of AOs and missions are no longer sustainable due to the sober realities of federal budgets and NASA risk postures. Yet a diversity of opinions and bold ideas have always been at the core of this exciting program—and their importance undoubtedly remains. Discovery continues to be a shining example of NASA's global leadership in space exploration, and I cannot wait to see what its future will reveal.

Dr. Louise M. Prockter
NASA Planetary Science Division Director

INTRODUCTION

In 2010, Dr. Susan Niebur, the former Discovery Program Scientist at NASA Headquarters, wrote a history of the mission line she helped establish. The NASA History Office published the manuscript in 2024 under the title *NASA's Discovery Program: The First Twenty Years of Competitive Planetary Exploration*. That book began with Discovery's founding, explaining the political, fiscal, and cultural circumstances necessitating a low-cost, high-cadence flight program with a dedicated budget. It covered mission development, launch, and operations of the first ten Discovery missions—Pathfinder through Kepler—and the science return of missions at the end of the program's second decade. Concurrently, it gave context to the far-reaching decisions made by agency leadership at NASA Headquarters.

This work is a companion to Dr. Niebur's book, picking up where *NASA's Discovery Program* concluded. It chronicles Discovery from 2011 through 2025, including the development of the next 6 missions selected by NASA, and the operations and science return of 10 missions flown in that timeframe. This book also follows the development of missions NASA failed to select, to get the principal investigator perspective of the science and engineering achievements of those projects, and an assessment of the reasons why they were not chosen for flight.

The first 20 years of Discovery were marked by efforts to establish a program culture, convince the planetary science community to develop restrained missions after decades of increasing spacecraft complexity, and carve out a place for a high-risk mission line within a generally conservative space agency—all with varying degrees of success. The next 15 years were defined by increasingly aggressive scientific goals within Discovery's cost cap and a marked decrease in the number of opportunities to submit missions for competitive selection. Ultimately, the program faced an existential threat because of cost overruns by its own missions and other

flight projects in the exploration portfolio and concurrent budget cuts. Its present looks very little like the Discovery of 1990. Its future is uncertain.

This work is a contemporary account of the Discovery Program's most productive years, if measured in science data and, like Dr. Niebur's book, endeavors to provide the political and fiscal circumstances of certain decisions by agency officials. In addition, it provides not only the science return of missions in flight, and rationale of missions in development, but also the scientific context for their proposals in the first place.

Much of this work was drawn from more than 100 interviews with scientists, engineers, managers, and executives who played key roles across the agency: an oral history project enabled by a NASA History Office effort to commemorate the 30th anniversary of Discovery and 20th anniversary of New Frontiers. It also draws from agency archives, when possible, as well as scientific journal articles. Because internal documents and correspondence from most of the missions covered have not yet been submitted for official archiving, this work also draws on memoirs, press releases, and news stories to build nuanced accounts. This book is structured chronologically, plotting the selection and development of each mission alongside the other flight projects of their day, and seeks to illustrate how unrelated missions can impact each other in ways positive and otherwise. This sometimes means other missions in the Discovery portfolio but can also mean contemporary NASA missions of any class. Moreover, Discovery projects tend to have overlapping personnel and international partners, which means the circumstances of a Discovery selection and its development are sometimes influenced by broader agency goals, and even the ambitions of foreign space agencies.

The health of the Discovery Program can oftentimes be seen as a reflection of the state of NASA and planetary science. Its urgency in the early 1990s was driven by the paucity of activity in the preceding decade. During the Reagan administration, for example, NASA did not launch a single planetary spacecraft. The painful spacecraft development pipelines in the 2000s suggested an agency reassessing its risk tolerance amid failures from elsewhere in the agency and diminishing planetary budgets. The 2010s saw a peak of five simultaneous active flight projects and an attempt to correct Discovery's faltering selection cadence, in a time of record budgets and a seemingly renewed Congressional commitment to planetary exploration. However, during the 2020s, the Discovery Program has not solicited proposals for any new missions, and indeed, has come close to losing its two missions still in development. The agency overall has had equal reason to worry.

NASA runs hundreds of projects simultaneously, most belonging to one of many different strategic programs within the agency. The life cycle of a typical planetary mission divides into several sequential phases.[1] Progression from one phase to the

next is governed by the results of extensive reviews. Each prospective mission begins with a concept study, which is matured during Phase A, when the team validates the mission's justification and feasibility. Teams also establish the mission's compatibility with NASA's strategic goals. During Phase B, the team refines the project's preliminary design and demonstrates the rigor of its budget and schedule. Phase C is the stage at which designs are finalized (including subsystems), hardware fabrication begins, and code is written. The spacecraft is assembled and integrated during Phase D, and systems are tested discretely and in unison. The spacecraft is launched to space. Afterward, a mission moves into Phase E, which includes spacecraft operations, science operations, and the return of data. Its team, during this phase, solves problems encountered in-flight. Lastly, during Phase F, a mission concludes, with a spacecraft performing its ending maneuvers and teams archiving returned data; scientific analyses can continue for years or decades.

Every phase is replete with its own human-scale dramas, and long after a mission has ended, its data can yield continued stories of setback and triumph. In presenting a chronology of events of the Discovery Program from 2011 through 2025, this book should clarify how missions at different phases, and broader national issues, all affected each other. A congressmember who was enthusiastic about Europa Clipper, a NASA flagship that was at the time in Phase A, negotiated record appropriations for the Planetary Science Division. Those funds, serendipitously, saved InSight, which was then-languishing in Phase D and tens of millions of dollars over budget. The expensive overruns might otherwise have jeopardized the selection of one or both missions in competitive Phase A development for Discovery at the time. A year later, problems exacerbated by the COVID pandemic threatened Psyche, one of those Discovery missions, which was in Phase D. Psyche's overruns, as well as those of the flagship Mars Sample Return, in turn imperiled VERITAS, a spacecraft to study Venus that was in Phase B. This communion between missions past, present, and future is in constant exchange.

In presenting a year-by-year, holistic account of the Discovery Program from 2011 through 2025, this work should illustrate the difficulty of bringing what sometimes amount to "budget-friendly flagships" to the launch pad, and underscore how failures to maintain selection cadence today starves the planetary science community of observations tomorrow. Weakened or arrested data flow constricts the field's intellectual pipeline. Graduate students turn to better-provisioned worlds and, over time, entire lines of inquiry are foreclosed before they can be replenished. Leadership at NASA Headquarters knows this but must balance fiscal and programmatic realities: selling visions to appropriators, keeping the NASA center workforce employed, and helping the contractor base maintain critical skills and capabilities. Through accounts from key figures across the program, this work should help

readers understand the balances struck, the reasons behind certain decisions, and how those choices reverberated. The Discovery Program emerges not as a sequence of separate missions, but as a latticework within—and microcosm of—a larger system of exploration. In that sense, its history is one of NASA negotiating with itself: defining, redefining, and placing value upon planetary exploration as a robotic scientific endeavor, and ultimately, a very human one.

Table 1. Discovery Program Missions.

Mission	Lead	Target	Launch
NEAR	APL	Eros	Feb. 17, 1996
Pathfinder	JPL	Mars	Dec. 4, 1996
Lunar Prospector	Ames	The Moon	Jan. 6, 1998
Stardust	JPL	Comet Wild 2	Feb. 7, 1999
Genesis	JPL	Solar Wind	Aug. 8, 2001
CONTOUR	APL	Comets	July 3, 2002
MESSENGER	APL	Mercury	Aug. 3, 2004
Deep Impact	JPL	Comet Tempel 1	Jan. 12, 2005
Dawn	JPL	Vesta, Ceres	Sept. 27, 2007
Kepler	JPL/Ames	Exoplanets	Mar. 7, 2009
GRAIL	JPL	The Moon	Sept. 10, 2011
InSight	JPL	Mars	May 5, 2018
Lucy	Goddard	Trojan Asteroids	Oct. 16, 2021
Psyche	JPL	Asteroid Psyche	Oct. 13, 2023
DAVINCI	Goddard	Venus	TBD
VERITAS	JPL	Venus	TBD

2011

JANUARY 10
Kepler Space Telescope team annouonces the discovery of Kepler-10b, the first rocky exoplanet orbiting a sun-like star.

FEBRUARY 15
Stardust-NExT flies by comet Tempel 1, revisiting the site of the 2005 Deep Impact mission.

MARCH 11
MESSENGER enters orbit around Mercury nearly seven years after launch.

MARCH 24
Stardust-NExT carries out a final engine burn and sends its last transmission, ending the mission.

MAY 6
Prospective missions narrowed from 28 to 3.

JULY
The ASRG fails its final design review, which extends its final design phase by one full year.

SEPTEMBER 10
Launch of GRAIL mission.

NOVEMBER
NASA Headquarters approves MESSENGER's proposed one-year extended mission.

DECEMBER 31
GRAIL-A spacecraft enters orbit around the Moon.

CHAPTER 1

2011

W. Bruce Banerdt just wanted to see the inside of Mars.[1] The ground, the sky—those were great, but his heart belonged to the core of things, and that meant waiting.

He got his first taste of Mars exploration in 1976, when the two Viking landers touched down on Chryse Planitia in the northern equatorial region of the Red Planet, and Utopia Planitia, in the northern lowlands. At the time, he was interning at Jet Propulsion Laboratory (JPL), the agency's research and development center in Pasadena, California. The Viking program was more famous for its habitability science, but for a geophysicist like Banerdt, the landers' seismometers were the real stars of the show—until they weren't. The Viking 1 seismometer failed to deploy.[2] Data from an instrument on Viking 2, in the final analysis, was largely unusable, despite collecting 2,100 hours of data. Scientists could not distinguish between vibrations caused by the lander and those caused by the Martian interior.[3] Wind proved especially vexing. Someone would

need to send another seismometer to Mars in order for Banerdt to get the data he so prized. There was historical precedent. The first Apollo seismometer was likewise a failure overall, but the lessons learned allowed for successful subsequent deployments. So would it be, Banerdt hoped, for Mars.

What he did not expect was that he would be the one to do it.

Across decades, to figure out what the interior of Mars looked like, Banerdt used gravity and topography data from the Mars Global Surveyor. There were severe limits to what he could achieve, however. When a team at JPL initiated, at last, a space seismometer project and sought a science figurehead to help hone its objectives, he figured, why not? He could be as good a figurehead as anyone and volunteered.

"That's how you get sucked into things like this, you know," Banerdt later said, and laughed.[4] Before he knew it, he had spent a couple of decades getting deeper and deeper into the design of a seismic mission that could itself see deeper and deeper into Mars. It was not only about design, however. At the sub-billion-dollar mission level, NASA generally put prospective missions such as the one Banerdt was helping develop into competition against one another. Before organizations would spend the money to develop a proposal, however, among other things, managers expected broad consensus in the scientific community that such a mission was even necessary. This necessitated not only working internally on the project, but "selling" the science and feasibility of it at conferences and in publications. By his own estimation, Banerdt's own scientific output started suffering because of the time he was investing in getting his Mars seismometer project going. Because every 26 months, Earth and Mars aligned properly for relatively short-duration interplanetary travel, "it always seemed like a seismic mission was right around the corner," said Banerdt, and he "always wanted to be in on the ground floor."[5]

Banerdt felt good about the technology JPL engineers were developing. Bill Kaiser, a former researcher at Ford Motor Company, and later a founding member of the Microdevices Laboratory at JPL, had developed an atomic force microscope, an instrument capable of measuring distances at the atomic level. What was a seismometer, Kaiser surmised, if not something that measures the displacement of the ground? Engineers set about adopting the technology. After Kaiser left the lab, other engineers, including Tom Pike, would help develop the instrument into a short-period seismometer.[6]

In the early 2000s, JPL proposed the Mars seismometer to the Scout program, the low-cost, high cadence Mars small mission line. They later repurposed it for the sub-billion-dollar New Frontiers class of missions, envisioning a four-lander network, called Cerberus.[7] That proposal never reached NASA Headquarters, however. JPL management had decided to condense the lab's portfolio and deemed Cerberus the weakest of the lot of prospective missions at the time. In 2010, after further

development—this time as a single lander using heritage hardware from Phoenix, an in-situ soil and ice sample analysis mission that landed on Mars in 2008—the lab submitted to the Discovery Program small mission competition a lander proposal called the GEophysical Monitoring Station (GEMS), but what would later be called InSight.[8]

A BRIEF HISTORY OF DISCOVERY

NASA's Discovery Program concerns itself with the agency's class of small, relatively inexpensive robotic deep space missions. It emerged in 1989, following decades of growth in the cost and complexity of planetary missions—particularly those from Jet Propulsion Laboratory—and a consequent paucity of launches.[9] Over the next four years, prominent members of the space science community would help NASA converge on a way to increase mission cadence at a lower cost. Notable among them was Stamatios "Tom" Krimigis, the eventual head of the space department at the Johns Hopkins University Applied Physics Laboratory, and Wesley "Wes" Huntress, the eventual Associate Administrator for Space Science. Krimigis wanted to emulate Explorer, a long-running, competitively selected science program with a line item in the NASA budget—meaning new missions would not require specific Congressional authorization. Huntress, meanwhile, nurtured the program at NASA Headquarters and used it as a way to break the grip held on robotic exploration by JPL. Both men viewed JPL's development practices as oftentimes complacent and profligate.[10]

After years of workshops, memoranda, and meetings that slowly shaped Discovery, in June 1992, Huntress formally introduced the program to the planetary science community, and announced a workshop dedicated to the new mission line to be held at San Juan Capistrano Research Institute in California.[11] Each mission in that class, he outlined, would be led by a single principal investigator and have focused scientific objectives; a small payload of only two or three instruments for making measurements; a cost cap of $150 million; a development time of three years or less; and be limited to small Delta class rockets or smaller. The goal of a Discovery mission would be to answer specific science questions. NASA Headquarters would solicit missions through "Announcements of Opportunity" (AOs), which are formal requests for organizations to submit proposals that aligned with scientific goals and technical and financial limitations.[12] The agency would select missions for flight through competition, as opposed to directing a NASA center to build a spacecraft to explore a target. Proposals would be evaluated, among other criteria, by their ability to answer the science questions, and the merit of the potential science return relative to the competing missions.[13]

In a sign of the pent-up excitement in the planetary science community to fly such missions, NASA received about 70 detailed, 15-page mission concepts in advance of the meeting.[14] On November 15, more than 200 scientists, engineers, and project managers converged on San Juan Capistrano.[15] Even NASA Administrator Daniel S. Goldin made a surprise appearance. He later described it at a regular meeting of the Space Studies Board, saying:

> You know, I just went to this Discovery meeting. It was the most wonderful experience I had. I think it's the world's best kept secret…. This is what the civil space program ought to be: a diversity of opinion; people that are bold, not afraid to take risks; a launch a month instead of a launch a decade; graduate students and professors building things; organizations that have the best idea and power to do things instead of the bureaucracy coming in and suffocating new ideas…. This is the most wonderful thing that ever happened to the space program.[16]

Less than a year later, Congress funded Discovery in the Fiscal Year 1994 federal budget, which President Bill Clinton signed into law on October 28, 1993.[17] After an intensive lobbying campaign spearheaded by Krimigis, Sen. Barbara Mikulski of Maryland inserted an additional $62 million in the budget so that NASA could develop two missions simultaneously: the Near Earth Asteroid Rendezvous, a mission to the asteroid Eros built by Maryland-based APL; and Mars Pathfinder, a lander and small rover to be built by JPL.[18] NEAR launched on February 17, 1996. Pathfinder launched that December.

The program would become the face of a Goldin-era NASA reform initiative called "Faster, Better, Cheaper."[19] It launched a string of successful subsequent spacecraft, including the first sample collection missions since Apollo, Stardust and Genesis; as well as an impactor mission, Deep Impact; and the first mission to Mercury in almost 30 years, MESSENGER (short for Mercury Surface, Space Environment, Geochemistry, and Ranging).[20]

The person NASA deems responsible for a Discovery mission is called the principal investigator (PI).[21] The PI is the mission's chief scientist and decisionmaker and frequently hails from academia. Because few universities are capable of managing multi-hundred-million dollar efforts at the magnitude of a NASA mission, PIs partner with a project manager, who is often an engineer, and who generally works for a NASA center or an academic nonprofit such as the Southwest Research Institute or the Johns Hopkins University Applied Physics Laboratory (APL). The project manager handles the day-to-day activities of a flight mission and is charged with bringing structure and rigor to the engineering process. He or she is the person who knows which engineer is working on what, and how they interface.[22]

Every team comes together a little differently. Sometimes, the management comes first, such as when private industry or a NASA center dreams up an idea for a mission, or engineers have developed some new piece of technology, and they need a scientist to help determine what science questions said concept or technology can answer.[23] They thus recruit a PI to lead the mission.[24] Sometimes, a scientist puts together a small team and seeks mission management support to develop systems that can answer those pressing questions.

"THE DRIVING FACTOR AT MARS"

Pathfinder was the first Mars mission that NASA flew under the Discovery Program banner, and the only Mars mission directed by NASA Headquarters (as opposed to being competitively selected). In part to protect Discovery from being overwhelmed by Mars, and to simultaneously keep spacecraft flying to Mars each time a Mars launch window opened, in 1994, the agency formulated the Mars Surveyor program, "an aggressive but cost constrained program" consisting of "small orbiters and landers built by industry and launched to Mars at 26-month intervals."[25] This too was part of the Faster, Better, Cheaper initiative. In 1999, however, Mars Surveyor program endured back-to-back failures: the loss of both Mars Climate Orbiter and Mars Polar Lander. In response, NASA Administrator Daniel Goldin stood up the Mars Program Independent Assessment Team, chaired by former Lockheed Martin executive vice president A. Thomas Young.[26] Among the panel's recommendations was a more formalized and visible Mars program to mitigate the inherent risk of smaller missions with high launch cadences.[27] This culminated with NASA Headquarters establishing a principal-investigator-led, low-cost, Mars-specific flight program called Mars Scout, analogous to the Discovery Program.[28]

For the next decade, Mars did not compete against the rest of the solar system. In that time, NASA Headquarters selected two Scout missions: the Phoenix lander, which launched in 2007 to study the Martian polar region; and the Mars Atmosphere and Volatile Evolution orbiter (MAVEN), selected the following year.

In 2008, however, NASA signaled the cancellation of the Scout program because of budget issues.[29] In 2010, the agency made it official, explaining that "surface science is becoming more and more the driving factor at Mars," and that the cost of surface science exceeds the $485 million cost cap of Mars Scout missions.[30] Curiously, to remedy this, NASA folded small Mars missions back into the Discovery Program, whose cost cap that year was $425 million.[31]

The inclusion of Mars would prove to be the first of three major complications for the 2010 Discovery competition. The second came only after NASA Headquarters narrowed the candidates to three. The third, though, was one of ambition, and

presented both opportunity and eventually, disorder: the planetary science community wanted Discovery to go nuclear.

AN OPPORTUNITY FOR A NUCLEAR MISSION

In general, it takes about two years to write an Announcement of Opportunity (AO) for the Discovery Program.[32] Before the Science Mission Directorate simplified and standardized the AO process in the mid-2000s, program managers at NASA Headquarters worked with acquisitions managers at the Science Office for Mission Assessments (SOMA), a program office at NASA Langley Research Center, to more or less write them from scratch, using the previously released AO as a guide to maintain continuity within a given program. SOMA supports the directorate in the acquisition of Earth and space science missions and instruments and leads the evaluations of proposals received in response to AOs.[33]

To write the 2010 AO, Michael New, the Discovery program scientist, consulted with experts across the agency ranging from the Environmental Management Division to the Launch Services Program. He used the information gathered to establish the big policies that the Discovery selection round would follow. The next Discovery mission would have a cost cap of $425 million in Fiscal Year 2010 dollars, not including the launch vehicle.[34]

When James L. Green, the director of the Planetary Science Division at NASA Headquarters, acquiesced to requests by the planetary science community to allow prospective missions to use Advanced Stirling Radioisotope Generators (ASRG), a power system still in development, New incorporated them into the AO.[35] The agency would provide the ASRGs as Government Furnished Equipment, and would cover any costs incurred for safety analyses associated with the power system's design. The requirement for flying an ASRG was that the radioactive power source would enable the mission.

The Discovery Program had never before launched a nuclear mission. Perhaps more importantly, NASA had never flown an ASRG. The generator was named for Robert Stirling, a 19th-century clergyman who in 1816 designed a revolutionary closed-cycle external combustion engine.[36] At its core, the ASRG used the same engine, converting heat generated by Plutonium-238 to mechanical motion, which was in turn converted into electrical power. It emerged from a 2002 call by NASA Headquarters for a reliable, scalable, multi-mission capacity, next-generation power conversion technology with higher efficiencies and specific power.[37] (The agency had, until then, primarily used radioisotope thermoelectric generators that lacked moving parts, but were inefficient.) Engineers at NASA Glenn Research Center

settled ultimately on a Stirling engine design that used a quarter of the plutonium as an equivalent radioisotope power generator.[38]

NASA needed a better way to power planetary science spacecraft, because Plutonium-238 had become an endangered resource. Typically, the agency used its dwindling supplies for its large strategic science missions—the "flagships"—such as Cassini to Saturn, and the twin Voyager spacecraft to the gas giants and ice giants. When the agency formally funded its medium-class, sub-billion-dollar New Frontiers mission line in 2003, the first selected mission, New Horizons, used a radioisotope thermoelectric generator to power it to Pluto and beyond, as well.

Plutonium was now a rare resource because two decades earlier, in 1988, the United States government closed the Department of Energy's Savannah River Plant, ending the domestic production of plutonium-238.[39] In 1996, the country ceased separating the isotope from preexisting mixed-isotope stockpiles. NASA continued the development of plutonium-powered spacecraft using existing stockpiles, and through periodic purchases from Russia.[40] This was, at the time, an "unthinkable" achievement, according to Ed Weiler, the associate administrator for space sciences, at NASA Headquarters. "The way I helped sell this to Congress was 'Hey, what a thought, taking plutonium away from Russia and using it here in America,'" he said.[41]

In 2009, however, Russia violated an agreement with the United States to provide 10 kilograms of plutonium-238 by 2011.[42] The ASRG, due to its efficiency, was one way the agency could stretch dwindling plutonium supplies much further. But because Congress had rejected proposals to restart domestic production of the isotope, NASA Headquarters began considering a future without plutonium.[43] The ASRG would theoretically give NASA up to four times the number missions otherwise possible to be flown with radioactive power sources.[44] A Discovery mission would be an ideal proving ground for a first flight of the ASRG, as they permitted a higher level of technical risk, enabling ASRGs for future, larger missions. By July 2011, Congress gave NASA approval to work with the Department of Energy to at least study the resumption of domestically producing plutonium-238.[45]

Still, at the time of the Discovery AO, no ASRGs sat in a NASA warehouse waiting for installation in the winning mission. The AO called for proposed spacecraft and trajectories to be versatile with respect to launch vehicle, and capable of flying on Atlas V, Delta IV, and Falcon 9 rockets. Moreover, it would need to be ready for flight by December 31, 2017.

After drafting the AO, New presented it to the Science Management Council, a weekly meeting composed of the division directors and deputy associate administrator of the Science Mission Directorate (SMD) at NASA Headquarters, agency procurement representatives, and lawyers. Thus began a process of getting various

officials within the division to sign off on it, the final signatory being the deputy associate administrator of the directorate.

FINDING MONEY FOR A MISSION

From the desk of Jim Green, the 2010 Discovery selection was important, but did not exist in isolation.[46] Green had assumed the division director role in 2006, after previously working as chief of the Science Proposal Support Office at NASA Goddard Space Flight Center. His job involved managing not only the planetary science missions under development, but also missions that were underway. Before authorizing an AO, he had to ensure he had the budget to add something else to his portfolio. Because the highest levels of NASA leadership, Congress, and the Office of Management and Budget were constantly examining, cutting, or threatening his division's budget, mission lines, it seemed, sustained blows with alarming regularity.

Of the SMD's four divisions, in Green's view, the Obama administration ranked its priorities as Earth science, astrophysics, heliophysics, and finally planetary science, which meant that the Planetary Science Division would need to be on a precautionary footing.[47] The president's fiscal year 2012 budget request saw the division's budget slashed by 23 percent by 2016.[48]

The Discovery budget was one of Green's most flexible budgets, because he was not limited simply to selecting and flying complete missions. Though in a perfect world, in his estimation, the Discovery Program would select two missions during each competition, the broader Planetary Science Division budget had proven challenging in recent years. The first full Discovery mission he selected was GRAIL, announced on December 10, 2007.[49] Otherwise, limited funds had confined him to resurrecting Discovery missions already flying, including Stardust, which was extended as Stardust-NExT (New Exploration of Tempel), and directed to visit comet Tempel 1, which had been visited previously by Deep Impact in 2005. (For the story of Deep Impact and Stardust, see: *NASA's Discovery Program: The First Twenty Years of Competitive Planetary Exploration*.) Its goal would be to see how the comet had changed following its close flyby of the Sun.[50] The other repurposed spacecraft was Deep Impact's flyby bus, extended as the Extrasolar Planet Observation and Deep Impact Extended Investigation (EPOXI) mission, which would explore comet Hartley 2, and also perform occultation studies of distant stars in search of exoplanets.[51] He could also afford individual instruments to fly on spacecraft operated by foreign space agencies. NASA Headquarters ran those in a competitive process called Stand Alone Missions of Opportunity (SALMON), first released in 2008. (NASA previously solicited such instrument contributions within the AO processes of Discovery and other such programs.)[52] In 2009, he worked with other

NASA Headquarters officials to select Strofio, a mass spectrometer that would fly on BepiColombo, a joint Japan Space Agency-European Space Agency mission to Mercury.[53] In addition, he could fund data analysis.

Once approved by Green, the Science Meeting Council, lawyers, accountants, and others, Michael New submitted the AO to the NASA Solicitation and Proposal Integrated Review and Evaluation System (NSPIRES), the agency's proposal submission and management system. Lastly, New sent out an email to approximately 56,000 people on the Discovery Program e-mail list announcing that the AO has been posted.[54] About 30 days later, proposers submitted "notices of intent" to give NASA Headquarters a heads-up on what to expect, with regard to science goals, team members, and possible instrument payloads. (These were not firm commitments, and details could, and often did, change.) New used the information in the notices of intent to determine the expertise that would be necessary for a science evaluation panel.

EVALUATING THE CANDIDATES

"So there are two kinds of expertise," New explained.[55] "There's the people who are really knowledgeable about the particulars of the science being proposed for each proposal. And then there are people who also know about the science, but who have a real insight into particular instrument types." New's goal was then to begin recruiting an unconflicted set of evaluators. He often drew these names from the academic literature—coincidentally published papers on prospective targets of exploration. He also drew names from people who had given talks at major conferences.

Ninety days later, the proposals arrived. Two independent and mostly noncommunicating teams evaluated them with three primary criteria.[56] The first was scientific and technical merit, examining the impact of the proposed science of the prospective mission. Evaluators asked how it coexisted in the broader NASA portfolio of missions and international space agencies. They considered whether the data the mission would collect could effectively answer the science objectives described in the proposal. The second criterion was science implementation merit, which considered whether the proposed mission, its hardware, and architecture could actually do what proposers claimed. The third criterion was the technical, management, and cost (TMC) risk. Evaluators examined the robustness of the proposal's engineering plans.

The science evaluation team oversaw the first two criteria. As Discovery program scientist, New led that team directly (in addition to being in charge of the overall review), and recruited evaluators from across the field of planetary science. After evaluators read and assessed the merits and weaknesses of each proposal, at

a later, in-person meeting, the gathered evaluators reviewed all proposals again to apply a consistent set of evaluation standards. Meanwhile, an office at NASA Langley Research Center called the Science Office for Mission Assessments, focused on the third criteria.

At the end of the months-long process, New put together a categorization committee of civil servants at NASA Headquarters, whose job was to go through each proposal and sort them into one of four types. A "category 1" mission was a proposal with excellent science merit and had the highest priority for selection. Category 2 proposals had good science but were secondary in importance for selection. Category 3 missions were considered meritorious, but in need of technical development. In practice, this meant typically that there was some piece of technology that was critical to the mission, but "not ready for primetime." The Discovery Program office could give Category 3 missions money to mature the technology. Category 4 missions had significant problems, and evaluators expressly did not recommend them for selection.

The evaluation process was thus complete. Afterward, a separate group of civil servants at NASA Headquarters, called a steering committee, had three charges. First, they looked over the entire process from the beginning to the end, asking whether all laws, regulations, policies, rules, and best practices were followed in the evaluation. They then looked at all documentation that evaluators generated during the process, ensuring that it was clear. Third, the committee reviewed each of the categorizations to determine whether evaluators properly sorted the proposals. During this process, the committee could confirm a categorization, dispute it, or confirm but request clarification.

Afterward, the whole package moved to the final selection phase. It was essentially a big meeting for selection officials, including, typically, the associate administrator and an assistance board composed of whomever he or she desired, though this generally meant the division directors. At this point, the program scientist—New, in this case—who was in charge of the whole thing stood in front of the room and gave a presentation describing exactly what the process entailed, and how it turned out. The director of the Planetary Science Division would then stand and recommend one of the missions for selection. After a wide-ranging discussion, the SMD head would make a final selection.

"I'M ONLY SORRY WE'RE NOT GOING TO DO ALL THREE."

On May 6, 2011, NASA narrowed the prospective Discovery missions from 28 to 3.[57] They were:

1. Comet Hopper, led by principal investigator Jessica Sunshine of the University of Maryland.[58] The mission would study a comet's compositional and morphologic diversity, building on insights from two previous Discovery missions—Deep Impact, led by Michael A'Hearn; and Stardust, led by Donald Brownlee at the University of Washington, which flew by comet 81P/Wild (Wild 2)—and one mission from NASA's New Millennium Program, which tested new technologies: Deep Space 1 (also led by Brownlee), which flew by comet 19P/Borrelly. Those three missions greatly advanced comet science and made manifest the need to understand a comet nucleus's origins and inherent diversity. Comet Hopper would study the inner coma and surface of comet P/McNaught 2 (P/2004 R1), and repeatedly land and take off from the comet's surface, an action possible because of the low gravity of comets. Comet Hopper would use two ASRGs, as the wide heliocentric distances involved made solar panels impractical.
2. GEophysical Monitoring Station (GEMS)—soon renamed InSight—led by Bruce Banerdt of JPL, with deputy principal investigator Sue Smrekar, also of JPL. GEMS was a seismometer and would help planetary scientists better understand the formation and evolution of terrestrial planets by studying the interior structure and processes of Mars.[59] Moreover, it would determine ongoing tectonic activity and the impact rate of meteorites. The spacecraft was solar powered, with extremely high heritage, based on the successful Phoenix spacecraft, including its landing system.[60]
3. Titan Mare Explorer (TiME), led by Ellen Stofan of Maryland-based consultancy Proxemy Research, with deputy principal investigator Jonathan Lunine of Cornell University. TiME was perhaps the most audacious Discovery Program mission concept ever to reach "step two" of mission selection.[61] It would also be the first Discovery outer planets mission, and the first interplanetary boat ever launched by any country. It would splash down into Ligeia Mare, an ethane sea on the northern polar region of Titan, the largest moon of the Saturnian system. There, it would spend several Titan days (just under 16 Earth days) performing in-situ science measurements and transmitting that data directly back to Earth. The mission was possible only because of the development of the ASRG.[62]

The 2010 Discovery competition marked the time that Mars would compete for flight against the rest of the solar system. Each of the three missions would be built by Lockheed Martin Space Systems in Denver, Colorado—which was another anomaly in the Discovery competition that year beyond the inclusion of Mars and the availability of a radioactive power source.

"These are cool missions: looking inside Mars, touching a comet, landing in Titan's sea," Paul Hertz, chief scientist of the Science Mission Directorate, said at the time. "I'm only sorry we're not going to do all three."[63]

A ROCKY PLANET AROUND A SUN-LIKE STAR

From Jim Green's desk, 2011 was part of a series of tight, uncertain budget years. From the outside, however, it would seem that NASA had rarely been busier—and Discovery was at the center of this.[64] On January 10 that year, the Kepler space telescope team confirmed the discovery of Kepler-10b, the first "definitively" rocky exoplanet orbiting a sun-like star.[65] "All of Kepler's best capabilities have converged to yield the first solid evidence of a rocky planet orbiting a star other than our sun," said Natalie Batalha, Kepler's deputy science team lead at NASA Ames Research Center.[66] "The Kepler team made a commitment in 2010 about finding the telltale signatures of small planets in the data, and it's beginning to pay off." Indeed, it was the smallest planet ever discovered outside our solar system. As described in *The Astrophysical Journal*, Kepler-10b would not be a pleasant place to live.[67] Though its day is 20 hours long, and the planet itself is only about 20 percent larger than Earth, its orbit is also 20 times closer to its star than Mercury is to the sun. There would be no water on such a planet, and indeed, the surface of its star-facing side would be molten, while its far side would be freezing. The discovery was a milestone for the mission and for the search for exoplanets similar to Earth and would not be the last.

EXTENDED MISSIONS

One month after the Kepler result, on February 14, 2011, Discovery's Stardust spacecraft encountered comet Tempel 1 as part of the Stardust-NExT mission. It was the first time scientists had revisited a comet to study how its surface had evolved over time in its orbit. Previous measurements of Tempel 1, by Deep Impact, had provided the first-ever look at the freshly-exhumed interior of a cometary body.[68] That spacecraft's refrigerator-sized impactor probe revealed a nucleus that was fluffy: "at least 50 percent empty space and the surface layer at the impact site at least 75 percent empty space," said Michael A'Hearn, Deep Impact's PI.[69] Moreover, the abundances of carbon monoxide ice, carbon dioxide ice, and water in the ejected interior material were broadly similar in composition to near-surface material—a finding contrary to prevailing theoretical models of cometary layering.[70]

Stardust had been spaceborne for over a decade by the time it arrived at Tempel 1 for a second look. The spacecraft was managed by Jet Propulsion Laboratory and designed, built, and operated by Lockheed Martin Astronautics. Its principal

investigator was Donald Brownlee, a professor of astronomy at the University of Washington at Seattle. Launched in 1999, Stardust visited the comet Wild 2 in 2004, where it captured dust samples of the comet's coma.[71] Afterward, mission engineers directed the spacecraft back to Earth, and in 2006, it safely released a sample capsule, which drifted by parachute to the Utah Test and Training Range eighty miles west of Salt Lake City.[72] Engineers put the spacecraft, with its camera and dust measurement instruments, into hibernation. It was a foregone conclusion that NASA Headquarters would extend the Stardust mission. The spacecraft still had plenty of fuel, and it was performing soundly. It was essentially a free spacecraft during a time of tight budgets.[73]

The way they would extend the mission, however, was new for NASA.

The agency had procedures in place for extending directed, multi-billion dollar flagships like Cassini (which was at the time orbiting Saturn). Generally, the same teams and institutions responsible for the prime missions would remain in charge, with revised science goals. For Discovery, however, different institutions and PIs could submit proposals to use the in-flight Deep Impact and Stardust spacecraft as though they were new missions entirely. The proposals would be placed into competition, including scrutiny in Step 1 and Step 2 review processes. It was first time that extended missions were competed.

EPOXI, the extended mission for Deep Impact, first demonstrated that the concept would be successful. In 2010, the spacecraft visited the hyperactive comet 103P/Hartley 2, collecting images and spectra.[74] Its measurements suggested that carbon dioxide outgassing excavated and lofted "chunks of nearly pure water-ice" from the comet. As the chunks sublimated, they dominated the comet's total gaseous H_2O output.[75]

"We suspected that comet Hartley might be different" than other comets, said Peter Schultz of Brown University, a co-investigator on the mission, "but we had no idea that it would be covered with chunks and acting like a champagne bottle."[76] Every second, observations revealed, the comet blasted hundreds of pounds of ice like dandelion puffs.[77] "My immediate thought was just awe. This is why we go there: you have no idea until you explore."[78]

With Stardust-NeXT, NASA had hoped to follow success with success. The extended mission was led by principal investigator Joseph Veverka of Cornell University and approved by NASA Headquarters in 2007. Though it took over four years to reach its new target, the critical Valentine's Day sequence of the Tempel 1 encounter, during which time the spacecraft would make the bulk of its scientific measurements, would only last just over an hour. In addition to images, the Stardust-NExT instrument payload would measure the composition, size distribution, and density of dust emitted into the coma. Its official, primary science objectives were:

- To extend our understanding of the processes that affect the surfaces of comet nuclei by documenting the changes that have occurred on comet Tempel 1 between two successive perihelion passages, or orbits around the sun.
- To extend the geologic mapping of the nucleus of Tempel 1 to elucidate the extent and nature of layering and help refine models of the formation and structure of comet nuclei.
- To extend the study of smooth flow deposits, active areas, and known exposure of water ice.

Moreover, scientists hoped to:

- Characterize, if possible, the crater produced by Deep Impact in July 2005, to better understand the structure and mechanical properties of cometary nuclei and elucidate crater formation processes on them.
- Measure the density and mass distribution of dust particles within the coma using the Dust Flux Monitor Instrument.
- Analyze the composition of dust particles within the coma using the Comet and Interstellar Dust Analyzer instrument.[79]

After the spacecraft completed the flyby, which took it within 178 kilometers of the comet's nucleus, Veverka explained what happened. "Was the mission 100 percent successful? No," he said at a press conference. "It was 1,000 percent successful."[80] The spacecraft achieved each of its science objectives.

Stardust-NExT identified the crater created by Deep Impact six years earlier, and it appeared that debris material created by the impactor had drifted back down, and "the crater partly buried, or healed, itself," said Pete Shultz of Brown University. The subdued depression suggested "surface properties similar to those of dry, loose snow."[81]

After the encounter, the spacecraft, which had by then flown 3.5 billion miles, continued observing Tempel 1 for another two weeks.[82] In total, the mission extended the overall coverage of the surface of the comet's nucleus surface to almost two-thirds. Among the findings the science team later published in the journal *Icarus* was evidence of layering, some because of smooth flows, and others potentially going back to the accretion of the nucleus.[83] For areas covered by both Deep Impact and Stardust-NExT, there were no large-scale morphologic or photometric changes. Of the changes identified, the most significant occurred along the edges of "a prominent smooth, flow-like feature, the margins of which receded in places by up to 50 meters." Half of the area captured by Stardust-NExT, but that Deep Impact

did not see, was smooth. Moreover, coma and jet activity during the Stardust-NExT observations were less than the 2005 observations by Deep Impact.

In all, as Veverka and his co-authors asserted, the measurements by Stardust-NExT made "Tempel 1 arguably the most geologically interesting and puzzling among the so-called 'primitive bodies' (comets and asteroids) explored by spacecraft so far."[84]

The Stardust flybys of Wild 2 and Tempel 1, as well as the Deep Space 1 flyby of Borrelly 20 years earlier and the Deep Impact/EPOXI flyby of Hartley 2, revealed most importantly "significant morphological diversity." In other words, "we are far from knowing what a 'typical' Jupiter family comet looks like."[85] Despite the morphology differences, the comets' surfaces were generally black with very low albedos and with restricted exposures of water ice. The comet nuclei revealed surface characteristics "indicating that processes by which comet nuclei evolve are varied and complex."

Twelve years after launch, on March 24, 2011, NASA ended the Stardust mission.[86] Engineers at Lockheed Martin instructed the spacecraft to burn its engines and expend its remaining fuel. This was an experiment designed to help determine the precise fuel consumption of previous its rocket motor firings. Because of the microgravity environment, spacecraft do not have fuel gauges as found in

Table 2. Stardust-NEXT Achievements.

Discovery/Achievement	Details
First Spacecraft to Visit Two Comets	Visited Comet Wild 2 in 2004 and Comet Tempel 1 in 2011.
Surface Changes on Comet Tempel 1	Observed and documented changes in the comet's surface between 2005 (Deep Impact) and 2011, including erosion and smoothing of the impact crater edges.
Imaging of Deep Impact Crater	Captured high-resolution images of the crater created by Deep Impact, showing it was shallow and partially filled, indicating the comet's nucleus is made of loose material.
Mapping of Comet Tempel 1's Surface	Extended mapping to almost two-thirds of the nucleus surface, providing detailed views of its geological features.
Physical Properties Measurement	Determined the comet's average radius (2.83 ± 0.1 km), uniform geometric albedo (about 6%), spin rate (213° per day), and dust production rate (130 kg/s).
Study of Smooth Deposits	Found that 30% of the nucleus is covered by smooth flow-like deposits, likely from material erupted from the subsurface, restricted to gravitational lows.

automobiles on Earth. The final Stardust burn would help determine fuel consumption rates of other spacecraft. The deactivated spacecraft's new permanent orbit would keep it more than a million miles from Earth, and 13 million miles from Mars, for at least the next century.[87]

NASA Headquarters has approved no comet missions since Stardust-NExT.[88] Stardust was the first sample collection mission attempted by NASA since the Apollo program and achieved both this goal and those of its extended mission. "This kind of feels like the end of one of those old Western movies where you watch the hero ride his horse towards the distant setting sun, and then the credits begin to roll," said Tim Larson, the JPL project manager of the Stardust-NExT mission.[89] "Only there's no setting sun in space."

"WE ARE IN ORBIT AROUND MERCURY"

As Lockheed Martin engineers were preparing Stardust for its final burn, on the evening of March 17, 2011—St. Patrick's Day—engineers at the Johns Hopkins University Applied Physics Laboratory (APL) in Laurel, Maryland, prepared for the final critical burn of the MESSENGER spacecraft's seven year cruise phase to Mercury.[90] NASA had selected MESSENGER in the Discovery Program on July 7, 1999, with Associate Administrator Ed Weiler promising a "flagship-quality" mission, for $286 million.[91] (For comparison, the Cassini flagship, at its launch in 1997, had an all-in cost of $2.64 billion for the American portion of the mission.)[92]

About 400 people in the Kossiakoff Center auditorium at APL watched the Mercury orbital insertion (MOI) events unfold with a festive, pensive anticipation.[93] On a large projection screen overhead, those present—which included much of the mission's science team, as well as the press corps and NASA and APL officials and guests—watched recorded interviews with key members of the MESSENGER team, intercut with a livestream of about two dozen engineers monitoring the spacecraft's progress and health from the lab's nearby mission operations center. Among those present was Tom Krimigis, one of the people most responsible not only for the first Mercury orbiter mission, but for the very existence of the Discovery Program itself.[94] Onstage, Ralph McNutt, the MESSENGER project scientist, entertained and informed. "MESSENGER is a flying gas can," he said at one point. "Over half the mass is propellant."[95]

Meanwhile, Eric Finnegan, the mission systems engineer, updated the team by e-mail as data reached Earth from Mercury. He had done so throughout the day. "At 6:03 EDT engineers in the MOC have reviewed all telemetry from the spacecraft," he wrote in an earlier message," and have confirmed that MESSENGER is a GO for MOI."[96]

If all went well, the propulsion system would fire for 15 minutes.[97] Afterward, the spacecraft would turn to planet Earth and beam back its telemetry data. It took around nine minutes for data from the spacecraft to reach the Deep Space Network. Members of the MESSENGER science team read these updates from cell phones and laptops.

At 8:56 p.m., Finnegan sent a one-word message: "Burning!"[98]

All anyone could do was wait. The audience chattered anxiously, the stakes enormous not only for their science and careers, but for national prestige. As Weiler had told the team earlier that day: "You only go into orbit around Mercury first once in human history, and that's what is accomplished tonight."[99]

For orbital insertion, Sean Solomon, the mission's principal investigator, sat with other members of MESSENGER team, in a room adjacent to the main missions operations center.[100] There wasn't much for them to do but wait like everyone else. They monitored a signal from the spacecraft. The signal's frequency, represented as a line in special software, changed based on the velocity of the spacecraft relative to the Deep Space Network antennas on Earth. Engineers had worked out in advance what the signal's slope would be for the maneuver's myriad key events.

Solomon had slept well the night before, though watching the line, he was anxious. He knew there are two events for every orbiter spacecraft that involve more risk than any other parts of the mission. One was the launch itself—and MESSENGER had a very successful launch in 2004. But the other was the orbit insertion. MESSENGER's especially, was a fairly complicated maneuver, involving firing the main propulsion system for a quarter of an hour, as well as changing the direction of thrust during the burn: what propulsion experts called a "turn and burn" event. They had tested it successfully earlier in the mission and convinced themselves that they knew the proper commands and performance of the propulsion system for that event. Nevertheless, everything had to go right. There was a lot riding on that last propulsive event.

Because of the signal delay between Mercury and Earth, success or failure of the spacecraft would have long happened by the time anyone knew. As they approached the fateful moment, Maria Zuber, the PI of the GRAIL mission, who was in the room with Solomon, collected colleagues and they left. Solomon would probably want his privacy if things went wrong.

Eighteen minutes after the burning began, however, Solomon heard clapping and saw handshakes in the room next door. So too did everyone in the Kossiakoff Center auditorium, by way of the livestream of the mission operations facility. Those cheers spread throughout the auditorium as team members received their final update from Finnegan: "Burn complete we are in orbit around Mercury."[101]

MESSENGER would orbit Mercury every 12 hours at an altitude below 500 kilometers.[102] To counter such forces as the gravity of the Sun, once every Mercury year—every 88 Earth days—the spacecraft would have to fire its thrusters and adjust its orbit.

The mission had six science objectives:

1. Determine the chemical composition of Mercury's surface.
2. Determine Mercury's geological history.
3. Determine the nature of Mercury's magnetic field.
4. Determine the size and state of Mercury's core.
5. Determine the volatile inventory at Mercury's poles.
6. Determine the nature of Mercury's exosphere and magnetosphere.[103]

Before MESSENGER, Mercury was the least-studied planet of the solar system, aside from Pluto.[104] Mercury's proximity to the Sun makes it a natural laboratory for understanding conditions of the early solar system, and processes like core formation and space weathering. Only Mariner 10 had flown by the innermost planet previously and that was in the 1970s. APL had been developing a Mercury orbiter concept since March 1996, just after NASA Headquarters announced the 1996 Discovery Announcement of Opportunity.[105] John Applebee, the head of development for the Space Department at APL at the time, personally recruited Solomon, a planetary geologist and geophysicist at the Carnegie Institution of Washington, to the science team for the proposal, saying: "We are looking to put together a team of scientists for a Discovery proposal, a Mercury orbiter. Would you be interested?"[106] Solomon soon learned that he wouldn't merely be one scientist of many on the proposal. Rather, when he visited the lab, they asked him to lead it as PI. He agreed on the condition that he could add to the science team APL had already built. Solomon had been a prolific Mercury scholar in the late 1970s, but by his own admission, he hadn't given the planet much thought in 20 years. Few people had, and he and his team had to develop the science questions of Mercury, and the measurements necessary to answer them.[107] NASA "down-selected" the mission—that is, chose it as a competition finalist—in the 1996 Discovery round, but did not select it for flight. Three years later, however, the MESSENGER team was successful.

The orbital phase of science operations did not begin immediately after the spacecraft entered Mercury's orbit. Rather, the MESSENGER team carefully and methodically brought spacecraft instruments online, turning on each element of the payload, and putting them through their paces. Moreover, they tested the solar arrays and the battery power systems, and thermal telemetry to validate that models

they'd devised to understand spacecraft and instrument payload heating as they flew over the day side of the planet.

Still, everyone got to work right away during all this. MESSENGER would race around Mercury in an eccentric orbit, meaning each time it lapped the planet, it would have a "closest approach." The team got a taste for how each of these encounters would work during MESSENGER's seven-year cruise phase following launch but before orbital insertion. Cruise phase, featuring six major planetary flybys—one of Earth, two of Venus, and three of Mercury (excluding insertion)—and each closest approach to a planetary body was a perfect training period to learn to understand the spacecraft, mission planning, science operations, and teamwork.[108] They treated every flyby but one as a scientific investigation. (The first Venus flyby occurred when Venus was at superior conjunction with Earth [i.e., the planets were on the opposite sides of the Sun in their orbit, inhibiting communication]).[109]

Each of the flybys of Mercury involved a very lengthy, complex development of observational planning and data acquisition sequencing. Most of MESSENGER's instruments were mounted to the spacecraft in fixed orientations. In order to change their observation geometry, you had to turn the entire spacecraft. Engineers designed the imaging system with a limited ability to pivot, adding another degree of freedom. The team would use the wide angle camera versus a narrow angle camera, depending on elevation. Likewise, the laser altimeter was sensitive to elevation, as were the instruments used in geochemical remote sensing. The x-ray spectrometer worked better on the day side of Mercury, because of the excitation of the near surface atoms by solar x-rays. The laser altimeter worked better on the night side, because darkness made the signal-to-noise ratio of the return laser pulse easier to resolve. The energetic particle and plasma spectrometer depended, in the value of its measurements, on the orientation of the instrument relative to the local magnetic field vector. Meanwhile, the Mercury atmospheric and surface composition spectrometer team wanted to spend a lot of time looking off the planet, at its limb, the exosphere, and the exosphere tail. In addition to these constraints, there were limits to how the team pointed the spacecraft and its payload because of the urgency to protect MESSENGER against direct illumination by the Sun, and the proximity of the spacecraft to the hot day side of Mercury. Complicating things further, there were limits on how fast you could change the orientation of the spacecraft and how fast you could move the pivot platform of the imaging system.

Planning a single flyby would take several months of effort by the science and engineering teams—obviously impossible for a spacecraft whose closest approach in orbit occurred twice a day. To solve this, during the mission's cruise phase, APL developed an automated science data acquisition system that could satisfy the spacecraft's myriad pointing constraints, and the data acquisition constraints of the

individual instruments, not only in terms of coverage but also in terms of viewing geometry.

"Before we went into orbit, we had a plan for the entire first year of orbital operations that had been thoroughly vetted against all of the constraints imposed by the engineering limits on pointing and temperature and power, and the volume of the solid state recorder—the data volume that could be recorded and had to be transmitted before it got overwritten by later data," said Solomon.[110]

On June 16, 2011, the MESSENGER team held a press conference in Maryland announcing the first preliminary science results from Mercury's orbit. In a matter of weeks, the spacecraft had returned 20,000 high-resolution scientific images, and many measurements with other instruments. Already, the mission had scientists rewriting the story of the solar system.

"We are confirming a few theories," said Solomon, but added that "many are being cast into the dustbin of science."[111]

Images of the planet's north pole showed a smooth lava field, compositionally distinct from its surroundings, half the size of the United States. The planet's high abundance of thorium and potassium surprised scientists, as many Mercury scholars expected that the elements would have evaporated, given the proximity to the Sun. This cast doubt on existing hypotheses about how Mercury first formed—and where.

"Taken together, these elements are changing our view of the origin of Mercury," said Larry Nittler, a mission staff scientist from the Carnegie Institution of Washington. "Mercury is not the Earth and it's not the Moon."[112]

Moreover, the laser altimeter found evidence of permanently shadowed regions on Mercury: cryogenic craters in the planet that, because of their depth and orientation, sunlight can never reach regardless of Mercury's rotation or revolution around the Sun. Earth's Moon has similar such regions in eternal darkness. Such places could be hospitable to water ice. Mercury also seemed to have an asymmetric internal magnetic field, implying the south polar region is "more exposed than in the north to charged particles heated and accelerated by solar wind–magnetosphere interactions." Such charged particles impacting the surface would contribute not only to the planet's tenuous atmosphere, but also to the space weathering of its surface.[113] "In many cases, a lot of our original ideas about Mercury were just plain wrong," said Nittler.[114] And they were, quite literally, just getting started.

REACTION WHEELS ENTER THE STORY

One month after the MESSENGER team shared its first results, on July 16, 2011, NASA's Deep Space Network array received word from the spacecraft Dawn that the probe had entered orbit successfully around the asteroid Vesta. It had been a four

year journey and was the first time a spacecraft had ever achieved orbit around an object in the Asteroid Belt—one of a series of firsts the spacecraft would achieve. It was also the first robotic spacecraft designed to travel to multiple bodies in the solar system, entering orbit around each, and performing orbital investigations around each of them with the same instrumentation.[115] Upon completion of its reconnaissance of Vesta, the spacecraft would depart for Ceres.

The scientific objectives of Dawn included:

- determining the inner structure, density and homogeneity of the two protoplanets Vesta and Ceres;
- determining their shape, size, composition and mass;
- studying the morphology of the surface (crater distribution) of both asteroids;
- determining the thermal history and size of the cores of Vesta and Ceres;
- gaining a greater understanding of the role of water during the development of the asteroids;
- checking the current hypothesis which sees Vesta as the mother body of the howardite, eucrite and diogenite (HED) meteorites;
- investigating which meteorites come from Ceres; and
- investigating the geological environment of the HED meteorites.[116]

The Dawn science team chose their targets to fundamentally improve the scientific understanding of the first ten million years of the solar system's history and better understand the growth of protoplanets.[117] The two formed around the same time and in the same place, and yet were very different—why? "We want to find out why their evolutionary paths diverged," said Carol Raymond, the Dawn deputy PI.[118] "Was it the time of the formation? Was it the chemical gradients in the asteroid belt? Was it the peculiarities of the bombardment history?" She described Vesta and Ceres as "time capsules from the very earliest part of solar system history. They represent windows into the processes which were going on during the formation of the planets. We're trying to use these as a window into what influences were acting upon the whole system during the time of planetary formation."

Vesta, whose radius was known at the time to be less than a sixth of that of Earth's Moon, with a moon-like basaltic surface, and possibly a small iron core, could thus be subjected to comparative studies with the Moon, and yield broader insights to early celestial history of the inner planets. Meteoritic material on Earth known to be of Vestal origin would aid in such an investigation. The fact that no meteorites of Cererian origin had been identified on Earth was itself puzzling and worthy of study. It's not that Ceres, the largest body in in the asteroid belt, was too big to lose material. After all, meteoriticists had long identified material from

the Moon and Mars, both much larger than Ceres. What then was the nature of Cererian surface material? So little, indeed, was known about Ceres that until 1851, it was considered one of the planets of the classical solar system.

Historically, subjecting two such small bodies to comparative planetology would have required two missions. Because of the change in velocity in space travel required to reach a celestial object, most of which was imparted by the rocket that launched the spacecraft, once a spacecraft entered orbit around its target, it stayed there until the mission's close. The Dawn spacecraft, however, leveraged an ion propulsion system that allowed it to change its own velocity equal to that of the Delta II rocket that carried it to space.[119] The mission therefore amounted to a savings for NASA on the order of a billion dollars, according to Chris Russell, the Dawn PI.[120] The NASA technical demonstrator mission Deep Space 1 had already proven the thrusters reliable. Dawn would employ them in service of a new kind of exploration.

Dawn's journey from Earth to Vesta was not without incident. One year earlier, on June 17, 2010, sensors on Dawn detected excess friction in one of its reaction wheels, used to point and stabilize the spacecraft. Dawn powered it off.[121] The spacecraft possessed four such reaction wheels, and used three for normal operation.[122] While it was a disappointment, it was not a total surprise: just before launch, Carol Raymond, the deputy PI later said, "we learned that we were launching with defective reaction wheels, and there was nothing we could do about it. We went into a mode where we were trying to preserve wheel lifetime."[123]

It wouldn't affect the mission, and engineers soon began to study whether the mission could perform entirely on reaction control jets—12 thrusters positioned around the spacecraft—alone.[124] It could, they found.[125] They made the decision to switch off the wheels for the duration of the cruise phase to Vesta, choosing to preserve them for orbital operations. As Marc D. Rayman, Dawn's chief engineer, based at JPL, wrote in his blog at the time, "Even before deciding to deactivate the wheels for the rest of the interplanetary phases of the mission, engineers began working on a technique to use the hydrazine more efficiently, ensuring that the supply would last to the end of the long journey."[126]

Because of Dawn's ion propulsion system, and the size, shape, and mass of Vesta, the spacecraft eased into the asteroid's orbit in a spiral pattern, looping slowly around it, getting ever lower, circling it with increasing speed.[127] Ultimately, the spacecraft would orbit Vesta for just over a year, until September 5, 2012. During this time, the performed scientific measurements using its instrument payload of

- a gamma ray and neutron detector (GRaND);
- a visible and infrared mapping spectrometer (VIR); and
- a pair of identical cameras.[128]

Immediately after entering orbit, it began capturing images of Vesta in a preprogrammed sequence, and the science team got to work.

"Although those results are not yet available," wrote Rayman on July 18, "we now know with certainty that Vesta does have a moon. Its name is Dawn!"[129]

GRAIL LAUNCHES FOR THE MOON

On September 10, 2011—less than two months after Dawn entered orbit around Vesta—NASA launched the Gravity Recovery and Interior Laboratory (GRAIL) mission from space launch complex 17B at Cape Canaveral, Florida.[130] Tom Hoffman, the deputy project manager of the mission, watched from a viewing area as GRAIL ascended atop a United Launch Alliance Delta II rocket, its destination: the Moon.[131]

Before he ended up on the GRAIL mission, Tom Hoffman had spent years working on various projects at JPL in various roles.[132] He was a contractor for the laboratory, and then an employee, working on the Integration & Testing team. Among other things, he worked with Lockheed Martin as the avionics systems lead on Stardust. Like many members of JPL, he was also part of the Mars Exploration Rover project and Cassini. In each of these roles, he had about two or three years before growing bored.[133] When GRAIL came along, it intrigued him and he joined during the "Step 2" portion of the mission competition as the flight system manager. Typically, that was when the teams staffed up, because that was the part of the project where engineers had to prove that the mission could actually be done, safely, on schedule and at cost without compromising the mission's science goals. When NASA selected the mission for flight, he stayed in that latter role, and before launch, the lab promoted him to deputy project manager, a role he would hold over the course of that mission.

GRAIL was a twin-spacecraft, solar-powered mission to map lunar gravity, improving the scientific understanding of it by one hundred times on the near-side, and by one thousand on the far side.[134] In doing so, scientists would have the dataset necessary to determine the Moon's composition and interior structure, work out its origin and evolution—and by extension, the history of the inner solar system. Maria Zuber, a professor of geophysics and the head of the Department of Earth, Atmospheric and Planetary Sciences at Massachusetts Institute of Technology, spearheaded the mission as its principal investigator.

From the start, Zuber had a clear vision not only for the science necessitating the mission, but how she was going to achieve it. "When you propose," she said in a 2016 interview for the MIT Infinite History Project, "it's a big deal. And it's a lot of people. You know, it's more than 100 people working on the mission."[135] A prospective PI should ask themselves, first: Do you even want to do something like this? "Do

you want to drop everything and write a proposal for six months? And then if you win, you get to spend six months writing another proposal." Measuring the gravity field of the Moon was something she had long wanted to do in her career, but it had never been technically or politically feasible, in her estimation.

Political winds shifted in 2004, when the China National Space Administration formally began its Chang'e Program, a series of lunar missions that would culminate with the exploration of the lunar far side.[136] The following year, President George W. Bush committed NASA to return astronauts to the Moon by 2020, and then to Mars.[137] Zuber decided it was time, and she began looking for the right team.

"The difference between winning and losing is getting the right group of people together and getting a chemistry together, so that you figure out how to write the correct proposal that needs to be written. And so all these people that I've been working with all through my career, you know, I just started calling people. And everybody was excited," she said.[138] Because of the amount of work necessary to bring a spacecraft from an idea to an operational spacecraft, a team should be "people that you can get along with, because this is all about managing resources, managing risk, which means managing resources."

Zuber's broader proposal strategy required the mission not only to fit within the Discovery Program cost cap, but to have generous financial headroom: to leverage heritage designs judiciously for the spacecraft, to have robust margins for technical resources, and to define measurement requirements on the basis of the spacecraft's instrument capability.[139]

She also wanted the mission to appeal to more than just physicists. To that end, she integrated an education and public outreach strategy deeply into the proposal. She called Sally Ride, the first American woman in space, whose own career had long included educational outreach, and especially so to girls in science, technology, engineering, and math. Ride and Zuber decided to include cameras on the spacecraft that had no scientific purpose. "The cameras," Zuber explained, were "entirely for outreach in education," designed to be programmed by students, with children choosing the observation targets.[140] Moon Knowledge Acquired by Middle School Students (MoonKAM), as it was called, was the first time such a thing had been done on a NASA science mission. "I'm convinced the only way I was able to do it [is] because I had Sally on the mission—otherwise, I doubt that would have flown in the review process. But of course, we wrote a really careful proposal."

GRAIL's "science floor"—its minimum scientific objectives for mission success—was to:

- Map the structure of the crust and lithosphere.
- Understand the Moon's asymmetric thermal evolution.

- Determine the subsurface structure of impact basins and the origin of mass concentrations.
- Ascertain the temporal evolution of crustal brecciation and magmatism.[141]

Complete success—the "baseline mission"—also included investigations to:

- Constrain deep interior structure from tides.
- Place limits on the size of a possible lunar core.[142]

Despite scores of spacecraft having explored the Moon, fundamental questions remained unanswered. "We still don't know why the front side of the Moon looks different than the back side of the Moon," Zuber told the *New York Times*.[143] "If you've taken a hundred spacecrafts' worth of measurements and you still don't know the answer to something fundamental like that, then it's likely the answer isn't on the surface, it's somewhere else. We're making a bet here, by really learning the internal structure very well, that we'll be able to answer those questions."

NASA Headquarters selected it as part of the Discovery Program in 2007, choosing it over 23 initial proposals, in a competition whose finalists included a mission to study the chemistry and dynamics of the middle atmosphere of Venus, called Vesper, and an asteroid sample return mission called OSIRIS.[144] (The same year GRAIL launched, NASA would select OSIRIS-REx, an iteration of the latter mission, for flight in the New Frontiers program.)[145]

For NASA, GRAIL came along at the perfect time. Zuber's instinct to preserve "financial headroom" proved a great asset. Even for Discovery, it was a relatively inexpensive mission, at $375 million from start to finish in FY 2007 dollars, including launch, mission operations, and data analysis.[146] (The cost cap for the competition was $425 million.)[147] Moreover, her assessment of the political appetite for a Moon mission was correct. James Green said in a statement at the mission's selection: "As NASA moves forward with exploration endeavors, our lunar science missions will be the light buoy leading the path for future human activities."[148]

It was a low-risk mission from a spacecraft heritage perspective. Lockheed Martin would build the spacecraft bus; its design was based on the Experimental Satellite System-11, a U.S. Air Force Research Laboratory program with a long lineage, in development since 2001, and with avionics derived from the Mars Reconnaissance Orbiter.[149] The spacecraft instrument payload was based from a mission called GRACE—the Gravity Recovery and Climate Experiment, which, among other things, measured Earth's gravity field changes using twin spacecraft.[150] The two would measure the difference in distance between them using GPS and a ranging system. Whenever the lead spacecraft passed over something dense, the feature's

greater gravity would change the spacecraft's speed—something the trailing satellite would register with high precision.[151]

"It [GRAIL] was GRACE at the Moon," said Hoffman, with one big technical difference: the GRACE mission used GPS.[152] "There's obviously no GPS at the Moon." The spacecraft would have to handle the precision time synchronization that's the basis of GPS—as well as determine their relative locations—by sending signals to each other. "That was kind of the new thing for the mission."[153]

Still, the gravity method employed by GRACE would be far more effective at the Moon than it was at Earth, according to Zuber. "On the Earth, the two spacecraft couldn't get down real low because of the atmosphere." The lunar airless environment meant "very, very super high resolution."[154] As she explained after NASA selected GRAIL: "After the three-month mission is completed, we will know the lunar gravitational field better than we know Earth's."[155]

On December 31, 2011, as planned, GRAIL-A entered a highly elliptical, near-polar orbit around the Moon.[156] A 40-minute main engine burn by a spacecraft the size of a washing machine thus ended perhaps the busiest year in the history of the Discovery Program. The next day, on January 1, 2012, GRAIL-B joined its twin in lunar orbit. This inaugurated Discovery's 19th year as a funded NASA program, and 16th year of continuous spaceflight.

2012

JANUARY 1
GRAIL-B spacecraft enters lunar orbit.

CHAPTER 2

2012

MARCH 1
GRAIL begins science operations.

MARCH 18
MESSENGER begins its extended mission.

JULY 14
One of Kepler's four reaction wheels fails.

AUGUST 8
Dawn powers off one of its malfunctioning reaction wheels.

AUGUST 20
NASA announces the selection of the InSight lander mission.

AUGUST 30
GRAIL begins its extended mission.

SEPTEMBER 4
Dawn departs Vesta en route to Ceres.

NOVEMBER 29
NASA announces that MESSENGER found water ice on Mercury.

DECEMBER 17
GRAIL mission ends with controlled crash of both spacecraft into lunar surface.

Comet Hopper was not Jessica Sunshine's first proposal to the Discovery Program.[1] At the start of 2012, however, it was the one she was absolutely convinced would actually fly. That's how it went when you were principal investigator of a mission, and particularly a mission down-selected by NASA Headquarters for further study. You believed with all your being that the mission was going to be chosen for flight, and you worked every single day to that end.

She wrote her first Discovery proposal in 2005. Actually, she wrote two of them at the same time. She was in Germany for a Deep Impact meeting when she got a literal tap on the shoulder. It was Michael Belton, the mission's deputy principal investigator. During a break, he asked her to take a walk with him. Joseph Veverka, who ran the mission's data processing and image analysis, stood, and joined them. "I'm from New Jersey, so I got Mafia vibes very quickly," she said with a laugh.[2] "Turns out I was right. It was an offer I couldn't refuse."

On the walk, they explained that the 2006 Discovery AO was just around the corner, and they wanted her to propose a build-to-print copy of the Deep Impact spacecraft, to go to comet 67P/Churyumov–Gerasimenko.[3] The European Space Agency had just launched a mission there, called Rosetta in 2004; it would arrive at its target a decade hence, in August 2014. While Rosetta studied the outside of Churyumov-Gerasimenko, and its surface with a small lander, Philae, this new iteration of Deep Impact that Belton, Veverka, and Sunshine were planning, would rendezvous with the comet. After Rosetta's prime mission had ended, their notional Discovery mission would release an impactor that would collide with the comet at 10 kilometers per second, exposing the comet's interior.

They would call the mission Deep Rosetta—or Deep R—and it would be able to leverage the data returned by the suite instruments already on the billion dollar Rosetta and its Philae lander and offer another scientific perspective. Back on Earth, scientists would be able to track the effects of the impact from two distinct vantage points with high precision in both time and space, capturing the crater's formation and subsequent transformations, as well as analyses of the comet's nucleus composition.[4]

Sunshine wrote the proposal with Michael A'Hearn, the principal investigator of Deep Impact. Concurrently, the two of them also had to write the proposal for the extended mission of Deep Impact. "In those days [an extended mission proposal] was just as big a proposal as a regular mission," she said.[5] Writing two mission proposals at a time was "crazy," she said, "and it got crazier because Maxine, [A'Hearn's] wife, had to have surgery—and he left me at JPL with two proposals. It was lots of fun."

This type of "mission of opportunity" mission extension was new, and it seemed to Sunshine that the details had not been fully worked out. "I don't know that I can count the number of times we wrote an extended mission proposal or budget thereof," she said. In the early days of Discovery, such a proposal was basically a phone call. This time, NASA wanted paperwork. "We needed something official—not a huge thing, but a document six months before the extended mission starts."[6] The problem for the Deep Impact team: only six months separated launch and the encounter with comet Tempel 1. They cobbled together what NASA wanted with weeks to spare. But NASA Headquarters decided that it would not be enough. "They decided it had to be treated formally, so now we've gone to this executive review process," said Sunshine. By the time of selection, she estimated that the team had written a second full budget and three-quarters of a full proposal—but it worked. NASA agreed to fly their extended mission, which the science team called DIXI: the Deep Impact Extended Investigation.[7] The Deep Impact spacecraft would fly to comet 103P/Hartley (Hartley 2) for a 2010 encounter.

"Half the discoveries at Tempel 1 were from the flyby data taken before impact," said A'Hearn at the time. "DIXI can return half the science of Deep Impact for much less than 10 percent of the cost."[8]

Meanwhile, a separate team, led by L. Drake Deming of Goddard Space Flight Center had written something called EPOCh—the Exoplanet Observations and Characterization—taking advantage of the Deep Impact instrumentation, which was well-suited for surveying stars for exoplanets. That mission would operate during the cruise phase of the extended mission while Deep Impact flew to Hartley 2. Sunshine thought the idea was "brilliant," but gluing together DIXI and EPOCh required writing a third budget. They called the combined mission EPOXI.

Though NASA extended the Deep Impact mission, it did not select Deep R. The review they later received, Sunshine recalled, said there was nothing wrong with the idea of the mission, and that because Deep Impact was a relatively young spacecraft, NASA had not lost any engineering or technology capability to build a second to print. "But the review literally said that you didn't have enough backing from ESA to do this, and ESA people aren't going to want to disturb their mission," she said.[9] "The problem with that is that we actually had the head of ESA—the science head—on the team. But nobody on the review panel knew that that's who he was."

It was a case, she later decided, of getting the science and engineering correct, but blowing the politics.

"A MISSION THAT NO ONE THOUGHT WAS A DUMB IDEA"

Discovery competitions are inseparable from politics. NASA Headquarters seeks to select missions based on scientific merit and engineering competence. But because NASA is an agency of the executive branch of the United States, and funded by Congress, budgets fluctuate, sometimes dramatically, depending on the parties in power in both branches of government, and based on external affairs. NASA is oftentimes limited in the number of programs it can sustain, and the number of new ones it can pursue. To help determine priorities, the agency's strategic planning process depends greatly on guidance by the planetary science community through analysis and assessment groups, and by way of independent studies and reports of the National Academies of Sciences, Engineering, and Medicine. The most prominent inputs to that end are the space science decadal surveys, written every 10 years "to take stock of the status and opportunities for Earth and space science discipline fields and aeronautics research and to recommend priorities for research and programmatic areas over the next decade."[10] The National Academies Planetary Science and Astrobiology Decadal Survey (shortened frequently to simply "the Decadal") is widely regarded as the gold standard planning document for policymakers and

NASA program managers. It is written by a steering committee and outside experts organized around key topics, such as the inner planets, the giant plants, and small bodies. Given the great expense and time involved in mission proposals, consensus among scientists both within a subdiscipline, and across all disciplines, is necessary to advance any prospective mission beyond the study stage.

Bruce Banerdt recognized this political element early on while trying to bring his seismometer to Mars.[11] In his estimation, selling a mission proposal had a big psychological element to it, on top of the engineering and scientific demands. For the Discovery competition, he knew there would be dozens of competitors, all great missions, with half of them so developed that they were practically ready to fly. Within the Mars science community, Banerdt decided to treat his seismometer as an inevitability. When he gave science talks or went to meetings, he aimed to be everybody's *second* choice. "A geochemist is not going to want a seismology mission as their first choice," he explained. However, if the same geochemist is thinking, "Well, if they can't do this geochemistry mission, that seismology mission sounds like a good one," Banerdt figured his mission would be a sure thing in the Mars community.[12]

In addition, the Mars Exploration Program Analysis Group (MEPAG) chose him to be on the Science Goals Document Writing Committee, where he could collaborate with other Mars scientists. He was "quietly persuasive," he recalled, accommodating and acknowledging the goals of other scientists—as well as his own. "I fought for seismology, I fought for geophysics, but I never tried to stand in the way of sample return," he said, which was among the most prominent goals of Mars robotic space exploration. "I never tried to stand in the way of surface geology, which also results in great missions and a lot of great science. But I was always saying, '…but also this geophysics, also this seismology. This is why you should care about it. This is why it melds with your science goals.'"

His quiet work would eventually ease the mission later called InSight through selection. After years of efforts, "people did sort of view this as a mission that's going to happen sometime—it's inevitable—and people were okay with that, and it was also a mission that no one thought was a dumb idea," he said. ("In general, at least," he added.)

While writing the proposal for InSight, JPL's formulation office impressed upon Banerdt the importance of developing the science traceability matrix (STM), which "traces" science goals down to necessary instrument-level measurements, and instrument capabilities. Done properly, a STM would require a scientist to define very precise numbers to answer very specific scientific questions. In the case of Mars, to understand the differentiation of a terrestrial planet, you would need to know its crustal thickness, its core size, possibly its core density, and something about the

structure of the mantle. How, for example, would you determine the crustal thickness? Seismology. But how specifically? To figure out the necessary measurements, the InSight proposal team had to use strawman analysis techniques that would, in principle, reveal quantities. By estimating things like the seismic activity of Mars and something about the properties of the interior, they could figure out things like how many quakes would be necessary on a planet to get data to a necessary precision.

"We put together a few of these sort of storylines," said Banerdt, "getting from a quake on Mars to a measurement of the thickness of the crust, and we were able to put numbers on that… just having that much specificity, saying, if we can get a seismometer that can measure 10 to the minus-nine meters per second squared per root hertz; and if we can do it with this level of noise background from all these different things on the spacecraft; and if Mars is giving us quakes at this frequency—which we have some reasons to believe, and these are the reasons—then we will satisfy these goals."[13] It was a very specific and concrete story, and looked like one that was technically possible to tell.

Among the challenges InSight faced in building its science case was choosing where, on an entire planet, is the best spot to land. That job went to Matthew Golombek, the Mars Exploration Program Landing Site Scientist at JPL. (Golombek previously was project scientist on Mars Pathfinder.)[14] Because InSight was primarily a geophysics mission, digging into Mars rather than looking outward, there were no science constraints on the landing site aside from the ability to deploy the spacecraft's science instruments. "That simplified things," said Golombek with a laugh. "I didn't have to talk to any scientist outside of myself."[15] Golombek offered his services as a geologist to enhance the mission's science. "Let me be in charge of the geology portion of the mission," he asked, "even though it's rather ancillary to the whole project and what it does."

Only a single paragraph of the initial proposal discussed the landing site.[16] At the time, engineers constrained the mission to an elevation deeper than 2.5 kilometers below the mean level of Mars' surface, with a latitude near the Martian equator, between 15°S and 5°N, the location being ideal for solar power considerations.[17] Golombek chose 0.83°S, 141.48°E—Elysium Planitia—because it met the first order engineering requirements so early in the development stage.[18]

Once it came time to refine the proposal for the next round of the selection process, Golombek, Banerdt, and the mission science team began studying where, in fact, they might want to land with specificity. "We knew from Phoenix that it was not what you call a rock-tolerant landing system, okay? It's got three legs and it can accommodate anywhere from 35- to 45-centimeter-high rocks, which was better than Viking, but not as good as the [Mars Exploration Rovers Spirit and

Opportunity] or Pathfinder, for sure," said Golombek. Those previous mission informed the landing site selection. Rocks threatened the legs of InSight, and wind threatened its parachute landing system. Only three areas met the latitude and elevation constraints of the spacecraft.[19]

First was the edge of Valles Marineris, where it opens up and debouches into the Chryse Planitia. ("That's in canyons, and there's a high rock abundance and you could never fit 130-kilometer ellipse in the canyon," said Golombek. "It was just impossible.") Second was an area near Isidis Planitia, though remote sensing data suggested a high rock abundance there, and atmosphere storm tracks that went north and south across the equatorial region. ("So we said, 'Well, that's not so good.'") Lastly, they looked again at Elysium Planitia. In the western part of it, they found a place of generally low rock abundance that met the elevation constraints and did not have high winds.

"We made a decision right then, during Phase A, which is somewhat unusual, and said, 'This is where we're going to land,'" said Golombek.[20] From that moment on, engineers optimized the spacecraft, including its power and thermal systems, for the volcanic region.

Unlike many previous Mars missions, which were directed by NASA Headquarters, the InSight team did not need to hold open community meetings for the landing site selection. "The PI is the selector of the landing site—not NASA," said Golombek. "The Concept Study Report after Phase A was quite specific about where we were landing and what we were doing. So the acceptance of that proposal is effectively the acceptance of that site with the details of that." The mission was still showing its work to NASA Headquarters and explaining their reasoning, "but it was fairly pro forma. There wasn't a whole lot more to it."

The Planetary Protection Review, however, was more stringent. Among other requirements, the mission could not land in an area with water or ice within five meters of the surface.[21]

InSight had a key advantage over the other prospective missions that NASA had down-selected. Namely, it had been rejected, in various iterations, several times by NASA, including in the Mars Scout program, and as instrumentation on other missions. "I tell people, as a joke, that if you put in enough losing proposals, you run out of ways to lose," said Banerdt.[22] "We knew what people had complained about on previous proposals. We had studied this a number of times and we had our own set of issues that we had come up against and resolved, or at least identified and knew needed to be addressed somehow."

COMET HOPPER

When NASA down-selected Comet Hopper as one of the three possible Discovery missions, the proposal team inherited a new set of engineers from NASA Goddard Space Flight Center in Greenbelt, Maryland. "It was a different scale," Sunshine explained.[23] "It was no longer a piece of paper. It was getting really real—and we were lucky. God, you have to be lucky in this business."

She had learned from EPOXI what can come from bringing diverse disciplines together in a single room. When the science team settled on Hartley 2 as its target, they learned that they would not be able to use the spacecraft's spectrometer, because it would be in sunlight. This meant they would be limited, essentially, to imaging. During a meeting at JPL, however, a relatively young orbital dynamicist asked what would be necessary to use the spectrometer. The scientists explained the myriad angles necessary and data sought, and not long after, the dynamicist returned with a plan.

"She gives us this crazy trajectory," said Sunshine, "and it was perfect. I mean, it was just the perfect trajectory, and we got, I think honestly, data that will never be seen in my lifetime of a comet because we were able to watch that comet as it's rotating all the way in, all the way out, and take spectral data." The only way such an outcome was possible, however, was having someone on the engineering side really understand what the scientists were saying. "That to me is a lesson learned: that when you get people in those two diverse fields together, the first thing you have to do is figure out how to communicate what's really important—and to not say 'no' before you understand what the parameter space is."

She applied that lesson to her Comet Hopper team. The Goddard engineers she inherited had been working on an astrophysics project called the Wide Field Infrared Survey Telescope (WFIRST)—it was later named the Nancy Grace Roman Space Telescope—but the project did not get hoped-for funding from NASA.[24] Members of its engineering group were thus left with time on their hands. They joined Comet Hopper, becoming the bulk of the planetary mission's engineering staff on the NASA side. (Lockheed Martin had its own engineers.)

One of the first things Sunshine did was invite the engineers to the University of Maryland and discuss what sort of issues they were encountering with WFIRST. "It was very clear to me that they were dealing with a level of precision in designing a telescope that was just almost incomprehensible to what we knew our level of constraints were—because we didn't know anything," she said of the target body. Where space telescopes require great specificity, Comet Hopper would "be a complete mind shift for them." She wouldn't even be able to say what the shape of the comet would be, because nobody knew. Indeed, they knew very few of the specific target constraints. "That's why we're doing this!" said Sunshine with a laugh.

Sunshine and A'Hearn realized that they needed to give the engineers a crash course in comet science. In addition to what engineers didn't know, there were also questions of what they knew incorrectly. For example: one of the mission's key objectives was to watch in-situ as the comet came to life as it approached the Sun. Inevitably, the comet would outgas and emit ejecta. Surely that would pose some risk to the spacecraft?

"We talk about dust coming off comets, sure," said Sunshine, adding, "but it's still a class 3 clean room!" Likewise, the largest comet "jet" of outgassing that scientists know of is equivalent, in terms of newtons of force, to holding a tissue in your hand on Earth. The jet is simply relative to dark space. Sunshine wanted them to know that the comet environment wasn't as scary as they might have thought.[25]

The engineers quickly caught up to speed and started asking questions. "That was the glue that set us off for the rest of the proposal," Sunshine said, explaining that because the engineers had explained what they were doing on telescopes, and the science team had explained what they wished to do at comets, they established immediately a common language and background to work effectively together.

It was a leadership lesson she would keep for the rest of her career. During the early development of any mission, there is always a conversation between scientists saying, "We have to do this!" and engineers saying, "We can't do that!" and the whole thing converging on "Well, what *can* we do?"

But for a mission to succeed, she said, "You have to have an environment where people are comfortable on both sides with letting things go and listening."

A MISSION OF PURE DISCOVERY

In many ways, Comet Hopper was a mission of pure discovery, in the spirit of the Discovery Program's initial promise.[26] Pre-Rosetta, NASA had only flown by a handful of comets and had never landed on one.[27] No one knew the detailed topography and resultant strength of a comet's surface. NASA had never orbited a comet and lacked anything close to a global dataset. There was no high-resolution gravity information, and relatively little compositional or structural data. Moreover, scientists had little understanding of how comets accreted, how they evolve, and what happens when they start to heat during their orbits on approach to the Sun.

Comets, said Sunshine, were little more than "spherical cows"—absurd simplifications of complex phenomena. To answer many of those questions, Comet Hopper would acquire diverse data sets. It would touch down multiple times at multiple places on a comet, beginning when the comet was at aphelion—the point in its orbit farthest from the Sun—when it was inactive. As the comet approached the Sun and

became more active, the spacecraft would build a data set in time the revealed how the comet evolved.

Which is why the power source the team selected was such a vital issue, not only for Comet Hopper, but for the future of all Discovery missions. Certainly during the 2010 competition, but even for flagship missions launched through at least the 2020s, solar arrays for missions beyond the asteroid belt were challenging.[28] The farther from the Sun the spacecraft flies, the larger the panels necessary to draw power sufficient for operations. Larger panels mean greater mass and more complex engineering and testing to stow inside a rocket's payload faring and deploy after launch. Solar panels also limit prospective mission architectures. Comet Hopper's scientific goals would have taken it to nearly the orbit of Jupiter, five astronomical units from the Sun (i.e., five Sun-to-Earth-distances).[29] Even if its engineers could have incorporated solar panels from a perspective of simple power draw, the mission would still have been impossible because Comet Hopper needed to land repeatedly on a comet with possibly hazardous geology. One unexpected spike jutting from the surface, and a shattered solar panel would end the mission.

"We can't land on a comet with Airbus wings," said Sunshine. "It's just not going to happen."[30]

For any such mission, NASA needed in its arsenal a heartier sort of power source. To that end, allowing a radioactive power source for Discovery was a deliverance, opening up the solar system beyond Jupiter, and introducing diverse spacecraft architectures to the sorts of first-pass science opportunities possible with Discovery. Comet Hopper got its start when Lockheed Martin approached Michael A'Hearn soliciting ideas.

As Sunshine recalled, "Mike got a phone call from Lockheed Martin saying, 'NASA has money on the table to write proposals to do a concept study for ASRGs in Discovery—Do you have any ideas?'" A'Hearn replied: "If we're doing anything, *I'm* not doing anything. It's going to be Jessica. Let's ask her what her ideas are."

He brought her into the conversation, and almost immediately they did, in fact, have an idea: They should build a comet multi-lander. "Really, alight like a butterfly," she explained, "because otherwise you just bounce right off." Comet Hopper would touch down at centimeters per second, much more like a capsule docking at the International Space Station than Perseverance setting down on Mars.

After an initial orbital campaign, during which time they would have mapped the comet and studied its topography, they would attempt a first landing.[31] This initial landing would not be for science, but rather, to test the system out. They would find the smoothest, flattest, most boring part of the comet, and land there. It was the robot-equivalent of Apollo 11. Just by landing, the team would learn a lot. (Comet Hopper could also use jets on top of the spacecraft to help them stay on the surface.)

The Comet Hopper mission proposal was 1,300 pages long, written for engineers and scientists. The science team assumed that the readers were not small body scientists and hadn't considered such things as the microgravity environment at a comet. When describing the spacecraft payload, they provided not only the science case for an instrument, but the engineering case, explaining the conditions under which the instrument had to operate, and how they would work together. Moreover, they sought to demonstrate that they knew the edge cases and stress cases the instrument and spacecraft might encounter. When, during the mission, would the power situation be worse? Would the entire instrument payload work during that time? What was the worst case scenario for a landing or orbit? If a level one requirement—that is, the mission science that must be completed (versus a level two requirement, which is how the mission would complete that science)—was to measure something, they sought to prove that an instrument could actually do that.[32] Not only technically, but physically: that it was on the correct side of the spacecraft. It was vital to try to cover every base and scenario in the proposal because of the lack of discourse in the early stages of the mission competition. Though there was a site visit during the selection process, by then it might be too late, and an otherwise great mission could be killed by an evaluator who misunderstood one of its components.

"You put in this 1,300-page proposal and there's really—you know, would it kill them to have a half a day or even a day of discussion so that someone can say, 'Oh, okay, I get what you're doing'?" she said. (During the site visit, when evaluators visited the science team for organized presentations, and to ask questions, Sunshine was surprised by the number of mistaken beliefs people had about how comets work.)

As a matter of engineering, the real breakthrough of Comet Hopper, in Sunshine's view, was the "snowshoe." Many planetary landers used a tripod system: three legs beneath the spacecraft with the mass evenly distributed. Even the Philae lander, which would be deployed by Rosetta, used a tripod system. But the Comet Hopper team realized right away that tripod legs would not work if they touched down on an under-dense comet: even though it would not weigh much in microgravity, the spacecraft would sink.

Given the number of landings necessary for Comet Hopper to achieve its goals, and the paucity of knowledge about cometary surfaces, it was a significant problem. Then a Lockheed Martin engineer went snowshoeing in Boulder after work one day, and the solution presented itself. They would design a snowshoe of sorts for the lander, which would distribute its weight without the mass of the spacecraft coming down on three legs. "That was one of those inspirational moments when people aren't thinking about what they're doing," Sunshine said. "It sounds like some

mythical story, but in truth, that's what happens. You get people thinking about a problem, and they go off in their life, and they have an 'A-ha!' moment."

"ASSUME THE ASRG WOULD BE READY AND AVAILABLE"

Not long after MESSENGER entered orbit around Mercury, Peter Bedini, that mission's project manager, joined the Titan Mare Explorer (TiME) project at the Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland.

"I actually did not know about it until it was down selected in step one to go into phase A, at which time it was made clear to me that I was listed as the project manager in the proposal," he said wryly.[33] To accommodate the new workload, he delegated some of his responsibilities on MESSENGER to a deputy. TiME would require 40-hour workweeks, on top of the 40-hour workweeks he would still have to put in for MESSENGER (even with his reduced responsibilities on that mission).

TiME would be the first seafaring vessel on another world. It would land in Ligeia Mare, the methane-ethane polar sea on Saturn's largest moon.[34] Titan had long excited the public and planetary scientists because it is the only moon in the solar system with a dense atmosphere, and the only non-Earth world with standing liquid lakes and seas. A boat leveraged everything that made Titan unique and was a drastic and thrilling departure from typical space exploration. Ultimately, TIME would help scientists understand Titan's methane cycle, and yield insights into Titan's history and the limits of life. Its science objectives were to:

1. Measure the sea chemistry to determine its role as a source and sink of methane and its chemical products;
2. Measure the sea depth to help constrain organic inventory;
3. Constrain marine processes including sea circulation and the nature of the sea surface;
4. Determine sea surface meteorology; and
5. Constrain prebiotic chemistry in the sea.[35]

The mission would fly on an Atlas V 401 rocket, with its launch window opening January 17, 2016.[36] Its cruise phase would involve a single deep space maneuver, one Earth flyby, and one Jupiter flyby on its way to Saturn. Once there, the cruise stage would separate from the lander just before entry. Once in the sea, the boat would communicate directly with Earth; the mission had a five Titan-day lifetime (about 80 Earth days), during which time the Earth and Sun would be above the horizon.

The TiME principal investigator was Ellen Stofan, the vice president and senior scientist at Proxemy Research, a consulting firm in the Washington area specializing in planetary research.[37] Critically, the mission relied on two ASRG power sources.

The "Step One" selection in the Discovery program is heavily focused on the mission's science. Down-selected missions are chosen specifically because NASA and reviewers from the planetary science community like the science the teams have proposed; going into Step Two, teams are expected to leave the science section largely unaltered, and to highlight any changes they might make in the new, expanded proposal. APL was going to manage Titan Mare Explorer and build one of its instruments, with Lockheed Martin building the spacecraft itself. In Bedini's view, the issues likely to turn up in these sorts of mission proposals usually came down to cost.

"You're allowed to have one 'miracle,'" he said, when developing a mission proposal.[38] When reviewers study a proposal, they might be skeptical about some aspect of it, but they'll give it a pass because everything else about the mission makes sense. For Titan Mare Explorer, their miracle was a spacecraft floating around in a sea of methane with an antenna that was going to directly send data to Earth. During the Step Two, the engineering teams at APL and Lockheed Martin put significant effort into demonstrating that capability.

Although the Discovery selection was not supposed to penalize prospective missions for using the ASRG in their designs—and indeed, was covering the costs for any safety analyses associated with power source—in the context of uncertain fiscal footing, the high annual expense to the agency for developing the power source certainly made the unproven technology a severe liability.

"We were told to assume the ASRG would be ready and available," said Bedini, with set performance characteristics, and no need for mass reserves. NASA Headquarters told them: "This what you were going to get, and it's going to work." The ASRG was not supposed to be part of the risk chart in the Step Two report.

Still, Bedini heard rumors that something was amiss. In July 2011, the ASRG failed its final design review, which extended its final design phase by one full year.[39] The generator passed its "delta" final design review in July 2012.[40] The review and delay led to the restructuring of the project management team.[41] But this delay must certainly have given pause to officials in the Planetary Science Division and Science Mission Directorate at NASA Headquarters.

When NASA down-selected the potential missions to Comet Hopper, InSight, and Titan Mare Explorer, it also happened that Lockheed Martin was the contractor behind all three missions. According to Sunshine, the company was "nothing but professional," and kept strict firewalls between the three missions so that no information leaked from one team to the other. The company even tried to keep the

teams apart before site visits (which was a doomed endeavor because the planetary scientists on the various teams randomly encountered each other all the time, and regardless, were oftentimes friends).

When it became clear to all involved that the ASRG program was troubled, an aerospace company might have had more leverage with NASA Headquarters in ensuring that the faltering power generator didn't bring down the missions that used it. "If Lockheed hadn't had a solar mission that was ultimately selected" she said, "they might have been more aggressive in helping us discuss and fight the ASRG issue, which was very hard to do."[42] Either way, "I always thought as an organization, [Lockheed] had much more to gain from either TiME or Chopper being selected, because we were very innovative. Most of us were doing new things in new ways," she said. "InSight was another lander on Mars."

GRAIL

GRAIL began science operations on March 1, 2012, during which time its two spacecraft, Ebb and Flow, orbited the Moon at an average altitude of about 55 kilometers.[43] Flying in formation at 5,800 kilometers per hour, the spacecraft measured fluctuations in the Moon's gravity by beaming microwaves back and forth between them. Subtle variations in the measured spacecraft distance—as fine as one-tenth of one micron—would reveal lunar surface landscapes like mountains, and hidden, subsurface features such as buried metals and hollow lava tubes.[44]

The engineers responsible for GRAIL remained mindful of unique aspects of the mission. NASA rarely flew dual spacecraft missions in which mission success required both to operate perfectly for the mission's duration. (Typically, if NASA flew two near-identical spacecraft to a destination, the loss of one of the spacecraft was factored into planning. For example, the Viking mission to Mars would have been successful even if one of the landers had been destroyed on landing.) Moreover, these two spacecraft were flying in perfect formation around the Moon, maintaining precise distances. Nobody had ever done that before. Working in the mission's favor was proximity. Unlike communications delays to Mars, which took signals between 4 and 24 minutes to travel each way, communication to the Moon had a delay of about 1 second each way.[45]

"We could send commands to the spacecraft and get an immediate response," said Humphrey "Hoppy" Price, the project system engineer of GRAIL, who oversaw all engineering of the spacecraft and also acted as the mission's engineering technical authority.[46] "We could do real-time commanding if we had to."

The spacecraft's initial science campaign ran from March 7, 2012, through May 29.

EXTENDING MESSENGER

Before the MESSENGER mission had even entered orbit around Mercury, the project team had started work on the extended-mission proposal, and by January 2011, Ralph McNutt, the project scientist, had already submitted a draft of the science section for review.[47] The goals at the time for an extended mission, according to the proposal, were "not a simple continuation of those of the primary mission," but rather, included "operation during a more active Sun, greater focus on observations at low spacecraft altitudes, and a greater variety of targeted observations."[48]

In November 2011, NASA Headquarters approved the extended mission, which would last for one year, beginning on March 18, 2012, the anniversary of Mercury Orbital Insertion.[49] (Coincidentally, one day earlier, NASA Headquarters approved a 90-day extension of the GRAIL mission as well.)[50] MESSENGER had already proven highly successful, returning nearly 100,000 images in its first year alone. During the Mercury flyby and orbital phases of the mission, the spacecraft found significant levels of water in Mercury's exosphere. "We were astonished, just astonished," said Thomas Zurbuchen, who led the spacecraft's Fast Imaging Plasma Spectrometer.[51] "Nobody expected that. I don't know a single person that did."

The first year of MESSENGER orbital observations revealed many surprises, according to Solomon, including an "extraordinarily dynamic magnetosphere and exosphere" and "an unexpectedly volatile-rich composition of its surface and interior."[52] It also found that Mercury possesses a much larger iron core than previously expected, covered by an iron and sulfur shell, making it unique among the terrestrial planets of the solar system.[53] Moreover, the world seemed to have been geologically active much longer than previously expected, and planetary scientists including Maria Zuber, who led MESSENGER's geophysics investigation in addition to her work on GRAIL, wondered whether the planet was still active, "though I note that this is not very likely, and for sure we have not observed an active eruption or extrusion."[54]

The prime mission achieved all its science objectives and project requirements.[55] The year ahead promised a "critical epoch" for the study of Mercury's magnetosphere and exosphere, which neither the Mariner 10 nor the MESSENGER prime mission had been able to study, nor would BepiColombo, the Mercury spacecraft approved by the European Space Agency in 2000 (but would not launch until 2018).[56] The spacecraft reduced its altitude by reducing its orbital period from 12 hours down to 8.[57] With the global map of Mercury completed, the team planned more-frequent targeted observations, using more of the spacecraft's instruments.[58]

The extended mission sought to determine:

- The sources of Mercury's surface volatiles;
- How late into Mercury's history volcanism persisted;
- How Mercury's long-wavelength topography changed with time;
- The origin of localized regions of enhanced exospheric density on Mercury;
- How the solar cycle affects Mercury's exosphere and volatile transport;
- The origin of Mercury's energetic electrons.[59]

On April 20, 2012, after three engine firings, MESSENGER shortened its orbit, lowered its altitude, and entered its most intense phase of operations since launch.[60]

THE SELECTION

Exactly four months later, on August 20, 2012, NASA Headquarters announced the selection of the InSight lander as the 14th mission of the Discovery Program.[61] "The exploration of Mars is a top priority for NASA, and the selection of InSight ensures we will continue to unlock the mysteries of the Red Planet and lay the groundwork for a future human mission there," said Charles Bolden, the NASA Administrator.[62]

The mission's science objectives on Mars were to:

- determine the thickness and structure of the crust;
- determine the composition and structure of the mantle;
- determine the size, composition, and physical state of the core;
- determine the thermal state of the interior;
- measure the rate and geographic distribution of seismic activity; and
- measure the rate of meteorite impacts on the surface.[63]

To achieve this, the lander would carry four instruments:

- A JPL-built onboard geodetic instrument to determine the planet's rotation axis;
- A robotic arm and two cameras used to deploy and monitor instruments on the Martian surface, also built by JPL;
- A seismometer to measure seismic waves traveling through the planet's interior, built by Centre National d'Études Spatiales, the French space agency; and
- A subsurface heat probe to measure the flow of heat from the interior, built by the German Aerospace Center.[64]

The foreign contributions were another significant shift in Discovery. While previous missions flew international instruments, never before had they been the primary investigations.

"We didn't start out with the strategy of saying, 'Let's get a payload from overseas that we don't have to pay for and then that'll help us get into the cost cap,'" Banerdt said, "but once we recognized that that's where the best instruments were, we definitely used that to our advantage and used that as a strategy for getting the most out of the Discovery cap."[65]

The selection did not go over well with members of the Titan Mare Explorer and Comet Hopper teams, particularly in light of the ASRG element of the selection process.[66] "It was a little bit disappointing when we were having a debrief at NASA Headquarters, and they had written in the non-selection letter that the two things they were concerned about were cost and schedule," said Peter Bedini.[67] Cost was a challenge because the $425 million included Phase E, the operations phase of the mission, which was a de facto penalization of the outer planets of the solar system. (It took longer to get there, which cost more money.) He was curious when no one elaborated on the schedule risk. At the end of the meeting, someone asked about NASA's objections.

"One of our Lockheed colleagues who was in the room said, 'What about schedule?' and there was a pause. And somebody said the ASRGs wouldn't be ready."[68] Bedini was shocked. It was "like having the rug pulled out from under you. They picked—and somebody on the panel actually said—they picked the most boring, low-risk science. And of course it turned out to cost a billion dollars to do that Discovery mission."

The late A'Hearn asserted in a paper published in *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, that Comet Hopper "was not selected at least in part, if not primarily, because it relied on advanced Stirling radioisotope generators that would not be available in time for flight."[69]

Jim Green, who helped choose which of the three missions would be selected for flight, disputed this, saying: "Whether the ASRGs were working, or not, was not part of the decision."[70] The Science Mission Directorate made its decisions based on the best information of the moment, including cost and schedule, and subject to the budget. He said that because SMD did not select a mission that used plutonium, the immediate need for a radioactive power source in the Discovery program was alleviated. On November 15, 2013, Green announced the end of the ASRG program in a press release.[71] "With an adequate supply of Pu-238, and considering the current budget-constrained environment, NASA has decided to discontinue procurement of ASRG flight hardware," he wrote. "For future planetary missions that require

radioisotope power systems the flight-proven MMRTG [multi-mission radioisotope thermoelectric generators] will be made available."

GRAIL AT THE MOON

Ten days later, on August 30, 2012, the two GRAIL spacecraft began their extended mission at the Moon by activating their Lunar Gravity Ranging System instrument above the Moon's Oceanus Procellarum—the Ocean of Storms.[72] This second phase of the mission involved the Ebb and Flow flying at an average altitude of 23 kilometers, down from the prime mission's height of 55 kilometers above the lunar surface.[73] "Mapping at a substantially lower altitude," said Maria Zuber, the mission PI, "and getting an even more intimate glimpse of our nearest celestial neighbor, provides the unique opportunity to globally map the shallow crust of a planetary body beyond Earth."[74] Such an altitude meant the spacecraft would fly as close as eight kilometers to some of the Moon's mountain peaks.[75]

This presented technical issues with the spacecraft telecommunications system. "Because we were so low to the ground, the radio signals would bounce off mountains and craters and stuff, and it would mess up our communication," said Hoppy Price.[76] The mission team ran analyses to determine what "multi-path" parts of the Moon would be most troublesome, and planned subsequent operations knowing that when the spacecraft flew over certain areas, communications would be unreliable. This was in addition to the times when Ebb and Flow were on the far side of the Moon, and completely unable to talk to Earth. During those intervals, the spacecraft recorded its science data for playback when emerging on the other side.

Such issues were examples of how a Discovery mission could buy down risk for future human spaceflight missions. NASA's Artemis program to return astronauts to the Moon was planned to land humans on the lunar south pole, where Earth is low to the horizon. "We know that they will have all kinds of multi-path problems communicating with the Earth," said Price. "The people in the Human Space Flight Program are aware of that, and they're trying to figure out how to deal with that. It won't be easy for them."[77]

During the prime GRAIL mission, the spacecraft had zero command errors. "I don't know of any other project that's done that," said Price. "There were no bad commands that we sent up that had any bad effect on the spacecraft." This streak ended during the extended mission, however, when the team sent a certain file to the spacecraft, but during execution, the spacecraft computer accessed the wrong file version, triggering the spacecraft fault protection.[78] (This was not an emergency state, however.)[79] There was also a "bad interaction with this non-science instrument called MoonKAM, which was made of commercial components," he continued. "It

had problems with solar radiation and it would sometimes just go on the fritz, and we'd have to turn it off, turn it back on again, and it would reset."[80] These were minor issues, however.

Throughout the mission, Zuber had been struck by the response from MoonKAM, devised by her and Sally Ride. Middle schoolers were going "far beyond the lesson plan" in studying the images returned—more than 100,000 by that November.[81] "The students targeted the images, the students uploaded the commands, and the students downloaded the pictures that they had targeted," she said. Moreover, to try to understand what was in the images, students went "well, well beyond" the engagement activities designed by University of California San Diego's nonprofit center, Sally Ride Science.[82]

"We really believe we're on to something in terms of creating a really, really transformative educational experience for students," Zuber said.[83]

The extended mission would see GRAIL fly for just over three more months.

DAWN SETS A COURSE FOR CERES

Just before midnight on September 4, 2012—two weeks after NASA selected InSight for flight—the spacecraft Dawn departed Vesta for the dwarf planet Ceres, the largest unexplored celestial object between the Sun and Neptune.[84,] The spacecraft had spent 13 months total in Vesta's orbit, where it took "31,000 photos, 20 million visible and infrared spectra, and thousands of hours of neutron spectra, gamma ray spectra, and gravity measurements," wrote Mark Rayman, the mission's director and chief engineer.[85] Among other findings, the spacecraft data revealed that Vesta was more akin to a terrestrial planet than an asteroid, with at least a partially differentiated crust, mantle, and iron-nickel core.[86] Its northern hemisphere is heavily cratered, while its southern hemisphere is much smoother, the result of a major impact two billion years ago, and another one billion years ago. The impacts left behind two large craters: Veneneia and Rheasilvia, the latter twice the height of Mount Everest on Earth.

Earth feels the implications of those craters. Meteorites that land on our world originate from many places, including the asteroid belt, Mars, and the Moon. (The asteroid belt is the primary source, accounting for 99.8% of meteorites.) Meteoriticists study them to better understand the history of the solar system. Before the Dawn mission, three classes of meteorites found on Earth—howardites, eucrites, and diogenites, or: "HED meteorites"—matched the spectral properties of Vesta as observed telescopically.[87] Planetary scientists hypothesized that Vesta had differentiated, and that eucrites and diogenites were from its crust and mantle, respectively.[88]

Dawn's spectrometers confirmed the connection of Vesta to HED meteorites, and that howardites are a mixture of the two from the asteroid's surface, caused by impact ejecta buried and lithified.[89] Strangely, much of Vesta's surface did not originate on Vesta. Hydrated material detected by the spacecraft instrument payload suggests that the Veneneia impactor was replete with hydrated and carbonaceous materials.[90]

Vesta's geology also proved interesting in that it seems to have had a dynamic past of landslides from asteroid-like slopes brought upon by its planet-like gravity. "That's created some interesting exposures of material, and very small-scale geology," Carol Raymond, the Dawn project scientist, told the Planetary Society.[91]

As geologist Emily Lakdawalla summarized, the Vesta revealed by Dawn was not one asteroid of many, but rather, "more appropriately compared to places like Mercury, the Moon, and outer planet moons."[92]

Table 3. Dawn Achievements at Vesta.

Discovery/Achievement	Details
Surface Composition	Vesta has a basaltic surface rich in pyroxene and olivine, indicating past volcanic activity.
Global Mapping and Geology	Provided the first detailed global map, revealing craters, mountains, and evidence of past volcanic activity, including the massive Rheasilvia crater, whose central impact mound is about the same height as Olympus Mons.[93]
Internal Structure	Gravity measurements indicate a metal-rich core approximately 220 km in diameter.
Evidence of Past Water	Observed gullies that suggest transiently flowing liquid water in the past.
Meteorite Parent Body	Confirmed as the source of the HED (howardite, eucrite, diogenite) meteorites.

In terms of spacecraft performance, during its weeks-long deorbit of protoplanet Vesta, one of Dawn's reaction wheels malfunctioned, continuing a problem that had plagued the mission since its cruise phase.[94] In response, the spacecraft automatically disabled all reaction wheels, switching to thrusters and awaiting further instructions from Earth. The Dawn team had planned to disable all reaction wheels during the cruise phase to Ceres anyway, and Rayman wrote, "having them off a few weeks early was not a significant change."[95] The spacecraft's teal-colored beam of xenon ions would send it 64 million kilometers to reach Ceres, and would arrive there in 2015.[96]

REACTION WHEELS VEX KEPLER

Those weren't the only reaction wheels to give the Discovery program headaches in 2012. On July 14, the Kepler space telescope likewise suffered increased friction in one of its reaction wheels, and it subsequently stopped.[97] The reaction wheels controlled the spacecraft's orientation, and kept Kepler fixed on its target stars.[98] Whenever the spacecraft drifted, the reaction wheels would spin up and restore its aim. Because stability was so essential to Kepler's operation, it carried four such devices: three necessary for operation, and one as a backup. Wheel 2 of four was now gone. The three remaining wheels were still working, said PI William Borucki, "but they've all had over a billion revolutions. If we lose another one, this mission terminates. We cannot track very well with two. We cannot track well enough to find planets."[99]

Unfortunately, wheel 4 had also shown signs of friction. For engineers on the mission, keeping it and the other two wheels spinning was now top priority. One technique they would employ to maintain reaction wheel health involved alternating rotational directions back and forth from clockwise to counterclockwise. If there was any good news from the failure of the reaction wheel, it's that it offered diagnostic data that might help engineers keep the others operational. The bad news about the ailing wheel 4 was that its increased friction brought with it increased heat in the spacecraft, affecting focus and precision.[100]

As if that weren't enough, the Sun was also beginning to menace the mission in 2012. Five coronal mass ejections hit the spacecraft from January to June, temporarily degrading data collected.[101, 102] (The solar flares also proved a minor nuisance to the GRAIL spacecraft.)[103]

By summer, Kepler had confirmed detections of 118 exoplanets, with thousands of candidates still in need of continued study and validation.[104] The process was slow, however, partly because the spacecraft had yet another issue with which the team was contending: noise in the data. Though they had written software to correct for this—it was caused mostly by spacecraft electronics—the algorithms to do so were slow and expensive to run. In part to mitigate this, but also because the mission had proven highly successful, three months earlier, NASA Headquarters extended the mission to 2016.[105] The Kepler Space Telescope completed its prime mission on November 14, 2012.

"The Earth isn't unique, nor the center of the universe," said Geoff Marcy, a Kepler co-investigator, and professor of astronomy at the University of California at Berkeley.[106] "The diversity of other worlds is greater than depicted in all the science fiction novels and movies. Aristotle would be proud of us for answering some of the most profound philosophical questions about our place in the universe."

MERCURY: "SURPRISINGLY HABITABLE"

Two weeks later, scientists on the MESSENGER mission announced three papers accepted by the journal *Science*, in which they presented evidence for "about the last thing you would expect on a planet so close to the Sun," as Matthew Siegler, author of one of the papers, described it.[107] Specifically, they had confirmed the existence of significant amounts of water ice on Mercury, particularly near its north pole.[108] Planetary scientists had for decades hypothesized the potential for the presence of water in the planet's permanently shadowed region: areas that because of geology and Mercury's near-zero axial tilt, never receive sunlight, regardless of orbital position or rotational state. "For more than 20 years the jury has been deliberating," said Sean Solomon.[109] "MESSENGER has now supplied a unanimous affirmative verdict." Three lines of evidence supported the claim: MESSENGER's neutron spectrometer found excess hydrogen at the north pole; reflective data from Mercury's laser altimeter; and models of temperatures of the surface and near-surface of the north polar regions (also collected by the laser altimeter). Moreover, the spacecraft identified darker, insulating material in the regions indicative of complex organics like those found in carbonaceous chondrite meteorites.[110] In addition to advancing the story of Mercury's geologic and thermal history, and solar system dynamics, it also meant Mercury was "surprisingly habitable."[111] It was, arguably, the first time a mission in the Discovery Program had returned such a significant habitability result.

THE SALLY K. RIDE IMPACT SITE

The year 2012 began with GRAIL entering lunar orbit. The year ended with GRAIL entering the lunar surface. The twin spacecraft completed their extended mission on December 3. With fuel depleting fast and time running out, the mission team was free to collect increasingly refined data at decreasing altitudes with every orbit, and they would continue to do so until impact.[112]

"We were flying at an average altitude of 50 kilometers in the prime mission, and near the end, we went so low, I joked that we were touching the treetops," said Sami Asmar, the project scientist of GRAIL.[113] Near the end, the spacecraft flew slightly more than a kilometer above the lunar surface, which was a "big risk," Asmar continued, because they were "intentionally crashing it because of [a] NASA directive for how you end a mission like this on the Moon," which involved a controlled landing at a known location.

Ultimately, GRAIL measured the lunar gravity field at a resolution almost 10 times higher than the science team had proposed.[114] It yielded the highest-resolution gravity field map of any celestial body.[115] The mission revealed that the lunar interior has been largely undisturbed for billions of years, in contrast with Earth,

Table 4. GRAIL Achievements.

Discovery/Achievement	Details
Detailed Gravity Mapping	Created the most detailed gravity map of any celestial body, with a resolution of degree and order up to 660.
Lunar Crust Structure	Determined the Moon's crust is thinner (average 34–43 km) and highly fractured due to ancient impacts.
Lunar Core Size	Estimated the Moon's inner core radius to be approximately 330 km.
Mascon Formation	Confirmed that mass concentrations (mascons) are from ancient impacts, with gravity anomalies associated with basins filled with dense mare material and upward-warped crust-mantle boundary.
Ancient Magma Intrusions	Discovered linear gravity anomalies indicating ancient magma intrusions or dikes.

whose plate tectonics erase much of its geologic history. It found also that the lunar crust, just beneath the surface, is pulverized, suggesting the Moon's first billion years involved impacts much larger than previously thought.

"It was known that planets were battered by impacts, but nobody had envisioned that the [lunar] crust was so beaten up," said Maria Zuber. "This is a really big surprise and is going to cause a lot of people to think about what this means for planetary evolution."[116] The reason is that if the Moon was so heavily impacted, so too were the other planets.

On December 17, at 5:28 p.m. Eastern Time, Ebb collided with a mountain near the lunar north pole.[117] Flow followed 30 seconds later. The spacecraft were flying 3,760 miles per hour on impact. Each spacecraft broke up due to the energy released by their impacts; the collisions buried any remnants in shallow craters.

"On this mission, with two spacecraft, everything had to go perfectly twice," said Zuber. "Imagine you're a parent raising… twins, and your children sit down at the piano and play a duet perfectly. That's how it feels."[118]

There was a bittersweet note to the GRAIL impact site. On July 23, 2012, Sally Ride died of pancreatic cancer at age 61.[119] She was the first American woman to fly in space, a pioneer in STEM advocacy, and among NASA's best-regarded strategic planners.[120] In her honor, NASA named designated the southern face of a 2.5-kilometer tall mountain near Goldschmidt Crater, as the Sally K. Ride Impact Site.[121]

"As we complete our lunar mission," said Zuber, "we are proud we can honor Sally Ride's contributions by naming this corner of the Moon after her."[122]

JANUARY 17
Deep Impact begins observing comet ISON.

CHAPTER 3

2013

MAY
Kepler's second reaction wheel failure ends its original mission.

AUGUST
NASA calls for white papers to study continuing the Kepler mission with only two reaction wheels.

AUGUST 11–14
Communications lost with the Deep Impact/EPOXI spacecraft.

SEPTEMBER 20
NASA ends efforts to contact Deep Impact/EPOXI spacecraft.

NOVEMBER 15
PSD Director Jim Green announces the end of the ASRG program.

NOVEMBER 18
Launch of the MAVEN mission.

The race was on to save Kepler's reaction wheel 4.[1] If it failed the mission was over. By January 2013, Ball Aerospace was testing new ways of operating the vehicle with thrusters alone, but they had not yet converged on a solution.[2] Meanwhile, the wheel's friction had raised the temperature of the entire spacecraft, affecting the telescope's precision. Engineers suspected that the wheel's lubrication was unevenly distributed, and that if they brought the wheel to rest, the issue would resolve itself. When they restarted the wheel, however, the issue was worse.[3]

Though the spacecraft was running on borrowed time, however, the data it had collected were proving timeless. Habitable planets elsewhere in the galaxy were proliferating. To choose one example of the 2,662 confirmed planets discovered ultimately by Kepler: In February 2013, astronomers at the Harvard-Smithsonian Center for Astrophysics announced that they had analyzed 95 planet candidates orbiting 64

red dwarfs that had been cataloged by Kepler.[4] Three, they discovered, are Earth-like: temperate and less than twice the size of our home planet. One of the planets was a mere 13 light-years away. Though they orbited their stars closer than Earth does the Sun, because red dwarfs are smaller and cooler than our star, the habitable zone in which stable water could exist on their respective surfaces was different than ours.

"This close-in habitable zone around cooler stars makes planets more vulnerable to the effects of stellar flares and gravitational interactions, complicating our understanding of their likely habitability," said Victoria Meadows, professor at the University of Washington, Seattle, and principal investigator with the NASA Astrobiology Institute.[5] "But, if the planets predicted by this study are indeed found very nearby, then it will make it easier for us to make the challenging observations needed to learn more about them, including whether or not they can or do support life."

Meanwhile, the spacecraft Deep Impact, which had last flown by the comet Hartley 2 in 2010 (as part of the EPOXI mission extension), seemed to be healthy, albeit running low on fuel. With the Hartley 2 flyby, the spacecraft had completed its extended mission, and the team used its remaining funds to analyze the collected data. At the end of 2011, NASA Headquarters had ordered a senior review of planetary missions requiring mission extensions, part of a grim budget cycle that in FY 2012 saw about $650 million cut from NASA's overall funding, year-over-year.[6] While the review continued into 2012, the mission entered what Michael A'Hearn called an "an unusual state."[7] The spacecraft was alive and making remote observations—including of the comet C/2009 P1 Garradd from February 12 to April 9, 2012, from a distance of approximately 150,000,000 km—but it didn't have an official mission.[8] Notably, the Garradd observations afforded the rare opportunity to study a dynamically young Oort Cloud comet in a Sun-grazing orbit.[9] Deep Impact data revealed that the comet's outgassing "varies with a period of 10.4 hours, presumably due to rotation of its nucleus," and was unexpectedly outgassing carbon monoxide.[10] The team made the first-ever measurements of Garradd's dry ice content, which was around 10 percent of its water ice content by number of molecules.[11] Given the relative paucity of comet data that had ever been collected by spacecraft, it was a showcase of Deep Impact's capability for comet remote sensing beyond its primary mission objectives.[12]

Afterward, on October 4, 2012, engineers used the spacecraft's remaining fuel to adjust its trajectory slightly, placing it on a course to rendezvous with Near Earth Asteroid 163249 (2002 GT) in 2020.[13] The asteroid—a "potentially hazardous object"—would soon swing within 0.012 AU of Earth. This would allow astronomers to make ground-based characterizations of the asteroid, setting the stage for

Deep Impact's eventual flyby. It was a solid, long-term objective for an otherwise healthy spacecraft.

Along the way it would continue making long-distance cometary observations. (Such observation potential "with probes like Deep Impact is why we want to keep NASA's [older] assets viable," said Jim Green.)[14] First up was the recently discovered comet C/2012 S1 (ISON), which was 5.1 astronomical units from the Sun, and 5.3 AUs from Deep Impact. The spacecraft began an imaging campaign on January 17, 2013.[15] For the next day-and-a-half, Deep Impact's Medium Resolution Instrument collected an 80-second exposure image every 15 minutes—146 images in all.[16] The team planned to begin taking infrared spectra in February, with its observation window ending in March, and to begin again in July through early September.[17] They even planned future observations in 2014, if the comet survived perihelion.

What they didn't plan for was the thing impossible to predict: that their spacecraft would become a cautionary tale, and an entry in the NASA Lessons Learned System.[18] Because in August 2013, Deep Impact disappeared.

Engineers first grew concerned after the spacecraft failed to send a carrier signal for a planned data downlink between August 11 and August 14. They typically talked to the spacecraft once a week.[19] There had been no previous issues. Sixteen days later, engineers had determined the likely cause.[20]

"Basically, it was a Y2K problem, where some software didn't roll over the calendar date correctly," said A'Hearn.[21]

The spacecraft fault management software, which was responsible for reporting and responding to problems and incidents, used the spacecraft's onboard clock for logging events.[22] Part of that process involved converting time from milliseconds to seconds, decimal values to integers. However, like all computers, the spacecraft system could only handle numbers up to a certain size. When the clock hit 429,496,729.6 seconds on day 223 of 2013, the number became too big for the computer to handle. This is called an overflow condition. When this happened, any minor issue triggering a restart (such as losing sight of stars used for navigation) would call the fault protection software, which would again encounter the error, and again restart. This created an infinite loop where the computers kept turning on and off, unable to run any software, including the one that controls the spacecraft's direction. As a result, the spacecraft couldn't point its antennas to communicate with Earth or its solar panels at the Sun to collect energy. The battery drained, and without power, the heaters stopped working. The spacecraft was dead in space.

Engineers continued sending low-level hardware commands to the spacecraft through the Deep Space Network, in hopes of a command getting through that might reorient the spacecraft and recover power and communications.[23] They were

unsuccessful. None of the ISON data collected from July onward by Deep Impact ever made it back to Earth.[24] Indeed, Deep Impact was never heard from again.

On Monday, September 16, A'Hearn reported that there were "no other plausible scenarios under which we could recover command and control of the spacecraft," and recommended to NASA Headquarters that it declare Deep Impact lost.[25] In a sense, the way the spacecraft died was a testament to the spacecraft's durability. It was "history's most traveled comet research mission," and it simply wasn't designed to last as long as it did.[26] It was also a powerful lesson for the Discovery Program going forward. The mission had launched on January 12, 2005, and accomplished its prime mission at Tempel 1 in spectacular fashion less than six months later. It was the first mission to probe a comet's interior, and its impact element—which ejected material from the comet's surface—was the first human-made spacecraft to achieve a hypervelocity impact of a celestial body.[27] The subsequent eight years of exploration—Hartley 2, Garradd, the initial ISON imaging, and the ancillary science that went into that exploration, such as ground-based observations of the targets and potential targets of exploration, and data analysis—were all bonuses: essentially a free spacecraft with which NASA could probe the solar system—including one body that hadn't even been discovered at the time of launch.[28] The "competed" mission extension even enabled an unexpected leveraging of cruise phase—an oftentimes "quiet" period for spacecraft—to make some of the first light curve measurements of transiting Earth-sized extrasolar planets from space. It also validated and improved the "spectral Earth" model; Deep Impact observed Earth as an exoplanet, providing ground truth for the future search for Earth-like planets orbiting a sun-like star.[29]

Table 5. EPOXI Achievements.

Discovery/Achievement	Details
Exoplanet Earth	Observed Earth from millions of miles away, as though it were an exoplanet, providing future telescopes with a "how-to" guide for recognizing habitable worlds with life.
Comparative Planetology of Two Comets	Made the first-ever observations of two different comets—Tempel 1 and Hartley 2—with a single spacecraft instrument payload, allowing for a true side-by-side comparison.
CO^2-Driven Comet Activity	Discovered that frozen carbon dioxide—rather than melting water ice alone—powered the jets of gas and dust shooting from Hartley 2.
Hartley 2's Unique Shape and Dynamics	Imaged Hartley 2's peanut-like shape and wobbly rotation, and observed jets of fluffy ice chunks, ranging in size from golf balls to basketballs, blasting from its rocky ends.
High-Precision Exoplanet Photometry	Performed as a space telescope during cruise phase, measuring the starlight from systems with known exoplanets.

NASA formally ended the mission on September 19, 2013.

"Despite this unexpected final curtain call, Deep Impact already achieved much more than ever was envisioned," said Lindley Johnson, the mission's program executive. In all, the spacecraft traveled for nearly five billion miles, returning a half million images, and "completely overturned what we thought we knew about comets," while also providing "a treasure trove of additional planetary science that will be the source data of research for years to come."[30]

"HOW MUCH MORE WOULD IT HAVE COST TO HAVE TWO SPARE REACTION WHEELS INSTEAD OF JUST ONE?"

The failure of the Kepler Space Telescope's reaction wheel 4 occurred in stages in May 2012, beginning with a thruster-controlled safe mode on the first day of the month, a recovery two days later, an immediate further failure and safe mode, another quick recovery, and finally, permanent failure on May 11.[31] The spacecraft exhibited an attitude error, consistent with a reaction wheel problem; it was oriented with solar panels facing the Sun, and slowly spinning about the sunline. Communications with Earth came and went depending on the orientation of the spacecraft.

Engineers had developed "thruster controlled safe mode" earlier in the year to mitigate the risk of a lower-level safe mode called "emergency mode control" (EMC).[32] If the solar-powered spacecraft lost the ability to maintain attitude, there were two opposing, catastrophic sun-related problems that imperiled the spacecraft: 1) Kepler could drift out of direct sunlight, eventually entering a negative power balance (i.e., its batteries drained faster than its solar panels charged); and 2) Kepler's telescope boresight—through which it actually detected exoplanets—could drift into direct sunlight, which would permanently damage the photometer. (The photometer's sensitivity was analogous to looking at the Rose Bowl from the Goodyear blimp, and detecting every time just one person walked in or out of the stadium.)[33]

By firing thrusters to maintain positive attitude control, EMC would prevent those two conditions from occurring, saving the spacecraft at a penalty: Kepler would be unable to return much telemetry, and mission operations on Earth would only be able to send the spacecraft a few commands. It would also quickly exhaust Kepler's fuel. As such, engineers sought to avoid reaching that level of peril at all costs.[34] It was meant to be an extremely short-term crisis mitigation strategy, and a last line of defense. Faced with the impending failure of reaction wheel 4, this last line of defense was suddenly becoming the status quo. In January 2013, the Ball operations team began devising new thruster-only strategies that could keep Kepler alive and outside of EMC.

On April 12, they enabled thruster-controlled safe mode.[35] Similar to normal safe mode, it used half the thrusters of EMC and kept the spacecraft solar arrays in sunlight and the photometer out of it. Its implementation was straightforward; conventional safe mode used reaction wheels to point the spacecraft at the Sun. Engineers simply told the spacecraft to use thrusters 5 through 8 instead.

Still, the system was inefficient; if triggered after the loss of reaction wheel 4, the remaining mission life would be reduced to less than 90 days. What was needed was a completely new spacecraft mode. To that end the Kepler Attitude Determination and Control Subsystem team at Ball quickly devised an ingenious strategy called Point Rest State (PRS), which leveraged the influence of the Sun on the spacecraft.[36]

Sunlight, though massless, has momentum. When photons strike an object, they transfer some of that momentum to the object. The momentum transfer is called radiation pressure. It is an extremely weak force, but in the vacuum of space, without any counteractions, can be significant. PRS worked by letting the Sun push against the spacecraft in a way that helped control its movement. Rather than constant thruster burn, thrusters only fired occasionally to push back in quick, small bursts. This solution conserved fuel, enabled continuous connection with the Deep Space Network, and leveraged existing software.

"The team began using the spacecraft in ways that were only meant for development and integration testing," wrote Kepler engineers in a 2014 paper.[37] "Yet, the architecture made all this possible without a single costly flight software update."

On May 14, when the Kepler mission team learned the spacecraft was in Thruster-Controlled Safe Mode (TCSM), they decided to activate PRS the following day. In addition, they optimized the TCSM as a new mode: Fuel-Efficient TCSM (FETCSM), causing a 50 percent savings in fuel burn when triggered. They uploaded FETCSM two months later.[38]

In all, these optimizations bought the Kepler spacecraft several years, if necessary, for the science and engineering teams to develop a new course of action. Their experiences manipulating the spacecraft even in its impaired state gave them hope that perhaps there were a few other things that might be possible, even with only two remaining reaction wheels.

Regardless, unable to maintain its stability, the telescope could no longer do its job. "A half-billion-dollar mission hinged on such a small part," wrote Jason Steffen, a member of the Kepler science team, describing his thinking at the time.[39] "How much more would it have cost to have two spare reaction wheels instead of just one?" Knowing that Kepler had enough hydrazine in its tanks to last through the end of the decade, and knowing the science lost and careers that were depending on the mission's success—its loss left a pit in his stomach.

The project scientist of the mission received condolences and best-wishes letters from people around the world.[40] Members of the Kepler team began sharing the news widely. Spacecraft science operations for the Kepler mission as conceived and extended were over. Kepler, it seemed, was dead.[41]

JANUARY 14
Passage of federal appropriations act for 2014 includes support for the Discovery program.

CHAPTER 4

2014

APRIL 17
Kepler's discovery of Kepler-186f, a potentially rocky planet in the habitable zone of its sun, reported.

MAY 30
K2 mission begins, repurposing Kepler for a new mission using solar pressure for stability.

When Congress passed the 1,500-page omnibus, titled "Consolidated Appropriations Act for 2014," on January 14 of that year, buried deep inside its companion explanatory statement were a few directives to NASA about how the agency's $17.7 billion should be spent. Among them was the passage:

> NASA shall use the funds provided for the Discovery program to support extended operations for the Messenger program and to increase the tempo by which Announcements of Opportunity (AOs) are released and missions are selected from those AOs. NASA is encouraged to initiate a new Discovery AO no later than May 1, 2014 with final phase two selection and award of one or more missions by September, 2015.[1]

NOVEMBER 5
Discovery Program Announcement of Opportunity released.

DECEMBER
NASA forms the Planetary Missions Program Office to bring the Discovery, New Frontiers and Solar System Exploration missions into a common management system.

It was an attempt by Congress to get the Discovery Program back on its mission cadence. When conceived, the objective of the program was to launch annually and release AOs for

PI-led, cost-capped, focused science missions every 12 to 18 months. From selection, projects had a maximum of three years to reach the launch pad. Spacecraft instrument payloads were to be mature and minimized. A mission that ran over budget or behind schedule would be terminated.[2]

The agency directed the first two Discovery missions, NEAR and Pathfinder, in 1993, and subsequently released AOs every 20 months, on average, through the turn of the millennium, in each instance selecting missions in pairs. In that time, missions launched on average just under once a year. However, after announcing Dawn and Kepler—two missions with tortured development phases—NASA lost its footing with respect to AO cadence. Nearly six years separated the AO yielding

Table 6. Announcements of Opportunities.

AO Solicitation	AO Date	AO Separation	Selection(s)	Date Selected	Launch Date
N/A	N/A	N/A	NEAR	N/A (Funded Oct. 28, 1993)	Feb. 17, 1996
			Pathfinder	N/A (Funded Oct. 28, 1993)	Dec. 4, 1996
AO-94-OSS-03	Aug. 4, 1994	280 days	Lunar Prospector	Feb. 28, 1995	Jan. 7, 1998
			Stardust	Nov. 22, 1995	Feb. 7, 1999
AO-96-OSS-02	Sept. 20, 1996	778 days	Genesis	Oct. 21, 1997	Aug. 8, 2001
			CONTOUR	Oct. 21, 1997	July 3, 2002
AO-98-OSS-04	Mar. 31, 1998	557 days	MESSENGER	July 7, 1999	Aug. 3, 2004
			Deep Impact	July 7, 1999	Jan. 12, 2005
AO 00-OSS-02	May 19, 2000	780 days	Dawn	Dec. 21, 2001	Sept. 27, 2007
			Kepler	Dec. 21, 2001	Mar. 7, 2009
NNH04ZSS002O	Apr. 16, 2004	1428 days	None	N/A	N/A
NNH06ZDA001O	Jan. 3, 2006	627 days	EPOXI (MoO)	July 3, 2007	N/A
			Stardust-NExT (MoO)	July 3, 2007	N/A
			GRAIL	Dec. 10, 2007	Sept. 10, 2011
NNH10ZDA007O	June 7, 2010	1616 days	InSight	Aug. 20, 2012	May 5, 2018
NNH14ZDA014O	Nov. 5, 2014	1612 days	Lucy	Jan. 4, 2017	Oct. 16, 2021
			Psyche	Jan. 4, 2017	Oct. 13, 2023
NNH19ZDA010O	Apr. 1, 2019	1608 days	DAVINCI	June 2, 2021	TBD
			VERITAS	June 2, 2021	TBD

those two missions from the next, which was GRAIL—the first single-mission Discovery selection. (NASA Headquarters chose none of the 18 proposals submitted to the 2004 AO, investing that money instead to "solve funding problems with Deep Impact, Stardust, and Kepler.")[3] Four years later, NASA released the AO that bore InSight, which was another single-mission selection. Launch schedules, however, remained as envisioned: there had never been more than two (calendar) years between a Discovery mission launch.[4] From the perspective of Congressional appropriators hoping to get NASA back on track, even if Mars InSight launched on schedule, five years would elapse between launches. But of course, it didn't.

INSIGHT IMPERILED

As 2013 drew to a close, at Jet Propulsion Laboratory, engineers on the InSight mission were starting to get an inkling that something was very, very wrong.[5] By May 2014, inklings had grown into serious concerns. Specifically, they were worried about the Seismic Experiment for Interior Structure (SEIS), the seismometer and primary science instrument of the lander, provided to the team by the French space agency, Centre National d'Études Spatiales (CNES).

"I started to have regular calls with the project manager from CNES," said Tom Hoffman, who was previously the deputy project manager of GRAIL, and then the project manager of InSight.[6] Maybe, he thought, "we should send some folks to the Paris area and kind of embed them with Sodern and IPGP." Sodern was the company developing the SEIS as the industry partner, while the Institut de Physique du Globe de Paris (IPGP) was the Parisian research institute essentially running the contract.

The seismometer for InSight was two seismometers in one. There was the "very broadband (VBB) seismometer," which was a three-pendulum design from IPGP (and "the most sensitive seismometer ever built for use in space exploration," able to detect ground motions "smaller than the size of a single hydrogen atom.")[7] There was also a system of three short-period (SP) seismometers: coin-sized sensors sensitive to seismic waves, designed and built by Oxford University and Imperial College London. Meanwhile, the electronics were made by ETH Zurich, the Swiss public research university; while the leveling system—which placed the seismometer on the Martian surface as flat and horizontally as possible—was made by the German space agency, Deutsches Zentrum für Luft- und Raumfahrt (DLR). CNES managed the overall project for the Europeans.[8]

Hoffman thought someone like Ken Hurst, the instrument engineer for SEIS at JPL, could embed with Sodern and IPGP. CNES pushed back on Hoffman's request, however, in part because CNES themselves didn't have anybody there, and certainly

didn't want JPL people meddling without CNES personnel present. That wasn't an unreasonable position, Hoffman had to admit. There was also a certain pride among the European engineers that it was *their* job—not JPL's—to deliver the instrument.

NASA had worked with international partners almost since the agency's inception.[9] InSight was the rare example, however, where a NASA mission depended entirely on foreign space agencies to deliver science hardware without which the mission could not achieve its minimum requirements, and therefore, without which the mission could not launch. InSight was a complex mission with a sophisticated instrument payload, and the NASA Office of International and Interagency Relations (OIIR) was not the only federal office involved in said negotiations and agreements.

A federal process called "C-175" drives the review, negotiation, and approval of international agreements involving NASA.[10] As the NASA Office of the Inspector General described in a 2016 report, the C-175 process "requires coordination with the interagency community, approval by State, and is rarely completed within established timeframes."[11] Particularly at the time NASA was hammering out the details with the European Space Agency, the system was fraught with inefficiencies; the State Department had limited staff available for the process, and only a single legal officer to review NASA agreements.[12] (Among the other federal agencies brought into the C-175 process are the Office of Science and Technology Policy, the Office of Management and Budget, the Office of the U.S. Trade Representative, and anyone else with relevant interest in the project.) Though government officials designed the process to take about 20 days, start to finish, at the time of InSight's C-175 process, the NASA OIIR submitted more than 80 agreement packages to the State Department for review; most took months on average, and some took years. The InSight implementing agreement between NASA and the German space agency alone took about 10 months for negotiation and finalization.[13]

Frustrating though that process could be, it was relatively easy from the project-level perspective. It was the day-to-day interaction between InSight mission management and foreign partners that proved most difficult. There was a learning curve to working with CNES and the European Space Agency. ESA was not known for strict adherence to launch schedules, a result, Hoffman felt, of their fixed-price contracts with the firms charged with delivering spacecraft hardware.[14]

"There was some aspect of surprise, almost, from contractors like Sodern that we were actually serious about trying to make a 2016 launch," said Hoffman.[15] "It was like, 'Well, we didn't think you were actually going to make it, so we didn't really put in the kind of effort that we would need to make it, because we figured everything slips, and we figured you were just going to slip.'" This vexed and annoyed Hoffman, and he "read them the riot act endlessly about the fact that that's not the case," he said.

He estimated that the lax schedule in Paris "certainly" contributed to InSight losing six months in the beginning portion of the project—a fact he didn't fully appreciate until that half-year was gone. "People just weren't working as hard as they could have or should have," he said. He learned that on Wednesdays, mothers with young children stayed home to watch the kids. "It's just a known thing," he said—a "built-in inefficiency." There was also a government-mandated two-week vacation during the summer. Hoffman had to work with the education minister of France to get an exemption, lest the company be fined by the government. Workers in Toulouse had to badge in and out of the cafeteria to ensure they had at least a full hour at lunch. At Sodern, there was an inflexible tradition of having barbecues on Wednesdays, with beer in the afternoon, meaning that no work could get done after 10 in the morning, because you don't want tipsy engineers touching flight hardware. Working with foreign partners for key spacecraft instruments was a geopolitical and cultural complication for which the InSight team in the United States was not fully prepared. "It was just fascinating, fascinating culturally," said Hoffman, laughing. "Irritating as a project manager for a planetary mission, but it was very interesting."

There was a deeply valuable management lesson in the experience: The standard American measurement of productivity was not universal; understanding the cultural expectations of international partners with respect to productivity—and developing strategies to motivate them in service of meeting a launch window—was essential. This was especially important when the partner was delivering a "free" piece of hardware for a spacecraft. In such a situation, a project cannot induce productivity by threatening to withhold payment; there is no payment to withhold. Rather, one strategy Hoffman employed, was appealing to pride, whether nationalistic, or professional.

To break the deadlock with the Europeans over whether JPL personnel would be welcome in France, Hoffman worked up the chain of command at JPL, including Firouz Naderi, the director of Solar System Exploration at JPL, and his deputy, Keyur Patel. They, in turn, communicated with Charles Elachi, the director of JPL. By July, when JPL had not received promised hardware, senior leadership managed to get Hurst embedded in France with the engineering teams.

Hurst was most concerned about the VBBs, because they were extremely complex, hand-assembled electro-mechanical devices, and could not be descoped by the project.[16] Right away, he discovered a problem with particulate contamination in the seismometer. To help remedy this, JPL sent over Mission Assurance personnel experienced in particulate control, and they rewrote clean room procedures. Engineers also worked to redesign instrument components to be less susceptible to contamination. Working the problem yielded a better collaboration between JPL, CNES, Sodern, and IPGP—within the limitations of the U.S. government's

International Traffic in Arms Regulations (ITAR, concerned with the control the export of defense and military technologies), at least.[17]

Though the particulate problem was solved, the VBBs Sodern delivered still did not meet requirements. Each performed in perplexing, idiosyncratic ways. This led engineers to the pivot—the heart of the seismometer that allowed the pendulum to move—which seemed to exhibit "nonlinear behavior." This, JPL and Sodern engineers later discovered, was because the elements of it were being deformed and buckling due to inconsistently applied torque during installation.

Such insight didn't come easily. Arriving at both the problem and the solution necessitated extensive modeling, as well as the redesign of certain parts, and adjustments in the assembly techniques employed, which included reducing the installation torque, to achieve the desired, consistent response for accurate seismic measurements. "We got that right eventually, and it worked, but it was a long road, a lot of hours of modeling and a lot of debate back and forth about what's going on," said Hurst.[18]

One of the selling points of the InSight mission was that its technical risk was low; the spacecraft had high heritage in the Mars Phoenix lander. The instrument deployment arm that would place the seismometer and heat flow sensor was derived from the arm that flew on the ill-fated Mars Polar Lander. Even the seismometer had heritage with Russian Mars 96 and French NetLander missions.[19] It had never flown to Mars, however.

"Even though we thought and we advertised that we had a seismometer that was basically ready to go, it turned out that it was not ready to go," said Banerdt.[20] "But I will tell you—and I think I've told other people who believe otherwise—that we were absolutely truthful in our proposal. We thought that we had it in hand." The InSight team believed they were just a step away from building a seismometer that was going to perform at the level promised. "It was as big a shock to me as it was to everybody else when it didn't."[21]

Regardless, as the team would soon learn, the seismometer woes were just beginning.

K2

In Spring 2014, the Astrophysics Division of NASA's Science Mission Directorate held a senior review of operating missions in order to maximize potential science return in a constrained fiscal environment.[22] (Astrophysics had assumed fiscal responsibility for Kepler during the mission's development, though the Discovery and New Frontiers Program Office would continue its management.)[23] The process emerged from a Congressional directive in the NASA Authorization Act of 2005 to

"determine the appropriate balance between supporting the operation of existing facilities and supporting the design, development, and eventual operation of new facilities."[24] It was the highest level peer-review process in the division, held every two years.[25] NASA Headquarters asked the Kepler team for ideas about what, if anything, they might be able to do with their moribund spacecraft.[26] In turn, the Kepler Science Office issued a call for white papers to solicit the astrophysics community "for alternate science investigations that may be performed using Kepler and are consistent with its probable two-wheel performance."[27] As Jason Steffen recalled, the announcement basically asked the community: "If we were to give you control of a slightly defective six-hundred-million-dollar telescope, what would you do with it? Oh, we need your proposals, in writing, in one month. Oh, and you're competing for money against Hubble, and Spitzer, and Chandra, and Fermi, and…"[28]

At the senior review, the Kepler team presented panelists with a way forward for the ailing spacecraft.[29] They noted that the two remaining reaction wheels showed no sign of wear, and aside from losing two of the photometer's 42 charge-coupled devices (which captured and measured the light from stars in Kepler's field of view), the spacecraft had shown little performance degradation, and still had fuel.[30] They could adapt to the loss by using solar radiation pressure to stabilize the spacecraft's roll axis, with the remaining two functional wheels controlling the pitch and yaw axes. The spacecraft would fire thrusters periodically to manage momentum. They would point Kepler toward the ecliptic—the imaginary plane created by Earth's orbit around the Sun—and would observe a series of interesting and well-characterized fields-of-view for long periods as the spacecraft circled the Sun. Pointing at the ecliptic allowed sunlight to hit the spacecraft relatively evenly, minimizing the torque from solar radiation pressure. It also allowed high-precision photometric monitoring across a range of galactic latitudes. Their plan minimized operational changes from the Kepler mission and used the same data processing infrastructure (modified only to accommodate the larger pointing drift and consequent artifacts). They would get less than a tenth of the data of Kepler, but that still meant around 10,000 targets annually.[31] They wouldn't even need to change the flight software. The team had tested the process. It worked.

To distinguish this inventive extended mission from its predecessor, they called it K2. It was a second Kepler mission, with two reaction wheels, analogous in challenge to the mountain peak of the same name. The science goals of K2 were to:

- Provide a yield of hot planets around bright stars for follow-up transit spectroscopy to facilitate rapid advances in the characterization of exoplanet atmospheres.

- Provide a yield of small planets around bright, small stars to facilitate the most precise follow-up measurements to date of masses, densities and compositions.
- Identify locations and characteristics of potentially habitable planets around bright M-dwarfs in the solar neighborhood.
- Determine if hot gas giants exist around young stars, or whether they migrate to small orbits at a later epoch by tidal or other interactions.
- Determine the relationship between stellar structure, rotation and activity within stellar associations over a range of ages and metallicity.
- Identify the progenitors of Type Ia supernovae from photometric structure in the rise to outburst maximum.
- Discover and characterize binary stars within open clusters and stellar associations.
- Characterize internal stellar structure and fundamental properties of stars using the tools of asteroseismology.
- Provide a large, regular cadence survey of active galactic nuclei activity in the optical bandpass.
- Participate in multi-mission, multi-band monitoring campaigns of ecliptic targets along with other space-based hardware or ground-based telescopes.[32]

The senior review endorsed the mission; indeed, it was the highest ranked proposal.[33] On May 16, 2014, NASA Headquarters approved it.[34] After a shakedown campaign to find problems with the new way of operating the spacecraft, the K2 team planned to begin the first K2 science observation run on May 30.

Kepler had made international news weeks earlier with the announcement that the telescope had found the first validated Earth-size planet in the habitable zone of another star—Kepler-186f. "It has the right size and is at the right distance to have properties similar to our home planet," said Elisa V. Quintana of the SETI Institute and NASA Ames Research Center, who was lead author on the paper describing the discovery in the journal *Science*.[35] It wasn't a perfect duplicate of Earth. It was 10 percent larger than our planet, with a year 130 days long. The brightness of its star at high noon would appear about as bright as Earth's Sun just before sunset.[36] ("Perhaps it's more of an Earth cousin than an Earth twin," said Thomas S. Barclay of the Bay Area Environmental Research Institute, who coauthored the paper.)[37] It was a high-profile validation of the data collected by Kepler, which had by then yielded nearly 1,000 confirmed planets, with just under 3,000 planet candidates awaiting analysis.

AT LAST, AN ANNOUNCEMENT OF OPPORTUNITY

NASA missed its Congressionally mandated deadline for a Discovery AO by six months—but it did make the calendar year cutoff.[38] On November 5, 2014, NASA Headquarters issued its solicitation for mission proposals, with a $450 million cost cap for phases A through D, excluding the rocket. The selected mission would launch by December 31, 2021. There were some big changes with this latest AO, among them:

- The value of foreign instrument contributions was limited to one-third of the PI-managed instrument cost;
- NASA would furnish only a standard launch capability; a mission that needed higher performance or a larger payload fairing would have to find the money to pay for it;
- Conversely, using a smaller launch vehicle would increase the effective cost cap;
- Proposals no longer had to contend with Phase E and F costs (excluding ground or flight system software development).[39]

Missions to Mars were allowed.[40] Missions studying exoplanets were not—they were the bailiwick of astrophysics. Proposals would be due mid-February 2015. As for previous Discovery competitions, there would be a two-step process; NASA Headquarters would narrow the initial batch of proposals to three for "phase A" studies, and from there, choose one or more for phase B.

All this would happen under a change implemented two weeks before the close of 2014, as part of the annual federal budget process, when President Barack Obama signed into law the NASA appropriations for 2015, allocating $1.4 billion to planetary missions.[41] The appropriation provided the necessary funding for NASA to implement internal restructurings, among them: the Planetary Missions Program Office at Marshall Space Flight Center in Huntsville, Alabama. As part of a strategic reorganization within the SMD, the office would bring together the Discovery and New Frontiers Program Office (itself a previous merging of two separate such offices: the Discovery Program Office and the New Frontiers Program Office, in 2004), which concerned small and medium-class, PI-led missions; and the newly-formed Solar System Exploration Program, responsible for large, directed missions—particularly the Europa Clipper flagship mission, and the NASA instruments for the European Space Agency's Jupiter Icy Moons Explorer (JUICE) mission.[42] The Planetary Missions Program Office would manage those programs in a streamlined way, and make contributions to problem-solving and decision-making, offering technical expertise when needed.[43] Because Marshall as a NASA center

was primarily concerned with human spaceflight, it didn't have any equities in any of the decisions being made; personnel there could be fair arbiters. As Todd May, the first head of the Discovery and New Frontiers Program Office explained, "We wanted to focus our energies almost entirely on enabling and supporting the success of these project teams. We strove for trust and mutual respect, not control."[44]

Program offices were located at NASA centers rather than NASA Headquarters because of early decisions by Dan Goldin, who was appointed NASA Administrator in 1992, to streamline the agency as part of President Bill Clinton's initiative to "reinvent government."[45] Previously, NASA Headquarters functions were spread across multiple buildings in Washington, DC, which posed challenges for coordination and efficiency. To consolidate NASA Headquarters into a single building, located at 300 E. Street, the agency moved certain functions—including program offices—to various centers across the country.

In practice, mission program offices existed as extensions of NASA Headquarters. The Planetary Missions Program Office at Marshall interfaced with NASA Headquarters through weekly tag-ups between the program manager in Huntsville and the lead Discovery program scientist and Discovery program executive in Washington, DC. In addition, each mission under the aegis of the Planetary Missions Program Office (PMPO) had a manager at Marshall who communicated on a weekly, and sometimes daily bases with the corresponding NASA Headquarters program scientist and program executive assigned to the respective mission. They addressed everything from ongoing management issues to mission statuses.

The 2014 reorganization, which manifested fully the following year, was in part a response to recommendations in the 2011 Planetary Science Decadal Survey, which encouraged a balanced exploration program and steady cadence of missions, and NASA's Strategic Plan, released in 2014, which sought strengthened program management and oversight and the centralization of functions to improve efficiency.[46]

Notably, the PMPO did not have a role to play in writing the 2014 Discovery AO. The interaction consisted primarily of Michael New, the Discovery Program Scientist at the time, and other NASA Headquarters interests, consulting with the program office for insight on things that they felt worked or didn't work with other missions. The execution of the Discovery competition, including the evaluation of the proposals and eventual mission selection, happened exclusively at NASA Headquarters.[47]

JANUARY 13
Dawn's images of Ceres reveal a white spot in its northern hemisphere.

FEBRUARY 18
Proposals to 2014 Announcement of Opportunity due.

MARCH 6
Dawn enters orbit around Ceres.

APRIL 30
MESSENGER impacts Mercury at end of its mission.

SEPTEMBER 30
NASA announces the 5 missions downselected from 27 submissions to the 2014 Announcement of Opportunity.

CHAPTER 5

2015

Lindy Elkins-Tanton, the principal investigator of a proposal for a mission called Psyche, was competing against 26 other teams for the Discovery competition announced in 2014. She did this while beginning a new job as the director of the School of Earth and Space Exploration at Arizona State University (ASU) and undergoing treatment for ovarian cancer.[1] Chemotherapy sessions kept her in a state of exhaustion and caused brain fog. She worked determinedly in the hours when she had energy and clarity. Her role on the Step 1 proposal, which eventually weighed in at 218 pages, involved writing the expansive science section and coordinating the overall document.

She had come to the project by way of research into planetary differentiation she had presented in 2011.[2] Bruce Bills and Daniel Wenkert, two researchers at NASA's Jet Propulsion Laboratory in California, invited Elkins-Tanton and others involved in her research to the lab's Innovation Foundry, which develops mission concepts.[3]

While discussing potential targets of exploration, they considered recently broken-up, differentiated asteroids so that a spacecraft could get a good look at its silicate outer parts and metallic inner parts, but the technical risks associated with such a mission (to say nothing of the fact that there was no such known family of asteroids in existence) meant that they had to lower their sights to asteroids with exposed metallic insides. They settled on an asteroid called Psyche, which was possibly the metal core of a planetesimal whose rocky exterior had been stripped away eons ago by a collision with another body.[4] Aside from that, virtually nothing was known about that body, which had never been explored.

Interest from the Innovation Foundry didn't mean instant interest from JPL management. Engineers and scientists at, and affiliated with, the lab are constantly devising planetary missions, relatively few of which move forward in development. But by 2013, JPL was sufficiently interested in the Psyche mission that lab leadership assigned David Oh, the former lead flight director for the Mars Science Laboratory, to be the Psyche capture lead. (That role was the equivalent of a project manager, but for a proposal.) He and Elkins-Tanton proceeded to build a proposal team and eventually drew up the mission architecture and the Step 1 proposal document.[5]

An early key decision that Oh and Elkins-Tanton made that drove everything to follow was to work with Space Systems/Loral (SSL, later rebranded as Maxar) as the prime contractor on the project.[6] Oh had worked previously for the company, and was very familiar with their solar electric propulsion technology, which in addition to being highly capable, allowed the Psyche proposal to come in under the Discovery cost cap.[7] JPL management pushed against the choice of SSL, arguing that the company had never been a prime contractor on a NASA deep space mission, but Oh, Elkins-Tanton, and Carol Polanskey, the proposal's incoming project scientist, remained firm.

"We all agreed that Maxar was absolutely our best bet for what we wanted to do," said Elkins-Tanton.[8] The company agreed to a firm fixed-price contract—that is, the company was fully responsible for any overages—which helped Psyche "unbelievably" with the proposal budget. "It saved us a tremendous amount of money over the NASA cost model."[9]

Elkins-Tanton also made the early decision to settle on the spacecraft's instrument payload before inviting investigators into the proposal. "A common thing that happens is that people invite on to the science team people who make instruments, and then those people lobby hard for their instruments to be put on the spacecraft, whether or not they are really the right choice," she explained. For Step 1, they chose imagers led by Jim Bell, a planetary scientist at ASU, and built in concert with Malin Space Science Systems; a magnetometer built by the University of California, Los Angeles (though they later changed this instrument); a gamma ray and neutron

spectrometer led by physicist David Lawrence of APL; and a gravity science investigation performed with Doppler radio and the spacecraft, led by Maria Zuber at MIT.[10] From the start, said Elkins-Tanton, the Psyche team's philosophy was to build the "absolute simplest spacecraft that we could possibly build, that would do exactly the science that we needed."[11]

That goal was a lot harder than it might have seemed at first glance. Explained Oh, "There were a lot of reasons to put, for example, a laser altimeter on, and there was a lot of discussion about whether we should have one, and it would have added tens of millions of dollars to the cost of the proposal, and there were people who felt passionately that we should have one."[12] Elkins-Tanton and the science team had to make hard decisions about what the mission didn't need, and cut ruthlessly. "That actually impressed me a lot with Lindy from the very beginning," Oh said, "because she was willing to make the difficult choices to make the mission fit the strategy."[13]

Moreover, the science team had to make such decisions without a budget to do so. While JPL had funds to pay its staff to work on the proposal, and Maxar did as well, on the academic side—critical to the proposal's success—there was no funding for the Step 1 proposal process. "It's very expensive and really difficult," said Elkins-Tanton.[14]

The Step 1 proposal submitted by the Psyche team at the start of 2015 began with the usual export control warnings and opened with a two-page graphic "story" of the mission.[15] From there, the text described the proposed science investigations and the instrument payload that would make it happen. It explained the measurements necessary to achieve the science goals, how the spacecraft would work, and the data to be returned to Earth. It described the anticipated orbits around the asteroid, how they would build the spacecraft, management methodologies, how much it would all cost, and an explanation for where those numbers came from. It was an exhaustive, exhausting endeavor, and no one really expected to ever get beyond that Step 1 proposal.[16] First time efforts rarely did, and moreover, she was a first-time PI working with a first-time prime partner and using a nonstandard cost model. Moreover, ASU had never been the lead institution on a Discovery mission before.[17] In a sense, however, that was par for the course. A colleague of David Lawrence was once asked what planetary scientists do for a living, and he replied, "Well, I write losing proposals."[18]

But not this time—or at least, not yet. On September 15, 2015, Elkins-Tanton received a phone call.[19] Psyche was moving on to Step 2. NASA announced the down-selected missions in a press release later that day. The final five were:

- Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI), a Venus atmosphere entry probe, developed by NASA Goddard Space Flight Center;

- Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy mission (VERITAS), a radar mapper of Venus, developed by JPL;
- Psyche, to explore for the largest known metallic asteroid in the solar system, developed by JPL;
- Near Earth Object Camera (NEOCam), a spacecraft designed to find potentially hazardous objects near Earth, developed by JPL; and
- Lucy, a probe to the Trojan asteroids along Jupiter's orbital path, developed by the Southwest Research Institute with Goddard Space Flight Center.[20]

"The selected investigations have the potential to reveal much about the formation of our solar system and its dynamic processes," said John Grunsfeld, the associate administrator for the Science Mission Directorate at NASA Headquarters, in the press release.[21]

NASA would allocate $3 million to each study.[22] On the outset, Elkins-Tanton and Oh were thrilled by the funding finally coming their way, planning things like test beds and demos, but Gentry Lee, the famed chief engineer for the Solar System Exploration Directorate at JPL, was quick to throw cold water on their plans. They weren't so flush with cash as it seemed.

"Three million isn't anywhere enough," he said.[23] It was going to take at least five million dollars to do Step 2. And it would be a far more intense process than what they had just done. As he explained, "It's the proposal you've written already, but with every single detail worked out and supported. It's the Step 1 proposal, only an order of magnitude bigger."[24] They also had to address the Step 1 proposal's shortcomings. The review panels had posed one big challenge to the Psyche team that Step 2 would have to address: If no one really knows what the asteroid Psyche is, and no one has ever seen its surface, how can a mission propose and test legitimate hypotheses?[25]

That, said Elkins-Tanton, was "a very, very challenging question." In comparison, for example, for an outer planets moon mission, you at least knew for certain that it was a small body made largely of ice. "That gives you a really good starting point—even more than what we have for Psyche." Missions to better-studied worlds allowed for extremely targeted hypotheses and high precision on what the data improvement would be. Psyche would be a true Discovery mission in every sense. The working assumption was that the asteroid was metal-rich—as much as 90 percent iron-nickel metal. If so, it would be an object unlike anything else ever explored in the solar system. It also increased the importance of the spacecraft's gamma ray and neutron spectrometer, which would be the first instrument to give such an indication (or whether, conversely, it was a more silicate-based body similar to the Moon and other planetary objects).[26]

PROPOSING PSYCHE'S SPECTROMETER

When David Lawrence of APL helped write the spectrometer proposal, he focused on the idea that the gamma rays and neutrons would respond in a very different manner for a metal-rich body than an object like Mars. To that end, they added a third sensor to the neutron spectrometer to handle some different energy neutrons. They targeted the instrument toward the case of the metal world.

Lawrence had a deep background in such an instrument. He went to APL after more than a decade at Los Alamos National Laboratory, where he also worked on space missions. Like many in planetary science, before building robotic spacecraft for a living, he wanted to be an astronaut. Born in 1968, the Apollo program was a formative part of his youth. As a child, he wrote to NASA, and to his utter delight, the agency sent him drawings and glossy photos of the Apollo spacecraft. He amassed a whole collection of such memorabilia. It energized him, as such public outreach efforts from the agency inspired so many.[27] Alas, to be an astronaut, the best path at the time was to first be a test pilot: a job he would never have because of poor eyesight.[28] But if he became a scientist, there was at least a possibility that he would one day get to space. So, he did. In his early 20s, while an intern at Sandia National Labs, he even cold-called Harrison "Jack" Schmitt, who was an astronaut on Apollo 17. To his astonishment, Schmitt answered the phone.

"I want to be an astronaut," Lawrence said.[29] "Do you have any advice?"

He expected the spaceflight legend to get off the phone as quickly as possible. Instead, to his greater astonishment yet, Schmitt said: "Sure, let's go to breakfast."

When they met, the two men spoke for two hours. Schmitt agreed with the advice Lawrence had long received: space science was the way forward, but the astronaut gave another bit of advice: "Definitely work *with* NASA, not *for* NASA." The agency's bureaucracy might hold him back.

Lawrence followed that advice. In the end, he applied twice for astronaut selection but was never chosen. Still, his pursuit led him to Los Alamos, where he was eventually invited to help work on the design for MESSENGER's neutron spectrometer. After the mission launched, APL hired Lawrence to help lead the lab's efforts to build other gamma-ray and neutron spectroscopy (GRNS) instruments.

The GRNS flown on MESSENGER was designed to determine the chemical composition of airless (and nearly airless) bodies.[30] Cosmic rays and high-energy particles were constantly impacting the surfaces of celestial objects, and the elements composing the surface material absorbed the energy, in turn emitting neutrons and gamma rays with signature properties. The spectrometer detected them.[31]

When it was proposed, the MESSENGER spectrometer was something of a gamble. It would use high purity germanium detectors, which would provide exceptional energy resolution—crucial for accurately identifying and measuring the

energy of gamma rays.[32] The catch was that because of Mercury's proximity to the Sun, the germanium would need to be mechanically cooled to cryogenic temperatures, which was something no space mission had done before.[33] This went to the heart of a constant tension in spacecraft development. Spacecraft managers valued low-risk, flight-proven technologies above all—but innovation was also essential; after all, every flight-proven instrument was once a gamble. "You need to be able to be light enough on your feet to do both the new stuff when you need to and be wise enough to stick to the old stuff when it makes sense," said Lawrence.[34]

But MESSENGER's success by then made the spectrometer not only flight-proven, but revolutionary; its measurements of Mercury's composition were key to the discovery that the planet is volatile-rich, which ruled out several models of its formation and early history.[35] It also helped confirm the water ice deposits at Mercury's north pole: two of the most important science results of the mission.[36]

The Psyche team invited thus members of the MESSENGER gamma ray and neutron spectrometer team to help develop the same instrument for the asteroid mission. "MESSENGER sought to perform the first-ever orbital investigation of an unexplored world with an anomalously high density." Lawrence explained.[37] "Interestingly, this goal applies equally to Psyche." Lawrence and the team used the GRNS from MESSENGER as a starting point, but sought to iterate on several of its components, whose design by then was 15 years old. They had been researching improvements with funding from a NASA program called MatISSE: Maturation of Instruments for Solar System Exploration, which funds the advanced development of promising spacecraft instruments for future missions (typically $1 million per year for three years).[38] The Psyche proposal process allowed them to put a lot of that MatISSE development into practice. Among the improvements they sought to make was the energy resolution of the GNRS, which determined the fineness of gamma-ray peaks that can be identified, the main metric for gamma-ray spectrometers.[39] Where the energy resolution of the Mercury mission's instrument was 5 kilo-electronvolts (keV), for Psyche, the team wanted a significantly higher resolution of 2 keV, which was the sort of performance found in Earth-based laboratories.[40]

THE DOWN-SELECT

NASA would select one or more mission for flight one year from the announcement of the down-select: September 2016. As a rule, once NASA Headquarters selected its five missions for Phase A concept studies, the Planetary Missions Program Office would enter the picture.[41] The common practice was for the technical, management, and cost evaluation (TMC) team that had evaluated the proposals to go down to Marshall Space Flight Center to give the PMPO a day or two of presentations on

the evaluations of the missions: what the TMC thought were the major risks of each mission.[42]

At the Phase A study kickoff, NASA Headquarters would explain to the leadership of the down-selected missions the rules of the competition, the nuts-and-bolts of things such as launch services, and the myriad requirements that each Concept Study Report—the culminating product of Step 2—should address.[43] That meeting essentially "started the clock" on the competition, and was generally when the PMPO would meet with the mission teams (now called "concept studies").[44] From that point on, the PMPO would maintain an active involvement in the competition, doing tasks ranging from getting the Phase A contracts written and organized, to working with the concept studies to generate their initial statements of work.[45] A single mission manager would be the point of contact for all the Phase A studies, usually with one or two other mission managers observing the concept study reviews, the eventual TMC evaluations, and ultimately, the site visit: the high-stakes, culminating event of the competition, in which teams would give formal presentations to NASA's professional review committees.

At NASA Headquarters, the associate administrator for the Science Mission Directorate, in consultation with the director of the Planetary Science Division, the Discovery Program Scientist, and other senior science officials, to sometimes include other associate administrators and division directors, would make the final mission selection. At that point, because the PMPO already had a relationship with the selected team (or teams), and knew with intimate detail the mission design and issues raised at site visits, they would be ready for NASA Headquarters to hand off the selected missions.[46] The program office would see them forward in development, beginning an ongoing, daily relationship with the mission or missions.[47]

ALIEN BASES ON CERES?

The inner workings of NASA competitive mission selections were interesting for a certain type of person, but not many. At the start of 2015, a very different Discovery story commanded the public's attention. On January 13, the Dawn spacecraft, approaching Ceres after more than two years and 40 million miles, imaged the dwarf planet on its approach, and found… something.[48] The camera caught a conspicuous white spot apparently flickering in the northern hemisphere of Ceres.[49] The Hubble Space Telescope had previously captured something similar during Ceres observations, but the spot was much less pronounced. Because Dawn's camera could collect enough images for a time lapse animation, the spot seemed alive somehow, and certainly distinct from its surroundings.[50]

"We do not know what the white spot is, but it's certainly intriguing," said Marc Rayman, the Dawn mission director.[51] "In fact, it makes you want to send a spacecraft there to find out," he added cheekily, noting Dawn would be that spacecraft. Subsequent images only added to the mystery. Not only had the spot grown sharper and whiter but set in relief against gloomy gray Ceres and its cratered face, they seemed somehow illuminated. A *Washington Post* headline the following month perfectly captured the development: "That spooky white spot on Ceres? New photos show two of them."[52]

As Dawn learned more about Ceres, said Chris Russell, "we expected to be surprised; we did not expect to be this puzzled."[53] Planetary scientists had no idea what the spots were, so the public took it from there. Was it alien bases emitting light?[54] Interstellar communications probes?[55] Some sort of artificial, high-albedo structures? The hull of a partially buried ship? A white monolith?[56]

Whatever they were, Earth would soon have its answer. At 4:39 a.m. PST on March 6, 2015, the Dawn spacecraft entered orbit around Ceres: the only spacecraft ever to orbit two planetary objects, and the first to orbit a dwarf planet.[57] Rather than a major burn by the ship's propulsion system, Dawn had spent the previous two and a half years propelled gently by its ion engine. When it left Vesta, it made its orbit around the Sun more and more like that of Ceres. When it arrived, the two were flying essentially in formation, differing in speed only by one hundred miles per hour. When Dawn was about 37,700 miles above its surface, the gravity of Ceres took hold, and orbit was achieved. As Rayman explained, "it would not have looked much different from the 1,885 days of ion thrust that had preceded it."[58] Unlike most orbital insertions, mission planners had not targeted a specific day for the key event. March 6 just happened to be when Dawn achieved orbit. Most members of the flight team were at home asleep when it happened.[59]

Over the next several months, the spacecraft would spiral nearer and nearer to Ceres. First it would perform reconnaissance on the dwarf planet from a "survey orbit" of 2,700 miles above the surface. Three weeks later, Dawn would begin its descent to 910 miles: the "high altitude mapping orbit." After two months of observations, it would descend again, now to 230 miles above Ceres, where it would round out the year in a "low altitude mapping orbit."[60]

The science team based the Ceres campaign largely on the successful 16 months at Vesta, with a couple of modifications.[61] First, the loss of two of its four reaction wheel assemblies meant developing a new attitude control mode that used the remaining two wheels, as well as a hydrazine-based reaction control system.[62] They called this "hybrid mode," and would eventually engage it at the low altitude mapping orbit of Ceres. Meanwhile, engineers had to keep a keen eye on the spacecraft's hydrazine supply. To stretch it a bit longer, they eliminated several spacecraft turns

from the operations plan.[63] The second major mission modification was a result of what Dawn would explore after Ceres: nothing. Unlike the Vesta campaign, designed to eventually get the spacecraft to another body, Dawn was never going to leave Ceres, which meant the team had no plans to ever ascend from the lowest altitude orbit.

The overarching science objectives of Dawn at Ceres were the same as at Vesta. The mission would:

1. Capture the earliest moments in the origin of the solar system enabling us to understand the conditions under which these objects formed.
2. Determine the nature of the building blocks from which the terrestrial planets formed, improving our understanding of this formation.
3. Contrast the formation and evolution of two small planets that followed very different evolutionary paths so that we understand what controls that evolution.[64]

The mission's Level 1, 2, 3, and 4 requirements took those objectives, and with increasing specificity and nuance laid out precisely the measurements and techniques necessary to achieve them. To fulfill the mission's Level 1 requirements at Ceres, for example, Dawn would have to:

- Determine the bulk density of Ceres to ≤ 1%.
- Determine the spin axis orientation of Ceres to ≤ 0.5°.
- Determine the gravity field of Ceres with a half-wavelength resolution ≤ 300 km.
- Obtain images of ≥ 80% of the surface of Ceres with a sampling ≤ 200 m/pixel and a signal-to-noise ratio ≥ 50 in the clear filter and in ≥ 3 color filters.
- Obtain a topographic map of ≥ 80% of the surface of Ceres, with a horizontal resolution ≤ 200 m and a vertical resolution ≤ 20 m.
- Measure and map the abundances of major rock-forming elements to a precision ≤ 20% with a resolution ~1.5 times the mapping altitude over the upper ~1 m of the entire surface of Ceres.
- Measure and map the abundance of hydrogen over the upper ~1 m of the entire surface of Ceres.
- Measure and map the abundances of potassium, thorium, and uranium over the upper ~1 m of the entire surface of Ceres.
- Obtain ≥ 8,000 spectral frames of Ceres' surface at wavelengths of 0.25–5 μm with a spectral resolution ≤ 10 nm. At least half of these spectral frames will be at a spatial resolution ≤ 400 m/pixel, with the rest at spatial resolution ≤ 1600 m/pixel.[65]

The first real question that needed answering, though, was the nature of those bright spots. To everyone's disappointment, they weren't illuminated alien cities after all. Rather, data revealed that the brightest clusters, called faculae, were made mostly of sodium carbonate, and located in Occator, a crater 57 miles wide.[66] The impact that created Occator melted salty ice that was present just beneath the surface of Ceres. It also caused fractures that led to a deeper reservoir. Brine percolated from the Cererian interior and evaporated in space, leaving behind a crust of salt.[67]

Beyond that, Ceres was largely terra incognita for the newly arrived spacecraft. The whole world was waiting to be discovered. One of the basic questions the mission would answer was whether Ceres has a moon. As Rayman wrote on his blog for the Planetary Society on March 6—just as he had written previously about Vesta—"as of today, Ceres most certainly does have one. Its name is Dawn!"[68]

"IT'S ALWAYS NICE TO TEAR UP THE TEXTBOOKS"

Elsewhere in the solar system, a spacecraft was about to disappear forever. At 11:15 a.m. Eastern Time on April 30, 2015, the MESSENGER spacecraft returned its final packets of data and images from planet Mercury.[69] From there, it went into "beacon mode"—essentially a kind of robotic heartbeat—and from the mission operations center at APL, Sean Solomon and the rest of the operations team waited. It was just a matter of time: the spacecraft was depleted of fuel. After more than four years and 4,105 orbits, MESSENGER would fly behind Mercury, and impact ultimately near the crater Shakespeare, becoming one of the youngest—and at an estimated 16 meters, one of the smallest—such impact features on Mercury.[70]

MESSENGER was flying on its second extended mission, which began in March 2013 after completion of the first extended mission. Six questions drove XM2, as the second extended mission was called:

1. What active and recent processes have affected Mercury's surface?
2. How has contractional deformation evolved over time?
3. How have compositions of volcanic materials evolved over time?
4. What are the characteristics of volatile sequestration in the north polar region?
5. What are the consequences of precipitating ions and energetic electrons at Mercury?
6. How do the exosphere and magnetosphere respond to extreme conditions near solar maximum?[71]

Moreover, the team sought to discover what novel insights into Mercury's thermal and crustal evolution might be obtained with high-resolution measurements

from low altitudes.[72] These questions and goals emerged both from discoveries made during the first extended mission, and from the projected timing of Mercury events, MESSENGER observations, and the geometry of the spacecraft's final two years in orbit.[73] The team tweaked MESSENGER's orbit four times in its final year of operation to bring it extremely close to Mercury, between 15 and 200 kilometers, letting it gather some of its highest resolution data to date. Over the course of 44 days—the final before impact—the team performed another seven orbital correction maneuvers to mount a "hover campaign" of observations between five and 35 kilometers above the planet's surface.[74]

Just from an operational standpoint, MESSENGER was stacking successes atop one another. Many of its instruments were not designed to collect data at such a close range to Mercury. The camera images had to be corrected for smearing. The laser altimeter had to be placed in a nonstandard mode, and had extra duties, not only measuring topographic heights, but also feeding that data back into the navigation systems to validate and update estimates of where the spacecraft was in its orbit. At such low altitudes, the team feared that Mercury's gravity field would cause trajectory perturbations.[75]

It even used a novel propellant, ejecting helium from the propulsion system for a little extra thrust during the final three orbital maneuvers. Helium was never intended as a spacecraft propellant, used instead to move hydrazine and oxidizer from the fuel tanks into the combustion chamber.[76]

After the projected impact time of 3:26 p.m., the mission operations team continued listening for another 20 minutes.[77] There was small chance that the mission team's calculations were off, and the spacecraft skimmed over a high surface feature rather than colliding with it. Were that the case, it would possibly have emerged for one final orbit.[78] But the heartbeat never returned.

"It was strange to think during that time MESSENGER had already impacted, but we could not confirm it immediately due to the vast distance across space between Mercury and Earth," said Andy Calloway, the mission operations manager at APL.[79]

MESSENGER's great achievement, in a sense, was narrowing that distance between our two worlds. Before the spacecraft arrived at Mercury, the sum of humanity's knowledge about the innermost planet consisted of data from a single probe, Mariner 10, which performed three flybys from March 1974 to March 1975. It was the least-studied planet of the classical solar system, save Pluto. Mariner 10 spacecraft was a phenomenal spacecraft: the first to perform a gravity assist to slingshot between two planets, a technique that would prove foundational for all NASA planetary missions going forward, and the first to return images of Venus up close. It was also the first cost-capped robotic mission in NASA's history, a concept that was

the basis of the Discovery Program just under two decades later.[80] Because planetary scientists knew virtually nothing about Mercury, nearly everything it returned was a first-time discovery: the planet's internal magnetic field, elements composing its atmosphere, and physical characteristics of some surface materials.[81] Still, the limitations of flyby missions, as well as 1970s technology, meant that scientists were left with more questions than answers. The spacecraft managed to image less than half of Mercury, and at relatively low resolutions. Mercury was key to understanding how the terrestrial planets formed and evolved, but the challenges inherent to its solar proximity limited any interest in returning.[82]

MESSENGER changed all that. For Solomon, the most fundamental discovery by the Discovery mission was the composition of Mercury's surface materials—the first time they had ever been measured, as Mariner 10 lacked instrumentation for such a task, and it could not be done remotely from Earth.[83] No confirmed Mercury meteorites had ever been collected.[84] Mercury, scientists knew, was unusually dense relative to other planets of its size, meaning it must have been made mostly of iron. The question was why. Perhaps a giant impact blasted away a rocky exterior, or maybe the temperatures of the circumstellar disc around the early Sun somehow cooked Mercury differently than Venus, Earth, and Mars. Regardless, the hypotheses for terrestrial planet formation depended upon Mercury's volatiles, vulnerable to high temperatures, having long been lost.

Astonishingly, the spectrometers on MESSENGER found high abundances of volatiles and elements easily removed at high temperatures, including sulfur, potassium, sodium, and chlorine. All of which meant scientists really didn't understand how the inner planets formed. "It's always nice to tear up the textbooks and have to rethink some of our basic assumptions," Solomon mused.[85]

Among MESSENGER's other achievements were the revelation of ancient volcanic activity on Mercury, and the confirmation of a northward-offset internal magnetic field; the detection not only of water-ice in the planet's permanently shadowed polar regions, but also significant water in its exosphere. Technologically, MESSENGER captured more than 200,000 orbital images yielding a highly detailed global map and produced a mosaic of the solar system from Mercury's orbit—a counterpart of sorts to Voyager's famed "family portrait."[86] Its second flyby of Venus yielded data on the particle and fields characteristics of the second planet, in coordination with ESA's Venus Express mission. It even imaged two comets during the second extended mission: Comet 2P/Encke and Comet C/2012 S1 (ISON). Put simply, the solar system after MESSENGER was very different from the solar system before. It was, as Ed Weiler said at the time of MESSENGER's selection, "a flagship-quality" mission in a Discovery mission box.[87]

Inside the operations center, Solomon reflected on the 19 years of his life he had dedicated to the mission.[88] The whole history of Mercury had been rewritten, and the hypotheses about its origin and the early eons of the inner solar system were utterly undone. There were hugs and handshakes all around, but it was a bittersweet moment: the successful end of one of the most ambitious missions ever flown by NASA, but also a painful goodbye, like the death of a beloved family member. Nothing could have prepared him completely for that loss.

Table 7. MESSENGER Achievements.

Discovery/Achievement	Details
Surface Composition	Determined Mercury's surface composition, finding high concentrations of magnesium and calcium on the night side.
Geological History	Revealed Mercury's geological history, including evidence of past volcanic activity.
Internal Magnetic Field	Discovered details about Mercury's internal magnetic field, identifying a significant northward offset.
Polar Deposits	Verified Mercury's polar deposits are dominantly water-ice, and found evidence of water ice at poles in permanently shadowed regions
Exosphere	Found large amounts of water in Mercury's exosphere.
Imaging and Mapping	Globally mapped the surface of Mercury in high-resolution monochrome and color, taking the 200,000th orbital image by Feb. 6, 2014.
Comet Observations	Photographed comet 2P/Encke and comet C/2012 S1 (ISON) during the second extended mission.
Coordination with Other Missions	Coordinated particle and fields studies with ESA's Venus Express during the second Venusian flyby.
Solar System Mosaic	Created a mosaic image of the solar system on Feb. 18, 2011, with all planets visible except Uranus and Neptune.

CHAPTER 6

2016

MARCH 9
NASA announces approval for the InSight mission to launch in 2018.

APRIL 7
Kepler is found in emergency mode during a scheduled check-in.

InSight did not launch in 2016.

To achieve a sensitivity necessary to detect ground motions the width of an atom, three of the SEIS instrument's sensors had to be protected from noise from atmospheric particles.[1] To do this, engineers sealed the sensors in a titanium sphere a little larger than a soccer ball, which was then brought to vacuum.

AUGUST 31
NASA gives final approval of the full mission replan for InSight.

Issues with that vacuum would plague the project. In mid-2015, while engineers at Sodern were putting connectors on an engineering version of the sphere, it collapsed: a very bad sign. Later, JPL engineers were testing one of the seismometer sensors, and an incorrectly connected tube caused an inadvertent vacuum.[2] While attempting to extract the sphere from the vacuum chamber equipment, one of Kenneth Hurst's fingers brushed across the top of the sphere. *BANG*. It imploded just like that, scaring everybody half to death.

DECEMBER 15
Scientists announce Dawn's discovery of widespread water ice on Ceres.

It later turned out that the sphere had not undergone a buckling analysis. Perturbations

would cause a collapse. In response, JPL's Division 35—Mechanical Systems Engineering, Fabrication and Test—launched a major, emergency effort to redesign the spheres. They even recruited engineers at Marshall Space Flight Center to build a set as well, in case the JPL spheres also turned out to have issues.

"It was on the critical path on a mission-critical instrument, and we were behind schedule, so they pulled out all the stops," said Hurst.

In August 2015, during the final stages of thermal vacuum test before buttoning up the French instrument in Toulouse and shipping it to Lockheed Martin for integration, engineers discovered a problem: the sphere had a leak. They soon identified the leak as being in the 37-pin electrical feedthrough connectors going into the sphere.[3] The French had procured the wrong type of connector—one that was not "going to ever work at our temperature or vacuum considerations," Hoffman recalled.[4]

After localizing the problem to a single pin and solving the leak, on October 8, yet again, the instrument failed testing. There was another leak on another pin of the same feedthrough, though much less significant than the previous one. A sealing compound helped with the leak, though days later, when exposed to cold temperatures, the leak resumed. The entire feedthrough required encapsulation. Moreover, engineers found a combination of outgassing and "virtual" leaks inside the sphere, which included things like "blind holes" (i.e., when a screw goes into a hole, it traps a trace amount of gas at the bottom of the hole, unless you have a vent). "A bunch of these things did not have vent holes," said Hurst. They later created little holes down the middle of all the screws so that they would vent.[5]

Another leak manifested in the "pinch-off" of the evacuation tube that draws a vacuum in the sphere. In early December, the team replaced the tube.[6] On December 22, during testing in extreme cold temperature, the instrument again failed to hold a vacuum. The problem was, again, the feedthrough.

"If your tire had a leak of this magnitude, you wouldn't have to put any air in it for about three centuries," Banerdt later said.[7] "It's not very fast, but it's too fast for us. We would actually come up to a pressure that was in excess of our requirement even before we ever got to the launch."

By then, it was too late to repair. They were going to miss the launch window. Tom Hoffman made the decision. "We've tried hard enough," he said. "We've done enough."[8] He called Firouz Naderi, the director of Solar System Exploration at JPL, and Charles Elachi, the lab's director. "I think I need to let Grunsfeld know," Hoffman said. "Do you guys want to call him? You want me to call him?"

They told Hoffman to do it, so that if the associate administrator had questions, he could answer them. Hoffman called Grunsfeld's cell phone and gave him the news. He explained what the engineers had tried. "It's not going to make it,"

Hoffman said. "I think really the right thing to do is to pull the plug." He added: "I'd like you to give me a chance to come back to you and tell you in March what we need to do to make a 2018 launch, because I think I can get to a plan by then."

Okay, said Grunsfeld. Let's do that.

Hoffman then emailed the InSight team that they were scrubbing for the 2016 launch window, but that they would pull together and figure out a plan for a 2018 launch. "Just don't do anything until we come back on the 4th [of January, 2016]," he recalled writing. "Don't think about InSight. Let's come back batteries partially recharged and let's figure out what we need to do to go forward."[9]

"A MAJOR PROBLEM."

Of course, there was still the matter of paying for it.

"One of the biggest problems I had as a division director was InSight," said James Green.[10] For the Planetary Science Division at NASA Headquarters, the seismometer delay meant more than a little extra time on the cleanroom workbench. It was "a major problem," he said, and would be an expensive one. "We were going to put the spacecraft in storage. That was going to cost the money. We were going to then take the rocket down. That was going to cost some money." There were also "marching army" costs: delays kept people on the payroll longer than anticipated on the outset. The various issues added up to an additional, nine-figure expense for InSight. "A $150 million overrun on a Discovery mission is a huge amount of money," he said—well above the price point that triggered an automatic cancellation.

The InSight team was aware of this. "The fact that I'm standing up here in front of you and talking, instead of gloating on the phone from the central California coast, is a clue that things have not gone as well as one might have hoped," said Banerdt at a meeting of the Mars Exploration Program Analysis Group (MEPAG) in Silver Spring, Maryland, held on March 2–3, 2016.[11] He refused to place blame for the launch delay, describing what went wrong as "kind of a systemic problem," explaining that whatever errors occurred were "made with the complicity of all the partners."[12] But the InSight team had developed a new plan, targeting the next Mars launch window, opening on May 5, 2018, giving them two additional years of development to solve any issues. JPL would redesign, build, and qualify the new spheres for the seismometer, while CNES would lead the integration and test at the instrument level. They would hold interim reviews over the next six months to stay on top of progress and setbacks.[13]

The InSight leadership also briefed the Science Mission Directorate and CNES on the problem and the recovery strategy. Given the unusual circumstances of the delay—a foreign partner responsible for a key instrument—NASA Headquarters

hesitated in cancelling the mission.[14] Aside from the French seismometer, everything else—the spacecraft built by Lockheed Martin, the heat probe built by the German space agency, and the Atlas 5 rocket built by United Launch Alliance—had been delivered on-time to Vandenberg Air Force Base in California, and was ready to launch.[15] The presentation, Banerdt said, involved "a lot of probing questions and a lot of difficult conversations," but overall had a positive response.[16]

In the end, Associate Administrator Grunsfeld listened to the arguments on both sides, and decided to continue with the mission.[17] "The science goals of InSight are compelling, and the NASA and CNES plans to overcome the technical challenges are sound," he said.[18] On March 9, 2016, NASA announced that it had approved the InSight mission to launch in 2018.[19] (The agency would give final approval of the full mission replan on August 31, 2016.[20] The total cost of the delay and hardware redesign came to $153.8 million.[21] This included the complete reworking, fabrication, and testing of up to five VBBs, with the best three selected for flight.)[22]

It fell to Green to figure out the programmatic path forward. "That was really a tough time," he said. "You have to go to Congress. You have to tell them we can't make this. It's going to cost more money. It's going to eat up the Discovery budget. You then can't pick another one. All those kind of things come into play. You're going to delay the AO, and you end up being the bad guy. And you get beat up for it, too."[23]

Easing the pressure was a more favorable budgetary environment than he had faced in 2012.[24] As the Planetary Society, a nonprofit advocacy group for space exploration, reported, the fiscal year 2016 NASA budget was "extraordinary."[25] Until then, it seemed as though if one division of the Science Mission Directorate had a good year, then another division likely suffered. But the 2016 budget was the "everybody wins" scenario. "Congress went to bat for NASA and pulled out a bigger increase than anyone expected."[26] NASA overall received an additional $1.3 billion in appropriations, with the Planetary Science Division receiving a $270 million above the president's request.

NASA overall and planetary science specifically owed their good fortune to Rep. John Culberson of Texas, who in 2015 was appointed chair of the House Appropriations Subcommittee on Commerce, Justice, Science, and Related Agencies.[27] Culberson had served in appropriations since 2003, specifically seeking out the subcommittee with jurisdiction over NASA.[28] He was an avowed supporter of space exploration, and lavished NASA's planetary exploration efforts with funds.[29] His keenest interest was the development of a Europa multiple flyby mission and lander. Other agency initiatives that benefitted from Culberson's largesses included the Mars 2020 rover and production of Plutonium-238.[30]

Also aiding Green was that other missions in the division's portfolio were performing well financially. OSIRIS-REx, for example, the third mission in NASA's

medium-class, sub-billion-dollar New Frontiers mission line, arrived on the launch pad $30 million under budget.[31] But it also demonstrated the enormity of InSight's overrun. NASA ultimately spent $596.3 million to develop InSight spacecraft.[32] The agency only spent $558 million to develop the OSIRIS-REx spacecraft, despite the latter being in a larger competed mission class.[33] Only five years earlier, the flagship-class Mars Science Laboratory spacecraft, carrying the Curiosity rover, launched, after missing its window and going over-budget by hundreds of millions of dollars.[34] As John Dove of the Astronomy and Planetary Research Institute observed in a white paper submitted to the Planetary Science and Astrobiology Decadal Survey 2023–2032, "InSight's objective was extraordinarily ambitious—perform teleseismic science with a single station on a planet with unknown seismicity. There is almost no precedent for performing deep interior seismic investigations with a single station, without making many other assumptions that cannot yet be made for Mars. The mission was relying on extreme luck to be successful."[35]

Among those concerned that the InSight overrun might harm the broader Discovery Program was Lindy Elkins-Tanton, whose Psyche mission was a finalist in the ongoing competition. "NASA has been trying to choose two missions out of this round instead of one, and the community's concern is that the likelihood of that happening might be falling," she said at the time.[36]

WRITING A STEP 2 PROPOSAL

Among the differences in a Step 2 proposal versus Step 1, as the Psyche team learned, was the selection criteria. Where science was the most important criterion during the first round, accounting for 40 percent of the total score, by far the largest criterion in Step 2 was technical, management, and cost feasibility, including cost risk, at 50 percent.[37] Could the mission really be executed, and would it be done so within its budget? The Psyche concept study would have to identify all potential factors in cost growth, and any technical uncertainties, and mitigate them. This was essential to the health of the Discovery Program, already facing a gap in its launch cadence. Psyche could not go over its $450 million allocation for phases A through D; moreover, it would have to maintain a 25 percent cost reserve at each of the project's "key decision points."[38]

Psyche was the only Discovery finalist in its competition to use solar electric propulsion, and the team had to prove its high system-level heritage and high technology readiness level. Solar electric propulsion had several advantages: It allowed for launch date flexibility with fewer critical events over the course of the mission. It had been proven by the Dawn mission, and SSL had used the technology in 26 previous spacecraft. The thruster system had completed its life qualification to

NASA standards earlier in 2016 and tested successfully to match Psyche requirements. Moreover, the myriad subsystems of the SSL spacecraft, flown exclusively on Earth-orbiting missions, had to prove well-adapted to the deep space environment. Among its weaknesses was the command and data handling (C&DH) subsystem, which would require greater autonomy far from Earth—but JPL's deep well of experience could make up for shortcomings there. The laboratory would provide the C&DH hardware and flight software.[39]

Ultimately the Psyche concept study sought to address a challenge issued by the review panels of the Step 1 proposal: how would a mission propose and test hypotheses with no one having ever seen Psyche's surface or certain of what Psyche is? The mission would observe key properties of the asteroid to test two "endmember" hypotheses: that the Psyche asteroid was a remnant core, or that Psyche was a primordial object. Different measurements would suggest different origins.

Table 8. Testing Endmember Hypotheses (reproduced chart).[40]

Observed Property		Psyche is leftover core material	Psyche is a primordial object
Heterogeneous density structure		✓	~
Strong magnetic field		~	×
No detectable field		~	✓
Chondritic silicates		~	✓
Achondritic silicates		✓	×
Nickel in metal	< 4 wt. %	×	~
	4–12 wt. %	✓	~
	> 12 wt. %	×	~
Sulfur-rich provinces		✓	×
No sulfur-rich provinces		~	✓
Intimately mixed metal		~	✓

For a given hypothesis, observed properties of Psyche are expected (✓), possible (~), or unlikely (×).

Psyche's objectives were to:

1. Determine whether Psyche is a core, or if it is unmelted material
2. Determine the relative ages of regions of Psyche's surface
3. Determine whether small metal bodies incorporate the same light elements as are expected in the Earth's high-pressure core

4. Determine whether Psyche was formed under conditions more oxidizing or more reducing than Earth's core
5. Characterize Psyche's topography.[41]

To write the Concept Study Report, JPL management assigned the Psyche team a windowless conference room on the laboratory campus. For the next year, members of the Psyche team worked daily on the project, some at laptop computers on the conference room table, others pinning draft pages to bulletin board walls, until, after months of effort, the room had been wallpapered in spaceflight know-how. Team members did everything from run models to write storyboards. As they revised report pages, they pinned new versions atop the old. Ultimately, the Psyche Concept Study report came in at over 1,000 pages (compared with the 218 pages of the Step 1 proposal).[42]

A "VERY SLOW AND PAINFUL" KEPLER EMERGENCY

On April 7, during a scheduled check-in with the Kepler telescope, the spacecraft reported that it was in "emergency mode"—it's lowest operational condition with the highest fuel-burn rate.[43] Thirty-six hours earlier, an onboard electrical component caused the spacecraft's pointing direction to wander, engineers later learned.[44] Kepler's computer therefore ordered the spacecraft to avoid pointing at the Sun at all costs and to await further instruction from Earth.[45] The spacecraft had reported no issues on its April 4 check-in, and the science team had been preparing to begin its ninth observation campaign, of a 3.7 square degree region of the Galactic bulge, the dense cluster of stars at the center of the Milky Way galaxy, in search of free-floating planets.[46] This was the first time Kepler had ever entered emergency mode—an alarming development.[47]

By April 15, engineers at Ball Aerospace had restored spacecraft function, and it was back in its lowest–fuel burn mode.[48] They studied the issue for the next week.[49] An internal data bus encountered a problem that caused the spacecraft's data traffic to lose synchronization with the previous seven years of data. This, in turn, triggered—nearly instantaneously—a series of false alarms. When the spacecraft computer tried to respond to all of them, in order of criticality, it soon became overwhelmed. While attempting to solve one urgent "fault," a higher priority fault would emerge. The spacecraft went into safe mode for one issue without having satisfactorily resolved the previous issue. After two hours of this, the spacecraft declared an emergency and went into what the Kepler team described as a "coma state." Engineers suspected that at some point during the safe mode, the spacecraft's heaters turned off, causing propellant lines to freeze, which meant thrusters could not

fire. This led to the spacecraft's orientation to wander, triggering emergency mode lest the telescope pointed at the Sun, which would have caused serious damage.[50]

It wasn't the last problem the spacecraft had during 2016. The synchronization issue remained and ultimately required four seconds to be added to the timestamps of some data—"a big deal given the tight timing of the observations," Steffen wrote.[51] Later that summer, the camera switched off. Telemetry suggested that blown fuses caused failures of multiple charged-couple devices: chips important for the telescope to make its observations. The spacecraft's distance from Earth complicated safe mode recoveries. The round trip time of data—about a half-hour—meant it was difficult to get commands to the spacecraft and also confirm that it actually executed the code. "Very slow and painful" is how one Kepler engineer, posting to social network Reddit, described the safe mode process.[52]

Astronomers by then had verified more than 3,000 exoplanets with 99 percent accuracy, using data from Kepler and other missions.[53] (In all, Kepler discovered 2,325 of those confirmed exoplanets.)[54] Twenty-two years earlier, no one knew for certain that exoplanets even existed, as none had ever been confirmed. The Kepler mission—which ended, officially, in 2013, with the loss of two reaction wheels—released its final tranche of data on May 10. It was the single largest collection of confirmed exoplanets so far, adding 1,284 to the list. The team also announced the first large-scale demonstration of a fully automated transiting planet validation procedure: software that could find planets in the data with a high degree of accuracy.[55]

The continued success of the mission, despite its technical glitches soon resolved, meant it wasn't going anywhere. On June 9, NASA Headquarters announced the extension of the Kepler mission through the end of FY 2019—at which point they expected the spacecraft's fuel to have been fully depleted. Earlier in the year, the astrophysics senior review had estimated that its observation campaign along the ecliptic plane would cost $10.4 million in 2017, and $8.9 million in 2018.[56] The agency left the price tag hazy for 2019, as no one yet knew precisely how long the spacecraft's fuel would carry it.[57]

A THIRD TARGET FOR DAWN?

Officially, the Dawn mission was set to end on June 30, 2016.[58] In just under nine years, the spacecraft had traveled over 3.5 billion miles and fired its xenon thrusters for more than 48,000 hours. It had returned 32 gigabytes of science data and collected 69,000 images. It circled Vesta and Ceres nearly 2,500 orbits and achieved all of its science objectives. The science team thought they might be able to get one more celestial body out of the mission, however. "The spacecraft has not been sterilized, so we aren't allowed to touch down on the surface of Ceres," said Chris Russell,

the Dawn principal investigator.[59] Instead, he said, they wanted to go "the other way"—away from Ceres, where Dawn orbited at an altitude of 240 miles, toward main belt asteroid 145 Adeona.[60] Dawn still had about 17 pounds of hydrazine fuel remaining—about double what engineers had expected after the reaction wheel failures.[61] They submitted a mission extension proposal to the Planetary Mission Senior Review, a biennial, independent evaluation commissioned by NASA Headquarters to study and rank the scientific merit of ongoing missions.[62] While the review panelists found that "visiting a new small body (Adeona) always has the potential for unanticipated, ground-breaking discoveries," so too did the idea of remaining at Ceres and studying "compositionally interesting regions." (The panel also found the extension "lacking science traceability, specifics and justifications," though attributed this to the last-minute nature of the proposal.) Ultimately, given budgetary constraints and the potential science return, the review endorsed a course that kept Dawn at Ceres—a recommendation NASA accepted.[63]

Over the next several weeks, the Dawn mission team gradually raised the spacecraft's altitude to about 920 miles, an elevation it reached on October 6, 2016. (It was, coincidentally, the ninth anniversary of the first time engineers switched on its ion engines in space.)[64] It mounted a month-long campaign collecting images and spectra, before engineers raised its altitude to 4,500 miles, which would help scientists better understand the data collected at its lowest altitude of 240 miles (which is nearer to Ceres than the International Space Station is to Earth). From the high altitude, Dawn would measure cosmic rays, the "noise" in its gamma ray and neutron detector (GRaND) measurements made at low altitude. By mathematically removing cosmic ray noise from the spectra collected earlier, the Dawn science team could retroactively improve the resolution of the atomic composition of Ceres.[65]

On December 11, in what was beginning to emerge as an end-of-year tradition, a Discovery-class mission announced the discovery of water ice on a celestial body. (MESSENGER's water ice discovery announcement at Mercury occurred in November 2012.) Measurements by the GRaND instrument suggested water ice not merely localized to Cererian craters, but rather, everywhere. Data collected in December 2015—during its 240-mile altitude observations—revealed the uppermost meter of Ceres's surface to be rich in hydrogen, particularly at high latitudes.[66] This would suggest a porous, rocky material, 10 percent of which (by weight), was water ice filling in the spaces. The discovery bolstered the case that water might be plentiful in the asteroid belt, with implications for the origin of life in the solar system.

THE PSYCHE SITE VISIT

While the Psyche concept study team worked on the Concept Study Report, they concurrently, for much of that time, began preparing for the "site visit," a culminating event in which 30 NASA reviewers would meet with the team in-person for an intense, highly technical evaluation of the proposed science and engineering, with an eye on how the team performs under stress.[67]

"The most surprisingly thing about the site visit was its scale," Elkins-Tanton said. "I thought it was overkill to start planning six months ahead, but it turns out that was almost not enough time. Presenting answers to these complex and technical questions about our mission really took the team of about 140 people many long and hard-worked days."[68]

The site visit was organized such that on the first day, NASA would send JPL a list of questions the team needed to answer. Some answers could be written. Some had to be presented to the reviewers. Some needed both. The questions would be things not answered in the thousand-page concept study report. "These were hard questions," Elkins-Tanton later wrote.[69] Five days was not much time.

The Psyche team opted to hold the site visit in Palo Alto, California, at the headquarters of Space Systems/Loral. Elkins-Tanton and Oh wanted reviewers to see the "technological tour-de-force" of a giant high bay filled with giant satellites being built, using the same bus and the same power system that Psyche proposed.[70] Because the company had never built a deep space mission before, it would be something of an introduction of the review board to a new potential NASA partner.[71] Before the site visit, she hired a speaking coach for the Psyche team members who would be giving presentations to the review board. The idea was to help decide who, perhaps, was unsuited for speaking parts in the presentations, and for those who would be talking, help them speak more eloquently and confidently during a high stakes presentation.[72]

The questions came on November 1, 2016. They centered on the spacecraft imagers and magnetometer, to the surprise of many on the team, who expected the questions to target the gamma ray and neutron spectrometer. Over the next week, the team wrote 400 pages to answer the 31 questions posed by the reviewers. On November 7, the Psyche concept study team presented to the NASA review team. Some questions were insightful. Some were not. In all, 140 Psyche team members were on-site, both to answer the reviewers' earlier questions, and to answer any questions that might be asked during the presentation. Nine hours later, it was done. They would know soon enough whether their work had been enough.

JANUARY 4
Lucy and Psyche missions selected for flight.

FEBRUARY 16
Organic material reported on the surface of Ceres.

APRIL 23
Dawn's third of four reaction wheels fails.

OCTOBER 26
Dawn finds possible ancient ocean remnants at Ceres.

CHAPTER 7

2017

The Lucy mission was born in 2010, led on inception by principal investigator Cathy Olkin of the Southwest Research Institute in Boulder, Colorado.[1] The mission sought to "look at the fossils from solar system formation," by studying remnants of small bodies that didn't accrete into the giant planets. The 2010 Discovery selection process fell under the 2003 planetary science decadal survey, titled *New Frontiers in the Solar System: An Integrated Exploration Strategy.*[2] The mission was based loosely on the New Horizons mission to Pluto, and would fly past a Trojan asteroid (that is, an asteroid parked in a stable gravitational point along Jupiter's orbital path) and a Centaur asteroid (a transient object from the deep outer solar system), using ASRGs for its power source. (Lucy was not down-selected as a finalist; Comet Hopper alone represented the small bodies of the solar system, and the competition ended ultimately with the selection of the solar-powered InSight lander.) The following year, in 2011,

the National Academies released the 2013 decadal, titled *Vision and Voyages for Planetary Science in the Decade 2013–2022*. Notably, among the missions recommended in the medium, billion-dollar spacecraft class, New Frontiers, was a "Trojan Tour and Rendezvous," which was "designed to examine two or more small bodies sharing the orbit of Jupiter, including one or more flybys followed by an extended rendezvous with a Trojan object."[3] This endorsement reflected a growing interest by the planetary science community in the small bodies. Among the Trojan mission proposals developed for the subsequent New Frontiers competition was Trojan Tour and Rendezvous (TTR).[4]

In 2014, when NASA Headquarters released the Discovery AO, Hal Levison of Southwest Research co-wrote a new proposal for a mission that would also be called Lucy.[5] Because the proposed science and hardware of the mission changed—the new Lucy would no longer visit a centaur and would not carry an ultraviolet spectrometer—the science team reformulated. Like Pluto before the New Horizons flyby, the trojans were entirely unknown objects of exploration, so part of the New Horizons payload carried over to Lucy, in the form of instruments as L'LORRI (Lucy Long Range Reconnaissance Imager, a high-resolution visible imager built by the Applied Physics Laboratory) and L'Ralph (the panchromatic and color visible imager and infrared spectroscopic mapper, built by Goddard). The thermal emission spectrometer from OSIRIS-REx was also adopted for Lucy, as L'TES. This gave the mission high heritage—something NASA Headquarters and technical evaluations panels liked to see when studying proposals.

Before Lucy, Levison was aware of the Discovery Program and its record of achievement—Kepler, especially, compelled him as one of the most important things NASA had ever done—but never imagined he would propose or lead a mission. The idea of a competitively selected, PI-led mission, however, intrigued him. It allowed for creativity, and represented an important paradigm shift for the agency, which, pre-Discovery, largely flew directed missions at a slow cadence. Levison was 55 in 2014, well-known for his work studying the history of the solar system, including planetary orbits and the evolution of celestial objects. After 20 years of theoretical work and contributing to spacecraft instruments, he was, he felt, in "a little bit in a rut" and looking for a new challenge. He had come to the conclusion that lacking more data, scientists had bumped up against a wall when it came to understanding solar system history. John Andrews, a drinking buddy of his at Southwest Research Institute (SWRI), convinced him that the two should write a mission proposal together. Andrews would be proposal manager. Levison loved Olkin's name for such a mission—Lucy—because it was named after the fossil that helped reveal the history of the human race: where we came from and how we evolved.[6] The small

bodies of the solar system were fossils in their own right: the preserved leftovers of planetary formation.

Through connections SWRI had with Lockheed Martin, a colleague in San Antonio helped put together a collaboration with the aerospace outfit, which wanted to design a spacecraft that fit within the Discovery budget. Lucy, like the other proposals responding to the Discovery AO, had a cost cap of around $450 million in phases A through D, excluding launch vehicle or operations (Phase E). Lacking enough personnel at SWRI to manage such a mission, they reached out to Michael Amato, the capture manager at Goddard Space Flight Center.[7] SWRI would run the science through the PI position, and Goddard would lead the management through the project manager. It took some persuasion to get Goddard on board; ultimately, SWRI and Lockheed agreed to do all the work at the proposal stage. (Ordinarily in such an arrangement, Goddard would have handled more of the proposal.)

One thing Levison felt like Lucy had going for it was a strong science case. In his view, a lot of people in planetary science approached such opportunities with the idea that they wanted to do a space mission, and as such, had strong interest in instruments and spacecraft. He believed that it wasn't really possible to be, simultaneously, an expert at cutting-edge of science and also the nuts-and-bolts of mission operations. Levison brought to the table the ability to paint a scientific picture of how important the Lucy science would be, and the impact it would have on the field, in a way that somebody who came at the problem purely from a mission operations standpoint would have greater trouble with.

"The way I think about it is the science wins the mission, and everything else in the proposal can just lose it," he said.[8] "If they look at your proposal and they say, 'This will never work,' or, 'You can't do that for this budget,' or, 'The schedule is all messed up and you can't build the spacecraft in time for the launch window you have,' that's losing it. But what's going to get people excited and say, 'Yes, we need to do this,' is the science case."[9]

Lucy was the first time Levison had ever actually worked with NASA. Olkin was the ideal partner, because she was not only an accomplished scientist, but also had a great deal of mission experience from New Horizons.[10]

On the cold Colorado morning on January 4, 2017, Levison's phone rang. He took the bus to work every day, and there was a three-block walk where he could never really talk because he wore thick gloves and he couldn't actually push the button to answer the phone. But he looked at the screen, and it was NASA Headquarters. He managed to answer and immediately dropped the phone. When he finally got it to his ear, the voice on the other end said, "This is Thomas Zurbuchen. Do you have time to talk to me?"[11]

That was the moment he learned Lucy had been selected as one of the two missions that would fly under Discovery. The other was an asteroid mission called Psyche.

LUCY'S GOALS

Jupiter's Trojan asteroids lead and trail the planet at gravitationally stable points in its orbit.[12] When scientists started studying them from the ground, they expected them to have all formed in the same area near Jupiter's orbit and probably led to the formation of Jupiter's core. That implied they should all look the same. As people studied them more closely with telescopes, however, they realized that the trojans could be very different from one another. For one thing, they were different colors: some gray and some red. The Nice model of solar system formation predicted that the material in the Trojan "swarms" formed at very different places in the solar system and were trapped during an unstable point in the history of the solar system.[13] But nobody knows why the red Trojans are red and the gray ones are gray. The only way to make sense of that diversity would be to visit several of them.

Lucy engineers developed a trajectory that would allow their spacecraft to visit several objects in a kind of Formula One track. Each five fast flybys of Trojans systems would last two hours per science encounter. Though Lucy would be a 12-year mission, all the important science would be collected in about a day, cumulatively; most of the mission's time would be spent simply traveling from one object to the next. It would be a reconnaissance mission. "Given that you have a population with a huge amount of diversity that you don't understand, the first thing you want to do is you want to get a broad-brush understanding of what the population looks like. And then you can go back later and do more detailed studies of the objects you think are most important," Levison explained.[14] The spacecraft payload would yield data on the geology, composition, and "fluffiness" of the Trojan surfaces.[15] Among the sought-after science was understanding the craters in the surface of the Trojans; by understanding them, scientists could work out the impacting population of small bodies. From a scientific point of view, that was important to know because planets formed from such small bodies moving around, hitting one another at low velocities, and growing. Sometimes, however, objects collided at high velocities, which meant that in addition to building ever-larger bodies, little things were also ground away. Understanding the sizes of objects that emerged from the accretion process of the planets would shed sorely needed light on the physics of how the collisions worked.

The science objectives of Lucy were to:

- Map the shape, albedo, and crater spatial and size-frequency distributions at each target; determine the nature of crustal structure and layering; and determine the relative ages of surface units
- Map the color, composition and regolith properties of the surface of each target, and determine the distribution of minerals, ices, and organic species
- Determine the masses and densities of each target, and study subsurface composition via excavation by craters, fractures, ejecta blankets, and exposed bedding
- Look for and study satellites and/or rings that might orbit each of the targeted Trojan asteroids[16]

Table 9. Lucy Level 1 Requirements.[17]

Description	Requirement
Target selection	Targets: Patroclus, Meneotius, Eurybates, Leucus, Polymele, and Orus
Shape and geology	Pan images: full rotation spaced by 1/25 to 1/13 of a rotation
Shape and geology	Pan images: series of phase angles separated by 15–25 degrees
Elevation models	Pan images: area ≥ 100 km^2; resolution ≤ 200 m, two stereo emission angles
Landform degradation	Pan images: area ≥ 500 km^2; equator to 60 degrees lat.; resolution <= 100 m
Cratering	Pan images: area ≥ 700 km^2; resolve craters d > 7 km
Cratering	Pan images: area ≥ 10 km^2; resolve craters d > 70 m
Satellites	Search: satellites d ≥ 2 km, $p_v > 0.04$ within R_{Sz}
Compositional units	Color images: full rotation spaced by 1/6 to 1/3 of a rotation
Exposed materials	Color images: area ≥ 700 km^2; resolution ≤ 1.5 km
Exposed materials	Color images: area ≥ 150 km^2; resolution ≤ 600 m
Spectral range	Spec: spectral range 1.0–3.8 mum
Spectral resolution	Spec: detect features with spectral depth ≥ 4% and width of ≥ 70 nm
Compositional variations	Spec: full rotation spaced by 1/6 to 1/3 of a rotation
Compositional variations	Spec: resolution (r) and areal coverage (A) satisfy $r \leq 2(A/1470.6)^{0.473}$ km
Mass determination	Targets: mass accuracy ≤ 25%, for $\rho \geq 1000$ kg m^{-3}
Thermal properties	Thermal: 1 unilluminated surface; 3 sunlit with 1 at < 30 degrees from subsolar point

NASA announced the results of the Discovery competition the same day Levison and Elkins-Tanton learned their missions had been selected. Lucy would launch in October 2021, and Psyche would launch in October 2023. "These are true missions of discovery that integrate into NASA's larger strategy of investigating how the solar system formed and evolved," said Jim Green at the time.[18] "We've explored terrestrial planets, gas giants, and a range of other bodies orbiting the Sun. Lucy will observe primitive remnants from farther out in the solar system, while Psyche will directly observe the interior of a planetary body. These additional pieces of the puzzle will help us understand how the sun and its family of planets formed, changed over time, and became places where life could develop and be sustained—and what the future may hold." Though nearly five years had elapsed since the last Discovery AO, leaving a cadence shortfall for a program conceived to launch missions annually, there was a glimmer of good news in terms of pace for planetary scientists: Between 2025 and 2033, the two spacecraft would visit eight distinct planetary bodies across eight years.

In addition to selecting the two missions, NASA also announced that it was extending funding for further development of Near Earth Object Camera (NEOCam), designed to find potentially hazardous asteroids in areas of space close to Earth's orbit.[19] Selecting two small bodies missions was a bold move by the Science Mission Directorate. It was the first time that a Discovery competition produced a thematic selection (excluding single-mission results, such as InSight in 2012). The two other finalists—both proposed missions to Venus—were passed over entirely, meaning that NASA would likely cross the three-decade mark without a single mission to Earth's "evil twin."[20] (The Magellan mission launched in 1989.)

Discovery was also feeling the shifting tectonic plates of the space program. Mars remained a potential target for Discovery, but JPL was deep into the development of the sample-caching flagship, Mars 2020.[21] The multi-billion-dollar rover and helicopter eased any programmatic urgency for competitive selection of a Mars mission. Likewise, Europa Clipper, NASA's next outer planets flagship, had moved into the preliminary design stage, called Phase B.[22] Congressman John Culberson continued pressing NASA to develop a companion lander for the icy moon mission, and ensuring appropriations to that end.[23] This too alleviated any potential urgency to explore ocean worlds using Discovery. The competitive New Frontiers program also affected Discovery priorities. The previous appetite to explore Titan with a Discovery-class boat had given way to a New Frontiers-class quadcopter, called Dragonfly.[24]

On March 21, President Donald Trump signed into law the NASA Transition Authorization Act of 2017, which had been in negotiation for years.[25] Congressional authorizations are necessary to "establish, continue, or modify federal programs"

that receive appropriations, and direct policy for the years ahead.[26] More generally, they are a kind of statement of purpose from Congress: an explanation of the things they like and would like changed. At 22,000 words, the authorization bill was the longest ever written for NASA and reflected keen Congressional interest in getting humans to the surface of Mars and continuing the major science missions in development or underway, including a Europa flagship and the James Webb Space Telescope.

The bill described planetary science as "critical to enabling greater understanding of the solar system and the origin of the Earth," and expressed pride that "the United States leads the world in planetary science and can augment its success in that area with appropriate international, academic, and industry partnerships."[27] It endorsed "a mix of small, medium, and large planetary science missions," necessary "to sustain a steady cadence of planetary exploration," and described robotic planetary exploration as "a key component of preparing for future human exploration." Congress directed NASA to "ensure, to the greatest extent practicable, the completion of a balanced set of Discovery, New Frontiers, and Flagship missions at the cadence recommended by the most recent Planetary Science Decadal Survey."[28]

DAWN AT ONE DECADE

Dawn celebrated its unlikely 10th anniversary of spaceflight on September 27, 2017, making it one of three Discovery missions to cross the decade threshold. This was a great achievement given the reaction wheel problems that threatened to derail the spacecraft early on. A third reaction wheel also failed in April 2017, after which the engineers switched attitude control to hydrazine thrusters alone for the balance of the mission. This had been widely expected, with Rayman referring to them as "two failed wheels and two doomed wheels."[29] (Rayman said the bigger surprise was that the wheels had lasted as long as they had.) Aside from said reaction wheels, the spacecraft remained in perfect health, limited only by fuel reserves. The following month, in October, Dawn had completed the goal of its extended mission, and NASA Headquarters approved the spacecraft for a second extended mission.[30] The agency considered yet again the notion of sending the spacecraft to 145 Adeona for a flyby; due to depleted fuel, Dawn would be unable to orbit the asteroid, but the flyby could be achieved at the glacial velocity of less than one kilometer per second.[31] However, NASA again opted to remain in orbit around Ceres, to collect data at the lowest altitudes it had ever flown.[32] The spacecraft would maneuver to a highly elliptical orbit with a periapsis under 200 km—nearly half the previous low.

Perhaps the two most significant science results of the year were the discoveries of a possible subsurface ocean remnant, as well as organics, on Ceres. "Ceres is a

complex, dynamic world that may have hosted a lot of liquid water in the past, and may still have some underground," said Julie Castillo-Rogez, the Dawn project scientist.[33] To work out the internal structure of Ceres, and its composition, researchers compared models of the asteroid's gravity with shape and gravity measurements taken by Dawn. "Gravity anomalies"—the places where models and observations diverged—around certain geographic features suggested subsurface structures: possibly expressions of cryovolcanism. A separate study, which modeled the crustal flow of Ceres, found that the "rheology and density of the shallow surface are most consistent with a rock, ice, salt and clathrate mixture."[34] (Clathrate hydrates are water molecule structures surrounding gas molecules, and are orders of magnitude stronger than water ice, but with the same density.)[35] Changes in surface features over time suggest a deformable subsurface, possibly containing some liquid. Though any ancient ocean would likely be bound up in the crust as ice, thermal evolution models suggested some remaining ocean might be liquid.[36]

The organics discovery intensified the importance of planetary protection around the body, which also was found in possession of water, chemicals, and internal heat. Data collected by the spacecraft's visible and infrared mapping spectrometer suggested organic compounds native to Ceres—that is: not delivered by impacts. It was "the first clear detection of organic molecules from orbit on a main belt body," said Maria Cristina De Sanctis of the National Institute of Astrophysics, Rome, and the lead author of the study.[37] The result did not mean Ceres was inhabited, but rather, suggested that it had all the ingredients necessary for life, including water ice, clays, salts, and organic material, and was a favorable environment for prebiotic chemistry in the early solar system. This placed Ceres in a small but critical set of bodies that might hold the keys to answering the most fundamental questions of the origins of life.

THE MOLE

Tom Hoffman was headed to an InSight science team meeting in Oxford when messages started to arrive.[38] It was springtime, and he had expected to have a nice time at the meeting, where he was presenting on the first day. Technically, the worst was behind them, but from a schedule standpoint, the news from Sodern was grim. They were going to lose more weeks of productivity. After his talk, he took a last-minute train to Paris with Brian Bone, the delivery manager for the rework of the SEIS instrument, so that the two would have an uninterrupted opportunity to work through the issues. The instrument had to be delivered in two months' time. By the end of the train ride, they'd worked out the scheduling problems.

JPL's total effort to get the SEIS delivered ended up costing somewhere between 30 and 40 million dollars over the course of the project—something it had not planned for. For their part, CNES spent well over 100 million dollars of their own money to deliver the instrument.

InSight, of course, contained more instruments in its payload than a seismometer. The inspiration for a Mars heat probe came to Sue Smrekar, the deputy PI of InSight, in the shower one morning.[39] She'd been at JPL for about a decade by then and had developed a strong interest in instrumentation. She'd been involved in a number of missions to develop heat probes, which are necessary for understanding a planet's evolution. They can provide information on planetary formation in terms of its radiogenic elements and how it accreted, as well as the present-day energy available to drive things like geologic processes, habitability, and the presence of water. While working on a comet penetrator mission that would measure heat flow, she met people at the German Space Agency who worked on heat flow instrumentation. This interest, and this collaboration, eventually brought Smrekar to InSight.

She'd first met Bruce Banerdt, the eventual InSight PI, before she started at the lab: he was the one who hired her and was her initial group supervisor. Over the years, Banerdt proposed various Mars seismometer missions. When he decided to propose to the Discovery program, there was room and budget for the lander to have a heat probe as well, and Smrekar joined the team as his deputy. One way the division of labor sorted itself was that Banerdt was the scientific liaison with the seismometer group, Smrekar dedicated herself more to the heat flow group.

The Heat Flow and Physical Properties Package (HP^3) was known affectionately as "the mole": a 16-inch, self-hammering "nail" about one inch in diameter, designed to pound itself up to 16 feet into the ground.[40] It would collect data on how heat radiates from the planet's interior.[41] "Everything in a planet is driven by heat trying to get out of the planet," said Banerdt.[42] "What a planet looks like at the surface depends on the mechanical happenings that are going on inside the planet. You have uplift due to heating, you have the crust pulling apart due to motions in the mantle, that are driven by convection, which, again, is driven by heating. You have volcanism, which is driven by heating." Measuring the rate of heat flow was a "no-brainer" from a geophysics standpoint, he added.

A drill would have required more energy than InSight's solar panels could provide.[43] The mole, essentially, was a spike with a small internal motor driving a cam mechanism that compressed a spring. When the spring released, it pushed an internal mass downward, punching itself a little deeper into the Martian surface, or so it was hoped. (A rear, internal suppressor spring absorbed the recoil and ensured that the energy was directed downward, rather than backward.) It did this

in a piston-like cycle, pulling a flat, ribbon-like, sensor-embedded tether behind it, which returned data to the InSight lander.

Smrekar worked to get funding to develop a test chamber at JPL for the heat flow probe, which would allow the team to test out the instrumentation at Mars pressures and temperatures. "It was very important to really test and calibrate the instrument under Mars conditions," Smrekar said. "Of course, in Germany [where DLR, the German Aerospace Center, was building the probe] they have tons of test chambers, but they didn't have any that were under Mars pressure, so that was a valuable asset for us."[44] It was essential to helping prove to review panels that the InSight team could execute the work.

Troy Hudson, the then-lead engineer for Team X, the lab's Advance Mission Design Group, implemented the chamber.[45] He'd joined JPL in 2008, after completing his doctorate in geology and planetary science at Caltech. JPL had some nascent test beds for the HP^3 instruments—specifically for the mole and its tether—that would allow engineers to verify that the temperature-sensing methodology was sound, and also to do penetration testing.[46] The biggest of the three was the geothermal test bed. The main piece of it—an approximately 2.5-meter-tall, half-meter-diameter vacuum chamber—had been purchased, as had the large insulation half-shell that went around it, but nothing else had been done to actually assemble the test bed or make it a functioning test chamber. Smrekar charged Hudson with getting it up and running for InSight engineering tests.[47]

In short, the chamber's purpose was to create a stable shallow thermal gradient from the top of the vessel to the bottom. It was essentially a chamber full of soil with an established temperature gradient in the low temperature, low pressure range. A line of temperature sensors, just as HP^3 would emplace on Mars, would test whether such small temperature changes were measurable as a function of depth. As best as Hudson could tell, there was no other facility like it on Earth.

Hudson became the instrument systems engineer for HP^3—the JPL counterpart to the HP^3 systems engineer at DLR—and the technical liaison between JPL and the German aerospace outfit, working both for the payload systems engineer at JPL, who at the time was Jason Feldman, and the payload manager at JPL, Ed Miller. Hudson became immersed in the complexities of international project coordination.

For HP^3, in addition to DLR, another local German organization was doing the overall systems engineering, with yet another producing the electronics. Hudson traveled quarterly to Berlin or Bremen (the latter where some of the actual construction and testing of the mole occurred), for face-to-face meetings and quarterly management reviews, with Tilman Spohn, who in addition to being the instrument PI of HP^3, was also the director of the Institute for Planetary Studies, one of the largest planetary geosciences research institutes in Germany. In addition, there were

weekly tag-ups via teleconference early in the morning, California time, but late in the day in Germany. There were also frequent emails exchanged daily, and the occasional topics-focused technical interchange meetings or tiger team work to help solve some problems related to the mole, the hammering mechanism, the motor, or other instrument components. Late in Phase B, when engineers determined that the design of the mole hammering mechanism could lead to the device essentially tearing itself apart, DLR brought in CBK (Centrum Badań Kosmicznych), the Polish space agency and their subcontractor, Astronika, to build the mole's hammering mechanism. This added travel to Warsaw to ensure project success.

"It was a lot of building spaceships with email and PowerPoint, and a lot of travel across the Atlantic," Hudson said.[48]

In his estimation, the international partnerships and the working relationships with the many individuals involved were very positive, but HP^3 itself was a great challenge. "It was literally a unique instrument," Hudson said. "People build cameras all the time, they build spectrometers, they build the sorts of things that fly on orbiters all the time, radar systems, even." Even though every such instrument is different, there's a general set of principles that apply to all of them, allowing engineers to make reasonable predictions about how well something will work. "The seismometer was sort of a new animal," he said. Viking carried a seismometer, and there were seismometers on the Moon, but no one had ever built an autonomous penetrator, smaller than a shoebox and using less power than a Wi-Fi router, designed to go five meters deep into an unknown surface and subsurface. "There were so many things about that that had no precedent, and even prototypes, on Earth," he said. "There were so many things about it where we had no guidelines, we had no template to follow. So, there was a lot of go-backs, a lot of redesign work, a lot of consternation." Among the concerns was whether the thin tether would be able to withstand the pulling forces applied to it whenever the mole hammered itself into the ground. They weren't even sure how they would qualify and test it to know for sure it was going to work.

The launch delay turned out to be a blessing for HP^3. Twenty-six extra months allowed the instrument team to improve the HP^3 design and address concerns discovered in testing. "The instrument that we ultimately built was incredibly robust," said Hudson. "The forces that this thing experiences within itself are very large—tens of thousands of Gs—and there's sensitive electronics parts and sensors and a motor and wires and all these pieces."

One issue not on the table for the InSight team was the landing site. They had already chosen the perfect place in Elysium Planitia, and presented it in March 2017 at the Lunar and Planetary Science Conference in The Woodlands, Texas.[49] When Matthew Golombek, who led the landing site selection, had learned earlier that the

mission would miss its 2016 launch window, he "just about [had] a heart attack," because the place they had selected was chosen very precisely for not only elevation and inclination, but also atmospheric pressure.[50]

"We hadn't done any work on any other landing sites," Golombek said.

Over the course of a Martian year, because of seasonal freezing and the sublimation of carbon dioxide at the poles, the atmospheric pressure of Mars fluctuated by as much as 25 percent. For the InSight site selection team, different pressures would mean different landing sites because the spacecraft might need more time for its Entry-Descent-Landing maneuvers. "If we need to search for someplace lower to give us more time for EDL, it means a whole new selection activity, and nobody wants that, including me," Golombek said.

As fate would have it, in 2016, Mars had reached a point just before its maximum atmospheric pressure. In 2018, the planet would be on the other side of that maximum atmospheric pressure at almost exactly the same place in the curve as it was in 2016. No change in landing site would be necessary. "We just said, 'Okay, we're done. We selected the site. We got nothing else to do,'" Golombek said, though his team continued imaging the landing site with the HiRISE camera on the Mars Reconnaissance Orbiter, mapping rocks and such. "But that was just kind of sweeping up," he said.

The remaining technical issues included mitigation strategies to address degradation of parachute strength found in testing. But by September 2017, the seismometer instrument and mole had been delivered and installed on the spacecraft, and managers concluded that the parachute strength was within the performance margin. InSight was on schedule for launch on May 5, 2018. JPL engineers began the final series of comprehensive spacecraft assessments, including vibration, acoustics, and thermal tests, to ensure all components functioned properly. The lander passed thermal vacuum testing on November 22, with plans to install the solar arrays in early 2018.[51] Finally, it seemed, InSight had turned a corner.

CHAPTER 8

2018

MARCH 14
NASA estimates that only a few months of fuel remain for Kepler.

MARCH 23
FY 2018 budget signed into law with a 10 percent boost in funding for the Discovery program.

MAY 5
InSight launch from Vandenberg Air Force Base, California.

OCTOBER 30
NASA announces end of Kepler/K2 mission after depletion of fuel.

NOVEMBER 1
NASA announces the end of Dawn's mission after the spacecraft runs out of hydrazine.

NOVEMBER 26
InSight lands on Mars's Elysium Plaitia region.

DECEMBER 19
InSight deploys its seismometer.

The FY 2018 budget, signed into law on March 23, 2018, marked "the best budget for planetary science this century," according to Casey Dreier of the Planetary Society.[1] This was, yet again, the work of Rep. John Culberson, who also directed $595 million to the Europa Clipper flagship, and a companion lander. The Discovery program line received a 10 percent boost in funding, allowing it to absorb the costs overruns associated with InSight without disrupting the effort to reestablish mission cadence, or causing the cancelation of other missions; guaranteed funding for the continued development of Lucy and Psyche; and covered the costs associated with mission extensions for Dawn and Kepler.[2] Moreover, the planetary science research and analysis, which funds planetary research for scientists not part of flight projects, grew to $197 million.[3]

Less than two months later—on May 5—InSight launched from Vandenberg Air Force Base in California at 4:05 a.m. atop a United

Launch Alliance Atlas V 401 rocket. This was a first: NASA had never before launched an interplanetary mission from the West Coast.[4] From the moment the boosters ignited, "there were a hundred or a thousand things that could go wrong, said Bruce Banerdt. "We didn't blow up on the launch pad. Check that one off the list."[5]

InSight had a six month cruise phase in store. Meanwhile, Discovery's other two missions in flight were drawing to a close—but nobody knew when, since spacecraft lack accurate fuel gauges. By July 1, Dawn was in a 27-hour elliptical orbit whose closest distance to Ceres was about 22 miles (an altitude that on Earth wouldn't even be considered space) and farthest distance was about 2,500 miles. At its nearest point—its peridemeter—it collected everything from up-close imagery to data on the nuclear radiation emitted by Ceres. It maintained this until October 31—not long after peridemeter—when the spacecraft realized that its hydrazine thrusters were no longer working, and that it could no longer control its orientation. It cycled through possible responses and backup systems and rebooted its computer. Nothing worked. It likely switched off its radio to conserve power until its solar panels were again in sunlight and maintaining a stable battery charge—a condition that would never be met. Dawn was the first spacecraft to orbit two planetary objects in deep space, the first spacecraft to orbit an object in the asteroid belt, and the first spacecraft to orbit a dwarf planet. The next day, NASA declared the mission ended.[6]

Table 10. Dawn at Ceres Achievements.

Discovery/Achievement	Details
Ceres as a Relic Ocean World	Crustal composition of ice, salts, and minerals indicates a global past ocean, with habitability implications.
Differentiated, Planet-like Interior	Gravity and topography data suggests a rocky mantle and less-dense outer crust, more akin to a small planet than a typical asteroid.
Widespread Water Ice and Hydrated Minerals	Confirmed abundant water ice at higher latitudes and permanently shadowed craters, and clays and carbonates globally.
"Bright Spots" Identified	Identified the iconic bright areas such as at Occator Crater as sodium carbonate and magnesium sulfate salt deposits, possibly remnants of upwelled briny liquid.
Endogenous Organic Molecules	Organic compounds formed within Ceres and brought to the surface suggest a complex internal chemical environment.
Geologically Active	Found cryovolcanism and signs of recent brine flows, indicating Ceres maintained internal activity longer than expected.

Engineers estimated with 99 percent confidence that the spacecraft would remain in orbit around Ceres for at least 50 years. The sheer volume of data collected—more than 167 gigabytes of data and 95,000 images—meant scientists would be studying Vesta and Ceres for many years as well.[7]

KEPLER'S LAST LIGHT

One week after InSight launched, on May 12, Kepler began its 18th observation campaign, of the Beehive cluster (also known as Praesepe).[8] It was set to be an 82-day observation, repeating the telescope's fifth campaign, which lasted from April 27 to July 10, 2018.[9] By repeating the observations, astronomers hoped to glimpse planets orbiting farther from their stars, and to confirm previous observations. At the time, the Beehive cluster was known to host six exoplanets orbiting stars less than a billion years old. (The repeat observation would also allow astronomers to see how the brightness levels of the stars changed, useful for understanding the sunspots of the young stars.)[10] In addition, the thousand-foot asteroid 99942 Apophis would cross into the field of view. Named for the Egyptian god of destruction, Apophis most famously was the asteroid whose discovery led to a brief uproar in 2004, when astronomers estimated an almost three percent chance of colliding with the Earth in 2029.[11] Subsequent observations revealed that it would not hit Earth within the next century, but it got the attention of Congress, which ordered NASA to get serious about planetary defense.[12] One mission to emerge when the dust settled (or more felicitously, didn't settle) was the Near-Earth Object Camera (NEOCam), passed over by the Discovery Program but given additional funds for further development.[13] (Two years later, a National Academies study recommended that NASA split planetary defense missions into their own line separate from science-oriented missions.[14] NASA reformulated NEOCam as the NEO Surveillance Mission, later called NEO Surveyor.[15] The Planetary Defense Coordination Office at NASA assumed responsibility for funding and flying the mission.)[16]

The first sign of trouble for Kepler occurred 51 days into the campaign, when the Kepler team learned that the spacecraft had experienced an anomalous drop in fuel pressure.[17] They ordered the spacecraft into a one-month "nap mode"—a no-fuel-use safe mode.[18] Their goal was to preserve the data collected thus far into the campaign, which it would transmit to the Deep Space Network on August 2, the previously scheduled downlink time. Meanwhile, engineers developed a follow-on Campaign 19, that would begin four days later.[19]

When Kepler awoke from its "nap," the spacecraft immediately went into safe mode.[20] One of its thrusters exhibited unusual behavior, with indications that the spacecraft's pointing performance might have degraded.[21] This delayed its next

campaign by just over three weeks, and when finally it started, it lasted less than a month before the K2 team again placed it in nap mode.[22] Again, the team downloaded the data collected, however degraded, and attempted a Campaign 20, "with the slimmest glimmer of hope."[23] It would observe the Taurus-Auriga star-forming region, with the Kepler team making "no guarantee that we will be able to download the science data."[24]

Taurus-Auriga molecular clouds would remain in darkness to Kepler's eyes. The spacecraft tried and failed to achieve its science-pointing mode and went into safe mode. It lacked the fuel to go on. On October 30, NASA "retired" the spacecraft, which left "a legacy of more than 2,600 planet discoveries from outside our solar system, many of which could be promising places for life."[25] On the evening of November 15—388 years to the day after the death of Johannes Kepler, the spacecraft's namesake—an operations team at the Kepler Mission Operations Center in Boulder dialed in to a telecon with scientists and engineers at Ames Research Center. NASA sent final "goodnight" commands to the spacecraft, formally ending the mission.[26] At 9:42 a.m. MST, it was over.

"Over the previous two decades countless scientists and engineers had toiled through seemingly insurmountable engineering and physics challenges to imagine, build, test, and fly the Kepler mission," wrote Colin Peterson, an engineer at Ball Aerospace. "I offer a thanks and acknowledgment to each and every person that made Kepler and its discoveries possible. Goodnight Kepler."[27]

Table 11. Kepler/K2 Achievements.

Discovery/Achievement	Details
Exoplanet Census	Discovered over 2,600 confirmed planets, revealing the ubiquity of planets in the galaxy
Habitable Zone Worlds	Identified the first Earth-sized planets in the habitable zones of other stars, such as Kepler-186f, providing the first direct evidence for potentially Earth-like worlds.
Diverse System Architectures	Revealed unexpected planetary system architectures, including tightly packed systems like Kepler-11 and planets orbiting two stars ("Tatooines") like Kepler-16b.
Astroseismology Pioneer	Provided an unprecedented dataset for astroseismology, enabling the precise measurement of stellar parameters (radius, mass, age) for thousands of stars.
Ongoing Science Revolution	Revealed that planets possibly outnumber stars in the night sky, in a data archive that continues yielding new discoveries years after the end of mission.

INSIGHT ON MARS

Two weeks after Kepler went silent, on November 26, InSight arrived at Mars.[28] The landing was textbook. Bruce Banerdt checked it off his list of things that could go wrong.[29] The successful touchdown marked the eighth consecutive successful Mars spacecraft arrival—a streak beginning with the orbital insertion of Mars Odyssey in 2001. First-year college students had gone their entire lives without a NASA failure at Mars—a stunning achievement after the back-to-back failures of Mars Climate Orbiter and Mars Polar Lander, the latter failing on January 17, 2000, leading to dramatically reduced risk margins (and commensurate budget overruns) that for years punished the Discovery Program.[30] Notably, InSight carried two CubeSats, MarCO-A and MarCO-B, comprising the Mars Cube One mission and the first successful interplanetary CubeSats ever launched.[31] They acted as communications relays between InSight and Earth during the landing, and suggesting a new age of low cost planetary exploration. Thomas Zurbuchen, the associate administrator for NASA's science mission directorate, declared that, if possible, every rocket launched by NASA's science program would include a small sat payload adapter for future such missions. "We're not going to ask whether we need it," he said. "You have to convince us that we don't need it."[32]

On December 18, around 5:00 p.m. in California, engineers sent InSight commands to lift the seismometer from the deck of the spacecraft and place it on the Martian surface.[33] The robotic arm's joint motors worked better in low temperatures, so they decided to deploy at sunset, when temperatures would have dropped to around forty-below-zero, but there was still a bit of sunlight for imaging the process.[34] The downside was that they wouldn't find out if the automated deployment was successful until the following evening, during the downlink from Mars Odyssey, which was relaying InSight's data. Bruce Banerdt described seismometer deployment as just as important as a safe landing. "The seismometer is the highest-priority instrument on InSight," he said. "We need it in order to complete about three-quarters of our science objectives."[35] Any number of things could have gone wrong. The tether was heavy.[36] The three frangibolts (pyrotechnic fasteners) securing the seismometer to InSight might not have released, leaving the instrument stuck to the spacecraft.[37] Or they might have released too well, and the shocks somehow damaged the VBBs, whose delicacy had so vexed InSight engineers.[38]

"We'd had so many problems with the seismometer, and every time we fixed a problem, we uncovered another problem," Banerdt said.[39] "There were a few weak spots in the seismometer that we knew of, and there were all the unknown weak spots which may or may not exist. So, until the seismometer was actually on the ground and leveled up and let go, we didn't know what we had."

Twenty-eight hours after issuing the command, however, the InSight team members had their answer: success. Telemetry, and then images, revealed that the InSight seismometer had been placed gently on the surface of another planet. The spacecraft timeline was far ahead of schedule; engineers had predicted at landing that it would take months to ready InSight for instrument deployment.[40] It was "an awesome Christmas present," said Tom Hoffman.[41] Bruce Banerdt checked the item from his doomsday list.

CHAPTER 9

2019

FEBRUARY 28
InSight's heat probe or "mole" gets stuck.

APRIL 1
2019 Discovery Program Announcement of Opportunity released.

APRIL 6
InSight detects its first likely quake on Mars.

JULY 1
Discovery Program Announcement of Opportunity proposal submittal deadline.

Louise Prockter, the director of the Lunar and Planetary Institute, was at a vegan restaurant near Caltech with Karl Mitchell, a planetary scientist at JPL, when the looming Discovery competition entered her life. She was in town for a workshop called "Accessing the Subsurface Oceans of Icy Worlds," being held at the W.M. Keck Institute for Space Studies.[1] She was there to give a talk titled, "Structure and Thickness of Europa's Ice Shell: What We Think We Know and What We Hope to Learn from the Europa Clipper," the flagship mission she had spent most of her career helping get off the ground.[2] She'd known Mitchell for a while; he was also English, so the two went way back. Dinner had been lovely, but it was obvious that Mitchell had something he was bursting with joy to bring up but was waiting for the right moment. Finally, he told her what it was: JPL had an idea to fly a mission to Triton, Neptune's mysterious moon, on a Discovery budget.

"No way," said Prockter. "That can't be done."[3]

The more he described it, however, the more she realized that JPL engineers really had come up with a clever, elegant way to do it. They would send a small spacecraft on a simple ballistic trajectory. That was favorable for a rare alignment of Jupiter coming up, which could give the spacecraft a gravity assist to Neptune, which was in the perfect place in its orbit for a reconnaissance mission. In a single, 10-day flyby, a spacecraft could do sweeping science: probe for an ocean, measure the ionosphere, map nearly the whole of Triton's unseen surface, and study its mysterious plumes.[4]

"Would you like to be involved?" he asked.

Would she ever.

Prockter asked who the mission's PI would be. Mitchell told her, coyly, that there were a few candidates. Not long after that meeting, JPL offered Prockter the job—PI of a mission they would call Trident—and she accepted. She was well-suited for the role of PI. She'd spent years working with JPL during development of various Europa missions, so she knew their way of doing things, and she had been deputy project scientist of Europa Clipper before taking the job at LPI. For seven years, until MESSENGER ended, she had worked as an instrument science lead for the Mercury Dual Imaging System. Sean Solomon eventually made her deputy project scientist. Years earlier, she'd even been a postdoc on NEAR (Near Earth Asteroid Rendezvous)—the first Discovery mission to launch.

She also had the science background for the job, having recently discovered plate tectonics on Europa: a significant result that directly contributed to NASA finally approving the flagship there.[5] "And as an icy satellite scientist," she said, "I knew as much as anyone else about Triton."[6]

Neptune's icy moon is an oddity in the solar system.[7] It is larger than Pluto, but smaller than Earth's moon. If Triton was placed in orbit around the Sun rather than Neptune, it would meet the criteria of being a dwarf planet. Indeed, planetary scientists hypothesized that its past was like Pluto's: orbiting the Sun as a large object in the distant Kuiper Belt.[8] Far back in cosmic history, Neptune "captured" Triton, which accounts for its retrograde orbit (i.e., it circles its host planet in the opposite direction of the planet's rotation). Triton has a tenuous, nitrogen-based atmosphere and a mysterious, unusually dense ionosphere. The Neptunian moon also has a young surface, which indicates that geologic activity is wiping away its craters through cryovolcanism and tectonic processes. The violent circumstances of its seizure by Neptune would have left the moon with its oblong orbit. The resultant tidal heating from Neptune's gravity would have warmed Triton's interior, much in the way a tennis ball repeatedly squeezed gets warm. This could have created an ocean beneath its ice shell. It even has plumes venting from its interior, possibly connected to that ocean.[9]

Despite Triton's distance from the Sun, a warm water ocean that interacts with a hot rocky seafloor can yield conditions favorable for life to take hold.[10] Trident would be NASA's third dedicated mission to a world with potential past or present oceans (the others being Europa and Mars).[11] If selected, it would also place the Discovery Program squarely in NASA's framework for exploration of habitability in the solar system.[12] This would once have been considered laughable. Virtually everything we knew about Triton came from a single flyby of the Neptune system in 1989. When Voyager 2 collected its data, only Venus, Earth, and Mars were believed to be in the so-called "habitable zone" of the solar system where life might take hold. If an ocean were discovered at Triton, the habitable zone would expand to include every planet circling the Sun.[13]

But first Trident had to get there. JPL designed the spacecraft for NASA's workhorse rocket, the Atlas V. After a couple laps around the Sun, flying by Earth and Venus, the Jupiter gravity assist would do the heavy lifting.[14] (So perfect was the Jupiter assist that Trident could forego carrying around massive fuel tanks, and it still afforded Trident an astonishing 52 percent dry mass margin, a part of spacecraft development that typically led to cost growth.)[15] Despite this, it would still take over 12 years to reach Triton, which is almost three billion miles from Earth.

During its encounter phase, the probe would inhale data about Triton for about 10 days. As it approached, Trident would use a high resolution camera and spectroscopy systems to map the geology and composition of nearly the entire surface of Triton, including the two-thirds of the moon left unseen by Voyager 2. On closest encounter, it would fly through Triton's ionosphere, making measurements of it, and would use magnetic field detections to verify an interior ocean. While flying away from Triton, the moon would experience an eclipse and be illuminated by Neptune-shine. This would enable the spacecraft to study Triton's atmosphere and image any plumes that might be venting from its interior. Because of the distances involved, it would take over a year for the entirety of the data collected to be returned to Earth.

But there was a catch: Trident was a one-shot deal. In 2040, Triton would enter its south polar night; its southern hemisphere would begin moving out of illumination, and plume activity could slow and cease.[16] The duration of the Discovery competition, plus development time of the spacecraft, plus the long cruise phase meant the spacecraft would arrive on exactly September 28, 2038—right at the cutoff, but it would make it.

That wouldn't be the first time NASA cut things close for Neptune. In 1966, JPL engineer Gary Flandro published a paper describing how the solar system would soon enter a rare planetary alignment.[17] With a single spacecraft, NASA could visit Jupiter, Saturn, Uranus, and Neptune. It would be the last time that happened for

175 years. When Flandro made this discovery, humans had been exploring space for less than a decade. We developed a space program just in the nick of time.

If NASA failed to select Trident under the 2019 AO, the orbits of Jupiter and Neptune would go out of the needed alignment, making the gravity assist impossible. The long stretch between AOs meant any future Discovery selection could come too late; the proposed plume science would be impossible, and with it, the possibility of characterizing the hypothesized ocean. If NASA wanted to expand the Discovery program to encompass the whole of the solar system, it had to be now—because the next opportunity wouldn't occur for a century.[18] In other words, for the proposed science at Triton, the 2019 Discovery selection really was the last bus leaving the station.

DISCOVERY'S CADENCE FAILURE MANIFESTS

NASA's failure to maintain Discovery mission cadence was truly apparent by 2019, with InSight the only operational mission left in the program to return science data. This would be the case through November 2023, when Lucy would collect its first science of the asteroid (152830) Dinkinesh.[19] At the time, however, no one knew such an observation was possible, meaning the planetary science community had to accept Mars as the last of the Discovery science data until 2025, when Lucy encountered asteroid (52246) Donaldjohanson. The Lucy team also eventually devised an opportunistic glimpse at the collision of the Double Asteroid Redirect Mission spacecraft with the asteroid (65803) Didymos I, but again, it would be years before anyone realized such a thing was possible.[20]

On April 1, NASA Headquarters released its ninth Announcement of Opportunity of the Discovery Program.[21] Though NASA has a rigorous internal process for developing Discovery AOs, which are written by the Discovery program manager, the agency did not generally dictate terms without community input. In addition to taking into consideration the recommendations of the Decadal Survey and NASA Strategic Plan, the Planetary Science Division first took the temperature of the community through a series of pre-proposal rollouts. It usually began with a sort of "Announcement of an Announcement of Opportunity," laying out what they expected to announce.[22] It signaled the broad parameters of the eventual AO: things like cost cap, approximate AO release date, what would be disallowed in the upcoming competition, and what NASA would furnish versus what must be accounted for by the proposers.

Later, NASA would release a Draft AO for community input.[23] This document would be the AO in much greater detail but not finalized. It was not unusual to get more than a hundred responses from interested parties, with requests for

clarifications (e.g., does spacecraft communication have to use Ka-band for communications, or is X-band sufficient?); pushback on mandated hardware NASA wanted to fly (e.g., some piece of experimental hardware); or even the identification of mistakes (e.g., a typo in the cost cap).[24] A few months later, Discovery Program management would post a response to the notes from the community, and what it would incorporate into the final AO. (e.g., "The text of the final AO will be adjusted to reflect the intent of an AO Cost Cap of $500M, not $500.")[25]

There would be a pre-proposal conference, in which various elements of NASA laid out, more formally: how Discovery works (e.g., What does a PI do?), what is the nature of science and technical evaluations, how export controls work, and what launch services look like.[26] Everyone involved took the process very seriously. Not long after, NASA would post the AO and the competition would begin.

In December 2017, when NASA released the long-range planning information for the 2019 AO, there was one injunction that vexed and annoyed Louise Prockter.[27] It stated: "Discovery Program investigations may not propose the use of radioisotope power systems."[28] Trident depended upon two multi-mission radioisotope thermoelectric generators (MMRTG), a type of power source first used on the rover Curiosity. Solar power was impossible in the deep outer solar system. So Prockter began rallying the planetary science community to push back. The document had released coincidental to the annual American Geophysical Union conference, held that year in New Orleans, Louisiana. She found Alfred McEwan, the chair of the Outer Planets Assessment Group. They went to a nearby park to chat. "Alfred," Prockter said, "I need OPAG to write a letter for me asking for MMRTGs to be included in Discovery."[29] She found Clive Neal, the chair of the Lunar Exploration Analysis Group. "Clive," she said, "you need MMRTGs for the Moon, don't you? I need LEAG to write a letter." The influential assessment groups wrote those letters, and when NASA Headquarters released the Draft AO, MMRTGs were indeed an option for the competition.[30]

By the release of the final AO, an exceptionally favorable NASA budget had been signed into law (which included a 24 percent boost to planetary science), and the agency stated that it might select two missions.[31] The AO listed the cost cap as $500 million in FY 2019 dollars for phases A through D, not including launch vehicle.[32] Everyone had learned their lesson after the ordeal of SEIS, and the AO forbade foreign contributions of instrumentation exceeding one-third of the science payload. (It also expected plans for how risks associated with such a contribution might be handled.) A selected mission would have to be ready to fly in mid-2025 through the end of 2026, or mid-2028 through the end of 2029. Notices of intent would be due on April 30. Proposals would be due on July 1.[33]

PSYCHE AND LUCY MATURE

Meanwhile, development of Psyche and Lucy continued apace. On March 11, 2019, Psyche had its preliminary design review (PDR) with its external Standing Review Board, "the culmination of all the planning and design work we will have done over the previous two years, and indeed, the six years before that," according to Lindy Elkins-Tanton.[34] "This is not the kind of thing you can study for the night before." The PDR was not a monolithic event; each instrument and spacecraft subsystem had its own separate review. They had begun six months before the project PDR, and Elkins-Tanton had embraced the gauntlet as "PDR season."

As she wrote, among the things the Psyche team would present at the project PDR were:

- "Mission and system designs, including architectures, key trade-offs, interfaces, operational concepts, and capabilities and margins;
- "Technology developments and engineering developments;
- "Project risk-management approach, including the significant risks, aggregate risk, mitigation options, scope margin and descopes;
- "Project life-cycle budget and its validation, budget profile, costing methodology, basis of estimate, budget reserves, and cost risk."[35]

Psyche had begun to evolve from its origins as an Earth orbiter into a capable vessel for deep space exploration. It now used a dedicated nitrogen cold gas propulsion system. Moreover, engineers had validated the thruster life for the duration of the mission and refined the mission operations strategy. They drew from lessons learned on the Dawn mission about safe, autonomous spacecraft operations beyond Earth.[36] Two months after the PDR, NASA officially approved the mission to enter Phase C, the final design and fabrication phase.[37]

Meanwhile, NASA settled on a launch vehicle for the Lucy spacecraft: a ULA Atlas V 401 rocket (the same type of rocket that launched InSight to Mars). The agency held the Critical Design Review for Lucy on October 15, 2019, at Lockheed Martin in Littleton, Colorado.[38] Engineers and scientists spent four days giving presentations on the mission and spacecraft. The Lucy team had two notable firsts with which to contend: no Discovery Program spacecraft had ever before traveled beyond the asteroid belt, and no solar powered mission had ever operated at Jovian distances (to say nothing of being the first mission to explore the Trojans). Its two seven-meter, Chinese-fan-like solar arrays traced their mechanical heritage to the Phoenix Lander at Mars, and their electrical heritage to Juno.[39] At Earth, the panels could generate 18,000 watts, but at the farthest Trojan asteroid it was set to encounter, at 5 AU, they would only be able to deliver 500 watts of power.[40]

The independent review board overseeing Lucy gave the mission a passing grade at the conclusion of the CDR. It was now cleared to bend metal. Lucy's launch window would open on October 16, 2021.[41]

Table 12. Lucy Targets.

Target Name(s)	Camp	Type	Date	Notable Details
(152830) Dinkinesh and satellite Selam	Inner Main Asteroid Belt	S-type	2023	Served as an in-flight test of Lucy's systems. The satellite, Selam, was discovered to be a contact binary. *Note that Dinkinesh was discovered after Lucy's launch.
(52246) Donaldjohanson	Inner Main Asteroid Belt	C-type	2025	A member of the Erigone collisional family, believed to have formed from a larger parent asteroid breaking apart. The flyby revealed it to be a contact binary with a "peanut" shape.
(3548) Eurybates and satellite Queta	L4 Trojan Swarm (Greek Camp)	C-type	2027	The largest member of the only known disruptive collisional family of the Trojans. C-type asteroids are more commonly found in the main belt, making Eurybates an unusual Trojan.
(15094) Polymele and unnamed satellite	L4 Trojan Swarm (Greek Camp)	P-type	2027	A binary asteroid that may be a fragment from a past collision. Its reddish color suggests a surface rich in organic tholin compounds.
(11351) Leucus	L4 Trojan Swarm (Greek Camp)	D-type	2028	A slow rotator, taking approximately 466 hours to complete one rotation.
(21900) Orus	L4 Trojan Swarm (Greek Camp)	D-type	2028	A possible binary asteroid.
(617) Patroclus-Menoetius	L5 Trojan Swarm (Trojan Camp)	P-type	2033	A rare binary system where the two asteroids are nearly equal in mass and orbit each other.

"A RAPID AND NEAR-CATASTROPHIC SELF-EXTRACTION"

On February 12, 2019, InSight's robotic Instrument Deployment Arm moved the mole from the lander deck to the Martian surface. The spike-shaped mole was housed in a vertical tube atop a support structure. To deploy, engineers would trigger a frangibolt, which would release a "launch lock."[42] The mole would drop under its own gravity, like Newton's apple, into the Martian regolith, and would commence self-hammering. It remained attached to the support structure and spacecraft by way of lightweight, ribbon-like engineering and science tethers. The mole

would pull the tethers behind itself as it drove itself deeper into Mars. The engineering tether was responsible for power and data; the science tether contained thermal sensors. The science tether also allowed the InSight team on Earth to monitor the distance traveled by the mole, by way of a "tether-length monitor," an optical device. Because of the way the tethers were folded into the support structure, the mole would have to travel 54 centimeters before the science tether would be pulled deep enough to register on the tether-length monitor.

On Sol 87, the mission team released the mole from its launch lock, committing to the target. It dropped as intended, stabbing approximately one centimeter into the Martian regolith.[43] On Sol 92, the mole began self-hammering. The team expected it to take as little as a half-hour for the mole to burrow 70 centimeters into the surface of Mars, at which point the instrument would automatically cease hammering. If such a depth were not reached, it would halt hammering at the four-hour mark.

Troy Hudson, the JPL technical liaison with DLR, which built the instrument, sat with other InSight Team members from a control room watching the downlink come through. He had been working on InSight since at least 2010, and he was excited and anxious, like everyone around him. The mole was, in most ways, an entirely new type of instrument in space exploration: a shoebox-sized autonomous penetrator system using less power than a Wi-Fi router and driving five meters into an unknown surface. This afforded its own development challenges no other instrument had before encountered—everything from just getting the internal hammer mechanism to work correctly to ensuring the tether could withstand the forces of being pulled by the mole. Its deployment would make history.

A few minutes after the data arrived, however, the energy "just totally drained out of the room," said Hudson.[44] "We realized that something wasn't right." The mole hammered away for the four full allocated hours, enough for 3,881 hammer strokes.[45] According to telemetry, the first five minutes had gone according to plan: the tip had reached a depth of 15.5 cm. (This data was drawn from the rear of the mole having dropped below a contact switch in the vertical tube.) Then it tilted slightly, according to an internal tiltmeter, suggesting it had hit something hard, such as a rock. Two Martian days later, the mole team resumed hammering. Five hours and 4,720 strikes later, the instrument was no deeper into Mars. "I had become very emotionally invested in the success of this instrument, and my colleagues in Germany as well," said Hudson, who first joined JPL in 2008.[46]

He took the lead in creating the Anomaly Response Team (ART) to get to the bottom of things. At the time, he didn't know just how long and intense the process would be, which included "putting together fishbone diagrams and fault trees. What are all the things that could be wrong? What are the things that we can do to

test it without damaging it or putting us down a path that we can't recover from?"[47] Approximately 10 engineers and managers comprised the ART, with scientists like Banerdt also contributing as needed. The total number of people fluctuated, doubling and even tripling at times, with participants joining from California, Germany, and Switzerland.[48]

The mole was concealed by its support structure, so it was impossible to see its exact situation. The ART team had only the telemetry data, so they had to be inventive. They used InSight's camera to take images of the structure before and after a series of "diagnostic hammerings." They did see slight movement, which suggested that it was performing mechanically. They even used the seismometer in a special digital filter mode to see, in a sense, inside the mole itself. It listened during another round of diagnostic hammerings to understand how the mole's internal hammering mechanism was performing. It seemed to be operating appropriately. Finally, in June, they accepted that without a better view, there was nothing to be done. The structure had to go.[49]

"That took a long time to make that call, because there was a lot of risk involved," said Sue Smrekar.[50] "We could knock the mole over or do something that would end our ability to keep trying." They would need to use the robotic arm to lift the structure away—something it had not been designed to do. They would have to do so gently, so that the ribbon didn't pull the mole out of the ground. If the mole fell over, that part of the mission would be ended. (Indeed, a snagged ribbon was one of the possible causes of the mole's inability to penetrate the regolith.) By every measure, it was a daring decision.

On June 28, 2019, InSight's robotic arm re-grappled the mole, and carefully lifted away the structure. The ribbon uncoiled behind the arm, as hoped, and the mole remained embedded in Mars. The subsequent view allowed the ART to see the mole's azimuth, depth, and the nature of the pit it had created during its penetration—which was surprisingly steep-walled.

"That was just the start of the now-what's," said Hudson.[51] Meanwhile, he worried that mole recovery operations "put a strain on the instrument mission, because their whole model behind it was we go there, we put the instruments down, and then we would just listen. The data would come in." Now, there was a "standing army" of mission operations members developing robotic arm sequences, mole sequences, and sending and receiving data to and from the spacecraft.

The mole hole revealed that it wasn't an obstacle in the soil beneath the mole that was causing all the trouble; the soil itself seemed to be the problem. Rather than being loose, sandy material, as seen at other sites on Mars, the area beneath InSight was an unusually thick duricrust: a layer of cemented soil.[52] The mole's self-hammering design relied on friction. If everything had gone according to plan, loose

soil, falling alongside the mole as it traveled downward, would have provided such friction. But the duricrust meant soil would not fall down the mole hole. The mole created only a void. The mole's hammering recoil caused it to bounce and wobble, carving a wider pit rather than digging deeper.

So, the ART converged on a strategy. Rather than rely on Mars to provide friction for the mole, the team would use InSight to do the job. The instrument deployment system had more than a five-fingered grapple for emplacing the seismometer and mole on Mars.[53] It also possessed a scoop that could operate similar to a backhoe, with four degrees of freedom. It was intended to excavate materials using digging and scraping motions, and to pile material, all part of a series of Tonka truck–like experiments designed to infer the mechanical properties of the soil at InSight's landing area.[54] During the summer, engineers used the scoop to push and chop the soil near the mole, hoping to collapse the hole inward. They were unsuccessful. They then decided to use the scoop to pin the mole against the wall of the hole, hopefully providing sufficient friction for the instrument to begin burying itself. It was a risky maneuver because of the tether interface on the back of the mole, which was irregularly shaped and vulnerable to damage. It took until September before the team felt comfortable executing the maneuver. On Sol 291—September 21 on Earth—the pinning campaign began.[55] After pressing the scoop against the mole, on Sol 308, the team commanded the mole to execute 20 self-hammer-strokes. The mole moved approximately five millimeters downward.

"We got the mole pinned on the side, and we hammered, and, oh, my god, it moved," said Hudson.[56] "I remember how relieved I was when I saw that and how excited, at the next science team meeting, when I just told everyone, 'We're going to get to dig!'"

Over the next 10 sols, they performed 3 more attempts, each more than 100 hammerings. At the end of the campaign, the mole had penetrated five centimeters deeper into Mars than it had been previously, with only minor tilt. In addition to making progress, this also allowed the ART to rule out a rock or other object obstructing the instrument.

Engineers then ordered the scoop to release pressure against the mole and press into the soil adjacent to the penetration site. (The mole was deep enough that the scoop now presented a hazard to the tether.) On Sols 322 and 325, the team commanded the mole to hammer 354 times into Mars. Rather than drive deeper into the planet, however, the mole began "a rapid and near-catastrophic self-extraction," backing out of the ground by about 18 centimeters, and tilting to a total of 24 degrees.[57]

"For a while, it wasn't even clear that we'd be able to recover from that," said Hudson.[58] At first, he didn't believe what he was seeing. "I remember I ended up

crying in my shower after that happened." He wasn't angry; all the decisions they had brought them to that point were well-considered and made sense at the time. "It was just a setback, and I knew that even if we could potentially recover from it, it was going to be a long road."

It was an easy decision to again attempt to pin the mole and execute a hammer maneuver. They did so on Sol 346 (November 16), to rapid success. Across five self-hammerings, the mole managed to recover all the ground it lost. Only three centimeters of the mole's rear jutted from the ground.[59] It was a far cry from the 16 feet the mole was designed to penetrate, but at least it was moving in the right direction again.[60]

CHAPTER 10

2020

MARCH 16
Federal government encourages agencies to implement "maximum telework" after COVID-19 is declared a pandemic.

On January 7, 2020, Chinese public health officials associated a novel coronavirus with an unsettling number of patients who had come down with a pneumonia-like illness that was resistant to standard treatments.[1] Symptoms included fever and shortness of breath. Three days later, the World Health Organization published information on what it was calling the 2019 Novel Coronavirus outbreak, caused by the SARS CoV-2 virus. On January 13, doctors discovered that that a patient in Thailand had contracted the virus, the first instance of it crossing borders. Two days later, it was in Japan. Then the Republic of Korea. One week later, it was in the United States. On January 31, a day after the seventh-known American contracted the virus, the Centers for Disease Control ordered a federal quarantine to anyone who had recently been in Wuhan, China.

AUGUST 10
Analysis of data from Dawn indicates that Ceres has remnants of a subsurface ocean and that its bright spots are deposits from a deep reservoir of brine.

DECEMBER
InSight mission extended through December 2022.

VENUS, VENUS, IO, TRITON

Meanwhile, at NASA Headquarters, leadership in the Science Mission Directorate had narrowed down the Discovery competition to four prospective missions.[2] They were:

- DAVINCI+ (Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging Plus), a Venus atmospheric probe designed to study how it formed and evolved and determine whether Venus ever had an ocean. James Garvin of Goddard Space Flight Center in Greenbelt, Maryland, was the principal investigator.
- Io Volcano Observer (IVO), a Jupiter orbiter exploring the planet's volcanic moon, Io, which would reveal how tidal forces shape planetary bodies. Through a series of close Io flybys, the spacecraft would study the origin and eruption of the moon's magma. Alfred McEwen of the University of Arizona in Tucson was the principal investigator.
- Trident, a flyby mission to Triton, Neptune's icy moon, perhaps expanding the habitability zone of the solar system to the farthest planet. The spacecraft would map Triton, search for its predicted ocean, and study its active processes. Louise Prockter of the Lunar and Planetary Institute in Houston was the principal investigator.
- VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy), a Venus orbiter designed to map the Venusian surface with a synthetic aperture radar. It would help explain the planet's geologic history, and why a planet so much like Earth ended up so different. Suzanne Smrekar of JPL was PI.

Each mission would receive $3 million for nine months of development, culminating in a Concept Study Report. NASA Headquarters would make its final selection in June 2021.

NASA IN A TIME OF GLOBAL PANDEMIC

On February 11, more than 1,000 cases of the mysterious coronavirus had been discovered worldwide. The World Health Organization announced the official name for the disease: COVID-19. One month later, the number of infected had leapt to more than 118,000 in 114 countries, and more than 4,000 people had died from it. On March 16, President Donald Trump announced at a news conference, "My administration is recommending that all Americans, including the young and healthy, work to engage in schooling from home when possible, avoid gathering in groups of more

than 10 people, avoid discretionary travel and avoid eating and drinking at bars, restaurants, and public food courts."[3] Federal workers were ordered to implement "maximum telework."[4]

NASA was not spared the effects of COVID and the practicalities of pandemic response, though some elements of the agency and its mission portfolio fared worse than others. NASA Headquarters moved fairly easily into a telework environment because its employees already operated with a remote work mentality. "For people who work at Headquarters, COVID did not have nearly the huge impact that it did for everybody else," said Curt Niebur, the then-Lead Program Scientist for the New Frontiers Program, the billion-dollar competitive, PI-led mission class.[5] "That's because for NASA Headquarters, on a daily basis, the people I interact with are not three doors down from me. The teams I interact with are scattered around the country, if not the world." Working from home and interacting with teams on Zoom and Microsoft Teams was "just another Tuesday," he said.

The same was not so for Psyche. "It was like crisis across the project at the individual level, at the group level, at the organizational level, and it started a whole series of crises which pushed us from being in kind of a project running normally into a project running in crisis mode," said David Oh.[6] Among other problems, at the start of 2020, the UCLA-built magnetometer that Psyche would carry was sufficiently behind schedule that it risked missing the launch date. As a result, mission management decided to switch to the Technical University of Denmark to build the instrument.

"We went out there [to Denmark] for that meeting, decided after that meeting—in February 2020—that we were going to switch, and then I never saw them again until basically it was delivered," said Benjamin Weiss, the deputy PI and magnetometer lead.[7] COVID basically ended all international travel.[8] The Danish company had its own problems. Many of the instrument's parts were delayed due to supply chain issues. They even had to get special permission from their government simply to go to the university to actually build the hardware. Afterward, in normal times, they would have then taken the instrument to an ultrasensitive, magnetically quiet facility in Germany, but when a COVID spike hit at the time, they couldn't get approval to fly there. Instead, they had to calibrate from a place they'd never done so before, in northern Denmark. "So, quite a challenging environment to do this," said Weiss.[9]

COVID made everything more difficult, said Lindy Elkins-Tanton. A spate of pandemic-driven retirements in the aerospace community led to a loss of institutional knowledge, and she soon became obsessed with companies that "lose the recipe" for their hardware.[10] General Dynamics, for example, had halted production of their Small Deep Space Transponders, used on spacecraft for X-band and Ka-band

communications with the Deep Space Network on Earth.[11] "They were having trouble building ours and Lucy's," said Elkins-Tanton, "to the point where we had to send a team in to meet with them in person right in the height of COVID."[12] She learned that there was only one person at General Dynamics who really knew how to tune them, and she had retired. The company had to somehow coax the retiree, named Helen, out of retirement, because she had never managed to train anyone else on how to tune them properly. Psyche had a similar problem with Lockheed Martin, which was building a cryo-cooler necessary to keep the gamma ray and neutron spectrometer's high-purity germanium sensor cold enough to work properly.[13] Lockheed couldn't successfully build the device, so the Psyche mission had to form a tiger team to explain to the aerospace company what was wrong with the cryo-cooler. It turned out that Lockheed's cryo-cooler expert had retired. Her name was also Helen. "My son and husband and I developed this idea that there's a least reduceable unit of technological knowledge called the Helen, and that the complexity of your project can be measured in Helens, how many Helens is your project, how many individual people's super expertise is required to get this done," Elkins-Tanton said.[14]

In addition to the psychological burden of people now having to work from home, oftentimes with kids—and on top of the ordinary stresses of pandemic life, from personal precautions to cabin fever to worrying about shortages of home staples at supermarkets—part of the challenge, for mission management, of remote work in aerospace engineering was simply keeping people connected and engaged. Psyche's gamma ray and neutron spectrometer and the imagers had significant problems that required people to travel to contractor locations—which otherwise might have been an ordinary solution, but which during COVID was highly unusual—in addition to working overtime and holding extra meetings during the pandemic. "A lot of our problems ended up being with contractors to the subcontractors, where they just didn't even feel the urgency. Like, they didn't see the vision. They didn't understand this was incredibly critical for them to keep going. They would have COVID shutdowns and then they would not respond or they would send in stuff that was subpar."[15] Everything ended up being more expensive. Maxar was the main Psyche contractor with a fixed-price contract: the vendor, in other words, would deliver its hardware for a price set in the contract, regardless of how much it ended up costing to develop. Others used cost-plus models, where NASA would cover all of the contractor's allowable costs, plus a fee for profit on top. Cost-plus contractors particularly vexed her when "they didn't have the personnel who knew how to do it anymore and they couldn't build it right, so we have to pay them another million dollars to build it right," she said, "that just makes me crazy."[16] She would lament to other Psyche managers that it seemed wrong that contractors didn't eat some of

the cost overruns. "The team would say to me, 'Lindy, you can have the ethical high ground or you can have a space mission. You choose.'"[17]

That, she said, was COVID in a nutshell. "It was unbelievable. *Unbelievable*." Psyche management studied the change in the effectiveness of its workforce pre- and post-COVID outbreak, using factors such as earned-value accounting metrics, and found a significant reduction in efficiency during COVID, which translated into higher costs. "[I] definitely don't recommend building spacecraft during a global pandemic."[18]

The pandemic wasn't through with Psyche yet. As Elkins-Tanton would soon learn, COVID contributed quietly to communications issues that would nearly lead to the mission's termination.

"IF YOU TRUST ME, I'LL KEEP THE TEAM SAFE"

Lucy had better luck. Because they had passed their Critical Design Review in October 2019, by March 2020, they were nearing the end of building things, and approaching ATLO: Assembly, Test, and Launch Operations. As such, they largely avoided the supply chain issues that bedeviled other NASA flight projects in development. For the engineers building Lucy, it was still an unprecedented challenge in American spaceflight.

Just before the quarantine began, Donya Douglas-Bradshaw, the Lucy project manager at Goddard Space Flight Center, began contingency planning. She told Levison straightaway: "If you trust me, I'll keep the team safe and we'll get to launch."[19] She was relatively new to the role, and when first offered it, she declined. Mike Donnelly, the outgoing project manager, was set to retire in three or four months, and she didn't think she would be ready.

Someone told her something, however, that made her rethink her position. "Here's the difference between men and women," she recalled him saying.[20] "Women want to make sure that they have the training and they have everything lined up and they want to feel comfortable before they jump in. Men just jump in and they'll figure it out on the fly." It bothered her a lot. She shared her reservations with her husband, who also worked for NASA. She'd not been on the project long enough. The role was different. There would be a lot of visibility. NASA Headquarters would be watching.

"He looked at me and he said, 'You say that every time but you do it, and you do great,'" Douglas-Bradshaw recalled. Still, she wasn't convinced. She called deputy project manager Vince Elliot. "Vince, I don't know. I'm being asked if I am interested in this job," she said. "I don't know."

"Donya, I've watched you," she recalled Vince saying. "I've watched you over the last four months or whatever. You're amazing. You're more than capable. I promise you that if you say yes, I will do everything I can to ensure you're successful."

She met with Levison in a one-on-one meeting and took the job.

Douglas-Bradshaw had wanted to work for NASA since she was a 10-year-old. She came from modest means.[21] When she was young, she worked on farms where she picked cucumbers and tomatoes with her great-grandmother. It was one of the ways her family earned a living. When she and her family lived with her great-grandmother, they did not have access to indoor plumbing. Her father, who was in the military, would send her books on space, and she was good at math and science in school. She wanted to be an astronaut—until she realized you couldn't poke your head out the window of a spacecraft and breathe. Then she didn't want to be an astronaut. But she continued excelling in science and math, eventually attending University of Maryland as a mechanical engineer. It was still a difficult time to be a woman in engineering. She had married young and had a child. One professor expressed doubt that she had it in her to graduate. "I think being an African American woman, being married, it was challenging to get through college for sure," she said. But the skepticism fueled her drive. "The worst best thing you can do with me is to give me the impression that you don't think I can do it. I remember making the dean's list that semester because the disbelief motivated me."

As one of the top students in the program, she got an internship at Wallops Flight Facility in 1991, where she worked on aircraft experiments. "I had already purposed in my mind that as a young African American woman I had to show up a particular way," she said. "I would dress a certain way. I would carry myself in a certain way. I held people accountable for what they said and how they acted, so if things were said that were not necessarily appropriate, I would challenge them."

She never left the agency. In her early career, she worked on thermal systems. Before she joined Lucy, she was systems engineer and then project manager of ATLAS (Advanced Topographic Laser Altimeter System), a space-based lidar used for measuring ice sheet balance on ICESat-2 (the Ice, Cloud and land Elevation Satellite). (ATLAS, at $500 million, was also the largest such instrument ever built in-house at Goddard.)[22] She joined the Lucy mission in 2019.

By the time COVID came along, she was project manager. She worked with Lockheed Martin program manager Matthew Cox and ATLO manager Chris McCaa to devise a concept that would keep Lucy on schedule. They called it FAST: Feasible ATLO, Shortened Timeline.[23] They compressed the schedule to accommodate the loss of productivity and get Lucy to the launch pad on time.[24] They divided the people required in the cleanroom into different, isolated teams—red team and blue team—and arranged their schedules so that teams never crossed paths with

one another.[25] Team assignments were permanent. It required long hours and constant reschedules, a process stressful to the team, particularly at Lockheed Martin.[26] Still, it worked.

"It was a brilliant piece of management to watch that happen," said Hal Levison.[27] "The idea was that if somebody were to get infected, we wouldn't be shut down entirely."

As a rule, the project didn't require people to travel. "The people who traveled wanted to travel. I traveled. I spent 171 nights in a hotel that year because I thought it was important for me to travel," said Douglas-Bradshaw.[28] "If my folks were going to be on-site, I was going to be on-site working with them." For those working remotely, the team used GoPro cameras for remote inspections in the cleanroom, and FaceTime on iPads. In-person work also involved what they called the Lucy 6-15 rule: everyone stayed six feet apart, but if anyone had to work in closer proximity, there was a 15 minute limit. Everyone remained in personal protective equipment. Because Levison worked from the Boulder facility of the Southwest Research Institute, he and other SWRI members of Lucy were able to visit the Lockheed Martin facility in Littleton, Colorado, without having to board a flight. It helped keep the project moving along, and keep everyone engaged, a problem that was vexing Psyche.

In October—one year before launch—Lucy switched to seven-day work weeks, all hands on deck. In practice the red team might work four days, and blue team three days, and then they'd swap the following week. Lockheed, meanwhile, maintained a nine-day work week, 10 hours a day, with every other Friday off. Despite the pandemic, Lucy remained on track to come in on budget—something few missions in Discovery ever managed.

KISSING THE MOLE

On the other side of the continent, at JPL, members of the InSight ART had to reconfigure themselves, and their instrument on Mars, simultaneously. They had come to realize that at a certain point, InSight wasn't going to have any more power, and that even if they successfully managed to get the mole digging, it would take months to get to a suitable depth, given penetration rates they'd seen. If they were successful, afterward, the mole would still have to cool down, so that it could return stable measurements not influenced by the action of penetration. "At a certain point we have to draw a line in the sand and say if we can't make progress by this date, then we might lose communication with the lander," said Troy Hudson.[29] That was because Mars was fast approaching aphelion, the farthest position in its orbit from the Sun, and meanwhile, InSight's solar arrays were becoming less efficient as the

mission progressed due to the accumulation of dust on its surface, at a rate of 0.2% per sol in its first year.[30] The ticking clock meant the spacecraft would turn off before a successfully buried mole returned any data. If they were going to succeed, it had to be in 2020.

The first setback (that year) came on January 12 on Earth, Sol 407 on Mars. The mole managed to get 1.5 centimeters deeper into Mars after the first 20 strokes of a 130-stroke self-hammering campaign.[31] During the subsequent 110, however, the instrument changed directions, again backing out by 3.5 centimeters. If there was any silver lining—and the team was looking hard for silver linings by then—it was that it hadn't withdrawn as far from Mars as the first time it reversed course.

So, they decided finally to just try pushing the thing into the ground. "Our positioning accuracy is around a centimeter or a little bit less than a centimeter, and the place where we had to place the scoop was about two-and-a-half, three-and-a-half millimeters wide—much less than our positioning accuracy," said Khaled Ali, the robotic arm's operations lead.[32] After all the manipulations with the scoop to lift the mole's cover, and later, to pin the instrument to build friction, engineers felt like they had developed an aptitude for using the robotic arm. This, they argued, lessened the risk of accidentally damaging the tether. Either way, said Ali, "People became less concerned about the tether as they became more desperate."

Because it was impossible to push the mole smoothly as it hammered, following it gently but firmly as it buried itself in the ground, the team had to break the campaign up into multiple hammering periods. They would push, hammer, observe what had happened, and reposition the arm to push yet again. Then the process would repeat. InSight allocated one cycle of operations per week for the mole, as the overall mission by then was supposed to be in a passive mode rather than an active one. The mole team decided that they would emplace the scoop every other week (usually on Saturdays), verify the placement on Mondays, and green-light the self-hammering, typically, the following Saturday.[33] So gingerly would they have to touch the rear of the instrument that they called each repositioning "kissing the mole."[34] Over the next eight months, they kissed the mole 12 times, 9 with the scoop in horizonal orientation, and 3 with it inclined. The dozen rounds of pushing totaled 1,280 hammer strokes.[35] Hudson held out hope that the mole might finally dig freely. There was a "definite possibility" of success, he felt, but added: "I have made such predictions before, and Mars has said, 'Nuh-uh. Nope.'"[36]

But the push campaign worked exactly as planned. Once the mole was underground, they used the arm to scoop enough regolith behind the instrument that it was nearly obscured.[37] They also filled the mole hole and packed it as best they could. Their goal was to maximize regolith contact and increase friction so that the mole could at last dig deeply on its own.

By December 19, they had given the mole all the help that they could. The InSight mission overall was faced with power and thermal issues as the Sun waned and a dust storm slowly blanketed the lander's solar panels with material. Even if the mole didn't go another inch into the ground, it was positioned to collect at least some science data on the average thermal conductivity of the top 40 centimeters of soil.[38] The best case scenario going forward would see the mole digging without interruption until it either stopped moving or reached its intended depth. At that point, they would wait out aphelion and conjunction. If InSight survived, they would then begin science operations.

JANUARY 14
NASA announces end to InSight's attempts to dig the mole into Mars's subsurface.

CHAPTER 11

2021

MAY 22
InSight science team successfully clears some dust from the spacecraft's solar panels.

JUNE 2
DAVINCI and VERITAS missions selected for flight.

The New Year brought some badly needed good news for InSight. On January 8, 2021, NASA Headquarters approved a two-year extended mission.[1] The Planetary Missions Senior Review, led by Sean Solomon of Columbia University, had deemed InSight a "success story" that "produced exceptional science."[2] The spacecraft, according to presentations by the mission team, was in excellent health, aside (as expected) from its power systems, besieged by dust and likely to reach critical levels as the extended mission progressed. Concurrently, the power needs of the thermal system would increase as the Martian winter set in. (The mole was deemed a minor issue; its data was complementary to seismology science, and unnecessary for InSight to meet its threshold requirements for mission success.)[3]

OCTOBER 16
Lucy mission launched from Cape Canaveral.

The major goals of the extended mission, building on InSight's prime mission goals and those endorsed by the Planetary Science Decadal Survey were to:

- Constrain the structure and state of the Martian interior;
- Constrain the dynamics of the Martian interior;
- Characterize the regolith and near-surface structure at the landing site;
- Constrain the dynamics of the Martian atmosphere and its surface interactions;
- Investigate time-varying behavior of the Martian magnetic field; and
- Constrain the impact rate on Mars.[4]

One day after the InSight team got a shot of good news about the extended mission, they got a chaser of heartbreak. On Sol 754, engineers executed what they called the "Free Mole Test." With the scoop pressed down on the soil directly above the buried mole, they commanded the hapless heat probe to self-hammer for 500 strokes. The ambitious number was chosen so that "the result, whatever it was, would be unambiguous."[5] But the mole did not dig deeper. Indeed, it tilted slightly, suggesting it was attempting to move backward. "There's no more we can do," Troy Hudson said.[6]

Thus ended the saga of the mole. "We've given it everything we've got, but Mars and our heroic mole remain incompatible," said Tilman Spohn, the principal investigator of the Heat Flow and Physical Properties Package.[7] "Fortunately, we've learned a lot that will benefit future missions that attempt to dig into the subsurface."

While unsuccessful as conceived, the fully submerged mole was repurposed as a thermal probe, and at intervals, across seven sols, measured conductivity and temperature fluctuations. The second year of the mission, it also acted as a thermometer of sorts, measuring daily highs and lows of the region.[8] (The average temperature it recorded was –56 degrees Celsius.) The data proved useful for understanding in greater detail why the top 20 centimeters of crust behaved so oddly and unexpectedly—something impossible to predict from orbit. During the Martian winter and spring, daily, 10-hour windows saw temperatures at levels conducive to forming, from atmospheric moisture, thin films of salty water. This is likely what caused soil to harden into the tough but porous layer that so frustrated the InSight team.[9]

With 22 months of his life devoted to the mole, Hudson was circumspect after it was laid to rest. "It's important for me to understand—and many people told me this, and it's true—that even though we didn't get to dig as deep as we wanted to, we still got good science out of the instrument and we learned some things that we didn't expect to learn," he said.[10] "That's still discovery. That's still information that is valuable. It's not the information we had set out to get, but it's useful. It's valuable."

THE WINDY SEASON FOR INSIGHT

After the mission extension, engineers put InSight into hibernation mode. So dusty had the solar array become that they were down to producing 27 percent of their capacity compared with a clean state.[11] The windy season had ended, with no hope of the Martian atmosphere sweeping the panels clean, as it had done previously. (Scientists determined that strong vortices had a direct impact on solar array performance: what they called "cleaning events.")[12] Engineers would have to choose carefully which instruments and systems ran when, because of the imperative to keep the spacecraft heaters running until the following July, when Mars began approaching the Sun, again, in its orbit, and full science operations could resume.

Around this time, members of the science team had an idea for how to dust things off, and it involved the lander's robotic arm, which was proving useful beyond measure. On May 22, they ordered the arm to scoop up some Martian regolith near InSight, and then, during the windiest time of day—around noontime on Mars—allowed the sand to trickle freely near the solar panels. The idea was that the wind might blow larger sand particles across the panels, and in doing so, drag some of the fine dust coating as they went.

After performing the maneuver, they saw an immediate increase in the available power to the spacecraft. "We weren't sure this would work," said Matthew Golombek, the geology lead who had helped select the landing site. "We're delighted that it did."[13] It was a sign that the InSight mission might last longer than anyone expected.

DAVINCI+

James Garvin's earliest memories were of being an explorer. He'd grown up with a deep fascination of the universe, the Moon, and rocks, as far back as age three, when he first started playing outside and getting dirty.[14] His family nurtured the interest and encouraged him to pursue them. His family lived all over the world, and he saw the deserts of Egypt as a child, went into King Tut's tomb (when the walls were still covered with gold leaf), saw the big, beautiful glassy rocks of the Libyan Desert, and the volcanoes of New Zealand and Hawaii. His imagination could hardly keep pace with such sights. Even after working for NASA for more than 35 years, he still felt like that little boy who told the Moon "goodnight" before bed, and wondering what that place was made of. Then as an adult, the Apollo samples were right there for him to study. (Of course he watched Apollo 11 on television.)

Garvin went to school at Brown University for his undergrad, where he took a course from Thomas A. (Tim) Mutch, the celebrated professor who later became the leader of the imaging investigation for the Viking Program lander on Mars.[15] The

class was about exploration as a mode of thought, rather than a science or history, and after that, Garvin felt like a NASA career was inevitable. For his first master's, he went to Stanford, and returned to Brown for his doctorate, where Mutch—who later became Associate Administrator for Space Science at NASA Headquarters—was his advisor. Garvin connected the landing panoramas of Venus, collected by the Soviet Union, to the observations the Viking Program made at Mars, and (to a lesser extent), what the Apollo astronauts saw on the Moon. He had a vision of interpreting human-scale views of other worlds: That's how the water flows. That's how the wind blows. It was, to him, like a Sherlock Holmesian, Victorian novel. In some part of his mind, it was like being there, gazing out at these wondrous vistas, experiencing them. When he graduated in 1984, Noel W. Hinners, the director of Goddard Space Flight Center, hired him. "Let's do Mars and Venus, Jim," Hinners told him. And so, Garvin did. Decades later, after the losses of Mars Polar Lander and Mars Climate Orbiter, he became the first NASA Chief Scientist for Mars Exploration.[16]

By the time he came to the DAVINCI+ proposal, he had a career of planetary missions under his belt as co-investigator, including a Mars lander, a Mars rover, and two Mars orbiters (one that succeeded wildly, Mars Global Surveyor; and one that vanished mysteriously, Mars Observer), two asteroid missions, and two international projects.[17] The DAVINCI mission had been proposed once before, as part of the Discovery AO announced in December 2014, under the leadership of Lori Glaze, the deputy director of Goddard's Solar System Exploration Division. Garvin was the deputy PI on that proposal, though NASA went with the Lucy and Psyche asteroid missions instead.[18] When the 2019 AO rolled around, Glaze had moved on to NASA Headquarters, serving as interim director, and then director, of the Planetary Science Division.[19] Garvin was the natural person to take up the Venusian mantle.

By then, there had been something of an uprising playing out publicly from the Venus community of planetary scientists—particularly after NASA passed over DAVINCI in favor of Psyche and Lucy. The last time NASA had launched a mission to Venus was Magellan in 1989, which mapped the whole planet with radar. That mission, following on NASA's Mariner and Pioneer spacecraft in the 1960s and 1970s, and the Soviet Union's ambitious sequence of Venera orbiters and landers in the 1980s, created a large community of Venus scientists. After 1994, when Magellan ended, a decade elapsed without any new science data. But the community didn't disappear; it waited in academia, increasingly vexed. Even if NASA Headquarters chose DAVINCI, or some other Venus mission, for flight, the earliest it would launch would be around 2029—40 years after the launch of Magellan. Scientists could have had entire careers without the United States ever having placed a Venus spacecraft on the launch pad. Planetary bodies without missions are ever at risk of losing their

scientists. No new data means no new crop of graduate students doing theses on that data. As Ellen Stofan, the former chief scientist of NASA, explained in a 2017 interview, "My huge concern is that the expertise is still there but it's going away. If we have no Venus missions, it will definitely be gone. We will have lost something. We will have lost this capability and it's really unfortunate."[20] David Grinspoon, then a senior scientist at the Planetary Science Institute, said that communities form around missions. When NASA approves, for example, multiple Mars missions, "you've trained a generation of grad students whose advisors were working on Mars missions who are then new scientists in the community, and they want to propose Mars missions," he said.[21] "The Venus community has shrunk because there haven't been any missions there, so there hasn't been funding, so there haven't been as many people writing papers, training students, holding meetings—the community has sort of dissipated and withered away a bit." After NASA Headquarters passed on the first DAVINCI proposal in 2017, as well as VERITAS, Grinspoon wrote in *Sky & Telescope* that since Magellan, "we Venus researchers have proposed orbiters, entry probes, balloons, and landers. Every one has been shot down." He added: "At what point are we no longer admirably committed, but merely pitiful?"[22] Venus, he explained, has a fundamental disadvantage in competed missions because, when judged against planets frequently explored, "we will always get less data with more risk, for the same money."

Still, Venus was starting to have a moment in the spotlight. In 2020, in the journal *Nature Astronomy*, scientists announced the detection of phosphine gas in Venus's cloud decks, "with no currently known abiotic production routes in Venus's atmosphere, clouds, surface and sub-surface, or from lightning, volcanic or meteoritic delivery."[23] In other words, it was a signature of life. Though the conditions on the surface of Venus precluded life as we know it, its clouds, though acidic, have everything life needs: water, organics, and sunlight. As you get deeper into the cloud layer, you get pressures and temperatures similar to those of Earth.[24] The finding wasn't completely out of left field. In 1967, Harold Morowitz and Carl Sagan had speculated in the journal *Nature* about the possibility of airborne life taking hold.[25]

By 2021, the phosphene findings had been largely discredited, and certainly the life hypothesis had been cast into doubt.[26] But the debate itself had in many ways changed Venus's standing among the desired targets of planetary missions.

To that end, DAVINCI+ was an orbiter and atmospheric probe.[27] The orbiter would incorporate two Venus flybys, separated by about nine months, followed by the release of an in-situ probe six months later, that would descend upon the planet.[28] The flyby element, called the Carrier, Relay and Imaging Spacecraft (CRIS) would study the Venusian clouds and map its highland areas during its two flybys, as well as the heat coming off Venus on its night side. It would carry two instruments in

its payload. First was the Venus Imaging System for Observational Reconnaissance (VISOR), derived from the navigation camera system used by OSIRIS-REx (a New Frontiers asteroid mission that launched in 2016). Secondly, CRIS would carry the Compact Ultraviolet to Visible Imaging Spectrometer (CUVIS): a technology demonstration instrument designed to use freeform optics and artificial intelligence to collect high resolution UV spectra of Venus' atmosphere, and image the cloud-top structure of its daylit hemisphere.[29]

CRIS would carry the DAVINCI+ "descent sphere"—a hermetically-sealed titanium pressure vessel about a meter across—with five instruments in its payload. The sphere was essentially a flying chemistry lab. Its instruments included the Venus Mass Spectrometer, surveying the noble and trace gases in the atmosphere; the Venus Tunable Laser Spectrometer, studying the chemistry and chemical processes of Venus in its upper clouds and near-surface; the Venus Atmospheric Structure Investigation, measuring pressure, temperature, and acceleration of the atmosphere throughout the descent; and the Venus Descent Imager (VenDI), a near-infrared descent-imaging camera.

After separation from CRIS, the "Pro Flight System," composed of the descent sphere, a heat shield, and a back-shell, would enter the Venusian atmosphere at a high velocity.[30] At approximately 70 kilometers above the surface, a drogue chute would pull the back-shell from entry system, and the descent sphere from the heat shield. The sphere's main parachute would deploy, thus beginning the science investigation. First, the sphere's ingestion ports would open, allowing VMS and VTLS to begin taking altitude-resolved high-fidelity measurements of atmospheric gases, including noble, trace gas, and isotopic abundances, while VASI recorded temperature, pressure, and wind data. Around the 38 kilometer mark, the sphere would jettison its parachute, and after passing through the thick, acidic clouds of Venus, at about 30 kilometers, VenDI would begin collecting descent near-infrared images. (Because of Venus's thick atmosphere, the probe would fall slowly once severing its parachute: more like a pebble through a pond than the way it might fall through, for example, Earth's atmosphere.)[31] The descent would take about an hour, total, for the sphere to reach the surface. Once there, the probe could continue collecting and returning data to CRIS for approximately 18 minutes. After the DAVINCI+ descent probe completed transmitting its data to CRIS, the spacecraft would point itself at Earth and transmit the data to the Deep Space Network. It would be the first unique characterization of Venus's deep atmosphere and its chemistry and composition; the definitive record of the chemical and isotopic composition of the Venus atmosphere; and would constrain the composition of rocks at its target, and the topography of a tessera.[32]

Venus had intrigued Garvin since the start of his career simply because of how much scientists simply didn't know. Why did it evolve so differently than Earth, despite being in the same general region of the solar system, being the same size, and made of the same stuff? "The Venus of today is not the real Venus," he said.[33] "There's no reason why Venus might not have had global oceans of liquid water, hundreds of meters deep, for maybe billions of years—and then something happened." Venus entered a greenhouse state: a surface more than 900 degrees, with swirling clouds 30 miles high. "There's a story there."

But Venus was hard, and DAVINCI+ had several engineering challenges to overcome, not the least of which was the one-time-only descent sequence: everything had to work, including the pilot chute. Moreover, the data collected by the descent sphere had to be successfully transmitted to the spacecraft. The spacecraft then had to relay the data back to Earth. If any of those events failed, the mission would fail.[34] Surviving on the surface for more than an hour or two is a thermal nightmare; just by getting there, however, and making measurements through the entire atmosphere before touching down on the surface, would fundamentally transform our understanding of that world. "We're going to wake up in a decade and say, 'There's a new Venus,'" he said.[35]

It would take a fusion of science and engineering to achieve that goal. "Scientists dream and the engineers produce the masterpieces that enable the dreams to become real," said Garvin. "NASA is an organization that produces masterpieces of engineering. Driven by ideas—in many cases by the wisdom of scientists. The science gives you the 'why.' The engineers tell you whether you can do the 'how' you think you want to do. That partnership is critical."[36] For Garvin, DAVINCI+ was more than a clever acronym. Rather, it represented the kind of person that aspired to use art, science, technology, math, and the humanities to solve problems and see the world differently, as the mission's namesake had once done.

Before Garvin accepted the DAVINCI+ principal investigator role, he had a condition. He wasn't exactly an early career scientist, and one of the achievements of the Discovery Program, in his view, was the way mission teams incubated the leaders of future missions. He wanted to bring such people onto the project—the sorts of rising stars who might not have been natural fits on directed NASA missions—if they were interested. He would expand the leadership pool so that talented, younger scientists could take over and run the show, write the papers, and lead the science teams.

Garvin developed a management plan where he had two deputy PIs: one an early career "rising star," and another a midcareer scientist with management and technical experience. "I look at ourselves as a triad of management as PIs," he said.[37] "I'm responsible, I'll sign my name in blood to do the DAVINCI mission, my colleagues in arms in that are two brilliant people who I can always use as sounding

boards and we work together on all major decisions, as we relate to our project management team." He chose, respectively, Giada N. Arney, a research space scientist at Goddard, and Stephanie A. Getty, the Deputy Director of the Solar System Exploration Division at Goddard.

Not even counting Glaze's first swing at DAVINCI, he and many members of his team spent two and a half years of their lives focused on Venus exploration. The step one proposal came out to about 100 pages, plus hundreds of pages of ancillary information. The proposal started with the science story, and how it connected to the planetary science community's goals. Then there was the science implementation section: how the mission's science goals could be met with an instrument payload, and what measurements it would need to take. There was the technical flight system section, describing how the spacecraft would get to its target, and how it would return data. The management section laid out how the mission's project manager would work with its PI and the PI team; and the science team; and all the engineers building instruments (i.e., the project systems engineering team). Finally, the proposal detailed the mission's cost and schedule. You were, in essence, proving that you could build a mission on time and on schedule. And that was just step one. Step two wanted all that in greater detail. Their final proposal was 1,470 pages of material, plus another 2,000 pages of spreadsheets of masses and budgets and schedules (not counting the material developed for the site visits and briefings to the selection officials).[38] They did all this remotely, because of COVID.

"THIS IS THE CALL YOU NEVER WANT TO RECEIVE"

On the morning of June 2, Louise Prockter sat at her kitchen table, waiting for her phone to ring.[39] She had been told to expect a call after 8:00 a.m. ET. She'd given up three-and-a-half years of her life by then, working full time on Trident in addition to working full time running the Lunar and Planetary Institute until 2020, and then as chief scientist of the Space Exploration Sector at the Johns Hopkins University Applied Physics Laboratory. It all came down to this call.

What a journey it had been. Karl Mitchell was the project scientist, and had built the initial team, and they worked together to build from that. The total numbers fluctuated. An engineer might come on only briefly to solve some technical problem and move on to the next thing. As they added people, they recognized that it was a very long mission, so they wanted a third of Trident members to be early career scientists, a third mid-career, and a third senior, with 20 years or more in the field. She tried to ensure at least half the team was made up of women and underrepresented groups. And the team, in the end, was just extraordinary. Everyone essentially worked for free during step one—and quite a bit for the second step, as well.

They did much of it virtually and also met at conferences and in a little war room at JPL. "You're working crazy hours, unpaid of course, just trying to get it done," she said. "So there's a sort of feeling of camaraderie among the team, but it is a huge amount of work."[40]

The Trident team made the decision to be very open about their idea, in part because they were pretty sure no one else would try and do something so audacious, and in part because Prockter knew she needed to bring the community on board and get them excited. When they would present posters at conferences and workshops and explain what they wanted to do, people always went in skeptical that such a mission were possible and came away believers. It was so exciting—outrageous, even—this idea of going to Neptune on a Discovery budget. Just proving that they could detect an ocean on a flyby was an epic achievement. When Galileo's magnetometer detected Europa's ocean, it required multiple orbits.[41] Corey Cochrane, a research scientist and technologist at JPL, had come up with a way of doing it on a fast flyby. Randy Persinger, an engineer formerly of Aerospace Corporation, worked alongside him to tell the story. They spent years getting it just right.[42]

Something Prockter had learned from Sean Solomon was the need to keep things simple, so the Trident team distilled the science to four straightforward questions the mission would answer:

- Is Triton an ocean world?
- What processes resurface Triton?
- What drives Triton's plumes?
- Why is Triton's ionosphere so intense?

Perhaps the most important thing was that Prockter and the team passionately believed it could be done. It was the only way to work such a punishing schedule on such an audacious project. Early on, the lab had more than a dozen different concepts, and every one of them was great, but it was too expensive to do full-up proposals for all of them. So, management conducted regular reviews to winnow down the number, and it felt to Prockter like they were fighting for survival all the way down the line right to the end. Finally, during the presentation at one gate review that wasn't going particularly well—they hadn't proven that the ocean detection would work, partly because it was just really complicated mathematics and nearly impossible to explain during a talk—she just laid it out there, to this room that included with a few high-level JPL managers: "You want to dare mighty things?" she asked, referencing JPL's motto. "I've got a mighty thing for you to dare and this is it."[43] And people responded to that.

The wait on June 2, from her kitchen table, was interminable. She had been told to expect a call from Thomas Zurbuchen with the selection news at some point. There was nothing she could possibly do to distract herself. She thought, at first, that it was a good sign the call was taking so long. Zurbuchen was probably calling all the people who weren't getting selected. But after a while she started getting nervous. Finally, the phone rang.

"Hi Louise," said Zurbuchen.[44] "This is the call you never want to receive."

He went into his reasons why he hadn't selected Trident. It was a great mission, very selectable, but for "programmatic" reasons, NASA decided to go in a different direction.[45] Mostly, Prockter spent the call just trying not to cry. It was all just devastating. "You have to believe it in your heart that you're going to win, because you've got to put your heart and soul into it," Prockter said. After, she had to tell the team. And because of the hard reality of orbital mechanics: losing the Jupiter gravity assist, Triton's southern hemisphere going out of illumination, the Trident story was over.

One of the people who called Prockter almost immediately was Jessica Sunshine. When NASA announced the two missions selected, it was pretty clear that Trident was never going to win. The pain of getting so close and then being passed over for reasons beyond your control—well, there weren't a lot of people who could truly understand what Prockter was about to go through, emotionally, but Sunshine did.[46]

VENUS RISING

On June 2, NASA Headquarters announced its decision. It had selected two missions: DAVINCI+, and the Venus radar mission VERITAS, for addition to the Discovery Program portfolio. The "science return and programmatic match," Zurbuchen said, put Venus on top.[47] After decades of neglect, NASA had effectively launched a new, focused program of Venus exploration. "The combined results of these missions will tell us about the planet from the clouds in its sky through the volcanoes on its surface all the way down to its very core," said Tom Wagner, the Discovery Program scientist at NASA Headquarters.[48] "It will be as if we have rediscovered the planet." Each mission had a development cost cap of approximately $500 million, to launch in the 2028–2030 timeframe.

The science goals of DAVINCI+ (the project later dropped the + from its name) were to answer the following:

- What is the origin of the Venus atmosphere and how has it evolved?
- How and why is Venus different or similar to Earth, Mars, and analog exoplanets?

- Was there an early ocean on Venus? If so, when and where did it go?
- What is the rate of volcanic activity on Venus?
- What exactly are the tesserae highlands, including origin and history?
- How do they compare with major highlands, such as Ishtar Terra?[49]

Meanwhile, VERITAS would answer its own set of questions:

- What are the composition and origin of the major geologic terrains on Venus?
- Is volcanism there steady or catastrophic in nature?
- What are the major tectonic processes that shape Venus?
- Is subduction currently active?
- What are the size and state of the core?
- How viscous is the mantle?
- Does Venus' surface have active deformation and volcanism?
- Are there signatures of recent volcanism?
- Are Venus' plateaus like Earth's continents?
- Is there water deep in the interior of Venus, and does it reach the atmosphere via volcanism?[50]

LUCY IN THE SKY WITH DARKNESS

Despite pandemic complications, the Lucy mission launched from Cape Canaveral in the pre-dawn hours of October 16, 2021.[51] It was one of the only Discovery missions, ever, to launch on time and on budget.[52] For Hal Levison, it had been a "brilliant day." Thirty second before liftoff, he raced to the roof of the ULA launch facility to get a better view as his spacecraft launched. He watched it disappear into the cloud deck. Later, he saw a video of the rocket emerging from the clouds, "like the opening scenes of Close Encounters of the Third Kind."[53] The spacecraft quickly established communications with Earth, and within hours, began to deploy each of its two 24-foot solar arrays.

The telemetry looked good, the data plotting according to a nominal deployment. The right panel unfurled exactly as planned—like opening a hand fan—and latched into place. Jessica Lounsbury, the Lucy project systems engineer at Goddard, and others, noticed something strange, however, with the power profile of the other solar array. The temperatures also weren't making sense.[54] Certain spots on the array were colder than they should be. Other spots were hot.

"What's going on here?" Lounsbury said.[55]

The microswitch telemetry revealed that the array had not latched.[56] Was it just the microswitch glitching, then? No, the currents and temperatures were

off-nominal too. The engineers looked at one another. The spacecraft was designed to attempt autonomous deployment for up to an hour. During the interval, Lucy's engineers began pulling their data to study the situation and figure out who needed to be involved in a possible recovery. Northrop Grumman had built the solar arrays, and happened to have a few experts at the Cape, watching the launch with their families. Lounsbury called them in to work. Lockheed Martin's Mission Support Area, just outside of Denver, was communicating with the spacecraft. The team kept them in constant contact. T. Tupper Hyde, the chief engineer of Goddard Space Flight Center, was onsite. "Let me sit in," he told Lounsbury.[57] "I'm an outside perspective." He joined the effort.

By day's end, they had assessed all they could with the available data, and determined that something was wrong, but the spacecraft was safe. The solar arrays were generating a power output at about 90 percent, and Lucy's batteries were fully charged.[58] The solar array had deployed at least partially and remained unlatched. Rather than make rash decisions or send orders to Lucy they might come to regret (for example: just telling the solar array to try again, and damaging something in the process), Lucy leadership stood up an Anomaly Resolution Team, with Colby Goodloe, the spacecraft systems engineer, as lead. They decided the tasks the ART would need to do, and who would do it, including engineers from Northrop Grumman, Lockheed Martin, and Goddard Space Flight Center, with chief engineering support through NASA. Lounsbury and Michael Sekerak, the deputy project systems engineer, also tasked the mission operations team with keeping long-planned spacecraft events on course, provided they didn't put the spacecraft at increased risk.[59] Mission ops would analyze the state of the spacecraft overall, and conduct ground tests of systems before executing them on the spacecraft. Meanwhile, a UAI team (Use As-Is) coalesced to answer the question of what happens if they just didn't do anything at all? Would the solar array be fine in a partially unfurled and unlatched state? Would the jolt of main engine burns cause problems? Would anything, such as trajectories, need to be changed to account for the reduced power?

One thing Lounsbury did was rely on the myriad chief engineers associated with the project and the broader space community. "We have chief engineers within our center," she said.[60] "We have chief engineers at Headquarters. We have chief engineers at our program office. We have chief engineers with our partners, at their industry and their locations." While it might have seemed like a cumbersome process to bring in so many people not necessarily familiar with the design of the spacecraft and solar panels, it brought it fresh perspectives. "The team was burnt out. We had gone through seven days a week, a year of COVID, on the floor, all of

this happening." New viewpoints were invaluable. "While we still were the experts on our system, it doesn't mean we were the experts in creative solutions," she said.

The solar arrays unfurled using a motor and lanyard system. The motor, attached to the spacecraft, pulled a Kevlar lanyard, which was attached to the pivot panel. It spooled the lanyard as it went, but apparently, they soon learned, the lanyard had walked off the bobbin-like spool.[61] Eight days after launch, engineers determined that the affected solar array was between 75 and 90 percent deployed, held in place by its lanyard.[62] (When optimally deployed and latched, the lanyard would be under no tension.)[63]

The ART would attempt to diagnose the array for the rest of the year, in search of the answers to two worrisome questions: what would happen if they again switched the lanyard motor on, and tried to fully open and latch the solar array; and what would happen if they didn't?

THE WORST CHRISTMAS PARTY EVER

Big trouble emerged at the Psyche Christmas party.[64] It was the first time the team had been together, face-to-face, in 18 months, since the COVID quarantine had begun. It was a perfect opportunity for everyone to relax, enjoy themselves, and just chat about life and work and the spacecraft they were building to explore a metal world.

Like many teams in many organizations, the isolation had made work and communication difficult. Overall, JPL was just plain overextended. Psyche, Europa Clipper, Mars Sample Return, and more—the lab had never before had such a portfolio of missions in simultaneous development.[65] The lab had also experienced a lot of turnover, and teams weren't gelling the way they might otherwise have in-person. People who would have been in the spacecraft testbed environment were unable to compare notes, relay information, and just generally learn the spacecraft system the way they had for previous spacecraft in less-interesting times.

The sorts of "water cooler" conversations that often led to free-flowing ideas and unofficial information exchange were impossible during the lockdown. No one "walked the floor" or dropped in the adjacent office or meeting to chat and listen. So, the Christmas party was something of a relief to everyone, a bit of normalcy, and a boon to the team's morale. The topic of the Guidance, Navigation, and Control (GNC) software came up. JPL had decided that it was going to change its core flight software. Europa Clipper would be the first to use it, and Psyche would benefit from that effort. It was months behind schedule. The staffing problems didn't help, but also, there were institutional experience problems: it had been a while since JPL had

written such flight software. Still, the end was in sight: the final build was set to be delivered to the Psyche mission in early 2022.[66]

Then there was the testbed that Maxar delivered to JPL to test the GNC. It was a bus simulator replicating the spacecraft's hardware. It was distinct from JPL's own testbed, a unified environment for running the GNC software. They had to be integrated, but the resultant testbed was "insufficiently robust"—it just couldn't handle all the tasks necessary for verifying and validating the flight software. There were also time synchronization issues between the systems.[67]

The more engineers at the party spoke, the more they realized something terrible was happening. GNC engineers knew that you needed a testbed that was fully working one year before launch.[68] Well, launch was eight months away.[69] Maybe Psyche's standing review board would have picked up on cues that would ordinarily have raised questions and allowed them to accurately gauge project progress, but the Critical Design Review took place just after the lockdown started.[70] Somewhere along the way, there had been a communications breakdown. Now that people were talking, however, the message was pretty clear: Psyche was in serious trouble.

CHAPTER 12

2022

MAY 4
InSight records an estimated magnitude 5 quake, the largest yet detected on another planet.

MAY
Ongoing Martian dust storm significantly reduces solar power to InSight.

JUNE 24
NASA announces that Psyche would miss its launch window for the year.

JULY–SEPTEMBER
The Psyche Independent Review Board meets at JPL for 15 full days.

OCTOBER 16
Lucy flies by Earth for its first gravity assist maneuver.

NOVEMBER 4
NASA Headquarters releases Psyche Independent Review Board report and announces postponement of the VERITAS launch.

DECEMBER 21
NASA declares InSight mission complete.

"Can we talk?"[1]

It was a text message from Henry Stone, the project manager of Psyche. Lindy Elkins-Tanton wasted no time in calling him. His first words were: "Are you sitting down?" At that moment, she knew whatever he had to say was going to be bad. It was Friday, April 22, 2022. He said that he was setting up a Webex for 7 o'clock that evening for himself, Elkins-Tanton, and Robert Mase, the Psyche deputy project manager.

"Henry, this sounds bad," said Elkins-Tanton.

"It's bad. I'll talk to you then."

That morning, Swati Mohan, the Psyche Guidance, Navigation, and Control lead, had met with the GNC team, and reported to Stone that she saw no way that Psyche would be ready for launch on August 1, 2022. Stone called a meeting with subject matter experts later that morning and into the afternoon, talking through what Mohan had reported, her data, and the schedule pressures. Stone left the meeting believing it was

unlikely that Psyche would make its launch. He explained all this in the Webex. They put together a tiger team that met over the weekend to look at the problem and hopefully find a solution. The tiger team found none.

On Sunday, Elkins-Tanton flew to Washington, DC for a meeting that had already been scheduled with the Science Mission Directorate Program Management Council, responsible for making sure programs and projects could meet their commitments to NASA.[2] Elkins-Tanton had expected to go into the meeting, set for Tuesday, with a good story, and needing only a small increase in resources to finish the spacecraft. After the Webex with Stone, however, the situation had changed. Now, she knew, the mission was in jeopardy.

"There's a new threat," she reported at the meeting. That's all she could share for certain, because that's all she knew. Over the next two months, "hundreds and hundreds and hundreds of people working as hard as they can" endeavored to make a 2022 launch. JPL delivered the spacecraft to Kennedy Space Center on May 2, and by all public accounts, the spacecraft was on track for launch.[3] Three weeks later, NASA announced a slight delay to September 20, to "confirm that all hardware and software systems are operating correctly."[4]

It wasn't until June that the Psyche team had completely convinced themselves, and NASA Headquarters, that 2022 was off the table. On Friday, June 24, 2022, NASA announced that Psyche would miss its launch window for the year, and was therefore indefinitely on hold.[5] "NASA takes the cost and schedule commitments of its projects and programs very seriously," said Thomas Zurbuchen.[6] "We are exploring options for the mission in the context of the Discovery Program, and a decision on the path forward will be made in the coming months."

Less than a month later, at the request of Zurbuchen and Laurie Leshin, the director of JPL, NASA formed an Independent Review Board (IRB) of 16 experts from across the agency, the private sector, and academia, to be led by A. Thomas Young.[7] That alone was telling. Decades earlier, Young had led the Mars Program Independent Assessment Team, formed in the aftermath of the Mars Climate Orbiter and Mars Polar Lander failures. The IRB's job was to figure out what went wrong, and how to fix it. Whatever they recommended would go into NASA's decision whether or not to cut their losses and terminate Psyche altogether.

TENSION FOR LUCY

The Lucy team was going to try again. The ART had done an extensive risk assessment, laying out every possible thing that could go wrong with redeploying the array, and conversely, everything that could go wrong if they didn't. Just figuring out the extent of the problem was a challenge. They couldn't see the solar array, and

there wasn't a percentage gauge they could read. So, engineers came up with a way to tilt the spacecraft back and forth, measuring the power received by each segment in its orientation.[8] That data would go into a mathematical model they wrote that could determine exactly how much remained to be deployed.

The array, they learned, had unfurled 345 degrees, with a goal of 360.[9] Next, they needed to determine if and how they could close the gap with a goal of latching. Northrop Grumman's "Deployables" team in Goleta, California, used solar array components as an improvised testbed for simulations. They determined that the array's primary and backup deployment motors, if used at the same time, could generate sufficient torque for pulling the lanyard around the axle, further unfurling and possibly latching the solar array.[10] (The dual motors were intended for redundancy—not simultaneous action.)[11]

Jessica Lounsbury was pleased with how comprehensive everyone involved in the process had been.[12] They had run 45 ground-based tests to be absolutely sure they understood what had happened in order to propose a solution. Meanwhile, Lucy had operations in its docket that had been planned pre-launch: things like turning on and testing instruments. They had to figure out what could be done, and what should be delayed. Hal Levison would sit in on technical meetings as a fly on the wall, and afterward, he, Lounsbury, and Mike Sekerak would hold a separate meeting with Lucy management and PIs.[13] These conversations could be blunt: an opportunity for Levison and others to push back on ideas or interrogate the rationale behind the engineering decisions being made. It was a chance for everyone to have their voices heard, and for Lounsbury and Sekerak to justify their decisions, or explain why other ideas wouldn't work.

In late April, senior members of the Lucy team met with Zurbuchen at NASA Headquarters to make a recommendation. Goddard Space Flight Center wanted to redeploy the array. Levison wanted to redeploy the array. Lockheed Martin, however, did not. But the decision didn't have to be unanimous. "We're going to redeploy," said Lounsbury.[14]

In Lounsbury's view, the disagreement between Lockheed and the other stakeholders came down to business models. Northrop Grumman's reputation was on the line: they had everything to lose if the solar array didn't open, because it was their technology and they wanted to continue producing solar arrays for other satellite missions. So, they were naturally in favor of redeployment. Lockheed Martin's job was to keep the spacecraft safe and flying. There was enough solar power to achieve at least some of Lucy's threshold requirements and still declare mission success. They had nothing to gain by tinkering with Northrop Grumman's hardware and everything to lose if something went wrong and it destroyed Lucy.

As a NASA civil servant, Lounsbury had no profit motive in her analyses or decision. She had to answer only to the data and tests and was motivated only to get the best science possible for the mission. And redeployment, for her, was the right call.

They made six attempts. The Lockheed Martin control center in Colorado uploaded command sequences to the spacecraft that would run the motors simultaneously.[15] On May 9, they ran three 47-second pull attempts to ensure the motors would not overheat, and to validate their ground tests.[16] Encouraged by the resultant telemetry, they tried again three days later, managing to pull the lanyard enough to increase its tension. On May 26, they ran five 47-second pulls, succeeding in opening the array further. So it went, with attempts again on June 2, June 9, and June 16, each time making incremental progress.[17] By the conclusion of the sixth try, engineers estimated that they had unfurled the array to somewhere between 353 and 357 degrees, with enough tension to keep it stabilized.[18] On November 7 and then December 13, they attempted final hauls on the tether in hopes of a latch, but made negligible progress.[19] (They had made the majority of their progress when Lucy was nearer to the Sun, and therefore warmer; the spacecraft was now moving farther away, not returning to Earth until December 2024 for a gravity assist in its trajectory.)[20]

A month later, with the solar array more than 98 percent deployed and stable enough to withstand the stresses to be encountered during the spacecraft's 12-year mission, the mission team decided to suspend any further attempts. They had managed to close the array 30 degrees more than it had previously been.[21] In its current state, the spacecraft would be able to generate more than enough power to fulfill its mission even at its Trojan encounters farthest from the Sun.

A LIVING, BREATHING PLANET

On April 24, 2022, the InSight lander transmitted its final "selfie." The image revealed a lander whose every exposed surface was coated in Martian dust the color of pennies.[22] It was virtually indistinguishable from the surrounding landscape. Like all non-nuclear landers and rovers, the moment InSight arrived on Mars, it entered into a losing struggle against the planet in powdered form. For four years, dust accumulated on its solar panels, steadily diminishing their output. By midyear 2022, InSight was down to less than 20 percent of its power-generating capacity.[23] At that point, engineers switched off its entire payload except for the seismometer. (They even disabled InSight's fault protection system, designed to trigger a diagnostic safe mode in the event of emergency.) "We'll keep making science measurements as long as we can," said Bruce Banerdt at the time.[24] "We're at Mars' mercy. Weather on Mars is not rain and snow; weather on Mars is dust and wind."

NASA would declare the mission complete if it missed two consecutive communications attempts with the agency's spacecraft in the Mars Relay Network: atmospheric and reconnaissance orbiters circling the planet overhead.[25] Those conditions were met on December 21, and NASA formally retired the InSight mission.[26] Its total lifecycle cost, including launch vehicle and operations, was approximately $829 million.[27]

For much of the mission's history, InSight had to contend with vague scorn by some members of the planetary science community.[28] It was the first Mars mission competitively selected in the Discovery Program (because of the termination of Mars Scouts), with unusual circumstances around its selection (the failure of the Advanced Stirling Radioisotope Generator program) and an imaginative pair of competing missions (a Titan boat and a comet multiple landing mission). None of that was InSight's fault, of course. InSight was a safe, pragmatic choice in a difficult budgetary environment, and allowed NASA to capitalize on the successful, well-publicized landing of the rover Curiosity. It vexed the non-Mars science community, however, that when selected by NASA Headquarters in 2012, the agency already had four operational missions either in Martian orbit or on its surface—and a Decadal Survey recommendation for a Mars sample return flagship mission in lieu of a Europa orbiter.[29] (The number of active missions at Mars grew to five in 2014, and InSight's successful landing made six.) It did not help when InSight missed its 2016 launch window, at a cost of approximately $150 million.[30] By the time Mars resisted the mole, the mission seemed cursed. The mission's stock, however, would soon skyrocket.

While the public drama of the mole took place, a quiet and profound success was emerging from the seismometer. On April 6, 2019, over a year after InSight landed on Mars, it recorded the first marsquake.[31] It was possible evidence that Mars is seismically active.

"There was a checkbox on my list that there aren't any marsquakes on Mars," said Bruce Banerdt with a laugh, referring to his list of things that could go wrong.[32] "I'd spent twenty years convincing people that there were—and pretty much succeeded in convincing myself." That first year of silence was harrowing, he said. "You don't hear anything for a week or two, that's nothing. Three weeks, four weeks, six weeks, you know, now I'm in the mode where I'm getting up every morning, the first thing I do is I get to my computer and I look at the seismometer website to look at the analysis from the data that came down the day before." But still nothing. He tried to remain optimistic, but a couple months into the mission, he got nervous, making dark jokes with Philippe Lognonné, the seismometer PI. When InSight registered its first quake, the team had to convince themselves that it was real, and not a problem with the spacecraft. A subsequent, "slam dunk" signal came a few weeks later.

The reason it took so long to hear anything was because InSight landed during the Martian "noisy season"—something no one knew existed.[33] During that time, which lasts about a year, gentle but relentless winds sweep across Mars. The seismometer was protected by a wind shield, but the winds, scientists learned, were shaking the ground itself in ways unexpected, concealing the planet's quakes. "Marsquakes were happening," said Banerdt. "We just couldn't see them because the noise level was too high—which is still below the noise level of the quietest place on Earth, by the way."[34]

A quiet season followed the noisy season, and that's when things got exciting. By the time NASA retired InSight, the seismometer had detected 1,319 seismic events, mostly from marsquakes at different locations in the Martian crust, but also from meteorite impacts.[35] The strongest quakes came from Cerberus Fossae, a region with enormous, semi-parallel fissures formed by faults, and evidence of geologically recent volcanism.

The most significant event occurred on May 4, 2022—just as the InSight team was preparing for the mission's inevitable conclusion. A magnitude 4.7 marsquake with a 10-hour coda caused Mars to vibrate like a bell.[36] The energy released was equivalent to the energy of all the other quakes recorded during the mission combined.[37] The seismic waves traveled through and around the planet, providing a high-fidelity signal that could reveal the planet's deep interior with unprecedented clarity. It was the most valuable dataset of the entire mission. A few months later, InSight fell silent.

The tectonic activity from start to finish gave planetary scientists data necessary to begin mapping the structure of the Martian interior. They determined with great precision the size of the planet's iron alloy core, with a radius around 1,650 to 1,700 kilometers—50 percent of the planet's radius.[38] It is overlain by a silicate mantle and a crust, like other differentiated terrestrial planets.[39] A magma layer approximately 150 kilometers thick separates the core and mantle. The crust is multilayered, the top-most being about 10 kilometers deep, with denser, iron-rich layers extending downward to approximately 40 kilometers below the surface.[40] All that, because the planet still thrums with activity. After InSight, Mars is no longer merely a landscape, but rather, a whole planet—inside and out. The enigma is resolved, said Banerdt. "It's actually a living, breathing planet."[41]

Table 13. InSight Achievements.

Discovery/Achievement	Details
First Definitive Detection of Marsquakes	InSight's seismometer cataloged over 1,300 marsquakes and confirmed that Mars is geologically active.[42]
First Detailed Map of Another Planet's Interior	Analysis of seismic waves traveling through the planet yielded the first empirical 3D model of the Martian interior: a multi-layered, 24 and 72 km crust, with a thick, rigid mantle.[43]
Characterized the Martian Core	Data revealed the core of Mars to be surprisingly large, and less dense than expected.[44]
Meteorite Impact Detection	The seismometer recorded reverberations from meteorite impacts, allowing for their real-time detection.[45]
Comprehensive Atmospheric Monitoring	The science payload on InSight provided the most continuous, detailed atmospheric data set ever recorded from the surface of Mars, including fronts and dust devils.[46]

PSYCHE REVIVED

The Psyche Independent Review Board met on-site at JPL for 15 full days between July and September 2022, holding structured reviews as well as informal sessions.[47] They conducted interviews with 77 people individually and as groups, at different levels of Psyche, JPL, Maxar, and Caltech. The meetings were "pretty intense," according to one member of the Psyche leadership.[48] On the outset, the review board developed a list of factors that historically led to project success at JPL:

1. Experienced project team with capabilities necessary for project success.
2. Motivated and committed project personnel, dedicated to engineering and scientific excellence.
3. Engaged JPL senior leadership with detailed knowledge of project status and issues.
4. Engaged Line management providing both independent technical assessment and the assignment of properly experienced personnel.
5. Informal safety net provided by highly integrated and committed JPL workforce.[49]

NASA Headquarters released the review board's report on Friday, November 4, 2022. The board found that the Psyche mission fell short in all but the second key practice. ("Motivated and committed project personnel, dedicated to engineering and scientific excellence.")[50] Yes, the delayed delivery of the Guidance, Navigation, and Control software, and the problems with the testbed, were the "proximate causes" of the Psyche launch delay, they found. But any or all of three

other significant problems could have, on their own, delayed the launch. These were: a large number of unresolved issues with the flight software; the project's incomplete verification and validation process (including an incomplete definition of all fault protection behaviors); and general operational unreadiness.

"Psyche's issues are much more extensive than originally understood when the launch was delayed," the review board explained in its report. They found that COVID-19, while playing a contributing role in the problems plaguing Psyche's development, was not the cause. Rather, it came down to communication in both formal and informal channels. "A combination of factors including continued problems with staffing, budget pressure, and remote work caused by COVID-19, created an environment where working-level personnel were challenged to prove that a problem existed before schedule and/or budget relief was provided or to change baseline plans," wrote the report's authors. There were multiple instances in which the project could have acted decisively on critical issues that had been reported but did not. Several Psyche workers, during development, raised concerns with project and line managers. Those concerns, they felt, were ignored. This was possibly because line managers and chief engineers felt like they lacked the authority to solve said problems, and therefore, took no action, and did not elevate their concerns through the Independent Technical Authority.

"We spent a lot of time with the working-level people on the project," said A. Thomas Young at a community media conference discussing the report, "and it's interesting. They were pretty aware of significant problems that existed, and these problems just did not move forward to the top of the program…. We found a kind of culture that said: you've got to prove a problem is a problem before we're going to act on it. And that really delayed any action."[51]

The work accomplished once members of the Psyche team realized the extent of the mission's peril, and the possibility that it might slip its 2022 launch date, was also suspect. Numerous problems with the spacecraft were marked as closed and approved to "use-as-is." One-off failures that could not be duplicated were waved through, and the spacecraft would possibly have flown with them, had it met the launch window. The review board encouraged the Psyche project to reevaluate all such issues. In addition, management would need to reconsider everything from the way it reported risk assessments (the panel recommended a straightforward green-yellow-red labeling for status reports, adding that "red scores should never be aggregated with green and yellow to obscure the severity of a red score") to the way it interacted with Maxar and other contractors, to ensure that differences in culture and process could be identified and resolved.[52]

Meanwhile, JPL staffing levels were untenable. There was more work at the lab than people to do it, and Psyche had to compete with Europa Clipper and Mars

Sample Return for engineering talent. The turnover in senior management at the lab's Planetary Science Directorate, as well as a recent organizational restructuring, also harmed Psyche. Had senior management become invested in the project's execution, they might have noticed the issues. (And the list of issues was long: "timeliness of the testbeds, timeliness of closed-loop simulations, operational readiness, an integrated view of the software and hardware products being delivered to testbeds and/or the ATLO environment, and the increasing number of open Developmental PFRs [Problem/Failure Reports] and PFRs against flight articles.")[53]

All this would have to change, the panel found. Line managers would need greater authority to elevate both technical and programmatic concerns, and reporting mechanisms and metrics would need to be improved to better reflect the project's actual status and issues. The project would need to bring in external experts, even temporarily, to get fresh eyes on problems. It would also need a dozen new, full-time, experienced leaders "at all levels." Psyche lacked, for example, both a Project Chief Engineer, (a senior person whose job was find and fix large technical problems) and a Cognizant Engineer for Guidance, Navigation, and Control: someone to take "intellectual charge" of validating the GNC's end-to-end technical performance, ATLO, and testing.

None of this would necessarily be easy. Projects, the review board explained, are "imprinted" by their initial situations, leaders, managers, and resource conditions—and these imprints on project culture and organization don't just go away on their own. Members of the Psyche project had internalized staff shortages, burnout, turnovers, and a lack of mentorship. Psyche would need a shakeup.

In addition, remote and hybrid work situations driven by the pandemic would have to be "substantially reduced." Historically, JPL had great success when people could walk the floor, drop in on meetings, and have casual conversations in office doorways. "Our recommendations really are: get back to the informal communications mode that has been so successful," said Young in the media teleconference.[54] As for hybrid work, he said, "minimize it to the maximum degree feasible practicable."

The review panel said that lockdown conditions "contributed significantly" to Psyche and JPL leadership's ignorance of the severity of problems with the GNC subsystem and the Verification & Validation process. "It is notable that team members exchanged valuable project information at the Christmas party in 2021, the first time team members had been face-to-face in over a year and a half," explained the review board in its final report.[55]

During the media teleconference, Thomas Zurbuchen emphasized the gravity of the review board's findings. "I want to make sure that everybody understands that

we're going to take these recommendations very seriously," he said. "And it's not just words—it's already actions we've implemented."[56]

The review board offered an assessment as well of the problems at Jet Propulsion Laboratory—everything from the "significant erosion of technical acumen" to the dilution of attention by senior management across multiple projects—and recommended how the lab might solve these problems, through things like the establishment of regularly scheduled meetings and the codification of the metrics employed for tracking a project's progress (particularly in the critical prelaunch period) in the lab's Flight Project Practices.

For the Psyche team, the bottom line of the review board report offered hope: "The IRB has reviewed the go-forward plan and believes JPL has established an executable plan for a 2023 launch."[57] And indeed, before the public release of the report, NASA Headquarters announced that Psyche had survived its continuation/termination review. "I am excited about the science insights Psyche will provide during its lifetime and its promise to contribute to our understanding of our own planet's core," Zurbuchen said.[58]

There would be collateral damage, however.

Zurbuchen had vowed in 2018 that CubeSat rideshares would be the default for all science missions.[59] Psyche's rocket was set to carry Janus, a $55 million, dual CubeSat flyby mission to binary asteroids (175706) 1996 FG3 and (35107) 1991 VH.[60] Psyche's delay meant a different trajectory. Janus no longer had a ride. NASA officially canceled the Janus mission eight months later.[61] ("Once we got taken off of Psyche, we were already pretty much over other than getting the spacecraft into storage," Dan Scheeres, principal investigator for Janus at the University of Colorado, later said.[62])

To offset the workload and increased budget the Psyche mission now needed, another mission would also bear the brunt of Psyche's delay. "The next JPL-managed Discovery mission is the VERITAS mission to Venus," said Lori Glaze, the director of the Planetary Science Division.[63] "After long deliberations, I have to say that we intend to postpone the VERITAS launch readiness date to no earlier than 2031."

The VERITAS team had thus far been responsible in their efforts, keeping their mission on-time and on-budget. Now, its engineering team would be dismantled, and the project placed in deep freeze for at least three years. There was no precedent for the directed delay of a selected mission in Discovery Program history. And another way of describing a launch "no earlier than" was to say it was "delayed indefinitely."[64]

JANUARY 25
NASA announces an additional asteroid flyby for the Lucy mission: (152830) 1999 VD57, later renamed Dinkinesh.

CHAPTER 13

2023

Darby Dyar, the deputy principal investigator of VERITAS, was attending a workshop at the Lunar and Planetary Institute in Houston, Texas, when she received a message from Sue Smrekar, the mission's PI: "Call me."[1] Dyar didn't know what it could be about. Sixteen months had passed since VERITAS had been selected for flight by NASA Headquarters. By October 2022, things had gone swimmingly. The team was well into the preliminary design and technology completion phase. They were on track, on time, and on budget. Dyar stepped into the hallway and called Smrekar back.

"Darby, we're in trouble," said Smrekar. "They are going to put us on indefinite hold or maybe even cancel us."[2] Dyar was speechless—what was going on? What could possibly have happened? She started tearing up. Development hadn't merely started at selection. Even by Discovery Program standards, they'd been working on VERITAS for a long time. The team proposed it to the 2014 Discovery AO.[3] Serious

OCTOBER 13
Psyche launch.

NOVEMBER 1
Lucy spacecraft observes contact binary moonlet orbiting asteroid Dinkinesh during flyby.

DECEMBER 11
Psyche transmits a cat video to Earth as part of a Deep Space Optical Communications experiment.

work had begun more than a year before that. It paid off, because VERITAS was one of the five missions selected for further study.[4] (Notably, in the decade to follow, each of the five would eventually be chosen for flight.)

That mission's science goals were to determine:

- What processes shape rocky planet evolution?
- What geological processes are currently active on Venus?
- Is there evidence of past or present water on Venus?[5]

It would achieve this with a payload of two key instruments: The Venus Interferometric Synthetic Aperture Radar (VISAR), which would create high-resolution 3D topographic maps of the surface; and the Venus Emissivity Mapper (VEM), a spectrometer for mapping the planet's surface composition.[6]

It wasn't meant to be. NASA selected Psyche and Lucy in January 2017.[7]

Meanwhile, Smrekar and the VERITAS team prepared a similar, parallel mission proposal to the New Frontiers program: the Venus Origins Explorer (VOX).[8] That work started around late 2015 in anticipation of a draft AO that went out in August 2016.[9] VOX retained the core architecture of VERITAS, including VISAR and VEM, and added a small probe called the Atmospheric Sample Vehicle, which would dip into the Venusian upper atmosphere, collect a sample, and return to space for analysis on the orbiter.[10] (This probe would later be developed as a separate CubeSat proposal called Cupid's Arrow.)[11]

Despite all the reviews, the reams of paper stacked inches high that went into the proposal and its iterations, the science attempting to extract new insights from the bottom of Venus's increasingly dry and dated barrel, VOX wasn't meant to be, either. In December 2017, NASA down-selected Dragonfly, a Titan quadcopter; and CAESAR (Comet Astrobiology Exploration Sample Return), a sample collection mission based on OSIRIS-REx, targeting comet 67P.

The VERITAS team kept at it, however, and proposed to the 2019 Discovery competition. The same years of effort, the same nagging doubts that David Grinspoon had eloquently described: "At what point are we no longer admirably committed, but merely pitiful?"[12] The mission, however, was finally selected for flight in 2021. It was essentially a refined and mature version of the orbiter proposed seven years earlier (which was, also, essentially the VOX orbiter element), with the same science goals and payload.

But since finally winning over NASA, the VERITAS team didn't waste a moment. They could have had the spacecraft ready to launch in 2026, but eventually went with 2027.[13] Then, one week before NASA Headquarters announced its choice of VERITAS and DAVINCI, the White House released the President's Budget Request

for fiscal year 2022. Though the agency and the Planetary Science Division both saw increases in their top line, the Discovery Program was cut by 19 percent.[14] This still allowed for the selection of two Discovery missions, but their launches would be permitted "no earlier than 2028." So, the VERITAS team would have to slow down a bit and replan for the later date. (This wasn't a delay per se, but rather, a NASA-directed planning parameter for VERITAS leadership to use when formulating its development plan, staffing profile, and budget.) The team planned to use the extra time to reduce technical risk on VISAR, and to work with the aerospace industry to make sure electronic parts procurement faced no COVID-induced delays.[15]

It was also a good opportunity to work with its international partners in Italy, Germany, and France. Sue Smrekar was the deputy PI of InSight. She had seen firsthand the devastation that a faltering international partner could inflict on a mission. The Italian Space Agency was providing low-power electronics, transponders, and the spacecraft's high gain antenna. The French space agency was building amplifiers for the telecom subsystem. The German space agency was building the Venus Emissivity Mapper (VEM) instrument, which would map infrared emissions from the Venusian surface to determine rock types and find active volcanoes, and contributing data processing algorithms for the Venus Interferometric Synthetic Aperture Radar (VISAR), a high-resolution radar.[16]

After all that, VERITAS was about as high-heritage and keep-it-simple as a NASA mission could get. The spacecraft was based heavily on the MAVEN mission to Mars. Its myriad subsystems were largely derived from InSight, MRO, OSIRIS-REx, Juno, and Lucy.[17] A two-instrument payload was a breeze compared to something like MESSENGER, which had carried seven.[18] It was the opposite of a Christmas tree: focused, as Discovery missions had been intended from the program's inception. And both instruments were no-frills. VISAR was basically an upgraded version of the synthetic aperture radars that were carried by Magellan. JPL had been building such radars since the 1970s.[19] VEM, meanwhile, was a "push broom" imager with no moving parts, based heavily on the MERTIS instrument on BepiColombo and SOIR on VenusExpress.[20] Mission operations were simple: circle Venus in a polar orbit—no landers, rovers, or moles to manage.

Dyar was stunned by Smrekar's news. Canceled? It was like having the rug pulled out from the team after a decade of late nights, lost weekends, and missed family events.[21] She was in her mid-60s. Even if VERITAS launched in 2028, she would be 70 by the time the spacecraft started returning data. Her runway was now very short. She couldn't plan another big mission from scratch at this point in her career.

As the months elapsed, the news didn't get much better. VERITAS wasn't canceled, officially. NASA Headquarters would allocate a small amount to spin down the mission.[22] Beyond that, the agency was cagey. They said VERITAS would launch

no earlier than 2031 because of Psyche and budget issues. Then it was, well, we can't stand up VERITAS until Europa Clipper launched and Mars Sample Return was on budget. (Given the track record of Mars missions generally, and Mars Sample Return in particular, they may as well have added "world peace" to the list of prerequisites.) Then there was the condition that the NASA-ISRO Synthetic Aperture Radar (NISAR) mission—which wasn't even funded by the Planetary Science Division, but rather, Earth Science—had to fly first as well.[23] One of the things that was so frustrating was that there was nothing VERITAS could have done to change its situation. Another was that by delaying the mission, NASA had put the foreign partners of VERITAS—space agencies contributing around $90 million—in a difficult situation. The European Space Agency was planning another Venus mission called EnVision.[24] The delay to VERITAS would mean ESA had to develop two Venus missions simultaneously, which they were not equipped to do. So, they decided to just proceed with what NASA agreed to and keep to the development schedule. But that increased risk significantly. "Imagine building something to go on a spacecraft and not having anyone in the U.S. to talk to about the spacecraft," Dyar said.[25] Between all that, and the possible obsolescence of basic components the project sought to procure (but could no longer pay for), and the likely loss of professional staff who would retire before launch—whenever that might be—NASA was also decreasing value of the DAVINCI mission, which could use VERITAS topographic and spectrographic data to inform its descent to the surface.[26]

Dyar had wanted to work on a Venus mission for more than 30 years, since graduate school in the Fall of 1980. The first class she ever took was on Venus. The United States was, at the time, developing a big mission there called Venus Orbital Imaging Radar (VOIR), and she was all-in—"bought the t-shirt," she said—was emotionally invested in the project.[27] Then, not long after Reagan was elected, he cancelled VOIR, among many other promising planetary science projects, to save money.[28] Magellan, which launched in 1989, was a successful and productive mission, but it could only do so much with the available technology of the time. Engineers called it the "spare parts" mission; it used antennas and electronics and thrusters sitting around from the Voyager spacecraft and stored its data on tape reels left over from Galileo.[29] All these years later, it was shocking to Dyar how little we knew about Venus. The available topographic data was primitive at best because after Magellan, NASA basically gave up on the planet. Scientists had better topographic data on Pluto—which wasn't even a planet—than they had on Venus. Nobody knew something as basic as Venus's rock type. But VERITAS would solve that. It wasn't going to deliver Venus nice-to-haves; it was going to deliver the fundamentals and set up the world for future exploration.

SAVING VERITAS

In January 2023, the VERITAS team requested bridge funding to pay for scientists and engineers to keep the mission on life support. Incremental progress would at least be progress. NASA denied the request.[30] Two months later, NASA released its fiscal year 2024 budget request. The agency allocated a shoestring $1.5 million to fund scientists a couple hours a week.[31] The budget request also projected the VERITAS budget for fiscal years 2025, 2026, 2027, and 2028. Each year, the number was the same: $1.5 million. In effect, the mission was canceled.[32] Virtually nothing could be achieved with such funding. (In comparison, the Fiscal Year 2023 budget proposal had allocated $57.2 million to VERITAS, for launch four years later.)[33]

"This mission that was on track is being effectively martyred for all those missions that are going over budget," said Sue Smrekar, at the Lunar and Planetary Science Conference in The Woodlands, Texas.[34] "The reason that so many in the community are outraged by this are these facts, that a mission that was on track is contingent on Earth science missions and all kinds of things that have nothing to do with us."

It got worse. Explaining that there were "no good options," Lori Glaze, said that NASA might be forced to choose between canceling VERITAS, or cancelling a future Discovery AO, slated for 2025.[35] The broader planetary science community pushed back hard on that, in favor of VERITAS. At an earlier meeting of the Mars Exploration Program Analysis Group (MEPAG), Bruce Banerdt said: "It would be very upsetting to miss the Discovery call, but if they're implying that they would defund VERITAS in order to fund the Discovery call, that's even less acceptable."[36]

By the end of the year, every such analysis group—Mars, the Moon, Mercury, the outer planets, small bodies, the exoplanets—all came out in favor of VERITAS.[37] So, too, did myriad universities and advocacy and professional organizations, including the Planetary Society, the American Geophysical Union, and the Geological Society of America.[38] MEPAG put it most succinctly in a slide to the Planetary Science Advisory Committee: "In short: VERITAS before a new AO."[39]

A LUCKY BREAK FOR PSYCHE

The Psyche mission launched on October 13, 2023. Because the solar system never stops moving, a spacecraft can't just launch any day, any time, to go anywhere. The asteroid Psyche spins on its side and is very seasonal; there are only certain places in its orbit where its surface is fully illuminated. Everything about the mission headed there had to be replanned. Carol Polanskey, the Psyche project scientist, and the mission navigation team first had to figure out if it was even possible to still achieve all its science objectives.[40] It was, but required a nearly six year cruise phase, and

reshuffling the order in which mission objectives would be achieved. (The original trajectory would have taken only three and a half years.)[41]

Two weeks before launch, the Psyche team realized that data they'd received from one of the mission's subcontractors was incorrect. Ground testing revealed that the spacecraft's nitrogen cold gas thrusters, which would be used to point the vehicle in various orientations, could potentially overheat at their intended power levels.[42] This included just after launch, when turning the spacecraft to face Earth. Had it launched as-is, planned operations "would probably damage the thruster," said Lindy Elkins-Tanton.[43]

Discovery of the problem was a lucky break. As Laurie Leshin, the director of JPL, observed, "a successful mission is dodging 1,000 bullets, and an unsuccessful one is dodging 999."[44] Correction of the problem did not require any new hardware or software, but did require the adjustment of operational parameters. The thruster would now operate at a 30 percent duty cycle to keep temperatures in check. This necessitated a week of round-the-clock testing to make sure it worked, and that there were no down-stream effects. It delayed launch by a week, and was "JPL at its best," said Ben Weiss, the Psyche deputy PI, "people staying all night, an intense team of engineers, several dozen people."[45]

Because the preceding year of development had been grueling and relentless—"the most difficult scientific [work] years that I've experienced," said Weiss—that week-long delay was in some ways a deliverance for Psyche leaders who'd spent so many years getting to that point.[46] It was the first time they could step back and say, "Whoa! We're actually about to launch this thing," he said. After a subsequent delay because of weather, the spacecraft left the launch pad at 10:19 a.m. EDT from Kennedy Space Center.[47]

Psyche was bound for an object that existed from Earth only as a few pixels on a computer screen. "We do not know what Psyche looks like," said Elkins-Tanton. "I always joke that it's shaped like a potato because potatoes come in many shapes, so I'm not wrong. But we're going to find out when we get there."[48] Whether it proved to be a planetary core, or some sort of primordial, un-melted body from the earliest days of the solar system, whatever awaited would be discovery in the truest sense of the word—and of the program.

LUCY'S FIRST FLYBY

The following month, on November 1, the Lucy spacecraft flew by 152830 Dinkinesh, an inner main belt asteroid a little less than a half mile in diameter.[49] It was a last-minute addition to Lucy's roster of targets, found as part of a side project of Raphael Marschall, a postdoc under Levison at the time. Marschall was searching

for tiny targets whose paths might cross with Lucy along the way, and there it was.[50] When the Lucy mission added it to the list, the object didn't even have a name.[51] (The International Astronomical Union soon named it for the Ethiopian name of the human-ancestor fossil Lucy, which happened also to be the namesake of the Lucy spacecraft.[52] Dinkinesh means "you are marvelous" in Amharic.) It was the nearest asteroid Lucy would cross paths with before encountering 52246 Donaldjohanson in 2025. And though much of the team was exhausted after the grueling effort to redeploy the solar array, it was a good chance to "really prove out that we could in fact fly by an object," said Jessica Lounsbury.[53]

Notably, it was not intended to be a science flyby, but rather, a targeting system test inspired in part by the New Horizons flyby of Pluto. "They took a significant fraction of data of blank sky because they didn't know where Pluto was accurately enough to be able to point their instruments," said Hal Levison.[54] "As a result, they just covered that uncertainty, and only a certain fraction of the images actually had Pluto in it." Dinkinesh would allow the Lucy team to test whether their system could keep a target in the instruments' field of view. Such a system had never before been flown, and things like shadows during indirect approaches, and the odd shapes of objects, tended to stress the algorithm responsible. (Lucy would approach Donaldjohanson head-on; it would approach Dinkinesh from 90 degrees.) "If something's not going to work, you want enough time to be able to fix it," said Levison.[55] "Doing it on encounter in 2023 rather than 2025 gives us a lot more time if we find something wrong for 2027 encounter with a Trojan."

The run-up to the Dinkinesh encounter, like all encounters with small bodies, was "exhilarating," said Jessica Sunshine. "These targets are a dot," she said. "They've been a dot forever." A few minutes before flyby, though, "they resolve before your eyes into this geologic world. Every one is different. Every one is surprising."[56]

Dinkinesh proved no different, because after its closest encounter at 264 miles, it turned out that the main belt asteroid was actually two asteroids.[57] On approach, the team had wondered why its brightness kept changing, raising the possibility of it being a binary system.[58] Now they knew. Dinkinesh's moonlet, later named Selam (after another fossil sometimes called "Lucy's baby"), was just over a tenth of a mile across.[59]

"There were just hearts all over the chats," said Lounsbury, of the first images coming down from the flyby.[60] "It was so exciting because finally the team got to celebrate where they hadn't got to celebrate after launch, going straight into anomaly after launch day."

Though it wasn't intended to be a science flyby, Dinkinesh turned out to have a surprisingly complex history, with much broader implications.[61] "To understand the history of planets like Earth, we need to understand how objects behave when

they hit each other, which is affected by the strength of the planetary materials," said Levison.[62] "We think the planets formed as zillions of objects orbiting the Sun, like asteroids, ran into each other. Whether objects break apart when they hit or stick together has a lot to do with their strength and internal structure." Because the surface of Dinkinesh, across millions of years, unevenly heated by the Sun, the object began to spin faster until it broke apart in a sudden, quake-like event, with some debris falling back to its surface, and other debris possibly coalescing into objects that in turn gently merged into Selam, making it a contact binary. It was one more puzzle piece in the story of the solar system: the first confirmed contact-binary satellite ever observed. Ultimately, said Levison, Dinkinesh really did live up to its name: "This is marvelous."[63]

CHAPTER 14

2024

MARCH 11
The FY 2025 budget request includes $36.1 million for VERITAS.

MAY 22
Psyche fires its solar propulsion system.

In 2024, NASA set a new Discovery Program record when it failed to release an Announcement of Opportunity—the first time since its inception that the program went five consecutive years without one. (They didn't even issue a draft AO.) It wasn't for lack of desire. Put simply, money was getting tight in the Science Mission Directorate. After several consecutive years of regular budget increases, the FY 2024 budget signed into law reduced NASA's budget by 2 percent relative to the previous year.[1] (The Biden Administration had requested an increase of NASA's budget by 7.1 percent, and even that would have merely kept up with inflation.[2] The money sought versus the money appropriated marked the worst drop since 1992.)[3] NASA not only had to contend with a poor fiscal climate across the whole of the federal government, but within, large missions such as Mars Sample Return were growing in price, and the division's

DECEMBER 12
Lucy skims Earth's atmosphere for its second gravity assist, putting it on a new trajectory to the Jupiter Trojan asteroids.

budget was not keeping pace.[4] This created a fragile environment for the rest of the planetary exploration portfolio.[5]

"We know we are definitely in an imperfect environment, and we acknowledge this is a very challenging time particularly for SMD," said Nicola Fox, the associate administrator for the Science Mission Directorate, at a community town hall meeting.[6] "We always want to do more science, and there are so many more great things we would have loved to have done." She said that NASA science leadership would "have to make tough choices with the resources we are provided."

There was a sliver of good news for the Discovery Program in all this.[7] In the Commerce, Justice, Science, and Related Agencies subcommittee report that accompanied the FY 2024 appropriations bill, Congress decreed: "The agreement supports the Discovery Program, including competitively selected missions such as VERITAS. As part of the fiscal year 2025 budget request, the agreement encourages NASA to request sufficient funding to ensure a launch by the end of the decade. Further, no later than 180 days after the enactment of this act, the agreement directs NASA to provide a budget profile and schedule for the VERITAS mission."[8] Though such reports don't have the power of law, the language was a direct rebuke to NASA's previous "indefinite delay." Through its oversight authority, Congress extended protection to VERITAS. The White House acquiesced. In its FY 2025 budget request, released on March 11, 2024, NASA requested $36.1 million for VERITAS.[9]

Division leadership called Sue Smrekar with the news, and Smrekar immediately called Darby Dyar. They were at the Lunar and Planetary Science Conference in The Woodlands, Texas, when they found out. "We waited about three hours, and then they announced it," said Dyar.[10] "We got to go out afterwards and celebrate."

There were a couple of catches, however. The mission would have to launch in the 2031–2032 timeframe—and DAVINCI with it. "We have very few knobs we can turn in trying to address these near-term funding challenges," said Lori Glaze at the town hall meeting.[11] "We did make the tough decision to shift DAVINCI out, commensurate with VERITAS."

The VERITAS team deduced that they would be launching in 2031, with June of that year returning the best science.[12] NASA Headquarters had previously asked them to calculate a series of "funding profiles," which are the dollars per year necessary to reach the launch pad on different dates.[13] NASA never formally committed to a specific date, but it did approve the profile that culminated in a 2031 launch.) For the VERITAS team, what once was an unthinkable delay was now a deliverance. Concurrent with the restoration of VERITAS, NASA would delay the next Discovery Announcement of Opportunity to no earlier than FY 2026.[14]

On October 1, with the beginning of the federal government's fiscal year, the VERITAS mission started spinning back up.[15] Engineering support began, and

ongoing low-level science support continued. Still, the lack of a formal date, in writing and signed, vexed VERITAS leadership. "There's a real possibility of a further delay, to '32," said Sue Smrekar during a presentation to the Venus Exploration Analysis Group.[16] NASA leadership was "not able at this time to commit to a particular launch date." Everything just depended on how budgets went.

Such a delay would have consequences—especially for the foreign partners building hardware for VERITAS. During the mission's hibernation, European engineers kept to their schedules because their own non-NASA funding was already allocated, and because VERITAS wasn't their only mission. (The European Space Agency had its own Venus mission—EnVision—to design and build.)[17] They planned to deliver their promised hardware at the original, agreed-upon time. If the launch was indeed pushed to 2032, this would create a problem because VERITAS would be receiving flight hardware and instrumentation before the actual spacecraft had even entered its preliminary design phase. There were also downstream effects. By the time VERITAS reached integration and testing, around 2030, there was concern that the members of teams who built the foreign hardware would be completely different than the ones validating it.

That wasn't even considering the impact to the mission's budget and science. Things just got more expensive the further you pushed to the right. A 2032 launch would also mean a different trajectory—one that precluded instrument calibration to the geochemical data previously-collected by the Venera and Vega missions. It would also yield greatly diminished spectroscopy science. "Venus spectroscopy is a whole new field," said Smrekar.[18] "It's still in its infancy, so we need to be able to get as much information as we can to make the most of this incredible asset, this compositional information." Another delay also meant possibly sending DAVINCI to its landing site without VERITAS having first provided context. This meant more potentially missed science.

SIMULATING VENUS

While VERITAS endured the vicissitudes of federal outlays, DAVINCI development continued apace.[19] After selection in 2021, at the request of NASA Headquarters, the DAVINCI team conducted a 60-day study to find launch opportunities to Venus in the late 2020s that preserved the mission's science goals and objectives. They presented their portfolio of options to NASA that Fall, and in July 2023, NASA Headquarters approved a launch in June 2029.[20] Eight years of development was longer than anyone preferred, but that's what NASA's budget could afford. Later, when it became clear that 2029 wasn't going to happen, they looked at a December

2030 launch (and other launches through mid-2031). They found some excellent windows for compelling science.[21]

So, the mission began the usual developmental processes, milestones, trades, risk mitigation, prototyping, and reviews inherent to Phase B.[22] Senior DAVINCI leadership spent the early days working with its partners to build up the teams for its seven different payloads, including establishing a leadership structure managing the project's development. They also solidified their level one and level two requirements.

The DAVINCI timeline with a June 2029 launch, as planned, would have seen the first Venus gravity assist on January 17, 2030, during which time the spacecraft would have performed near-infrared imaging of Alpha Regio, for target analysis of where they would later deploy the descent sphere.[23] (During that flyby, they would have also performed dayside ultraviolet imaging with the VISOR and CUVIS instruments.) The second flyby would have occurred on November 30, allowing for near-infrared imaging of four other tesserae, additional ultraviolet dayside imaging, and the completion of the baseline remote sensing mission.[24] On June 22, 2031, during the third Venus gravity assist, DAVINCI would have deployed the atmospheric entry system, which would have in turn released the descent sphere to the Venusian surface. (A December 2030 launch would push the probe deployment to January 2033.)[25]

The paramount engineering challenge was the Pro Flight System's separation from the CRIS spacecraft. It was a one-time, must-succeed event, and the descent sphere absolutely had to transmit data successfully from start to finish, lest the mission fail. DAVINCI had an engineering ace in the hole for this: many members of the Lucy team were part of, or would soon be joining, the DAVINCI team. (Michael Sekerak, for example, was both deputy project systems engineer for Lucy, and project systems engineer for DAVINCI. He was drawn to the latter mission because of the technical challenges inherent to the punishing environment at Venus: the pressure, the temperature, the sulfuric acid clouds… it was an engineer's dream.)[26] There was a common design philosophy between the two missions, in that each Trojan flyby was also a single-opportunity event. The Lucy mission had developed special tests, documentation, and critical events personnel to ensure that the spacecraft worked every time. The crossover team brought such procedures and methodologies to DAVINCI planning.

The mission conducted its two-day mission requirements review in May 2023, and three systems requirements reviews during the second half of the year. They even conducted the first helicopter drop of a descent sphere test article at the Utah Test and Training Range, to categorize its performance.[27] During a 30-second fall from an altitude of about one mile, it successfully recorded acceleration, attitude

rates, and camera data. All that would feed the aerodynamic model that engineers were developing for the actual Venus mission.[28] Using the images, they were also able to construct topographic maps just as they would on Venus.[29]

"It worked beautifully," said Jim Garvin in a video of the event, adding that it would be "the first of several tests we do to get to understand how to get to know the real Venus up close."[30]

POINTING LASERS AT PSYCHE

For the two Discovery missions in flight, 2024 was a quiet year, mostly about maneuvers, with no primary science data collected or returned. Psyche entered the year evaluating the performance of its various subsystems and instruments. Everything performed nominally. By happenstance, the magnetometer detected a coronal mass ejection.[31] Later, the Gamma Ray and Neutron Spectrometer team tested the instrument's capabilities at measuring space weather during solar storm; measurements corresponded with storm tracker models (the spacecraft experienced a "glancing blow").[32]

In terms of engineering, Psyche demonstrated two significant firsts during its opening act as a spacefaring vessel. Among its payload was a Deep Space Optical Communications (DSOC) transceiver: a technology demonstration whose goal was to test the use of optical communications for deep-space missions rather than traditional radio frequencies.[33] The technology had been developed and improved in Earth orbit, and NASA flew an early iteration on the Lunar Atmosphere Dust Environment Explorer (LADEE) spacecraft.[34] The need for a next-generation communications technology emerged because spacecraft instrument payloads were increasing in resolution, and the Deep Space Network was overly subscribed. Data were becoming a bottleneck for science missions. DSOC, using lasers, could transmit 10 to 100 times faster than radio signals in both directions, and alleviate the DSN's burden.[35]

At the close of 2023, engineers used the DSOC system to transmit a preloaded video from Psyche to Earth. History records "Taters the Cat" as the first ultra-high definition video ever sent from deep space.[36] Four months later, the DSOC system interfaced with the Psyche spacecraft and returned engineering data to Earth from 140 million miles away. ("Until then, we'd been sending test and diagnostic data in our downlinks from Psyche," explained Meera Srinivasan, the project's operations lead at JPL.)[37] Rather than talk to the Deep Space Network, the transceiver talked to its own primary downlink ground station: the famous 200-inch Hale Telescope at the Palomar Observatory in San Diego County, California. The data validated. The farther from Earth Psyche traveled, the slower the signal would be. Even so, on

a clear night on Earth its speed could be an order of magnitude faster than comparable radio transmissions.

Lasers weren't a replacement for the Deep Space Network—yet. No dedicated ground infrastructure existed, and building out such a network to worldwide sites with favorable cloud statistics would take time and money.[38] But work was underway, with the European Space Agency developing its own, interoperable ground network, and plans to point its lasers at Psyche as well.[39]

Psyche's second first occurred in May, when the spacecraft entered "full cruise" mode, starting its solar electric propulsion system. It was the first time Hall-effect thrusters had ever been used in space.[40] (The Dawn spacecraft, and before it, Deep Space 1, used gridded ion engines, a different type of solar electric propulsion.)[41] Ionized xenon glowed blue behind the spacecraft. The pressure exerted was about the same as holding three American quarters in your hand, but over time, that was enough. It would gradually increase the spacecraft from 84,000 miles per hour to 124,000 mph, relative to the Sun.[42]

Elsewhere in the solar system, Lucy fired its main engines for the first time since leaving Earth—and more critically, since the redeployment of its solar array.[43] On January 31, engineers performed a six-minute test-run to make sure no surprises turned up. None did. Three days later, the team fired the engines for 36 minutes—the longest planned burn of the 12-year mission—consuming half the spacecraft's fuel and changing its velocity by approximately 2,000 miles per hour. The maneuvers set up Lucy for an Earth gravity assist that would hurl the spacecraft through the asteroid belt and into its new orbit, where it would encounter the "Greek" Jupiter Trojan asteroid swarm (which lead Jupiter in its orbit).

For Discovery, orbital dynamics would soon prove to be the only certainty the program had left.

CHAPTER 15

2025 and Beyond

APRIL 1
Psyche's xenon thrusters shut down after a pressure drop in the line that feeds the xenon gas.

APRIL 20
Lucy spacecraft flies by asteroid DonaldJohanson, revealing that it is a contact binary.

JUNE 16
Psyche resumes full thruster operations using backup propellant line.

Donaldjohanson was the first asteroid to be visited while its namesake was still alive.[1] In 1974, paleoanthropologist Johanson was in the field, surveying a small gulley in a basin near Hadar, Ethiopia.[2] It had been searched twice before, but Johanson wanted to be thorough. As he and Tom Gray, his graduate student, turned to leave, Johanson noticed something on the ground that resembled hominin elbow.

"This can't be true," he said to Gray. "How could this be?"[3]

When he looked closer, he saw a shard of skull. He and his team soon found more. A femur. Vertebrae. Ribs and a jaw. That night, they celebrated the findings back at the camp. "Lucy in the Sky with Diamonds," by the Beatles, was a commonly played song among the team, so they named the skeleton Lucy. For the next three weeks, they excavated her. They soon realized that Johanson had discovered the skeleton of a three-and-a-half-foot-tall, 3.2-million-year-old *Australopithecus afarensis*—an early human

ancestor. It was the oldest such hominin fossil ever recovered, and was astonishingly complete, with 40 percent of the skeleton accounted for. Lucy was proof that our ancestors had learned to walk before our brains evolved and placed the cradle of humankind in Africa.

Forty-nine years later, in 2025, Johanson visited the Southwest Research Institute in Boulder, Colorado. The spacecraft Lucy was about to fly past the asteroid named after him.[4] The event was also the final dress rehearsal before the Lucy spacecraft encountered its first Trojan asteroid, 3548 Eurybates, in 2027. This time, it was Lucy exploring a relic named Donaldjohanson.

Until the day of the encounter, April 20, the asteroid remained an unresolved point of light.[5] After closest encounter, at 1:51 p.m. EDT, during which time Lucy passed within 600 miles of the asteroid, the spacecraft phoned home to let Earth know it was in good health.[6] Engineers asked Lucy to begin returning the data it collected. What it found, scientists soon learned, was "strikingly complicated," said Hal Levison.[7] The asteroid was an elongated contact binary, possibly formed during a slow-motion collision. Models suggested that it had formed 150 million years earlier.[8] The asteroid's features, their distributions, and morphologies suggested processes common to all asteroids, from craters to boulders.[9]

The April 20, 2025 flyby was a success for the team, the spacecraft, and its instrument payload.[10] It took a week for the full dataset to arrive back on Earth.[11] Afterward, Lucy continued on its way, away from the Sun at 30,000 miles per hour, and headed for a region of space never before visited, and discoveries as-yet unknown.[12]

DISCOVERY AT A CROSSROADS

The Donaldjohanson flyby returned the only Discovery science data of 2025, and Lucy's success represented the program's only unqualified good news. When compared with the program at inception, Discovery today is hard to recognize. That is not necessarily a bad thing, but with change comes risk.

The Discovery Program emerged in reaction to flagship missions, an unpredictable budget process, and "last bus out" syndrome, described by Wes Huntress as a condition in which planetary scientists "treated each mission as if it was the last bus out of the station—which it often was, for a long time."[13] When the Space Race ended and NASA budgets diminished, scientists could prudently treat any mission the agency announced to some celestial object as the final one they might see in their career. Twenty-one years separated the Viking launches and the next successful Mars mission, for example. Accordingly, it became imperative to maximize the scientific scope of every mission. This, inevitably, increased spacecraft

cost and complexity (which, ironically, decreased the likelihood of subsequent such missions).

Though the model existed in the Explorer program for heliophysics and astrophysics missions, Discovery was a radical departure from directed planetary missions. Since its establishment, the program has launched 14 missions (losing only 1, shortly after it left Earth) and spawned the New Frontiers program, which has launched 4 other missions, plus the sort-lived Mars Scout program, which launched 2. It also inspired competed flagship studies in 2006, which advanced Europa, Titan, Ganymede, and Enceladus science, and led eventually to the Europa Clipper mission.[14] The successes of the PI-led competition model in planetary exploration directly influenced programs elsewhere in the Science Mission Directorate, including like Earth Venture in the Earth Science Division, and Astrophysics Explorers in the Astrophysics Division.[15] Though the Discovery Program's success, in retrospect, is undeniable, at the time of its creation, there was significant institutional resistance to the program's premise of low-cost, competitively-selected missions. That resistance has not been fully resolved.

Early on, Discovery sought to launch annually and release an Announcement of Opportunity every 12 to 18 months. The cost cap of a mission was $150 million in 1992 dollars (about $320 million, adjusted for inflation). If rigidly adhered to, those three factors would constitute a solid foundation for the program, because spacecraft would launch relentlessly. The planetary science community would have a continuous flow of data from multiple missions, and students would be able to work on missions from start to finish during their academic careers.[16] This meant increased risk, but as Dan Goldin explained in 1992, extolling the merits of the nascent program: "This is the most wonderful thing that ever happened to the space program. Here we can have a launch a month and with a launch a month, you could go to the cutting edge, and you could lose three or four spacecraft a year. It would be okay because you keep launching."[17] As NASA Headquarters explained to Congress in its pitch for funding for the small mission line, "Once the project is under way, a strong resistance to change must be present to contain cost growth. The small scales and short lifetimes of these projects permit them to be terminated if they grow out of scope."[18]

The idea, in other words, was a solar system awash in spacecraft, many of which would fail, but would always be followed by successors. Huntress warned proposers at the time of Discovery's formation not to "propose to the cap," so that a rapid mission cadence might be maintained.[19] In the purest possible sense, it was incumbent upon NASA not to maximize the potential of each spacecraft in the mission line, but rather, to minimize it. In retrospect, Huntress's injunction seems almost charming. Mark Saunders, the first Discovery Program manager, observed that it

quickly became difficult for a focused mission, well below the cost cap, to compete against missions promising sweeping, flagship-like science return.[20]

As historian Michael Neufeld pointed out, the fundamental assumptions at NASA Headquarters were perhaps optimistic. Discovery missions overran their budgets, but terminating mission projects in the development phase was "much easier said than done."[21] It was hard to ignore the tens of millions of dollars spent during development of an overrunning spacecraft when only a little more money would solve the problem. And despite Goldin's belief that NASA could lose "three or four spacecraft a year" and keep charging forward, such losses would amount to hundreds of millions of dollars of taxpayer money, exploding over Earth, vanishing in deep space, or adding new craters to the surfaces of planetary bodies. While a solar system swarming with robots holds deep appeal, the back-to-back failures of Mars Climate Orbiter and Mars Polar Lander—neither Discovery missions, but both cost-capped and flown under the "faster, cheaper, better" banner of the 1990s—proved embarrassing to NASA. (If nothing else, the response to the failures proved that people still cared about space exploration and wanted—and expected—NASA to succeed.)

Beginning in 2000, NASA corrected—and some have argued, overcorrected—for the problem of risk. One way to ensure spacecraft success is by testing them rigorously during development. How rigorously, however, depends on the level of acceptable risk. New NASA mandates—what the agency called "mission success enhancements"—greatly increased spacecraft development costs and lengthened development.[22] Speaking about the MESSENGER mission to Mercury, which was in development during the aftermath of the two Mars failures, Tom Krimigis said, "I complained to Headquarters at one time that we had a third of the staff acting on the recommendations from the previous review; another third preparing for the next review; and the final third was actually doing work."[23] In addition to the System Requirements Review, Confirmation Assessment Review, Preliminary Design Review, and NASA Confirmation Review, the spacecraft was put through 33 formal external reviews at the subsystem and system level, plus another 29 formal preliminary and critical design reviews for instruments.[24] In comparison, said Krimigis, the NEAR mission had six reviews.[25] ("You can't test for everything," said Ralph McNutt, the MESSENGER project scientist. "Now, I'm not supposed to say that, because you're supposed to test for everything, but it's not going to happen.")[26] The new requirements increased the cost of MESSENGER by $40 million and delayed its launch.[27]

Adjusted for inflation, Discovery mission costs have roughly doubled since the program began. With higher cost caps came even less appetite for failure, which meant more reviews and longer development times. Ambitious missions have led,

in Saunders's view, to commensurate, "overly optimistic estimates of the cost of increasingly sophisticated instrumentation," which means more overruns and delays.[28] (As one report put it, "a culture of optimism permeates every aspect of NASA. While essential to producing the types of unique spaceflight projects NASA undertakes, this optimistic culture may also lead managers to overestimate their ability to overcome the risks inherent in delivering such projects within available funding constraints.")[29]

Low-risk, $630 million missions with largescale science return look more like the missions that led to Discovery's formation in the first place. Announcements of Opportunity and launch cadences have likewise been impossible to maintain. Overall, this has not hindered science return: Discovery spacecraft have had sometimes-surprising longevity. This might reflect a bias in the Discovery selection process in favor of missions with long science-operations phases versus shorter missions with large science return. (GRAIL, for example, was the only Discovery-class mission since 1998 to fly less than two years, excluding the program's only failure, CONTOUR [COmet Nucleus TOUR], in 2001). Such lifespans can mislead the casual observer as to the robustness of the Discovery fleet. The program had five spacecraft flying at the start of 2012. By 2019, that number had fallen to one. With the conclusion of InSight in 2022, only Lucy has returned science data, and that will remain the case until 2029, when Psyche is scheduled for its first science. The failure to maintain an AO cadence is a short term solution that creates long term problems. Discovery justifies itself in part with its flow of data, which fuels graduate studies and builds healthy scientific communities.

The costs of Discovery missions have gone up for reasons beyond decreased appetite for risk, or any perceived profligacy by NASA centers. "A lot of the low-hanging fruit, the really inexpensive missions, were done in the first ten years of Discovery," said Michael New.[30] There's a big solar system out there, but the lower cost cap afforded "only enough for visiting near-Earth objects, small bodies. The question came up: Do we want that? Is that what we want the Discovery Program to evolve into, just a small body program, maybe occasionally a Moon mission? The answer was no, we don't want to do that. That meant increasing the budget a little bit." To broaden the palette of mission targets and concepts, NASA Headquarters also separated the cost of building a mission from the cost of operating it, because the latter, Phase E, can vary wildly. "One of the big constraints we were running into was that if we were only going to give this much money for operations, you were drastically limiting the kinds of science that people could do," said New.[31] Lucy's prime mission lasts 11 years; the first 6 in flight are just to reach the first Trojan. GRAIL, on the other hand, needed a little over three months to reach the Moon, and then had three three-month mapping phases. The availability of rockets, and wild

fluctuations in lost costs, led NASA Headquarters to separate that part of missions from the cost cap as well. "The total soup to nuts cost of a Discovery mission has gone from sub-$300 million now to $800 million, $900 million," said New. "Because it's increased so much, if the budget doesn't keep pace with that, what we wind up doing is stretching out the cadence of missions, how often we solicit."

The doubled Discovery cost cap is not necessarily a bad thing. It places the outer solar system within reach. Trident would have expanded the aegis of the program to 30 AU: the entirety of the classical solar system, minus Pluto. That part of space, and the decade-spanning cruise phases that come with it, are something the Discovery selection process has never had to internalize. There is an apocryphal story about the administrator of NASA selling the Voyager mission to President Nixon. "The last time the planets were lined up like that," said the administrator, "President Jefferson was sitting at your desk—and he blew it."[32] In the case of Trident, because the circumstances enabling that mission and its science only occurred every century, and because of its 12 years in cruise, NASA could choose it during the 2019 competition, or in the 2100s. For that Triton science, there was no "next bus out." NASA missed its only ride.

The Discovery Program could veer, conceivably, in the opposite direction, halving its cost caps in the interest of maintaining cadence. One example of this is Venus Life Finder, a collaboration between MIT and Rocket Lab.[33] The sub-$100 million atmospheric probe will detect organics in Venus's clouds by measuring light signals unique to those molecules. The science result will be narrow, and worlds apart from the rich data return of DAVINCI and VERITAS—but unlike those two missions, the privately-funded Venus Life Finder is built, and set to launch. It remains unclear whether such a mission can advance the field of planetary science in a meaningful way, as Discovery missions, historically, have done. The informal standard for "advancing the field" is for a spacecraft to make a new measurement or improve a measurement by one order of magnitude. InSight, for example, carried only one major instrument, but its measurement was new, difficult to make, and told scientists about the entire planet—something impossible at half its cost. And missions similar in cost to Venus Life Finder exclude the outer planets entirely, if only because of the exceedingly long cruise phases required to reach them. The fundamental strategic tradeoff Discovery Program mangers face is more, smaller missions with narrow data return (and fewer possible targets), versus fewer, larger missions, returning deeper science. There is no clear optimal balance.

The fortunes of the Planetary Science Directorate ebb and flow. The ordeal that the VERITAS team has endured is evidence enough that this is a period of ebbing. The FY 2019 NASA budget was "NASA's best budget in a decade."[34] The proposed FY 2026 budget was, adjusted for inflation, the smallest budget proposed for NASA

since 1961, featuring a 47 percent budget cut to space science and canceling more than 40 missions either active or in development, including VERITAS and DAVINCI—essentially ending the Discovery Program.[35] Congress restored many of the losses to planetary science, but even after passage into law, the Office of Management and Budget directed NASA to "pause all activities that would create new financial commitments" on 10 science missions, including the two to Venus.[36] Such a level of instability would be untenable for any enterprise, but especially an organization like NASA, whose missions and planning require long-term commitments.

Discovery's troubles continued. In FY 2022, the President's Budget Request sought to cut the Discovery Program budget by 19 percent "due to other missions being in peak development and COVID-related challenges."[37] Days later, almost immediately after the selection of DAVINCI and VERITAS, NASA delayed the Venus missions by a year due to "budget constraints in fiscal years 2021 and 2022." The constraints specifically were "cost overruns in implementation projects, including Mars 2020," leaving "limited ability to budget for new Discovery projects," according to a GAO report.[38] The pattern continued in FY 2023, when the President's Budget Request called for cutting funding to the Planetary Defense Coordination Office's NEO Surveyor because "the Mars Sample Return and Europa Clipper missions are experiencing cost growth and will continue to place pressure on other parts of the Planetary Science portfolio."[39] Congress doubled the requested funds to NEO Surveyor, and in its committee report, stated that it expected NASA to "continue the selection and launch cadence of Small Innovative missions for Planetary Exploration [SIMPLEx], New Frontiers, and Discovery class missions in spite of any cost pressures from planetary flagship missions or the Mars program and to include appropriate funding within the 2024 budget request."[40] In other words, Congress seemed to identify a clear programmatic hierarchy at NASA, and that the agency was growing comfortable with turning the Discovery Program and small missions generally into a kind of cost reserve for flagships.

Mission delays come with a penalty. By NASA's admission, NEO Surveyor increased in cost because of delays the agency imposed on the mission.[41] The NASA Inspector General found the same to be true of Dragonfly, a New Frontiers mission.[42] This is to say nothing of the complexity and risk that delays introduce into missions. Schedule adherence is critical to maintaining cost control.[43] In the case of VERITAS and DAVINCI, it's not that NASA Headquarters has an ax to grind against Venus: cancellation of one or both Discovery missions there would have been easier. Faced with extreme fiscal uncertainty, NASA managers did what they could specifically to preserve the missions. But invariably, budget cuts, proposed in the interests of efficiency and cost savings, make everything less efficient and more expensive.

If Discovery survives the skepticism of space science presaged by the FY 2026 NASA budget request and manages to avoid becoming a casualty of flagship overruns, there is another problem the program must overcome: the AO process and subsequent competitive phases need modernization. NASA and competing institutions spend millions of dollars to develop proposals that are hundreds of pages long and bearing price tags that have proven historically to be very optimistic. "Every time we build one of these missions it's something we've never done before. It's the first of its kind," said Paul Hertz, a former Discovery program scientist and later, division director of astrophysics.[44] "We have a lot of tools for trying to estimate the cost dollar, but they're all estimates. We don't really know how much something costs until after we build it and we add up how much we spent on it."

Cost caps shape mission design, and the selection process buys down the risk of cost and schedule overruns during development. They cannot fully prevent overruns, however. A significant driver of cost overruns are schedule delays, whether encountered due to technical issues, or more commonly, imposed by NASA Headquarters because of budgets. When a mission in development is delayed, cost assumptions break almost immediately, because of inflation and extended staffing costs. This creates a feedback loop: delays raise costs which cause delays, all of which means fewer future missions.

Most Discovery missions experience cost overruns. The program is not unique in this. Neither is NASA. Decades of research, across industries, reveal that the vast majority of major projects go over budget.[45] On average, said Curt Niebur, Discovery missions selected more recently overrun less than the missions selected 20 years ago, percentagewise.[46] It would be tempting to attribute that to higher fidelity proposals, he said, "but you also have to ask yourself the question: is that cost performance improving because of more detailed proposals, or because just overall, we are all getting better at pulling these missions together? We don't have an answer to that."

Given the small sample size, it is perilous to draw conclusions about the nature of mission selection today, but it seems possible that some of those millions of dollars were spent in service of competitions where some missions had unknowingly lost before they started. The Discovery Program has issued only a single Announcement of Opportunity in the last decade. Expanding the timeline slightly, however, the last two AOs have yielded thematic missions: two asteroid missions, and two Venus missions. "It's long overdue that we had Venus missions," said Jessica Sunshine.[47] "I just wish sometimes they [NASA Headquarters] would make an adult decision and *say*, 'It's long overdue that we had Venus missions, so this round of Discovery is going to be Venus,' and not waste everybody's time and money."

There is no sure path to ensure the program's future. "The real threat to Discovery is that it is slowing down," said Alan Stern, a planetary scientist at Southwest Research Institute in Boulder, Colorado, PI of the New Horizons mission to Pluto, and a former associate administrator for space science at NASA, in 2012.[48] That remains true today. Velocity and audacity have been essential to some of Discovery's greatest achievements, but it doesn't seem that an AO every two years is feasible in the current fiscal environment. The 2023 Decadal Survey endorsed one possible solution: a new Discovery cost cap of $800 million, inclusive of phases A through F, but excluding the launch vehicle, to improve "budgetary forecasting needed to maintain a predictable cadence of frequent selections and launches."[49] This, however, would have precluded the selection of the only two Discovery missions in flight today.[50]

Discovery is certainly among, and perhaps is, the most innovative program developed by NASA since the Apollo era. Even with a diminished cadence, it has still launched relentlessly, accumulated a staggering list of firsts; left the planetary science community flush with data not yet studied; and proven, as Ed Weiler said of MESSENGER, that NASA can fly a flagship-quality mission on a budget.[51] The technologies it has developed and demonstrated have ended up in such flagships as Europa Clipper and Perseverance.[52] Such a program must be guarded. In the early years of Discovery, NASA launched 11 spacecraft in 15 years. It's unclear how to find that kind of cadence again. What's certain is that today, NASA science budgets are diminishing and unpredictable. This would be the perfect time for a low-cost, high-cadence mission line.

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Brian Odom
NASA Chief Historian

ACRONYMS AND ABBREVIATIONS

AO	Announcement of Opportunity
APL	Johns Hopkins University Applied Physics Laboratory
ART	Anomaly Response Team
ASRG	Advanced Stirling Radioisotope Generator
ASU	Arizona State University
ATLAS	Advanced Topographic Laser Altimeter System
ATLO	Assembly, Test, and Launch Operations
C&DH	command and data handling
CAESAR	Comet Astrobiology Exploration Sample Return
CBK	Centrum Badań Kosmicznych
CNES	Centre National d'Études Spatiales
CONTOUR	COmet Nucleus TOUR
CRIS	Carrier, Relay and Imaging Spacecraft
CUVIS	Compact Ultraviolet to Visible Imaging Spectrometer
DAVINCI	Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging
DIXI	Deep Impact Extended Investigation
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DSOC	Deep Space Optical Communications
EMC	emergency mode control
EPOCh	Exoplanet Observations and Characterization
EPOXI	Extrasolar Planet Observation and Deep Impact Extended Investigation
FAST	Feasible ATLO, Shortened Timeline
FETCSM	Fuel-Efficient Thruster-Controlled Safe Mode

GEMS	GEophysical Monitoring Station
GNC	Guidance, Navigation, and Control
GRACE	Gravity Recovery and Climate Experiment
GRAIL	Gravity Recovery and Interior Laboratory
GRaND	gamma ray and neutron detector
GRNS	gamma-ray and neutron spectroscopy
HED	howardites, eucrites, and diogenites
HP^3	Heat Flow and Physical Properties Package
ICESat-2	Ice, Cloud and land Elevation Satellite
IPGP	Institut de Physique du Globe de Paris
IRB	Independent Review Board
ITAR	International Traffic in Arms Regulations
IVO	Io Volcano Observer
JPL	Jet Propulsion Laboratory
JUICE	Jupiter Icy Moons Explorer
K2	The second Kepler mission
keV	kilo-electronvolt
L'LORRI	Lucy Long Range Reconnaissance Imager
L'TES	Lucy Thermal Emission Spectrometer
LADEE	Lunar Atmosphere Dust Environment Explorer
MatISSE	Maturation of Instruments for Solar System Exploration
MAVEN	Mars Atmosphere and Volatile Evolution
MEPAG	Mars Exploration Program Analysis Group
MESSENGER	Mercury Surface, Space Environment, Geochemistry, and Ranging
MMRTG	multi-mission radioisotope thermoelectric generator
MOI	Mercury orbital insertion
MoonKAM	Moon Knowledge Acquired by Middle School Students
NEAR	Near Earth Asteroid Rendezvous
NEOCam	Near Earth Object Camera
NISAR	NASA-ISRO Synthetic Aperture Radar
NSPIRES	NASA Solicitation and Proposal Integrated Review and Evaluation System
OIIR	NASA Office of International and Interagency Relations
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, and Security – Regolith Explorer
PDR	preliminary design review
PFR	Problem/Failure Report
PI	principal investigator

PMPO	Planetary Missions Program Office
PRS	Point Rest State
PSD	Planetary Science Division
SALMON	Stand Alone Missions of Opportunity
SEIS	Seismic Experiment for Interior Structure
SIMPLEx	Small Innovative Missions for Planetary Exploration
SMD	Science Mission Directorate
SOMA	Science Office for Mission Assessments
SP	short-period (seismometer)
SSL	Space Systems/Loral
STM	science traceability matrix
SWRI	Southwest Research Institute
TCSM	Thruster-Controlled Safe Mode
TiME	Titan Mare Explorer
TMC	technical, management, and cost
TTR	Trojan Tour and Rendezvous
UAI	Use As-Is
VBB	very broadband (seismometer)
VEM	Venus Emissivity Mapper
VenDI	Venus Descent Imager
VERITAS	Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy
VIR	visible and infrared mapping spectrometer
VISAR	Venus Interferometric Synthetic Aperture Radar
VISOR	Venus Imaging System for Observational Reconnaissance
VOIR	Venus Orbital Imaging Radar
VOX	Venus Origins Explorer
WFIRST	Wide Field Infrared Survey Telescope

ABOUT THE AUTHOR

David W. Brown is the author of six books, including *The Mission*, a history of NASA's Europa program, and *The Outside Cats*, a forthcoming account of Antarctic exploration, scientific rivalries, and the race to study rapid sea-level rise. His work appears regularly in *The New Yorker*, *The New York Times*, and *Scientific American*. Brown is a deep-field Antarctic expeditioner, a former U.S. Army paratrooper, and a veteran of Afghanistan. He is a graduate of Louisiana State University and holds a Master of Fine Arts in creative writing from the University of Arkansas at Monticello. He lives in New Orleans.

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INDEX

*Page numbers in **boldface** indicate tables.*

A

Adeona (asteroid 145), 89, 97
Advanced Stirling Radioisotope Generators (ASRGs), 1, 6–7, 42–43, 49, 149, 181–182n43
  Comet Hopper, 11, 38–39, 42
  Lucy, 91
  TiME, 37–39
Advanced Topographic Laser Altimeter System (ATLAS), 126
Advance Mission Design Group (Team X), 100
A'Hearn, Maxine, 28
A'Hearn, Michael (Mike)
  Comet Hopper, 11, 34, 35, 42
  Deep Impact, 12, 50–52
  Deep R, 28
Ali, Khaled, 128
Alpha Regio, 166
Amato, Michael, 93
American Geophysical Union, 113, 159
Ames Research Center, 12, 106
Andrews, John, 92
Announcements of Opportunity (AOs), 3, 57–59, **58**, 65–66, 112, 163–164, 171, 176
  Announcement of, 112
  cadence, vii, 58, 96, 173, 174, 177
  Draft AOs, 112–113
  pre-proposal conferences, 113
Anomaly Resolution Team (ART) (Lucy), 142, 143, 146–147
Anomaly Response Team (ART) (InSight), 116–118, 127–128
Apollo, 2, 71, 134
Apollo 11, 133
Apophis (asteroid 99942), 105
Applebee, John, 18
Applied Physics Laboratory (APL), 3, 4, 18
  automated science data acquisition system, 19
  GRNS instruments, 71
  Kossiakoff Center, 16, 17
  L'LORRI, 92
  MESSENGER, 16
  Psyche, 71
  Space Exploration Sector, 138
  TiME project, 37–39
Aristotle, 46
Arizona State University (ASU), 67–69
Arney, Giada N., 138
Artemis program, 43
Asmar, Sami, 47
ASRGs. *See* Advanced Stirling Radioisotope Generators (ASRGs)
Asteroid Belt, 21, 44, 115
asteroid missions, 176

Astrobiology Institute, 50
Astronika, 101
Astronomy and Planetary Research Institute, 85
The Astrophysical Journal, 12
Astrophysics Explorers, 171
astroseismology, **106**
ATLAS (Advanced Topographic Laser Altimeter System), 126
Atlas V rockets, 7
  InSight, 84, 103–104, 114
  Lucy, 114
  TiME, 37
  Trident, 111
ATLO: Assembly, Test, and Launch Operations
  FAST: Feasible ATLO, Shortened Timeline, 126
  Lucy, 125
  Psyche, 153
Atmospheric Sample Vehicle, 156
Australopithecus afarensis, 169–170

B

Ball Aerospace, 49, 53, 54, 87, 106
Banerdt, W. Bruce
  InSight, 1–2, 11, 30–32, 42, 62, 83–84, 99, 103–104, 107–108, 117, 148–150
  on VERITAS, 159
Barclay, Thomas S., 64
Batalha, Natalie, 12
Bedini, Peter, 37, 38, 42
Beehive cluster (Praesepe), 105
Bell, Jim, 68
Belton, Michael, 27, 28
BepiColombo, 9, 40, 157
Biden Administration, 163
Bills, Bruce, 67–68
binary satellites, 162
Bolden, Charles, 41
Bone, Brian, 98
Borrelly (comet 19P), 11, 15
Borucki, William, 46
Brown, David, vii
Brownlee, Donald, 11, 13
Brown University, 133–134
budget-friendly flagships, xi–xii, 177. *See also* funding
bureaucracy, 71
Bush, George W., 24

C

C-175 process, 60
CAESAR (Comet Astrobiology Exploration Sample Return), 156
California, 117
Calloway, Andy, 77
Caltech, 109, 151
Cape Canaveral, Florida
  GRAIL launch, 23
  Lucy launch, 131, 141, 142
Carrier, Relay and Imaging Spacecraft (CRIS), 135–136, 166
Cassini, 7, 13, 16, 23
Castillo-Rogez, Julie, 98
Category 1 missions, 10
Category 2 missions, 10
Category 3 missions, 10
Category 4 missions, 10
cat video "Taters the Cat," 155, 167–168
CBK (Centrum Badań Kosmicznych), 101
Centaur asteroid, 91
Centers for Disease Control and Prevention (CDC), 121
Centre National d'Études Spatiales (CNES)
  Convection, Rotation et Transits planétaire telescope, 183n65
  InSight seismometer, 41, 59–62, 83, 84, 99
  VERITAS amplifiers, 157
Cerberus, 2–3
Cerberus Fossae (Mars), 150
Ceres (dwarf planet), 21–22
  Dawn achievements, 67, 73–76, 81, 88–89, 91, 97–98, **104**, 105, 121
  Dawn orbit, 104, 105
  Hubble observations, 73
  Occator Crater, 76, **104**
  Rheasilvia, 44
  Veneneia, 44, 45
Chang'e Program (China), 24
China National Space Administration, 24
Christmas (2021), 143–144, 153

Chryse Planitia (Mars), 1, 32
Churyumov-Gerasimenko (comet 67P), 28, 156
Circular 175 policy (State Department), 197n10
clathrate hydrates, 98
clean room procedures, 61
Clinton, Bill, 4, 66
Cochrane, Corey, 139
Cognizant Engineer role, 153
comet 2P/Encke, 78, **79**
comet 19P/Borrelly, 11, 15
comet 67P/Churyumov-Gerasimenko, 28, 156
comet 81P/Wild (Wild 2), 11, 13, 15
comet 103P/Hartley (Hartley 2)
  Deep Impact/EPOXI observations, 13, 15, 50, 52, **52**
  DIXI flyby, 28–29
comet C/2009 P1 (Garradd), 50, 52
Comet and Interstellar Dust Analyzer, 14
Comet Astrobiology Exploration Sample Return (CAESAR), 156
Comet C/2012 S1 (ISON)
  Deep Impact observations, 49, 51, 52
  MESSENGER observations, 78, **79**
Comet Hopper, 11, 27, 33–39, 42, 91
comet P/McNaught 2 (P/2004 R1), 11
comets
  Deep Impact/EPOXI observations, 13, 15, 28, 29, 49–52, **52**, 53
  missions to, 16, 34–37
command and data handling (C&DH) systems, 86
communication(s)
  informal communications mode, 153
  Ka-band, 123–124
  lessons learned, 33, 34
  Moon delays, 39
  Psyche, 152
  X-band, 123–124
Compact Ultraviolet to Visible Imaging Spectrometer (CUVIS), 136, 166
Concept Study Reports, 73
Consolidated Appropriations Act for 2014, 57–59
CONTOUR (COmet Nucleus TOUR), **xii**, **58**, 173
contracts
  cost-plus, 124
  fixed-price, 60, 124
  Phase A, 73
Convection, Rotation et Transits planétaire telescope, 183n65
coronavirus (COVID), 121
CoRoT-7 (exoplanet), 183n65
cosmic rays, 89
cost management
  budget-friendly flagships, xi–xii, 177
  cost-capped robotic missions, 77–78
  cost caps, 3, 5, 6, 42, 93, 113, 171–174, 177
  cost overruns, xi, 83–85, 99, 149, 173–176
  fixed-price contracts, 60, 124
  marching army costs, 83
  Phase E costs, 173
  technical, management, and cost (TMC) risk evaluation, 9, 72–73
cost-plus contractors, 124
COVID pandemic, xi, 121, 122–125, 138, 142, 143–144, 152, 153, 175
Cox, Matthew, 126
creativity, vi
CRIS (Carrier, Relay and Imaging Spacecraft), 135–136, 166
cruise phase, 52
CubeSats, 107, 154, 156
Culberson, John, 84, 96, 103
culture
  of optimism, 173
  workplace, 153
Cupid's Arrow, 156
Curiosity, 85, 113, 149
CUVIS (Compact Ultraviolet to Visible Imaging Spectrometer), 136, 166

D

data noise, 46
DAVINCI (Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging), **xii**, 133–138, 158
  Alpha Regio imaging, 166

Carrier, Relay and Imaging Spacecraft (CRIS), 135–136
Concept Study Report, 122
design philosophy, 166
development, v, 165–167
funding, 70, 122
launch date, v, 164, 165–166, 169, 175
name, 140
orbiter, 135–136
principal investigators (PIs), 122, 137–138
Pro Flight System, 136, 166
proposal, 134, 138
science goals, 140–141
selection, **58**, 69, 122, 131, 140–141, 156
systems requirements reviews, 166–167
timeline, 169
Venus gravity assist maneuvers, 166
Dawn, **xii**
10th anniversary, 97–98
Ceres achievements, 67, 73–76, 81, 91, 97–98, **104**, 121
Ceres observation campaigns, 89
Ceres orbit, 67, 74, 81, 88–89, 97, 104, 105
cosmic ray measurements, 89
course for Ceres, 44–45
cruise phase, 22, 45
data collected, 105
development phase, 58
end of mission, 103, 104
extended missions, 88–89, 97, 103
funding, 103
gamma ray and neutron detector (GRaND) measurements, 89
gravity measurements, **45**
hybrid mode, 74–75
launch, **58**
lessons learned, 114
modifications, 74–75
propulsion system, 22, 67, 85, 168
reaction wheels, 22, 27, 45, 91, 97
scientific measurements, 22
scientific objectives, 21, 75
scientific results, 97–98
selection, **58**
targets, 88–89
timeline, 27, 67, 81, 91, 103, 121
Venus orbit, 88–89
Vesta achievements, **45**, 76
Vesta orbit, 20–23, 44, 45, 76
Decadal. *See* National Academies Planetary Science and Astrobiology Decadal Survey
decision-making, vi. *See also* mission selection
key decision points, 85
Planetary Missions Program Office (PMPO), 65–66
principal investigators (PIs), 4
Science Mission Directorate (SMD), 42–43
Deep Impact, **xii**, 4, 8, 11, 27
asteroid observations, 50–51
cometary observations, 12, 49, 51
disappearance, 51–52
end of mission, 53
extended mission. *See* EPOXI (Extrasolar Planet Observation and Deep Impact Extended Investigation)
fault management software, 51
funding, 59
launch, **58**
long-term objective, 50–51
Medium Resolution Instrument, 51
prime mission, 52
selection, **58**
timeline, 1, 49
Deep Impact Crater, 14, **15**
Deep Impact Extended Investigation (DIXI), 28–29
Deep Rosetta (Deep R), 27–29
Deep Space 1, 11, 22, 168
Deep Space Network (DSN), 17, 20, 51, 54, 123–124, 136, 167
Deep Space Optical Communications (DSOC), 155, 167–168
Delta IV, 7
Deming, L. Drake, 29
Deployables team (Northrop Grumman), 147
De Sanctis, Maria Cristina, 98
Deutsches Zentrum für Luft-und Raumfahrt (DLR)
InSight, 41, 59, 60, 84, 99–101, 116, 117

VEM, 157
Developmental PFRs (Problem/Failure Reports), 153
Didymos I (asteroid 65803), 112
Dinkinesh (asteroid 152830), 112, **115**, 155, 160–162
diogenites, 21, 44, 45, **45**
Discovery and New Frontiers Program Office, 62, 65, 66
Discovery Program. *See also individual missions*
16th year of continuous spaceflight, 26
19th anniversary, 26
30th anniversary, x
1994 Announcement of Opportunity (AO), **58**
1996 AO, 18, **58**
1998 AO, **58**
2000 AO, **58**
2004 AO, **58**, 59
2006 AO, 28, **58**
2010 AO, 5–12, **58**
2014 AO, 57, **58**, 65–67, 92, 134, 155
2019 AO, v, **58**, 109, 112–113, 134
2025 AO, 159
Announcements of Opportunity (AOs), 3, 6, 57–59, **58**, 163–164, 171, 173, 174, 177
brief history, 3–5
cost caps, 3, 5, 6, 42, 93, 113, 171–174, 177
cost overruns, 83–85, 99, 149, 173–176
extended missions, 12–16, 28
first mission to launch, 110
foreign contributions, 41, 42
funding, 4, 8–9, 57–59, 65–66, 96–97, 103, 157, 163–164, 175
future directions, 170–177
introductory workshop, 3–4
launch cadence, 85, 173
launch schedules, 59
lessons learned, v–vi, 33, 34, 36–37, 51–52, 61, 114, 139
management of, 57
Mars missions, 5–6
mission cadence, vii, 57–58, 66, 97, 103, 112–113, 171–172, 174, 175, 177
mission competitions, vi, 29, 65–66, 171–172
mission concepts, 4
mission costs, 172–174
mission development times, 3
mission goals, 3
mission lifespans, 173
missions, **xii**
mission selection, x–xi, 3, 9–10, 38, 57, 67, 69, 72–73, 85–87, 91, 174, 176
missions of opportunity, 28
notices of intent, 9
nuclear missions, 6–8
number of missions launched, 171
objective when conceived, 57–58
office locations, 66
principal investigators (PIs), 4
project managers, 4
prospective missions, 1
purpose, vi
spacecraft fleet, 173
timeline, 57, 67, 103, 109
Discovery Program Office, 65
DIXI (Deep Impact Extended Investigation), 28–29
Donaldjohanson (asteroid 52246), v, 112, **115**, 161, 169–170
Donnelly, Mike, 125
Double Asteroid Redirect Mission, 112
Douglas-Bradshaw, Donya, 125–127
Dove, John, 85
Dragonfly, 96, 156, 175
Dreier, Casey, 103
DSOC (Deep Space Optical Communications), 155, 167–168
Dust Flux Monitor Instrument, 14
Dyar, Darby, 155–158, 164

E

Earth
Deep Impact/EPOXI observations, **52**
Lucy flyby, 145
MESSENGER flybys, 19
TiME flyby, 37
Earth Venture, 171
Ebb, 39, 43, 48

Elachi, Charles, 61, 82
Elkins-Tanton, Lindy
  COVID challenges, 123–124
  Psyche, 67–70, 85, 90, 96, 114, 123–125, 145, 146, 160
Elliot, Vince, 125, 126
Elysium Planitia (Mars), 31, 32, 101–103
Enceladus, 171
Encke (comet 2P), 78, **79**
Environmental Management Division, 6
EnVision (ESA), 158, 165
EPOCh (Exoplanet Observations and Characterization), 29
EPOXI (Extrasolar Planet Observation and Deep Impact Extended Investigation), 8
  achievements, **52**
  asteroid observations, 50–51
  cometary observations, 13, 15, 28, 29, 49–52, **52**, 53
  cruise phase, 52, **52**
  exoplanetary observations, 52, **52**
  launch, **58**
  proposal, 28
  selection, **58**
  timeline, 49
Erigone asteroids, **115**
Eros, 4
ESA. *See* European Space Agency
ETH Zurich, 59
eucrites, 21, 44, 45, **45**
Europa (planet), 84, 109–111, 139, 171
Europa Clipper, 109, 158, 177
  cost overruns, 175
  development, 143, 171
  engineering staff, 152–153
  funding, xi, 96–97, 103
  Phase A, xi
  Phase B (preliminary design), 96
  project management, 65
Europa missions, 110
European Space Agency (ESA), 29, 60, 168
  BepiColombo, 9, 40, 157
  EnVision, 158, 165
  Jupiter Icy Moons Explorer (JUICE), 65
  Philae, 28, 36
  Rosetta, 28, 36
  Venus missions, 78, **79**, 157, 158
Eurybates (asteroid 3548), **95**, **115**, 170
exoplanets
  confirmed detections, 12, 88, **106**, 183n65
  Deep Impact/EPOXI observations, 52, **52**
  fully automated transiting planet validation procedure, 88
  missions studying, 65
Experimental Satellite System-11, 25
expertise, 9
Explorer, 3, 171

F

FaceTime, 127
faculae, 76
Falcon 9, 7
FAST: Feasible ATLO, Shortened Timeline, 126
Faster, Better, Cheaper. initiative, 4, 5
fault management software, 51
Feldman, Jason, 100
FG3 (asteroid 175706 1996), 154
financing. *See* funding
Finnegan, Eric, 16, 17
fiscal management. *See* cost management; funding
fixed-price contracts, 60, 124
flagship missions, 7, 97, 103, 109, 110, 149, 170–172, 176
  budget-friendly, xi–xii, 177
  planetary, 175
Flandro, Gary, 111–112
Flight Project Practices (JPL), 154
flight software, 143–144
Flow, 39, 43, 48
flyby missions, 78
Fox, Nicola, 164
Free Mole Test, 132
French Space Agency. *See* Centre National d'Études Spatiales (CNES)
Fuel-Efficient TCSM (FETCSM), 54
funding
  appropriations, xi, 57–59, 65–66, 84
  authorizations, 62–63, 96–97
  budget-friendly flagships, xi–xii, 177
  DAVINCI, 70, 122

Dawn, 103
Deep Impact, 59
Discovery Program, 4, 8–9, 57–59, 65–66, 96–97, 157, 163–164, 175
Europa Clipper, xi, 96–97, 103
GRAIL, 8
InSight, xi, 83–85
Kepler Space Telescope, 59, 103
Lucy, 70, 103
Mars missions, 4, 96–97
NASA, 3, 4, 50, 57–59, 65–66, 84, 96–97, 113, 159, 163–164, 170, 174–177
NEAR, 4
New Frontiers, 96–97
planetary missions, 50, 65–66, 96–97, 113
President's Budget Request, 156–157, 175
private, 174
Psyche, 70, 85, 103
timeline, 57
VERITAS, 70, 122, 159, 163, 164

G

Galileo, 139, 158
gamma ray and neutron detector (GRaND) measurements, 89
gamma ray and neutron spectrometers, 68–72
Gamma Ray and Neutron Spectrometer team (Psyche), 167
Ganymede, 171
Garradd (comet C/2009 P1), 50, 52
Garvin, James (Jim), 122, 133–134, 137–138, 167
GEMS (GEophysical Monitoring Station), 1–3, 11. *See also* InSight
General Dynamics, 123–124
Genesis, **xii**, 4, **58**
Geological Society of America, 159
GEophysical Monitoring Station (GEMS), 1–3, 11. *See also* InSight
German Aerospace Center. *See* Deutsches Zentrum für Luft-und Raumfahrt (DLR)
Getty, Stephanie A., 138
Glaze, Lori, 134, 154, 155, 159
Glenn Research Center, 6–7
GNC (Guidance, Navigation, and Control) software, 143–144
Goddard Space Flight Center
ATLAS, 126
Comet Hopper, 33
DAVINCI, 69, 138
L'Ralph, 92
Lucy, 70, 93, 125, 141, 142, 147
Mars missions, 134
Solar System Exploration Division, 134
Venus missions, 134
Goldin, Daniel S. (Dan), 4, 5, 66, 171, 172
Golombek, Matthew, 31–32, 101–102, 133
Goodloe, Colby, 142
GoPro cameras, 127
Government Furnished Equipment, 6
GPS, 26
GRACE (Gravity Recovery and Climate Experiment), 25–26
GRAIL (Gravity Recovery and Interior Laboratory), **xii**
achievements, **48**
conclusion of mission, 81
controlled lunar crash, 27, 48
extended mission, 27, 40, 43–44, 47
final mission data analysis, 81
funding, 8
launch, 23–26, **58**
lifespan, 173
lunar gravity field measurements, 47–48
Lunar Gravity Ranging System, 43
lunar orbit, 47
lunar surface entry, 47
prime mission, 43–44, 173
scientific investigations, 25, 27, 39
scientific objectives, 24–25
selection, 23, 25, **58**, 59
solar flares, 46
timeline, 1, 27, 81
unique aspects, 39
GRAIL-A, 1, 26, 27
GRAIL-B, 26–27
GRaND (gamma ray and neutron detector) measurements, 89
gravity anomalies, 98
Gray, Tom, 169

Green, James L. (Jim), 12, 51
ASRG program, 6, 49
InSight, 83, 84–85
mission selection, 8–9, 25, 42–43, 96
Grinspoon, David, 135, 156
GRNS (gamma-ray and neutron spectroscopy) instruments, 71–72
Grunsfeld, John, 70, 82–84
Guidance, Navigation, and Control (GNC), 143–146, 151, 153

H

habitability
habitable zone, 111
Kepler results, 49–50, 57, 64, **106**
Mercury results, 47
Hale Telescope (Palomar), 167
Hall-effect thrusters, 168
Hartley 2 (comet 103P)
Deep Impact/EPOXI observations, 13, 15, 50, 52, **52**
DIXI flyby, 28–29
Harvard-Smithsonian Center for Astrophysics, 49–50
Heat Flow and Physical Properties Package (HP^3, "the mole"), 84, 99–102, 108, 127–129, 149
Anomaly Response Team (ART), 116–118
end of digging attempts, 131, 132
Free Mole Test, 132
hammering periods, 128
repositioning ("kissing the mole"), 128
self-hammerings, 116–119, 128
thermal probe measurements, 132
timeline, 109, 131
HED (howardite, eucrite and diogenite) meteorites, 21, 44, 45, **45**
Helen (least reduceable unit of technological knowledge), 124
helium, 77
Hertz, Paul, 12, 176
Hinners, Noel W., 134
HiRISE camera, 102
Hoffman, Tom
GRAIL, 23, 26
InSight, 59–61, 82–83, 98, 108
House Appropriations Subcommittee on Commerce, Justice, Science, and Related Agencies, 84
howardites, 21, 44, 45, **45**
Hubble Space Telescope, 73
Hudson, Troy, 100–101, 116–119, 127–128, 132
Huntress, Wesley "Wes," 3, 170, 171–172
Hurst, Kenneth (Ken), 59, 61, 62, 81, 82
hybrid work situations, 153
Hyde, T. Tupper, 142

I

ICESat-2 (Ice, Cloud and land Elevation Satellite), 126
imagers, 124–125
impactor missions, 4
Imperial College London, 59
Independent Review Boards (IRBs), 146
Independent Technical Authority, 152
Innovation Foundry (JPL), 67–68
InSight, **xii**, 112
achievements, **151**
Anomaly Response Team (ART), 116–118, 127–128
C-175 process, 60
cleaning events, 133
completion of mission, 145, 149
cost overruns, 83–85, 99, 149
cruise phase, 104
CubeSats, 107
Entry-Descent-Landing (EDL) maneuvers, 102
extended mission, 121, 131–132
final selfie, 148
foreign partners, 41, 42, 59, 60
funding, xi, 83–85
goals, 131–132
Heat Flow and Physical Properties Package (HP^3, "the mole"), 84, 99–102, 108, 109, 115–119, 127–129, 131, 132, 149
hibernation mode, 133
Instrument Deployment Arm, 115–118, 128, 133
lander instruments, 41, 59, 62, 99, 102

lander mission, 27
launch, **58**, 81–84, 101, 103–104
launch vehicle, 103–104, 114
Mars landing, 103, 107
Mars landing site, 31–32, 101–102
Mars observations, 145
Phase A, 32
Phase D, xi
Principal Investigator (PI) role, 32
project management, 59–61
proposal, 1–3, 30–32, 38–39
rejections, 32
replan, 84
scheduling, 98
science measurements, 148, 174
science objectives, 41, 84, 85
science operations, 129
science results, 174
Seismic Experiment for Interior Structure (SEIS) instruments, 11, 41, 59–62, 81–85, 98–99, 101–103, 107–108, 148–150, **151**
seismometer deployment, 103, 107–108
selection, 11, 30, 41–44, **58**, 59, 91, 96
solar arrays, 127–128, 131, 133, 148
timeline, 103, 109, 121, 131, 145
total lifecycle cost, 149
Institut de Physique du Globe de Paris (IPGP), 59, 61–62
Institute for Planetary Studies, 100
International Astronomical Union, 161
international collaboration, 61–62, 65, 83, 101, 113, 157
C-175 process, 60
InSight, 41, 42, 59, 60
VERITAS, 158, 165
International Space Station, 89
International Traffic in Arms Regulations (ITAR), 62
Io Volcano Observer (IVO), 122
iPads, 127
Isidis Planitia (Mars), 32
ISON (Comet C/2012 S1)
Deep Impact observations, 49, 51, 52
MESSENGER observations, 78, **79**
Italian Space Agency, 157

J

James Webb Telescope, 97
Janus, 154
Japan, 121
Japan Space Agency, 9, 40, 157
Jet Propulsion Laboratory (JPL)
Atlas V design, 111
Cassini, 23
Comet Hopper proposal work, 33
development practices, 3
Division 35—Mechanical Systems Engineering, Fabrication and Test, 82
Europa Clipper, 143, 152–153
factors that historically led to project success, 151
Flight Project Practices, 154
flight software, 143–144
funding, 69, 70
future directions, 174–175
Guidance, Navigation, and Control (GNC) software, 143–144
informal communications mode, 153
Innovation Foundry, 67–68
InSight, 1–3, 41, 59, 61, 81–83, 99, 100
InSight Mission Assurance, 61–62
Integration & Testing, 23
international collaboration, 61–62
key practices, 151
Mars 2020, 96
Mars Exploration Program Landing Site Scientists, 31
Mars Exploration Rover, 23
Mars Sample Return, 143, 152–153
Microdevices Laboratory, 2
NEOCam (Near Earth Object Camera), 70
Planetary Science Directorate, 153, 174–175
Psyche, 69, 70, 86, 143, 145, 146, 151, 152–153, 160
Psyche Independent Review Board, 145, 151–154
Psyche site visit, 90
radars, 157
recommendations for, 153
science traceability matrix (STM), 30–31
senior management, 153

staffing levels, 152–153
Stardust, 12–13
Team X (Advance Mission Design Group), 100
Trident, 109, 139
VERITAS, 70
workplace culture, 153
Johanson, Donald, 169–170
Johns Hopkins University Applied Physics Laboratory (APL). *See* Applied Physics Laboratory (APL)
Johnson, Lindley, 53
Juno, 114
Jupiter
Io Volcano Observer (IVO), 122
TiME flyby, 37
Trojan asteroids, v, 70, 91, 92, 94–95, **115**, 170
Jupiter Icy Moons Explorer (JUICE), 65

K

K2, 57, 62–64, 103, 106, **106**
Ka-band communications, 123–124
Kaiser, Bill, 2
W.M. Keck Institute for Space Studies, 109
Kennedy Space Center, 146, 160
Kepler, Johannes, 106
Kepler-10b, 1, 12
Kepler-11, **106**
Kepler-16b, **106**
Kepler-186f, 57, 64, **106**
Kepler Attitude Determination and Control Subsystem (Ball), 54
Kepler Mission Operations Center (Boulder, Colorado), 106
Kepler Science Office, 63
Kepler Space Telescope, **xii**
achievements, **106**
Campaign 19, 105, 106
Campaign 20, 106
coma state, 87–88
confirmed detections, 12, 46, 49–50, 64, 88, **106**, 183n65
costs, 88
development phase, 58
emergency mode, 81, 87–88
Emergency Mode Control (EMC), 53
end of mission, 103, 105–106
extended mission, 46, 54–55, 88, 103. *See also* K2
final tranche of data, 88
fiscal management, 62–63
Fuel-Efficient TCSM (FETCSM), 54
funding, 59, 103
habitability results, 49–50, 57, 64, **106**
launch, **58**
Levison on, 92
no-fuel-use safe mode (nap mode), 103, 105
noise, 46
observation campaigns, 87–88, 105–106
Point Rest State (PRS), 54
prime mission, 27, 46, 49, 55
reaction wheels, 27, 46, 49, 53–55, 88
safe mode, 87–88, 103, 105–106
selection, **58**
solar flares, 46
synchronization issue, 87–88
Thruster-Controlled Safe Mode (TCSM), 53, 54
timeline, 1, 27, 49, 57, 81, 103
"kissing the mole" (repositioning HP^3), 128
Korea, Republic of, 121
Kossiakoff Center (APL), 16, 17
Krimigis, Stamatios "Tom," 3, 4, 16, 172
Kuiper Belt, 110

L

LADEE (Lunar Atmosphere Dust Environment Explorer), 167
Lakdawalla, Emily, 45
Langley Research Center, 6, 10
Larson, Tim, 16
lasers, 167–168
"last bus out" syndrome, 170
launch schedules, 59
Launch Services Program, 6
Lawrence, David, 69, 71, 72
leadership, vi, 34, 137
leadership lessons, 34, 36–37
Lee, Gentry, 70
Leshin, Laurie, 146, 160

lessons learned, v–vi, 33, 34, 36–37, 51–52, 61, 114, 139
Leucus (asteroid 11351), **95**, **115**
Levison, Hal, 92–94, 96, 126–127, 141, 147, 160–162, 170
Ligeia Mare (Saturn), 11, 37
listening, 34
L'LORRI (Lucy Long Range Reconnaissance Imager), 92
Lockheed Martin
  Comet Hopper, 33, 35–39
  GRAIL, 23, 25, 38–39
  InSight, 82, 84
  Lucy, 93, 126–127, 142, 147, 148
  Lucy Critical Design Review, 114
  Mission Support Area, 142
  Psyche, 124
  TiME, 38–39
  work weeks, 127
Lockheed Martin Astronautics, 12
Lockheed Martin Space Systems, 11
Lognonné, Philippe, 149
Los Alamos National Laboratory, 71
Lounsbury, Jessica, 141, 142–143, 147, 148, 161
L'Ralph, 92
L'TES, 92
Lucy (fossil skeleton), 92–93, 161, 169–170
Lucy (mission), **xii**
  Anomaly Resolution Team (ART), 142, 143, 146–147
  asteroid flybys, v, **115**, 155, 160–162, 169, 170
  ATLO: Assembly, Test, and Launch Operations, 125
  birth, 91
  cost cap, 93
  Critical Design Review (CDR), 114, 115
  design philosophy, 166
  development, 114–115
  Didymos I observations, 112
  Dinkinesh flyby, **115**, 155, 160–162
  Dinkinesh observations, 112, 161–162
  Donaldjohanson flyby, v, **115**, 161, 169, 170
  Donaldjohanson observations, 112, **115**, 170
  Earth flyby, 145, 163
  funding, 70, 103
  goals, 94–97
  gravity assist maneuvers, 145, 148, 163, 168
  instruments, 92, 124
  Johanson visit, 170
  launch, **58**, 96, 115, 131, 141
  launch vehicle, 114
  Level 1 requirements, **95**
  name, 92–93, 161
  power source, 91
  prime mission, 173
  project management, 125–127
  proposal, 92–93
  science objectives, 91, 94–95
  selection, **58**, 70, 91, 93–94, 96, 134, 156
  solar arrays, 114, 141–143, 146–148
  targets, **115**, 160–161
  timeline, 91, 131, 145, 155, 163, 169
  Trojan flybys, 94
  UAI (Use As-Is) team, 142
  work weeks, 127
Lucy 6-15 rule, 127
"Lucy in the Sky with Diamonds" (Beatles), 169
Lucy's baby (fossil), 161
Lunar and Planetary Institute (LPI), 109, 110, 122, 138, 155
Lunar and Planetary Science Conference, 101, 159, 164
Lunar Atmosphere Dust Environment Explorer (LADEE), 167
lunar crust, 48, **48**
Lunar Exploration Analysis Group, 113
Lunar Prospector, **xii**, **58**
Lunine, Jonathan, 11

M

Magellan, 96, 134, 157, 158
magnetometers, 123
Malin Space Science Systems, 68
marching army costs, 83
MarCO-A and -B (CubeSats), 107
Marcy, Geoff, 46
Mariner 10, 18, 40, 77

Mars (planet), 111
atmospheric data, 102, **151**
average temperature recorded, 132
Cerberus Fossae, 150
Chryse Planitia, 1, 32
crust, 132
dust storms, 145
Elysium Planitia, 31, 32, 101–103
final InSight selfie from, 148
InSight landing on, 103, 107, 149
InSight mission to, 11, 41, 109, 145, 148–149, **151**
iron alloy core, 150, **151**
Isidis Planitia, 32
meteorite impacts, **151**
mole self-extraction on, 115–119
NASA Chief Scientist for Mars Exploration, 134
noisy season, 150
quiet season, 150
Utopia Planitia, 1
Valles Marineris, 32
Viking Program to, 133, 134
windy season, 133, 150
Mars 96 (Russia), 62
Mars 2020, 84, 96
Mars Atmosphere and Volatile Evolution orbiter (MAVEN), 5, 49
Marschall, Raphael, 160–161
Mars Climate Orbiter, 5, 107, 146, 172
Mars Cube One, 107
Mars Exploration Program Analysis Group (MEPAG), 30, 83, 159
Mars Exploration Rover, 23, 31–32
Mars Global Surveyor, 2
Marshall Space Flight Center (Huntsville, Alabama), 57, 65–66, 72–73
Mars heat probe. *See* Heat Flow and Physical Properties Package (HP^3, "the mole")
Mars missions, 111, 170. *See also* InSight
cadence, 175
driving factors, 5–6
funding, 96–97
landing site selection, 32
launch cadence, 2–3, 5
proposals, 65
prospects, 10–12, 96
selection, 41–43
Mars Odyssey, 107
Mars Pathfinder, **xii**, 4, 5, 31–32, 58, **58**
Mars Phoenix Lander, 3, 5, 62, 114
Mars Polar Lander, 5, 62, 107, 146, 172
Mars Program Independent Assessment Team, 5, 146
marsquakes, 145, 149, 150, **151**
Mars Reconnaissance Orbiter, 25, 102
Mars Relay Network, 149
Mars Sample Return, xi, 143, 152–153, 158, 163, 175
Mars Science Laboratory, 85, 181–182n43
Mars Scout, 2–3, 5, 32, 149, 171
Mars Surveyor, 5
Mase, Robert, 145
mass concentrations (mascons), **48**
MatISSE: Maturation of Instruments for Solar System Exploration, 72
MAVEN (Mars Atmosphere and Volatile Evolution orbiter), 5, 49
Maxar, 68, 69, 124, 144, 151, 152
May, Todd, 66
McCaa, Chris, 126
McEwan, Alfred, 113, 122
McNaught 2 (comet P/2004 R1), 11
McNutt, Ralph, 16, 40, 172
Meadows, Victoria, 50
Menoetius (asteroid 617), **95**, **115**
MEPAG (Mars Exploration Program Analysis Group), 159
Mercury
BepiColombo mission to, 9, 40, 157
crater Shakespeare, 76
habitability results, 47
Mariner 10 flybys, 77
MESSENGER achievements, vi, 20, 27, 40, 47, 72, 77–79, **79**, 89
MESSENGER flybys, 19, 20
MESSENGER impact, 67, 76, 77
MESSENGER objectives, 18
MESSENGER orbit, 1, 16–19, 40, 77
Mercury Dual Imaging System, 110
MERTIS, 157

MESSENGER (Mercury Surface, Space Environment, Geochemistry, and Ranging), v, **xii**
achievements, vi, 20, 27, 40, 47, 72, 77–79, **79**, 89
automated science data acquisition system, 19
beacon mode, 76
Confirmation Assessment Review, 172
costs, 172
cruise phase, 19
development of, 4, 172
end of mission, 67
extended mission, 27, 40–41, 57, 76, **79**
final critical burn, 16–17, 76–77
first extended mission, 77
flybys, **79**
hover campaign, 77
instrument payload, 157
launch, 17, **58**, 172
Mercury impact, 67, 76, 77
Mercury orbit, 1, 17–19, 40, 77
Mercury orbital insertion (MOI), 16, 17, 40
NASA Confirmation Review, 172
orbital maneuvers, 77
planetary flybys, 19, 20, **79**
Preliminary Design Review, 172
Principal Investigator (PI), 18
project management, 37
propellant, 77
published papers, 47
questions that drove XM2, 76
reviews, 172
science objectives, 18
science operations, 18–19
second extended mission (XM2), 76, **79**
selection, **58**, 78
spectrometer, 71–72, 78
staffing levels, 172
System Requirements Review, 172
timeline, 1, 27, 67
turn and burn event, 17
Venus flybys, 78, **79**
meteorites
HED (howardite, eucrite and diogenite), 21, 44, 45, **45**
Martian impacts, **151**
Microdevices Laboratory (JPL), 2
Microsoft Teams, 123
Mikulski, Barbara, 4
Milky Way, 87
Miller, Ed, 100
miracles, 38
mission cadence, vii, 3, 57–58, 66, 92, 97, 103, 112–113, 171–172, 174, 175, 177
mission competitions, vi, 29–30, 65–66, 171–172
mission costs, 172–174
mission lifespans, 173
mission program offices, 66
mission proposals, 176
mission selection, x–xi, 3, 9–10, 12, 42–43, 57, 67, 72–73, 91, 164, 174, 176
Step 1, 38, 69
Step 2, 38, 73, 85–87
missions of opportunity, 28
mission teams, 73
MIT, 174
Mitchell, Karl, 109–110, 138
MMRTGs (multi-mission radioisotope thermoelectric generators), 43, 113
modernization, 176
Mohan, Swati, 145–146
the mole. *See* Heat Flow and Physical Properties Package (HP^3, "the mole")
Moon
Apollo observations, 134
communications delays, 39
GRAIL gravity field map, 47–48, **48**
Oceanus Procellarum (Ocean of Storms), 43
Sally K. Ride Impact Site, 48
seismometers, 101
MoonKAM (Moon Knowledge Acquired by Middle School Students), 24, 43–44
Morowitz, Harold, 135
multi-mission radioisotope thermoelectric generators (MMRTGs), 43, 113
Mutch, Thomas A. (Tim), 133–134

N

Naderi, Firouz, 61, 82

Nancy Grace Roman Space Telescope, 33
NASA Authorization Act of 2005, 62–63
NASA-ISRO Synthetic Aperture Radar (NISAR), 158
NASA Solicitation and Proposal Integrated Review and Evaluation System (NSPIRES), 9
NASA Transition Authorization Act of 2017, 96–97
National Academies of Sciences, Engineering, and Medicine, 29–30, 91
National Academies Planetary Science and Astrobiology Decadal Survey (Decadal), 29–30, 85, 112, 131–132
  2003 Decadal (*New Frontiers in the Solar System: An Integrated Exploration Strategy*), 91
  2011 Decadal, 66
  2013 Decadal (*Vision and Voyages for Planetary Science in the Decade 2013–2022*), 91–92
  2023 Decadal, 177
National Aeronautics and Space Administration (NASA)
  appropriations, xi, 57–59, 65–66, 84
  Artemis program, 43
  authorizations, 62–63, 96–97
  bureaucracy, 71
  C-175 process, 60
  Chief Scientist for Mars Exploration, 134
  comet missions, 16, 34–37
  cost management, 77–78
  culture of optimism, 173
  Discovery Program. *See* Discovery Program
  Draft AOs, 112–113
  Environmental Management Division, 6
  executive review process, 28
  extended missions, 28, 50
  Faster, Better, Cheaper initiative, 4, 5
  funding, 3, 4, 50, 57–59, 65–66, 84, 96–97, 113, 159, 163–164, 170, 174–177
  Human Space Flight Program, 43
  Independent Review Boards (IRBs), 146
  Inspector General, 175
  international partners. *See* international collaboration
  Mars missions, 2–3, 5–6, 10–12, 32, 41–43, 65, 96–97, 111, 170, 175
  Mars Surveyor program, 5
  mission cadence, 3, 92, 175
  mission competitions, vi, 29–30, 65–66, 171–172
  mission failures, 172
  mission rejections, 32
  mission selection, 42–43, 57, 72–73, 164, 176
  missions of opportunity, 28
  mission success enhancements, 172
  New Frontiers Program. *See* New Frontiers
  New Millennium Program, 11
  nuclear missions, 6–8
  office locations, 66
  Office of International and Interagency Relations (OIIR), 60
  Office of the Inspector General, 60
  Phase A studies, 72, 73
  Planetary Defense Coordination Office, 105
  planetary missions, x–xi, 32, 50, 65–66, 72, 73, 77, 93, 96–97, 113, 170, 171, 173, 175
  Planetary Missions Program Office, 57
  pre-proposal conferences, 113
  professional review committees, 73
  proposal development, 176
  Psyche Independent Review Board report, 145
  Psyche site visit, 90
  reorganization, 65–66
  restructuring, 65–66
  sample collection missions, 16
  Science Mission Directorate. See Science Mission Directorate (SMD)
  Strategic Plan, 66, 112
  strategic planning process, 29–30
  telework environment, 123
  timeline, 57
  Venus missions, 134–135, 140–141, 156, 158, 176

VERITAS delay, 157–158
National Institute of Astrophysics, Rome, 98
Nature, 135
Nature Astronomy, 135
Neal, Clive, 113
NEAR (Near Earth Asteroid Rendezvous), xii, 58, 110, 172
Imaging Team, v
launch, 4, **58**
selection, **58**
Near Earth Asteroid 163249 (2002 GT), 50–51
NEOCam (Near Earth Object Camera), 70, 96, 105
NEO Surveillance Mission (NEO Surveyor), 105, 175
Neptune, 109–111, 139
NetLander (France), 62
Neufeld, Michael, 172
neutron spectrometers, 71–72, 78
New, Michael, 6–10, 66, 173
New Frontiers, 2–3, 7, 25
20th anniversary, x
Dragonfly, 96, 156, 175
funding, 96–97
mission cadence, 175
number of missions launched, 171
OSIRIS-REx, 25, 84–85, 92, 136, 156
telework, 123
timeline, 57
Trojan Tour and Rendezvous (TTR), 92
Venus Origins Explorer (VOX), 156
New Frontiers in the Solar System: An Integrated Exploration Strategy (National Academies), 91
New Frontiers Program Office, 65
New Horizons, 7, 91–93, 161
New Millennium Program, 11
The New York Times, 25
Nice model, 94
Niebur, Curt, 123, 176
Niebur, Susan, ix, vi–vii
NISAR (NASA-ISRO Synthetic Aperture Radar), 158
Nittler, Larry, 20
Nixon, Richard, 174
noise, 46
Northrop Grumman, 142, 147
notices of intent, 9
nuclear missions, 6–8

O

Obama, Barack, 8, 65–66
Occator Crater (Ceres), 76, **104**
Oceanus Procellarum (Ocean of Storms), 43
Odom, Brian, vi
office locations, 66
Office of Management and Budget (OMB), 8, 60, 175
Office of Science and Technology Policy, 60
Office of the U.S. Trade Representative, 60
Oh, David, 68–70, 90, 123
Olkin, Cathy, 91–93
Oort Cloud comets, 50
OPAG (Outer Planets Assessment Group), 113
Opportunity (Mars Exploration Rover), 31–32
opportunity, missions of, 28
optimism, culture of, 173
Orus (asteroid 21900), **95**, **115**
OSIRIS, 25
OSIRIS-REx, 25, 84–85, 92, 136, 156
Outer Planets Assessment Group (OPAG), 113
outreach in education, 24
overflow conditions, 51
Oxford University, 59

P

Palo Alto, California, 90
Palomar Observatory, 167
Patel, Keyur, 61
Pathfinder. *See* Mars Pathfinder
Patroclus-Menoetius (asteroid 617), **95**, **115**
Perseverance, 177
Persinger, Randy, 139
personal protective equipment (PPE), 127
Peterson, Colin, 106
PFRs (Problem/Failure Reports), 153
Phase A contracts, 73
Phase A studies, 72, 73

Philae (European Space Agency), 28, 36
Phoenix lander. *See* Mars Phoenix Lander
Pike, Tom, 2
Planetary Defense Coordination Office, 105, 175
planetary missions
  cost caps, 171
  flagship, 175
  funding, 50, 65–66, 96–97, 113
  "last bus out" syndrome, 170
  Phase A, xi, 32, 65, 72, 73
  Phase B, xi, 65, 96
  Phase C, xi
  Phase D, xi
  Phase E, xi, 93, 173
  Phase F, xi
  selections, 96
  techniques, 77
  typical life cycle, x–xi
Planetary Mission Senior Review, 89, 131
Planetary Missions Program Office (PMPO), 57, 65–66, 72–73
Planetary Protection Review, 32
Planetary Science Advisory Committee, 159
Planetary Science and Astrobiology Decadal Survey (National Academies), 29–30, 85, 112, 131–132
  2003 Decadal (*New Frontiers in the Solar System: An Integrated Exploration Strategy*), 91
  2011 Decadal, 66
  2013 Decadal (*Vision and Voyages for Planetary Science in the Decade 2013–2022*), 91–92
  2023 Decadal, 177
Planetary Science Directorate (JPL), 153, 174–175
Planetary Science Division (PSD)
  Announcement of an Announcement of Opportunity, 112
  appropriations, xi, 84
  budget, 8, 83, 157
  Director, v, 134
  mission selection, 73
Planetary Science Institute, 135
Planetary Society, 76, 84, 159
Pluto, 18, 77, 91, 158, 161
Plutonium-238 (Pu-238), 6–7, 42–43, 84, 181–182n43
PMPO (Planetary Missions Program Office), 57, 65–66, 72–73
Point Rest State (PRS), 54
Polanskey, Carol, 68, 159–160
politics, 29
Polymele (asteroid 15094), **95**, **115**
PowerPoint, 101
Praesepe (Beehive cluster), 105
President's Budget Request, 156–157, 175
Price, Humphrey "Hoppy," 39, 43
primitive bodies, 15
principal investigators (PIs), 4, 32, 171
private funding, 174
Prockter, Louise, v–vii, 109–110, 113, 122, 138–140
Pro Flight System (DAVINCI), 136, 166
Project Chief Engineer role, 153
project management, 4, 61
propellants, 77
Proxemy Research, 11, 38
PSD. *See* Planetary Science Division
Psyche (asteroid), 159–160
Psyche (mission), v, **xii**
  ATLO: Assembly, Test, and Launch Operations, 153
  Christmas party (2021), 143–144, 153
  Cognizant Engineer for Guidance, Navigation, and Control, 153
  Concept Study, 85–87, 90
  cost overruns, xi
  COVID pandemic, xi, 123–125, 127
  Critical Design Review (CDR), 144
  cruise phase, 159–160
  Deep Space Optical Communications (DSOC), 167–168
  development, 114–115, 143
  Developmental PFRs (Problem/Failure Reports), 153
  endmember hypotheses, 86, **86**
  engineering staff, 152–153
  first scheduled science, 173
  full-cruise mode, 168
  funding, 70, 85, 103

Gamma Ray and Neutron Spectrometer team, 167
goals, 96
Guidance, Navigation, and Control (GNC), 143–146, 153
imagers, 124–125
Independent Review Board (IRB), 145, 146, 151–154
instruments, 123–125
key decision points, 85
launch, **58**, 96, 145–146, 151–152, 155, 158–160
objectives, 86–87, 159–160
PFRs (Problem/Failure Reports) against flight articles, 153
Phase D, xi
preliminary design review (PDR), 114
Project Chief Engineer, 153
project management, 145, 153
proposal, 67–70, 85–87
propulsion system, 114, 163, 168
revival, 151–154
selection, **58**, 70, 91, 94, 96, 134, 156
site visit, 90
solar propulsion system, 85–86, 163, 168
spectrometer, 68–69, 71–72, 124–125
Standing Review Board, 114
supply chain issues, 124–125
"Taters the Cat" video, 155, 167–168
team philosophy, 69
thruster operations, 169
timeline, 91, 145, 155, 163, 169
Verification & Validation process, 153

Q

Queta (satellite), **115**
Quintana, Elisa V., 64

R

radiation pressure, 54
radioisotope generators
advanced. *See* Advanced Stirling Radioisotope Generators (ASRGs)
multi-mission radioisotope thermoelectric generators (MMRTGs), 43, 113
thermoelectric, 6, 7
Rayman, Marc D., 22, 23, 44, 45, 74, 76, 97
Raymond, Carol, 21, 22, 45
reaction control jets, 22
reaction wheels
Dawn, 22, 27, 45, 91, 97
Kepler, 27, 46, 49, 53–55, 88
Reagan, Ronald, x, 158
Reddit, 88
red dwarfs, 50
remote work, 121, 123, 127, 138, 152, 153
Rheasilvia (Ceres), 44
Ride, Sally, 24, 44, 48
robotic missions, cost-capped, 77–78
Rocket Lab, 174
Rosetta (European Space Agency), 28, 36
Russell, Chris, 22, 74, 88
Russia, 7, 62

S

Sagan, Carl, 135
Sally K. Ride Impact Site (Moon), 48
Sally Ride Science (University of California San Diego), 44
sample collection missions, 16
Sandia National Labs, 71
San Juan Capistrano Research Institute, 3, 4
SARS CoV-2 virus (COVID), 121
satellites
binary, 162
CubeSats, 107, 154, 156
Lucy Level 1 requirements, **95**
Queta, **115**
Selam, **115**, 161, 162
Saturn, 7, 11, 13, 37
Saunders, Mark, 171–173
Savannah River Plant (DOE), 7
Scheeres, Dan, 154
Schmitt, Harrison "Jack," 71
Schultz, Peter, 13
science, v–vi
Science, 47, 64
Science Goals Document Writing Committee, 30
Science Management Council, 7–9
Science Mission Directorate (SMD)
Astrophysics Division, 8, 62–63, 171

Earth Science Division, 8, 158, 171
mission selection, 12, 42–43, 73, 96, 164
Planetary Science Division (PSD), xi, 8, 73, 83, 84, 112, 134, 157
Program Management Council, 146
Science Management Council, 7–9
Science Office for Mission Assessments (SOMA), 6, 10
science traceability matrix (STM), 30–31
Seismic Experiment for Interior Structure (SEIS), 11, 41, 59–62, 81–85, 98–99, 101–103, 107–108, 148–150, 151
seismometers
astroseismology, 106
deployment on Mars, 103, 107–108
InSight, 11, 41, 59–62, 81–85, 98, 99, 101–103, 107–108, 148–150, 151
short-period, 59
VBBs (very broadband), 59, 61, 62, 84, 107
Viking, 101
Sekerak, Michael (Mike), 142, 147, 166
Selam (moonlet satellite), 115, 161, 162
Shakespeare crater (Mercury), 76
Shultz, Pete, 14
Siegler, Matthew, 47
SIMPLEx (Small Innovative missions for Planetary Exploration), 175
Sky & Telescope, 135
Small Deep Space Transponders, 123–124
Small Innovative missions for Planetary Exploration (SIMPLEx), 175
small missions, 171
SMD. *See* Science Mission Directorate
Smrekar, Sue
InSight, 11, 99–100, 117
VERITAS, 122, 155–157, 159, 164, 165
Sodern, 59–62, 81
SOIR, 157
solar electric propulsion, 85–86, 163, 168
solar flares, 46
solar power, 113
solar system
habitable zone, 111
images of, 78, **79**
Nice model, 94
Solar System Exploration Division (Goddard), 134
Solar System Exploration Program, 57, 65
Solomon, Sean
lessons learned from, 139
MESSENGER, 17, 18, 47, 76, 78, 79, 110
Planetary Mission Senior Review, 131
Southwest Research Institute (SWRI), 4
Johanson visit, 170
Lucy, 70, 92–93, 127
Soviet Union, 134
spacecraft
command and control of, 52
Discovery fleet, 173
fault management software, 51
spaceflight, continuous, 26
Space Race, 170
Space Systems/Loral (SSL, later rebranded as Maxar), 68, 85–86, 90
spectral Earth model, 52, **52**
spectrometers
CUVIS (Compact Ultraviolet to Visible Imaging Spectrometer), 136
gamma ray and neutron, 68–72, 124–125
MESSENGER, 71–72, 78
neutron, 71–72
Psyche, 68–72, 124–125
VEM (Venus Emissivity Mapper), 156
VMS (Venus Mass Spectrometer), 136
VTLS (Venus Tunable Laser Spectrometer), 136
Spirit (Mars Exploration Rover), 31–32
Spohn, Tilman, 100, 132
Srinivsaan, Meera, 167
staffing levels, 152–153, 172
Stand Alone Missions of Opportunity (SALMON), 8
Stanford University, 134
Stardust, **xii**, 4, 8, 11, 23, **58**, 59, 183n72
Stardust-NExT (New Exploration of Tempel), 1, 8, 12–16, **15**, **58**
steering committees, 10
Steffen, Jason, 54, 63, 88
Stern, Alan, 177
Stirling, Robert, 6–7
Stofan, Ellen, 11, 38, 135

Stone, Henry, 145–146
Strategic Plan (2014), 66
strategic planning, 29–30, 170–177
Strofio, 9
Sunshine, Jessica, 140, 176
  Comet Hopper, 11, 33–37
  Deep R, 27–29
  leadership lessons, 34, 36–37
  Lucy, 161
supernovae, Type Ia, 64
supply chain issues, 124–125
survey orbits, 74
Switzerland, 117

T

"Taters the Cat" video, 155, 167–168
Tatooines, **106**
Taurus-Auriga star-forming region, 106
teamwork, vi, 5, 33, 34, 36–37, 73
Team X (Advance Mission Design Group), 100
technical, management, and cost (TMC) risk evaluation, 9, 72–73
Technical University of Denmark, 123
telework, 121, 123
Tempel 1 (comet), 1, 8, 14
  Deep Impact/EPOXI observations, 28, 29, 52, **52**
  Stardust-NEXT Achievements, 12–15, **15**
Thruster-Controlled Safe Mode (TCSM), 53
TiME (Titan Mare Explorer), 11, 37–39, 42
timeline, 1, 27, 49, 57, 67, 91, 103, 109, 121, 131, 145, 155, 163, 169
Titan, 171
Titan Mare Explorer (TiME), 11, 37–39, 42
Trident, v, vi, 109–113
  proposal, 122, 138–140
  timing, 174
Triton, 109–111, 122, 138–140
Trojan asteroids (Jupiter), v, 70, 91, 94–95, **115**, 170
Trojan Tour and Rendezvous (TTR), 92
Trump, Donald, 96–97, 122–123
TTR (Trojan Tour and Rendezvous), 92

U

UAI (Use As-Is) teams, 142
United Launch Alliance (ULA)
  InSight, 84, 103–104
  Lucy, 114, 141
United States Congress, 105
  budget, 8, 84, 174–175
  Consolidated Appropriations Act for 2014, 57–59
  NASA Transition Authorization Act of 2017, 96–97
United States Department of Energy, 7
United States State Department, 60, 197n10
University of Arizona, 122
University of California, Los Angeles (UCLA), 68, 123
University of California San Diego, 44
University of Maryland, 33, 126
U.S. Air Force Research Laboratory, 25
Use As-Is (UAI) teams, 142
Utah Test and Training Range, 13, 166–167
Utopia Planitia (Mars), 1

V

Valles Marineris (Mars), 32
Vandenburg Air Force Base, 84, 103–104
VASI (Venus Atmospheric Structure Investigation), 136
VBBs (very broadband seismometers), 59, 61, 62, 84, 107
VD57 (asteroid 152830 1999), 155
VEM (Venus Emissivity Mapper), 156, 157
VenDI (Venus Descent Imager), 136
Veneneia (Ceres), 44, 45
Venus
  DAVINCI (Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging), v, **xii**, **58**, 69, 122, 131, 133–138, 140–141, 158, 164, 165–167, 169, 175
  landing panoramas, 134
  Magellan observations, 134
  Mariner 10 images, 77
  MESSENGER flybys, 19, 78, **79**
  simulation, 165–167

VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy) mission, v, xi, **xii**, **58**, 70, 122, 131, 140–141, 154–159, 164–165, 169, 175
Venus Atmospheric Structure Investigation (VASI), 136
Venus Descent Imager (VenDI), 136
Venus Emissivity Mapper (VEM), 156, 157
Venus Exploration Analysis Group, 165
Venus Express (ESA), 78, **79**, 157
Venus Imaging System for Observational Reconnaissance (VISOR), 136, 166
Venus Interferometric Synthetic Aperture Radar (VISAR), 156–157
Venus Life Finder, 174
Venus Mass Spectrometer (VMS), 136
Venus missions, 134–135, 140–141, 156, 158, 176
Venus Orbital Imaging Radar (VOIR), 158
Venus Origins Explorer (VOX), 156
Venus Tunable Laser Spectrometer (VTLS), 136
VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy), **xii**
  Concept Study Report, 122
  development, v
  engineering support, 164–165
  foreign partners, 158, 165
  funding, 70, 122, 159, 163, 164
  key instruments, 156
  launch date, v, 154–159, 164–165, 169, 175
  Phase B, xi
  restoration, 164
  science goals, 141, 156
  science support, 164–165
  selection, **58**, 70, 122, 131, 140–141, 155–157
  spacecraft, 157
  support for, 159, 164
  timeline, 155, 163, 169
  trajectory, 165
  two-instrument payload, 157
Vesper, 25
Vesta (asteroid), 20–23, 27, 44, 45, **45**, 76, 88–89, 105
Veverka, Joseph, 13–15, 27, 28
VH (asteroid 35107 1991), 154
Viking, 1, 31, 39, 101, 170
Viking Program, 133, 134
VISAR (Venus Interferometric Synthetic Aperture Radar), 156–157
Vision and Voyages for Planetary Science in the Decade 2013–2022 (National Academies), 91–92
VISOR (Venus Imaging System for Observational Reconnaissance), 136, 166
VMS (Venus Mass Spectrometer), 136
VOIR (Venus Orbital Imaging Radar), 158
VOX (Venus Origins Explorer), 156
Voyager, 7, 158, 174
Voyager 2, 111
VTLS (Venus Tunable Laser Spectrometer), 136

W

Wagner, Tom, 140
Wallops Flight Facility, 126
Washington, DC, 66
The Washington Post, 74
Webex meetings, 145, 146
Weiler, Ed, 7, 16, 17, 78, 177
Weiss, Benjamin (Ben), 123, 160
Wenkert, Daniel, 67–68
WFIRST (Wide Field Infrared Survey Telescope), 33
Wild 2 (comet 81P/Wild), 11, 13, 15
workplace culture, 153
World Health Organization, 121, 122–123
Wuhan, China, 121

X

X-band communications, 123–124
XM2, 76, **79**

Y

Y2K problems, 51
Young, A. Thomas, 5, 146, 152

Z

Zoom, 123
Zuber, Maria, 17, 23–26, 40, 43, 44, 48, 69
Zurbuchen, Thomas, 40, 93, 107, 140, 146, 153–154



Velocity and audacity defined the Discovery Program when it emerged in response to limited flagship mission opportunities and budget uncertainty in the 1990s. Designed for focused, low-cost planetary exploration, Discovery marked a shift from traditional directed missions.

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The Discovery Program's accomplishments are nothing short of extraordinary, from landing on an asteroid, to revolutionizing our understanding of exoplanets, and returning comet samples to Earth. This program's unique history is now captured here.

On the Cover: (Front) Mars as seen by NASA's Psyche spacecraft during its gravity assist maneuver in May 2026. Credit: NASA/JPL-Caltech/ASU. (Back) View of Mercury as seen by NASA's MESSENGER spacecraft. Credit: NASA/JHU-APL/Carnegie Institution of Washington.

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