

Space Science and Astrobiology

Strategic Plan 2019



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Division Vision Statement

Provide science leadership and stewardship that enhances and enables the NASA community to make new scientific and technical discoveries, thus assuring the success of NASA's strategic goals and space missions.

Division Mission Statement

The Space Science and Astrobiology Division will continue to provide interdisciplinary core scientific expertise and capabilities that advance NASA's goals and our understanding of the Universe.

The Division's strategic approach will focus on enabling long-term investments in our core scientific research areas. Our unique expertise will advance the Community's science knowledge while driving innovative technology and instrument concepts. The Division will pursue primary leadership roles in NASA missions and mission support activities, based on our current capabilities in the following key strategic focus areas:

- Life Detection Research and Technology
- Mission Driven Analog Research and Mission Concept Operations
- Radiative Transfer Modelling
- Laboratory Astrophysics Research
- (Exo)planetary Formation, Evolution, Characterization, and Technology Studies

The Space Science and Astrobiology Division

The Space Science and Astrobiology Division at NASA Ames Research Center (ARC) provides unique interdisciplinary scientific expertise and capabilities that advance human understanding of the Molecular Evolution of Galaxies, the Evolution and Formation of Planetary Systems and our Understanding of the Origin and Evolution of Life in the Universe. Our core science capabilities in theoretical, observational, experimental, and instrument development work enable NASA missions and are focused to enhance and enable the science and exploration goals of NASA and the scientific community.

The Division's scientific breadth and expertise provide the Agency with a unique interdisciplinary workforce utilizing multidisciplinary teams of astronomers, astrophysicists, chemists, microbiologists, physicists, and planetary scientists and are organized into three core science areas:

Astrophysics: Researchers study the physical and chemical properties of astronomical phenomena by observing their radiation at optical, infrared and ultraviolet wavelengths,

Planetary Systems: Researchers acquire new, fundamental knowledge about the origins of stars and planetary systems, their evolution and formation, and astrobiology.

Exobiology: Researchers study the history, distribution, and chemistry of biogenic elements in the solar system; prebiotic chemical evolution and the origin of life; and the history of Earth's early biosphere as recorded in microorganisms and ancient rocks.

Foundations and Approach of the Strategic Plan

A strategic plan is an organization's process of defining its strategy and direction, as well as setting priorities on making decisions and allocating resources. A strategic plan also extends to control mechanisms for guiding the implementation of the strategy. It is not a science paper, proposal or an implementation plan, but a forward-looking positive document capturing the ideas, goals, and objectives of the people involved. The 2019 strategic plan has again taken a bottoms-up approach. "Tiger Teams" were formed and given the charter to self-organize and report on specific but broad science core capabilities within the Division while one additional team investigated administrative support within the Division. Teams were told to concentrate on the future while seeking to align their core areas with NASA's goals and missions. Each team produced a white paper on their core subject area, that is, what are we leaders in across the Agency and community, and what work should be accomplished over the next 1, 5, and 10 years.

The Division next held an all-day retreat in which 90+ members participated, roughly two-thirds of the Division. At the retreat, each "Tiger Team" was challenged with taking their white paper report and distilling it into a small number of slides (five) to present – concentrating on high level Objectives, Milestones, Core Capabilities, alignment with NASA's goals, and what mission and mission support work would be accomplished. The bulk of this strategic plan stems from the white papers and associated presentations from the Division retreat.

Strategic plans, by definition, describe a vision for the future. They also represent a set of objectives built on an organization's recognized expertise. The focus of the ARC Space Science and Astrobiology Division's strategic plan is on the world-class core capabilities built up over decades. A vital commitment of the Division is to harness these capabilities in the service of the Agency – and to maximize the scientific return from NASA's flight missions. Division scientists will continue to serve on competitively-selected Science Teams for projects and programs external to ARC. They will continue to develop the technologies needed to enable new advances in planetary sciences, astrophysics and astrobiology. They will continue to conduct impactful science research that will frame future scientific inquiry, aid the community, and define the requirements for future NASA missions.

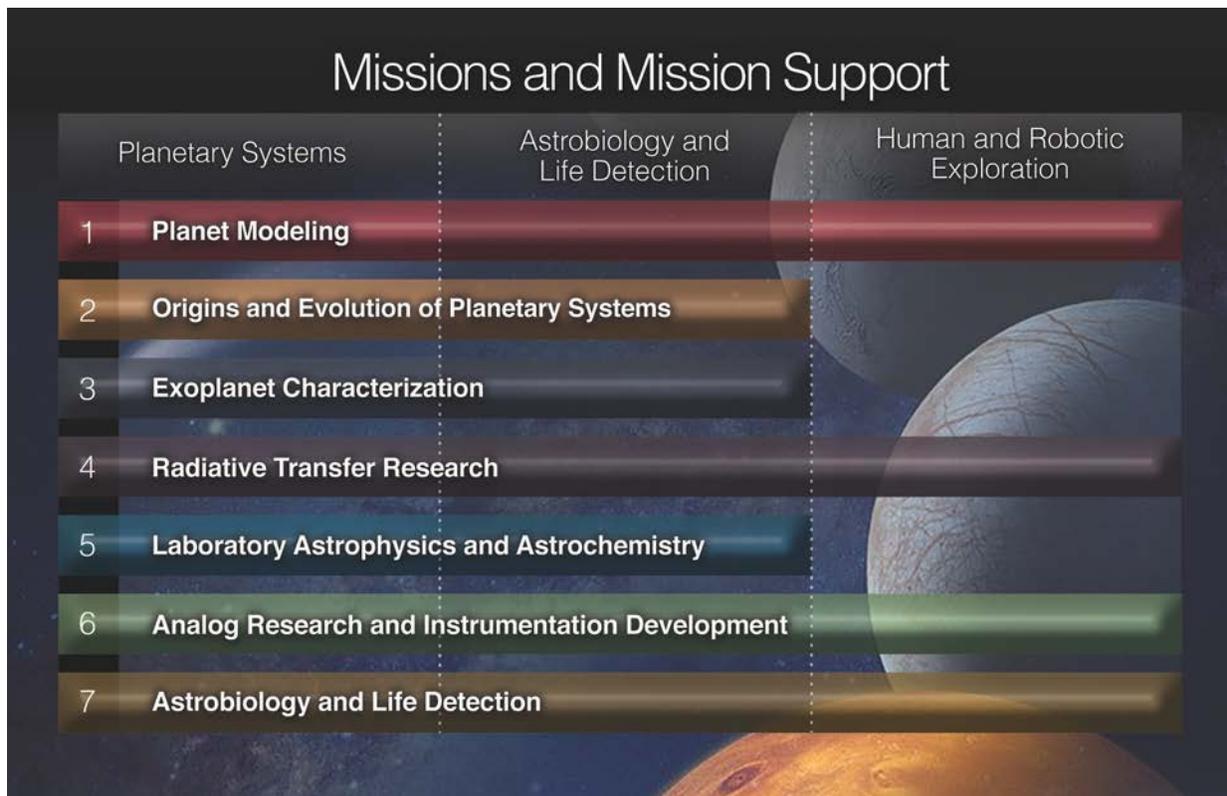
The Division is committed to devoting its resources and expertise to ensuring a successful science return from the *Stratospheric Observatory for Infrared Astronomy (SOFIA)*, working closely with the prime science and mission operations contractor, the Universities Space Research Association. Additionally, it will provide scientific leadership (and science payloads) for lunar missions as well as ground-based and mission support for the next generation of planetary and exoplanet space missions.

The Divisions' scientific and administrative visions have been collected here. We have organized the plan into "Core Capabilities of Excellence" within the Division with a view to provide core science capabilities to the Agency. Ames scientists within the Division often work in one or more of the core scientific areas, as they are spread across Branches, Divisions, and even NASA Centers. This is a living document that should be reviewed and modified on a yearly basis. The milestones listed for each core research area should serve as metrics by which to judge the progress and efficacy of this plan as well as providing signposts for change. We set down here our 2019 strategic plan for the next decade, laying out our hopes and dreams as we reach for the stars.

This document is available from the Space Science and Astrobiology Division office or on our website: <https://www.nasa.gov/content/space-science-and-astrobiology-ames>

Steve B Howell

Chief, Space Science and Astrobiology Division
NASA Ames Research Center, May 2019



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The Role of a NASA Scientist: Missions & Mission Support

Our Division believes that the role of a NASA scientist at a field center is to perform work which is aligned with the Agency and community needs and focused on areas of research that are consistent with NASA's strategic plans and targeted at missions and mission support. Likewise, the Agency needs to maintain a robust corps of scientists to carry out its mission. An essential role of these scientists is to perform the functions required to enable and ensure successful space flight missions. They contribute to long term mission-focused research, developing new techniques and technologies that are needed to achieve NASA's research priorities and perform work which the community is ill-equipped or not well-suited to accomplish. Additionally, they work with and for NASA Headquarters in the development of planning, proposal review, and many other service functions and are often the primary interface with the community in regards to space-based research. Scientists who work for NASA as civil servants put NASA's and the communities' needs above their own scientific stature.

In order to have high credibility within these communities, NASA scientists at Field Centers must be regarded as leaders and experts by their peers in the scientific community. This requires that they be practicing scientists who fully participate, along with their university- and industry- based peers in the scientific process. ARC scientists have and continue to provide long-term and deep commitments to NASA science taking on the roles of Mission Scientists, Project Scientists, scientists serving on missions as team members and on instrument teams, scientists spending their careers enabling the community to fully exploit mission data, scientists at the forefront of theory, modeling, and instrumentation, scientists working in study groups for future space missions, and scientists performing cutting edge ground-based observations in support of space missions.

This strategic plan outlines the Division's core scientific capabilities, each directly aligned with a methodology and purpose which exemplifies our role as NASA scientists. Everything we do is directed toward the goal of enabling successful NASA missions and to provide the community insights, tools, data products, and help in order to achieve the highest quality results from space missions. ARC has had a long history of such service work, and while we currently do not have large missions nor are we likely to get them again, the value of ARC scientists to missions and mission support success should not be viewed as unnecessary or of little use. Independent assessments, unique expertise and tools, cross-disciplinary teams, and a willingness to get involved for the good of the Agency are shared attributes within the Space Science and Astrobiology Division. The Core Capabilities discussed within tell our story, we hope you too can see the value and unique assets available to the Agency within the Space Science and Astrobiology Division at Ames Research Center.



Planet Modeling

Synergies matrix: Exoplanets, Solar System Bodies, Exobiology, Astrophysics

Partner matrix: Code T, Earth Science, JPL, Ames Supercomputer

Missions supported: HST, SOFIA, JWST, WFIRST, FINESSE, Europa, STARDUST, ROSETTA, OSIRIS-Rex, New Horizons, Juno, Cassini

Core Capability 1: Planet Modeling

The goal of performing computer simulations of natural phenomena in a planetary environment is to define what processes and conditions are necessary for such phenomena to take place, based on existing remote sensing and in situ observations. How accurately the observations can be replicated within the simulation is dependent on the extent to which the construction of the model is grounded in the relevant physics and chemistry, and to which the physical parameters in the simulation are constrained. The last few decades have witnessed great advancement in the complexity and spatial resolution attained by models that simulate atmospheric, landform, and geochemical processes. While this field is constantly evolving, it is presently directly and centrally applicable to a range of strategic NASA goals and provides essential guidance in the development of upcoming planetary missions and associated technologies. The synergistic relationship that exists between atmospheric, landform, and geochemical modeling strengthens each of them beyond what any one is capable of alone. Computer modeling of these processes fundamentally contributes to planetary research at NASA ARC and to NASA's science vision, in general.

2018 Highlight Accomplishments

Development of a Pluto/Triton global climate model (GCM)
Bertrand et al., 2018, 2019

Venus thermospheric GCM now includes planetary waves and a non-uniform lower boundary - Brecht et al., 2018
Geochemical models of early Mars have been enhanced based on mineralogical analysis by MSL -Bristow et al., 2018

Use of color imaging to estimate water ice abundance in Martian regolith and advanced (radiative transfer reflectance code that includes emission by fluorescence and Raman scattering – Dobrea, Gyalay et al., 2019

Deciphering the nature and origins of landforms in the Pluto system: Pluto's bladed terrain (Moore et al., 2018), Pluto's washboard and fluted terrain (White et al., 2019), and Charon's smooth plains (Beyer et al., 2019)

Formation mechanisms examined for the formation of spiked and bladed textures known as penitentes in the equatorial regions of Europa, of significance for any future lander targeted there – Moore, Orkan, Hopley et al., 2018)

The Ames Stereo Pipeline is being used to generate stereo topography of Ultima Thule

Objective 1.1 – Atmospheric and Global Climate Modeling (GCM)

The primary goals of Planetary Atmospheric and Global Climate Modeling (GCM) are to isolate, quantify, and understand physical processes (**Figure 1.1**) that control current and past (i.e., paleo-) atmospheric thermal, chemical, and dynamical states of solid-surface bodies with atmospheres in our solar system, and to investigate how these processes have controlled the evolution of atmospheres/climates over time. Additionally, these processes are compared from one solid-surface planetary body to another. Key to this enterprise is utilizing scientific expertise in atmosphere/climate studies, the vast experience within the Agency Mars Climate Modeling Center (MCMC), and the local high-end computing (HEC) capabilities established at NASA ARC. Modern geophysical fluid dynamics (GFD) global computational frameworks will be leveraged at high spatial resolutions that are highly scalable on massively-parallel HEC architectures. The investigations will include examining the interaction between planetary atmospheres, their surfaces, and the solar environment, and how the evolution of planetary atmospheres can be conducive for habitability. To date, the primary focus within the Planetary Systems Branch and the Space Science and Astrobiology Division has been toward terrestrial-like (i.e., solid surface) planets with significant atmospheres in our solar system as well as the Moon's exosphere. Over the next five years, the investigations will be broadened to cover newly discovered exoplanetary atmospheres and their climates.

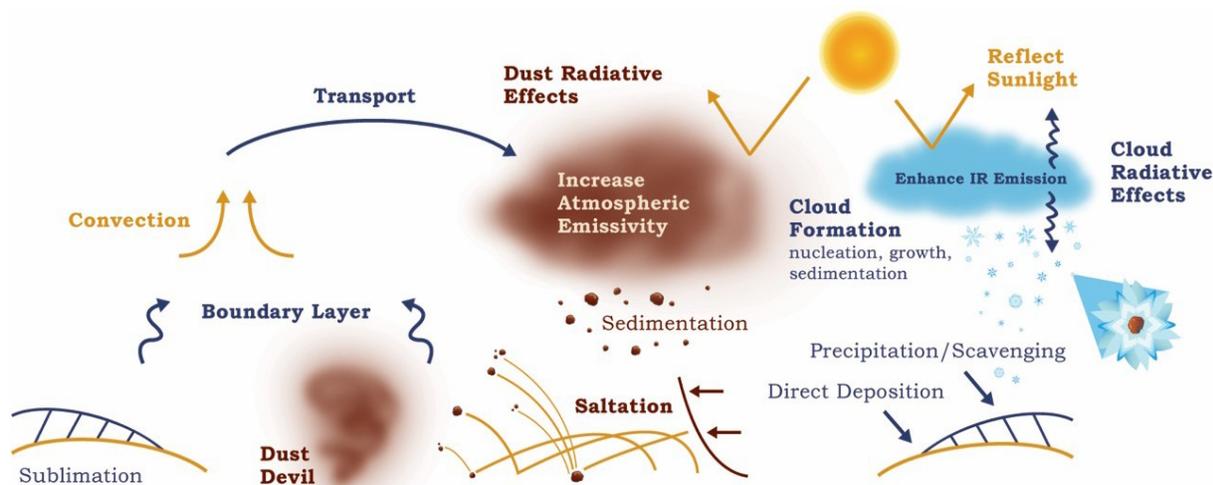


Figure 1.1: A depiction of the major processes influencing Mars' lower atmosphere. Each of these processes are handled within the NASA ARC Mars GCM. Most of these physical processes occur in other planets'/satellites' atmospheres as well.

Objective 1.2 – Geochemical and Spectroscopic Modeling (GSM)

The primary goal of geochemical and spectroscopic modeling (GSM) studies at ARC is to reconstruct ancient physicochemical conditions in near-surface environments in order to identify the characteristics and distribution (both temporally and spatially) of potentially habitable solar system environments and assess their astrobiological potential. This approach utilizes remote- and ground-based observations of the chemistry, mineralogy and geological context of planetary materials and surfaces, and is a crucial activity in the search for evidence of life beyond Earth. The constraints obtained from GSM studies provide important inputs and conditions, and are thus synergistic with the LEM and GCM efforts.

The quality of predictions and output of geochemical models depend on three key aspects: 1) reliable input parameters (observations), 2) use of appropriate thermodynamic and kinetic datasets, and 3) appropriate scaling of model complexity based on the information at hand and the problem being addressed. The approach to enhancing ARC GSM capabilities and supporting the goal of assessing astrobiological potential in the solar system promotes all three of these aspects, involving development of

space-flight instrumentation designed to catalogue mineralogy and geochemistry; curation of mineralogical standards and astrobiologically relevant analogues and materials; and establishment of a database of these materials with detailed mineralogical and geochemical information and supporting thermodynamic and kinetic information. There exists here a strong connection with the Analog Research capability.

Objective 1.3 – Landform Evolution Modeling (LEM)

The goal of Landform Evolution Modeling (LEM) is to simulate the evolution of planetary landscapes through multiple, concurrent, interacting geological processes (e.g., wind, rain, impact cratering, weathering, etc.) acting either simultaneously and/or sequentially at different rates upon the terrain (Figure 1.3). The landscapes of worlds with atmospheres are a record of their climate evolution. This makes LEM a very powerful tool for planetary evolution investigations, as simulation results can be quantitatively compared to observations provided by NASA missions in order to constrain and quantify. 1) The parameter space of an environment in question, such as the compositions and abundances of materials composing the landscape, and atmospheric properties that are necessary to accommodate certain landform evolution processes (e.g., rainfall and runoff, sublimation and condensation of volatiles, etc.); 2) The initial geological and environmental conditions, in particular whether a certain initial topography and subsurface structure (e.g., layered, fractured) is necessary to evolve a landscape into its present appearance; and 3) The identities of the major landform evolving processes that have acted upon the landscape to shape it to its present state, including the rates and episodes at which the processes have been operating. LEM can determine the timescales over which the climatic conditions responsible for these processes have operated, and whether they are episodic, progressive, or cyclical, or some combination.

The value of LEM relies very much on topography modeling (i.e., generation of digital elevation models for a planetary surface using spacecraft data) as it essentially provides the observations by which the products of LEM are judged, in order to identify what parameter space, initial conditions, and process suite produces a final topography that matches what is seen in reality. ARC is where the Stereo Pipeline (NASA's open source automated stereogrammetry software) was created and where the expertise resides within the active planetary topography community. As NASA re-emphasizes the Moon as a target, many opportunities for the modeling of the Moon's topography at meter scales in the circum-polar region have arisen, and application of state-of-the-art shape-from-shading techniques will prove to be an essential and mission enabling skill.

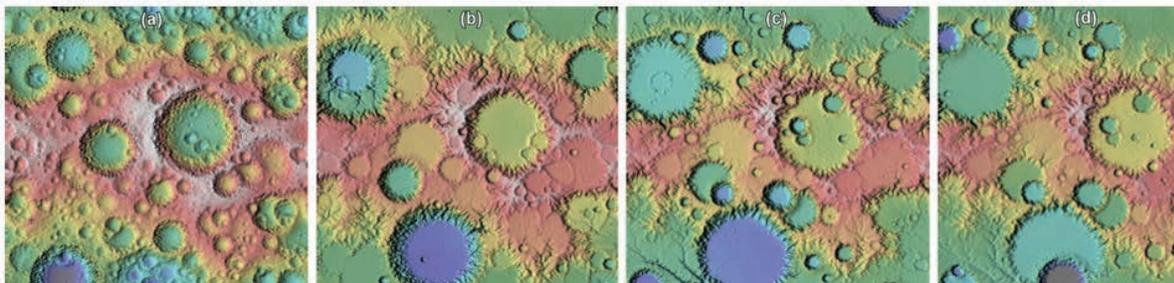


Figure 1.3: Simulated Martian landscape eroded by fluvial processes with ongoing impact cratering. Elevation range is 3000 m. Simulation domain is 102×102 km. Initial conditions, a saturation-cratered landscape, are shown in (a). Simulated elapsed times are 0.26 Myr at (b), 0.40 Myr at (c), and 0.46 Myr at (d).

Objective 1.4 – Establishing an Integrated Planet Modeling Group at ARC

An integrated NASA ARC Planet Modeling effort will provide to NASA and the community a unique and interdisciplinary team with a broad range of expertise not found elsewhere. By fostering close collaboration between separate areas of modeling within ARC and across the Agency, an integrated planet atmosphere and surface modeling group can directly influence the design and priorities of future NASA planetary missions. This core competency will sustain, improve, and create the next generation of NASA science planet models and provide a resource for Agency and community scientists to call upon the abilities and models facilitating the path toward new scientific discovery.

Objective 1.5 – Relevance to NASA Goals and Missions

Planet modeling is a fundamental step towards “Understanding the Sun, Earth, Solar System, and Universe” in Strategic Objective 1.1 of the [2018 NASA Strategic Plan, in particular Strategic Goal 1 “Expand Human Knowledge Through New Scientific Discoveries” for the NASA Ames Research Center, pp. 46–47](#)). Our objectives also address ARC strategic goals 1 and 2 in the 2018 NASA Strategic Plan, specifically to “expand human knowledge through new scientific discoveries” based on the “basic and applied research” that we conduct in “astrobiology and the planetary sciences”, and to “extend continuous human presence deeper into space and to the Moon for sustainable long-term utilization” based on our “work in life, lunar, and planetary sciences”. Our objectives will address the requested capabilities in the level 3 Science Modeling goal (11.2.4) as described in the [2015 NASA Technology Roadmap for Modeling, Simulation, Information Technology, and Processing](#), in that we will “sustain, improve, and create the next generation of NASA science models that will facilitate the path toward new scientific discovery in... Planetary Science”. Planet modeling is directly relevant to the [Space and Earth Science and Astrobiology and Life Science Core Areas of Expertise of ARC](#). In the search for life in the universe, our model results will identify the characteristics and the distribution of potentially habitable environments on Mars and other solar system bodies, and guide the hunt for organic remnants of potential inhabitants. As such, our modeling directly pertains to the topic in the [2015 NASA Astrobiology Strategy](#) of “identifying, exploring, and characterizing environments for habitability and biosignatures”, in particular with respect to determining the astrobiological potential of ancient Mars. Planet modeling constrains the probable range of conditions and materials (surface and atmospheric) that prevail at target sites based on existing remote sensing and *in situ* observations, and so provides guidance for future missions by allowing instrumentation and observation planning to be designed accordingly, e.g. *Mars 2020 rover / Next Mars Orbiter* (GCM, LEM, GSM) & *Europa Clipper* (LEM, GSM). In anticipation of forthcoming NASA-related lunar missions (e.g. *Commercial Lunar Payload Services*), LEM and GSM will yield results on the transport and stability of lunar volatiles that are not only highly relevant to lunar science, but also to *in situ* resource utilization and associated exploration.

Milestones: Planet Modeling

The NASA Ames Planet Modeling effort will provide NASA and the community a unique and interdisciplinary team with a broad range of expertise not found elsewhere, and the totality of which can offer the community science-enabling research products, codes, and databases.

Year 1 (2019)

- GCM: Test and validate the new Mars GCM dynamical core framework for the current Mars climate to understand important cycles in the Mars’ atmosphere (water, CO₂, dust).
- GCM: Incorporate physics packages for early Mars climates into the new Mars GCM framework to explore the potential warming effects of reducing greenhouse gases in the early Mars atmosphere.
- GCM: Analysis of Pluto’s current climate in the light of New Horizons observations.

- GCM: Provide active modeling support to the Mars community and update the engineering-level MARS-GRAM.
- GCM: Develop an exoplanet GCM.
- GSM: Develop radiative transfer modules to establish the theoretical framework and tools needed to support SSW, PDART, and Mars 2020 proposals and laboratory investigations into the geochemical evolution of the surfaces of Mars, the Moon, and Europa.
- GSM: Update spectroscopic and analytical capabilities of the already existing geochemical laboratory in preparation for these investigations.
- LEM: Develop new LEM modules that are applicable to fluid behavior (e.g., dissolution, plastic deformation, and glacial erosion) on Mars, Titan, Venus, and Pluto.

Years 2-5 (2020-2024)

- Organizational: Integrate GCM, LEM, and GSM to establish an Agency core capability for planet modeling.
- Organizational: Establish an organized hiring regime for the LEM and GSM groups, akin to what currently exists for GCM. Necessary skills include programming, interface development, and numerical techniques for model optimization.
- Organizational: Establish a standing working group to gauge how the skills and interests of the GCM, LEM, and GSM groups complement and feed into those of other groups, both within and outside of ARC.
- Organizational: Acquire a VNIR spectrometer, UV spectrometer and refurbished environmental chamber to support spectroscopic modeling.
- Organizational: Ensure a consistent level of funding for topography modeling and the Ames Stereo Pipeline.
- For GSM and GCM, establish a framework and infrastructure for consolidating and publishing web-based, model-relevant databases/libraries and codes.
- GCM: Continue development of the Mars, early-Mars, Mars-like exoplanet, and Venus GCMs in support of missions and understanding the physical processes controlling behavior in the atmosphere and assessing their potential habitability where applicable.
- GCM: Continue development of the Pluto GCM, in particular: haze microphysics, radiative transfer, and solid mixture exchanges modeling.
- GSM: Develop a quantitative model for evaluating the habitability of subsurface environments on Earth.
- GSM: Develop a model for evaluating the habitability of ancient Martian environments encountered in its rock record based upon iron mineralogy and biogeochemistry.
- GSM: Make the Map-X elemental mapping instrument flight-ready.
- GSM: Derive and catalog optical constants for a variety of materials relevant to ongoing efforts in planetary exploration.
- GSM: Extend existing spectral reflectance and thermal emission models to include fluorescence and Raman spectra.
- LEM: Adapt existing LEM modules (in particular cratering processes) to model exhumation, transport, and re-burial of volatile constituents on the Moon, especially at the poles where cold trapping can occur.
- LEM: Fully incorporate the role of flowing ice into the MARSSIM landform evolution model and apply to Mars.
- LEM: Develop a version of MARSSIM that uses GCM results to predict global sand flow on Mars and explain the location of sand seas.
- LEM: Examine various scenarios involving ammoniated creeping water ice and its capacity to form cryovolcanic flows on icy satellites such as Charon and Ariel.
- LEM: Adapt MARSSIM to make it more accessible to the wider planetary geomorphology community, including constructing a graphical user interface.

Years 6-10 (2025+)

- Organizational: Provide a path towards tenure for promising scientists as civil servants, while concurrently hiring recognized civil servants from elsewhere.
- GCM: Adapt existing GCM capabilities for multiple planetary bodies (e.g. Triton and exoplanets), while continuing previous science and development of the existing GCMs.
- GSM: Develop a quantitative model framework to characterize the environmental conditions and habitability of past planetary environments using observations of the chemistry and mineralogy of crustal materials.
- LEM: Develop a version of MARSSIM that simulates the interaction of water condensation/sublimation, dust deposition, and climate to explain the age, distribution, and physicochemical properties of the extensive mid-latitude mantles and pasted-on terrain on Mars.
- LEM: Couple climate history models of precipitation and evaporation on Mars and Titan to MARSSIM hydrologic and runoff routines to explain the distribution of valleys and related landforms on these worlds.
- LEM: For Pluto, couple atmospheric circulation and atmosphere/surface condensation and sublimation with glacial flow to model the evolution of Sputnik Planitia and its surroundings. Additionally, develop and implement models of bedrock erosion by moving N₂ ice and evaluate the sculpting of ancient glaciated valleys and features.



Origins and Evolution of Planetary Systems

Synergies matrix:

Characterization – instrumentation, exobiology, habitability
Planet modeling – radiative transfer, USGS
Planet systems - NAS

Partner matrix: Code T, GSFC, JPL, NASA
Exoplanet Archive

Missions supported: Kepler, K2, TESS, HST, SOFIA, JWST, WFIRST, FINESSE, 2020 missions, Europa, CORSAIR, Lucy, STARDUST, ROSETTA, OSIRIS-Rex, New Horizons, Juno, Cassini, Mars Missions

Core Capability 2: Origins & Evolution of Planetary Systems

Observations from Earth and space continue to demonstrate that planet formation is a poorly understood process leading to diverse outcomes, and that the protoplanetary disks in which planets form are both common and varied. Given the many future missions (e.g., SOFIA, ALMA, TESS, JWST, FINESSE, Origins, LUVOIR) focusing on star and planet formation, missions to satellites and primitive bodies (Europa, CORSAIR and Lucy), possible entry probe missions focusing on our own giant planets, and the importance of terrestrial planets to astrobiology, understanding the origins of planetary systems will always be a major focus of research at NASA.

The Division “Origins” group provides NASA and the community a unique interdisciplinary resource with a broad range of expertise and a long-term perspective on major outstanding problems not commonly found in academia. Ames is recognized as having the primary agency role in this crosscutting research capability (per NPD 1000.3E chapter 6.2 and APMC 2016-09-15). The team’s research covers the full range of planetary formation from the nebular gas and dust to the planets, satellites and surviving primitive bodies we see today, tying together the disciplines of astrophysics, exoplanetary and planetary science, and meteoritics.

During 2018, the Origins group began weekly group meetings to share our research, broaden our individual understanding, review ongoing developments in the field, and identify research gaps and emerging opportunities. As a result of these discussions we have identified several interdisciplinary tasks of wide community interest we plan to pursue in more depth.

One new focus area will be a detailed study of The First Million Years of protoplanetary nebula evolution. A lot happened in the first Myr of our own protoplanetary nebula. Meteoritic data reveals that planetesimals had already formed by 0.1Myr in the inner nebula, and 0.4Myr in the outer nebula. It also appears that the composition of these planetesimals changed dramatically within that timeframe, but not much subsequently. It is a popular idea that a Jupiter core formed in that general timeframe, separating these regions. Models and observations show that this period is a time of elevated stellar brightness, ongoing infall from the parent cloud, and outward-flowing disk winds. This critical period has, however, received little attention because of modeling and observational challenges. We believe the time is right for a dedicated focus on including all the relevant fluid dynamics and energetics self-consistently with particle growth, drift, planetesimal

formation and core formation, with a close eye to observations. We plan to hold a workshop next year, attracting an interdisciplinary mix of community participants.

Objective 2.1 – Understand Evolution of Protoplanetary Nebulae

Infall from dense clouds of gas and dust leads to the formation of flattened, rotationally supported, disks in about 10^5 years. This nearly-Keplerian flow state follows a poorly understood, shorter stage in which infall, gravitational instabilities, disk fragmentation and episodic accretion may all be going on at once. These early processes have important long-term consequences for planet formation, including removal of angular momentum by jets or winds in the inner disk, intense radiation from young stars, and strong, turbulence-driven disk expansion and mixing of thermally processed solids into the outer disk. Ionized and neutral gases both play important roles. Nebula gas turbulence, in particular, remains very poorly understood. These same processes describe exoplanet formation around single and binary stars.

Chaotic dynamics accounts for some of the diversity of exoplanetary systems, but most of it must arise from the diversity of their parent disks. To understand the chemical and physical structure of disks, we will build upon existing expertise and develop informed, global 3D disk models that simulate all the key processes relevant to planet formation. We will study basic transport processes in irradiated disks, the removal of material by thermal and MHD winds and outflows, and transport and mixing of chemical and isotopic species in the gas and solid phases. In collaboration with Code T and academic partners we will have a focus on the generation, intensity, and spatial-temporal distribution of turbulence in all stages of disk evolution, because of its critical importance to growth of objects from pebble to planetesimal size. Another focus on physical-chemical disk models will predict line and continuum emission from radio to optical/UV wavelengths, giving a connection to current (JWST, SOFIA) and future missions (LUVOIR, OST, SPICA). With the upcoming launch of JWST, the improved sensitivity of HIRMES on SOFIA, and the full ALMA array, there will soon be immense amounts of observational data requiring models and theory to interpret.

Objective 2.2 – Understand Particle Growth from Dust to Planetesimals

A main objective of our global nebula evolution models is to determine how condensables (from silicates and higher-temperature condensates such as Calcium-Aluminum rich inclusions or CAIs, through H_2O , to CO , CH_4 and other highly volatile materials) are redistributed in the disk before being accreted into planetesimals. The physics should be general enough to extend to stars and disks of all masses. Our models capture state-of-the-art growth-by-sticking physics, in plausible turbulence, with all the associated diffusive mixing, radial drift, and opacity changes that then determine nebula temperature structure and the locations of condensation fronts for all these materials as functions of time. Ultimately these models will be applied to understand more subtle aspects of meteorite parent bodies such as their chemical and isotopic composition.

The size distribution, internal structure, and composition of the earliest planetesimals provides a critical initial condition to all models of subsequent stages of planetary accretion, and a tangible connection to today's comets, asteroids, the meteorite record, and Ames' lead role in Planetary Defense. Ames has been a leader in planetesimal formation by developing one of the two "leapfrog" models that avoid all the barriers to growth in turbulence. This work continues as we incorporate subtle relative velocity effects in growth of chondrule aggregates that have recently been identified in primitive meteorites. The regimes of validity of candidate leapfrog planetesimal formation mechanisms depend strongly on how large aggregates of solid particles can grow. This growth in turn depends on composition, turbulent intensity, and the inward drift of particles towards warmer areas where they can evaporate. The goal is to understand all the observations - initial mass functions of asteroids and KBOs, the conditions and timing of planetesimal formation, and the diverse properties of meteorite constituents. Another poorly understood property we will address is the predominance of equal-size wide binaries in the KBOs, thought to be due in some way to bifurcation of a collapsing, rotating particle clump such as our models envision forming. The team will explore how the

diversity of outcomes depends on the diversity of nebula properties, determines subsequent evolution of giant planet properties, and connects with the diversity of exoplanetary systems.

Objective 2.3 – Understand Formation of Planets, Satellites and Rings, and their Long-Term Evolution and Dynamics

Modeling the late stages of terrestrial planet growth, including fragmentation in high-velocity impacts, is an astrobiological priority. The emphasis will be determining the flux of large impactors arriving late enough to severely perturb a biosphere, and quantifying the delivery of volatiles. Simulations will address both single stars with various giant planet configurations, specifically including our own solar system, and multiple star systems such as Alpha Centauri.

The Ames-led group has developed the most complete and comprehensive model of giant planet growth, capturing the most critical physics. The biggest question for the formation of warm/hot (sub-)Neptune planets that Kepler found in abundance, and TESS is now locating around bright stars, is whether they accreted in situ, as suggested by their nearly circular orbits and paucity of strong resonances with their neighbors; or whether they formed at larger distances and then migrated to their current locations, which makes accretion and retention of their voluminous atmospheres much easier to understand. Several new modules will be integrated, and new physics added to address the new hypothesis that growing cores accrete mm-cm “pebble”-size objects even faster than the traditional 10-100km size planetesimals. For giant planets, an important new question is how formation and evolution sculpted the gradual transition between core and envelope at Jupiter and Saturn implied by Juno and Cassini data. With Code T and academic collaborators, we will incorporate mixing of condensibles with H/He inside giant planets, and sophisticated models of atmospheric escape, while streamlining our codes, to address these issues.

Formation theories for satellite and ring systems of the giant planets are in their infancy. Most current models omit experimentally constrained models of dust aggregation and do not treat the circumplanetary (sub-)disk as a dynamically evolving medium with dynamical times 100x shorter than in the parent nebula. Additionally, there is a complex interplay between turbulence, sub-disk formation, cooling, and dispersal, and the mechanisms of solids delivery, determining which volatiles actually did condense out. Here we can synergistically apply all the work in Objective 2.2, on incremental growth and drift of solids, and “leap frog” processes of planetesimal formation. Some large icy moons are apparently only partially differentiated (e.g., Callisto), while some small mid-size moons manage to be differentiated (e.g., Dione, Enceladus). Modeling their internal histories will support NASA’s new “Ocean Worlds” initiative, and gives the group a strong collaborative connection with the Planet Modeling, Atmospheres and Climate, and Landforms groups at Ames. We will also assess a promising new hypothesis that the Saturn ring-moon system underwent a catastrophic disruption scenario 100-200Myr ago.

Much of what we know of multiple-planet exosystems, in particular regarding the internal density of their planets, has been learned by detailed dynamical modeling of their interacting orbits. Determining how many planets can stably orbit within a star’s habitable zone is of fundamental value, is important to designing planet detection missions, and is also of importance to astrobiology. We will continue this work. Predictions will also be made about the expected architecture and composition of exomoon systems.

Objective 2.4 – Integration with NASA Science Missions and the Scientific Community

Ames’ Origin of Planetary Systems research has a long history of contributing to the success of NASA Planetary and Astrophysics missions and continue making this a cornerstone of our strategic planning. This interdisciplinary group, including cross-Division, other Codes at ARC and community members, will participate actively in design, development and execution of missions to primitive bodies, the moon, planets, satellites and rings, and exoplanet space observatories. We will apply our theory and model efforts to understand and leverage data from current missions including Hubble, Spitzer, and SOFIA (and

ALMA) observations of circumstellar disks and Kepler / K2 / TESS observations of planetary system architectures.

Division scientists have also developed community-related capabilities for the JWST NIRCams and MIRI instruments and will be executing a guaranteed time observer program to study the photospheric properties of the youngest (Class 0) protostars and how they impact their forming planetary systems (JWST GTO program 1186). Division researchers are on the science and technology definition team of the Origins Space Telescope and LUVOIR Astro2020 Decadal Survey mission studies and will contribute to the scientific definition of other future space telescopes.

These connections will be formed and strengthened by holding organized, focused workshops on timely interdisciplinary subjects for the community, and continuing to train the next generations of theorists and observers via the highly successful NASA Postdoctoral Program and mentoring of graduate student researchers and student interns.

Milestones: Origin of Planetary Systems

Year 1 (2019)

- Publish at least one paper on turbulence in protoplanetary disks.
- Publish models of limits on orbital stability to guide searches for habitable planets in single star systems.
- Apply newly developed chemical models to ALMA protoplanetary disk data, to determine carbon chemistry, infer disk masses, and study how the gas/solids ratio evolves in disks. Accurately model the late impact flux onto potentially habitable worlds.
- Incorporate disk winds and mass infall (with new NPP); model elemental depletion seen in chondrites/planets.
- Conduct and interpret Keck observations of protostars to guide future guaranteed time JWST observations.
- Test planetary system formation models against observational stellar orbital data for Kepler exoplanet systems.

Years 2-5 (2020-2024)

- Conduct and interpret JWST guaranteed time observations of protostars.
- Predict organics & winds emission spectra for JWST/NIRSPEC, SOFIA and ALMA.
- Conduct atmospheric retrieval studies on simulated JWST spectra of young gas giant planets to understand the fidelity to which O, C, and other abundances can be extracted from data. Relate accuracy of retrieved abundances to constraints on formation mechanisms.
- Build full, self-consistent models of evolving protoplanetary disk thermal structure and solids mass density, including turbulence, particle growth and opacity.
- Include infall and disk winds in nebula evolutionary model.
- Model temporal variation of O-isotopes, abundances of ices in outer protoplanetary disks and Solar System objects.
- Accurately model the late impact flux onto potentially habitable worlds.
- Develop dynamical instability scenario to explain Saturn's young rings.

Years 6-10 (2025+)

- Continue to conduct and interpret JWST guaranteed time observations of protostars.
- Characterize disks via their line emission and determine the chemical signature of planet formation processes.
- Utilizing observed JWST spectra of young gas giant planets, retrieve abundances of major species including H₂O and CH₄ to help constrain formation mechanisms.
- Establish a complete picture of the turbulent state of protoplanetary disks and effects of turbulence on the growth and distribution of grains.

- Understand the primary accretion of planetesimals in the inner and outer Solar System, explaining size distributions and internal structure.
- Model growth of planets accounting for “pebble” accretion of solids (rock, organics, ices) and gas (H/He). Apply to giant planets in the Solar System and large exoplanets. Understand how formation sculpted core-to-H/He envelope transition.
- Develop models for evolution of satellite-forming disks to make predictions about exomoons.



Exoplanet Characterization

Synergies matrix: characterization – instrumentation, exobiology, lab astrophysics
Planet modeling – radiative transfer, USGS
Planet systems - NAS

Partner matrix: Code T, GSFC, JPL, NASA
Exoplanet Archive

Missions supported: Kepler, K2, TESS, HST, SOFIA, JWST, WFIRST, FINESSE, 2020 missions, Europa, CORSAIR, Lucy, STAR-DUST, ROSETTA, OSIRIS-Rex, New Horizons, Juno, Cassini, LUVUOIR, OST

Core Capability 3: Exoplanet Characterization; Enabling NASA's Search for Life

There are now over 4000 confirmed planets listed in the NASA Exoplanet Archive, and most of these were discovered via the Ames-conceived Kepler/K2 missions. We now know that most planetary systems are different from our own and the most common type planet is not one we have in our solar system. The TESS mission is now finding more transiting planets, many around nearby bright stars that are amenable to detailed characterization. The upcoming James Webb Space Telescope and Wide Field Infrared Survey Telescope missions will further add to our knowledge of exoplanets and open new windows for exoplanet characterization through spectroscopy and direct imaging observations. Ames scientists are leading important efforts to facilitate characterization of the exoplanet discoveries and helping to enable NASA's search for life in the universe.

Major Division efforts include developing an innovative high-resolution imaging capability to allow correct measurements of exoplanet radii, which lead to improved occurrence rates and atmospheric studies as well as a better understanding of exoplanetary system formation and evolution. Ames scientists are also leading efforts to characterize exoplanets through JWST spectroscopic observations using detailed atmospheric models and spectral retrieval techniques. New modeling techniques, including innovative treatments for clouds and hazes, are being developed to enable the interpretation of spectroscopic data from both JWST and WFIRST. Robust spectral characterization of a variety of exoplanets is needed to ultimately understand their diversity, formation, evolution, and how they relate to our own solar system and its planets, ultimately including Earth. Additionally, spectroscopy and direct imaging are critical in the search for biosignatures and life elsewhere in the Galaxy. These efforts are deemed as critical needs in New Worlds, New Horizons, the 2010 Decadal Survey, and the 2014 NASA strategic Science Plan. We anticipate similar needs will be highly ranked in the Astro2020 Decadal Survey as well.

In addition, Ames scientists are contributing to the scientific success of the Kepler/K2, TESS, JWST, WFIRST, and other NASA exoplanet mission concepts through unique ground-based mission support observations, exoplanet atmospheric modeling efforts, and community science activities for JWST, WFIRST, and beyond. Ames scientists develop and contribute valuable exoplanet related data, data products, and software tools to the community via public archives. These diverse, multi-faceted, and substantive efforts will help ensure that NASA will successfully meet its exoplanet discovery and characterization goals in the 2020s and beyond.

Ames Scientific Contributions to Exoplanet Characterization

Development of specific JWST's transit spectroscopy instrument modes and optimal data reduction processes

Lead large JWST guaranteed time (GTO) exoplanet characterization programs

Design, build, and deliver high-resolution imaging instruments for exoplanet characterization by the community.

Advancing the development of coronagraphic imaging technology for use in WFIRST and future high contrast imaging of small, Earth-like planets in the 2030s and beyond.

Advancing the development of coronagraphic imaging technology for use in WFIRST and future high contrast imaging of small, Earth-like planets in the 2030s and beyond.

Exobiology work that seeks to identify what measurements are needed to assess habitability with future missions and lead the search for life.

Objective 3.1 – Provide Unique Leadership and Contributions for Exoplanet Discoveries and Characterization

Our goal in exoplanet studies is to expand Agency capabilities to characterize exoplanets with both ground- and space-based telescopes and instrumentation - leading to a better understanding of exoplanet radii, mean densities, atmospheric compositions, planetary architectures, formation and evolution scenarios, planet occurrence rates, direct imaging technologies, and remote detection of the signatures of life. These areas of research are deeply interdisciplinary across the ARC Space Science and Astrobiology Division. ARC scientists are leading major programs in high-resolution imaging, IR spectroscopy, model atmosphere calculations, experimental and theoretical laboratory astrophysics atmospheric and surface studies, and biosignatures for remote sensing life detection. New directions in the Agency plan to examine exoplanet atmospheric structures utilizing global circulation model (GCM) expertise developed at Ames for Mars and for other solar system planets. Additionally, large space missions being studied for the 2030s (LUVOIR, HabEx, OST) are focusing on characterizing the atmospheres of habitable worlds, and Ames will continue work on exoplanet imaging technologies and far-IR observations that will enable JWST, WFIRST, and future missions to fully exploit exoplanet science.

We also incorporate the significant expertise Ames has in laboratory astrophysics, radiative transfer processes and modeling, and exobiology into the broader theme of exoplanet characterization and the search for life. This cross-cutting effort provides a near-term community resource as well as a longer-term Agency capability to advance the design and requirements for future NASA missions (**Figure 3.1**) and prepare the NASA community to fully exploit their data.

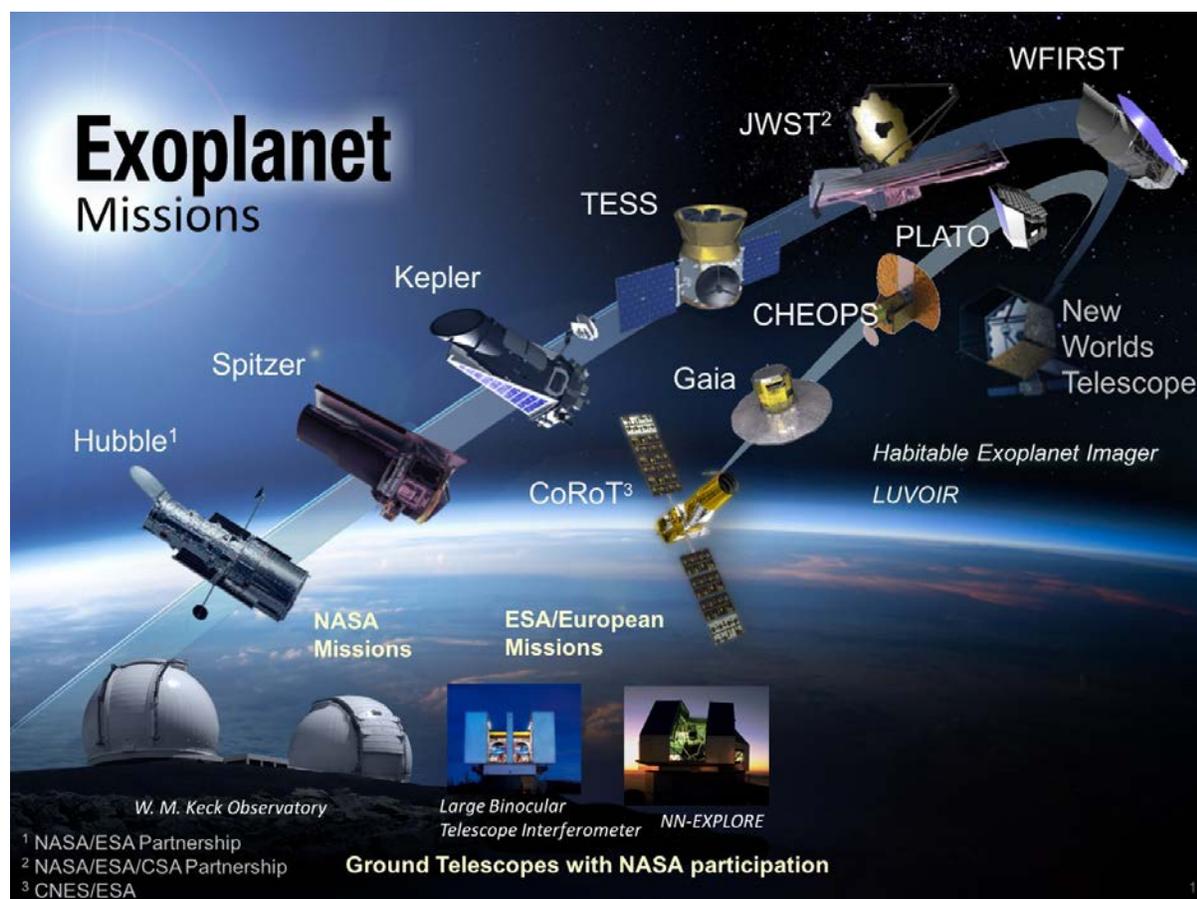


Figure 3.1: A graphic of present and future exoplanet missions from space agencies and observatories around the world. Credit: NASA/JPL-Caltech

Objective 3.2 – Validating and Characterizing High-value Exoplanets for JWST and Beyond

Ames scientists provide an unparalleled resource for detailed analyses in the key area of high-resolution exoplanet host star imaging. The exoplanet community is in the midst of identifying as many planet candidates as possible while beginning to characterize individual systems in order to understand both the diversity of planets as well as the formation mechanisms involved. High-resolution exoplanet speckle imaging, pioneered at and unique to Ames, makes a significant contribution to this work and has become the standard technique to validate and characterize exoplanet candidates. This capability addresses six of the twelve science gap areas identified by the community and tallied by the Exoplanet Program Office (ExPO). Not only does this program identify false positives and validate exoplanets, it provides the only method of assessing critical physical parameters for the exoplanets discovered. All reduced data and data products are sent to the NASA Archives for immediate use by the community. These data are required in order to determine the correct radius of any exoplanet discovered by the transit technique, without which the calculated mean density and atmospheric structure (scale height) will be unknown or incorrect. Such characterization is especially critical for small, rocky planets in long period orbits, which are not amenable to RV mass determinations or any form of direct imaging. These “earth-like” exoplanets will be the prime targets in the search for life and their physical characteristics are of key importance. Incorrect planetary radii can also give rise to systematic errors in star and planet counts, which lead to biases in planet occurrence rates. In particular, occurrence rates of planets with radii less than approximately 2 Earth-radii,

a key regime for understanding the formation and evolution of rocky super-Earths and sub-Neptunes with thick atmospheres, may be underestimated by as much as 50%.

Objective 3.3 – Characterizing Exoplanet Atmospheres with JWST

JWST will drive the field of exoplanet atmospheric studies for the next decade. Hubble Space Telescope observations have shown us that H₂O is common in giant planet atmospheres, and that high-altitude clouds are often detected in emission spectra. JWST will allow precision determinations of molecular content in giant planets, expanding from only H₂O to include CO, CO₂, CH₄, NH₃, and other species (e.g., photochemical products) as can be seen (**Figure 3.3**). Such observational discoveries will greatly inform the formation and thermo-chemical structures of exoplanets. JWST's sensitivity will enable expanding atmospheric analyses to planets that are Neptune mass or below.

Recent work at Ames has shown that multi-wavelength 1 to 11 micron transmission or emission spectral observations will be required to characterize the compositions, metallicities, and C/O ratios in cloudy or high mean molecular weight atmospheres of warm exoplanets. Ames scientists are leading over 200 hours of JWST GTO programs that will characterize the atmospheres of 8 mostly warm (400 – 850 K), low-mass (Earth mass to Saturn mass) exoplanets. These observations will be among the first exoplanet spectroscopy programs conducted by JWST. Our design of the instrumental modes used in these observations and the analysis of their data will inform the community about exoplanet compositions, formation, and evolution as well as provide a template for further observations and archival data use.

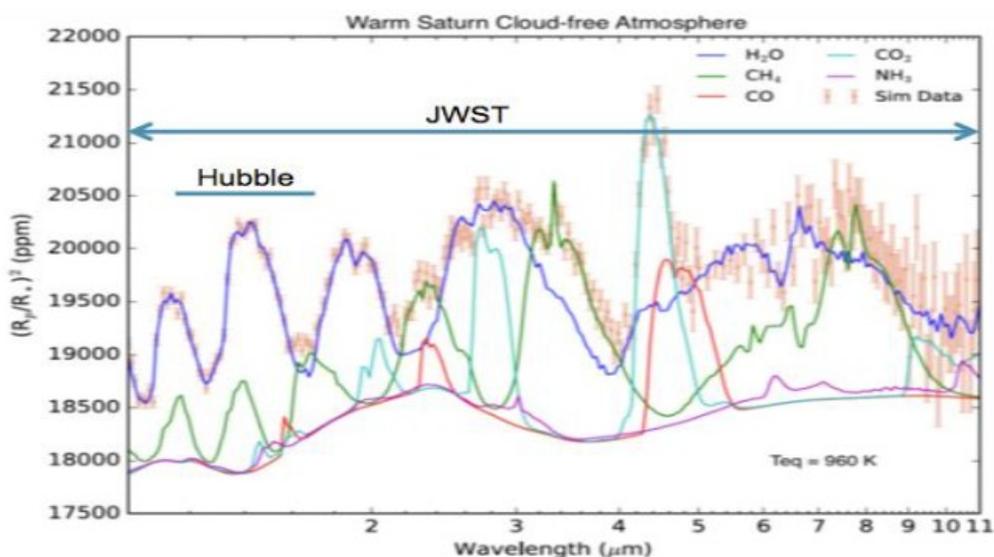


Figure 3.3: Model atmospheric spectra of a warm, cloud-free Saturn type exoplanet showing the wavelength range covered by HST and the larger, more complete range that will be covered by JWST.

Objective 3.4 – Develop Exoplanet Atmosphere Models

The interpretation of and planning for spectroscopic observations of exoplanet atmospheres relies upon our understanding of the atmospheric structure, composition, clouds, hazes as well as the global atmospheric dynamics of the studied exoplanets. The traditional method of pursuing such studies has been to construct ‘forward models’ of atmospheric structure which combine assumptions about the atmosphere with sophisticated radiative transfer atmosphere software models.

In the past half dozen years, ‘retrieval’ methodology, pioneered in the Earth sciences community, has seen a major ascendance as the current method of choice for atmospheric studies. In this approach, hundreds

of thousands to millions of models are computed on a supercomputer and directly compared to observational data. Those sets of model parameters that best fit the dataset, provides a rigorous description of the information content of the data. New retrieval efforts and methodologies are needed to support the types of space-based exoplanet observations expected in the coming decade.

Clouds and hazes populate every solar system atmosphere and have been demonstrated to be present in exoplanet atmospheres as well. These common atmospheric entities can block radiation from deeper atmospheric levels and through scattering can complicate retrievals of atmospheric abundance. Clouds and hazes are also tracers of atmospheric dynamics. Thus, to fully characterize exoplanet clouds, they must be accounted for in both retrieval and forward models of exoplanet atmospheres. Any characterization of habitable planets, for example, will be definition entail accounting for water clouds. Studies of clouds in the atmospheres of other types of exoplanets will inform habitability research and build the foundation needed by the future space telescope missions in their search for life.

Objective 3.5 – Conduct Technology Development for Direct Imaging of Exoplanets

Several planets or "planetary-mass objects" have already been directly imaged with coronagraphs from space and from the ground as shown in the right-hand corner of **Figure 3.5**.

NASA’s next flagship telescope after the James Webb Space Telescope (JWST) is likely to be WFIRST (Wide-Field Infrared Survey Telescope) and will have a coronagraphic instrument for direct imaging of exoplanets. It is currently not designed to be capable of directly imaging potentially habitable worlds, but with future advances in post-processing or starshades such detection is not entirely out of the question. The telescope will be 2.4m in size and is scheduled to launch in 2024. NASA is also currently undergoing four studies of large flagship missions for the 2030s, two of which (Habitable Exoplanet Imaging Mission or HabEx, and Large UV/Optical/IR Surveyor, or LUVOIR) are designed to be capable of detecting and spectrally characterizing a statistically significant number of exo-Earths, as well as many larger planets.

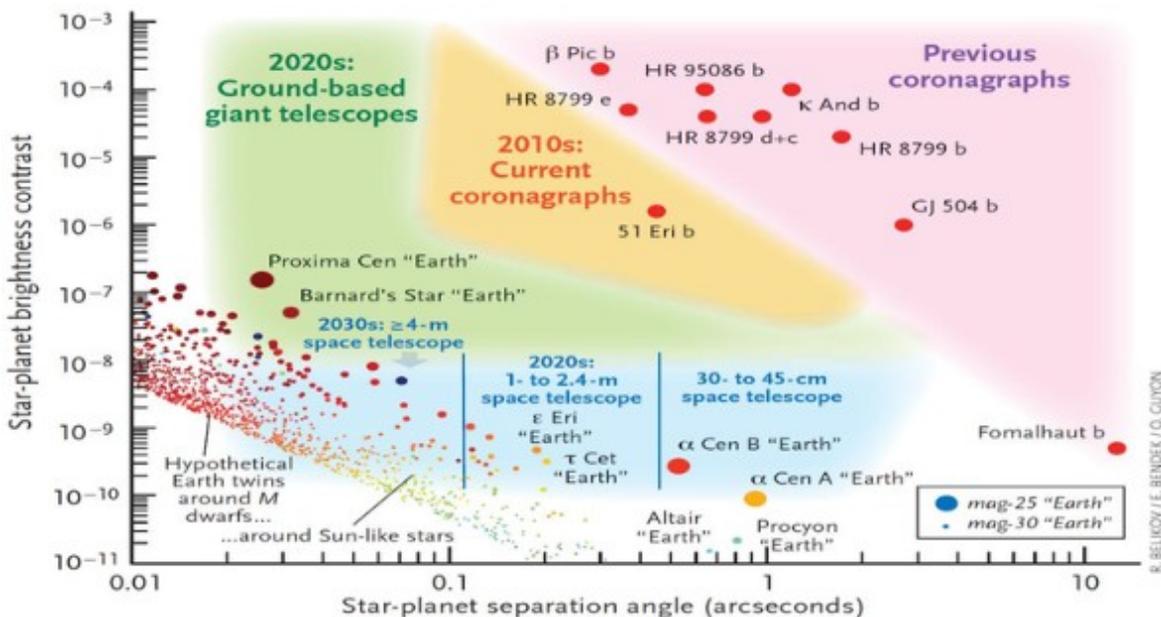


Figure 3.5: Overview of the field of exoplanet direct imaging in visible and infrared light. Capabilities of past, current, and future direct imaging instruments are shown. Red dots in the upper right are known

directly imaged planets. Dots in the bottom left are out goal: hypothetical Earth twins around many nearby stars (out to 20 parsecs).

If there is a planet around Alpha Centauri, it is in principle possible to detect and take a low-resolution spectrum with a very small 30-45cm space telescope, due to Alpha Centauri being ~3x closer to the Sun than any other Sun-like star. As can be seen in Figure 3.5, Alpha Centauri is an extreme outlier and “low-hanging fruit”.

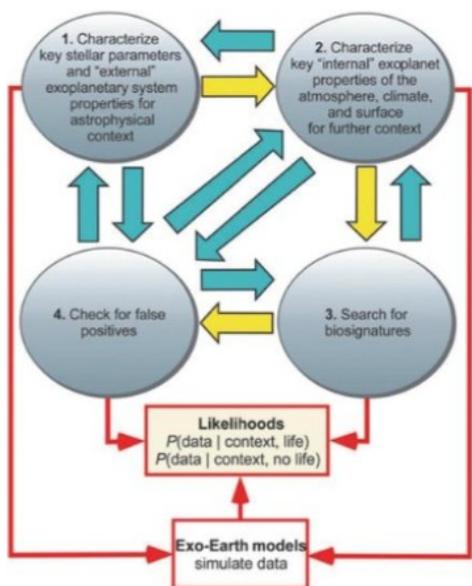
The Technology that will be enabled at Ames is:

- *Direct imaging with a small (30-50cm) space telescope.* ARC is pioneering the idea of imaging exoplanets in the Alpha Centauri system with a small space telescope, with several related mission concepts that have been developed or are under development, such as ACESat and Project Blue.
- *Direct imaging with a large telescope such as WFIRST, LUVOIR, and HabEx.* ARC is leading the development of Multi-Star Wave Front Control, which can enable all of the above missions to target binary stars such as Alpha Centauri. This enables increases in both the quantity of targets, as well as the quality of the signal. In addition, ARC is leading the lab development of the PIAA coronagraph, which is a candidate for LUVOIR and HabEx.
- Assess the scientific potential of astrometry to detect and measure exoplanet masses around nearby F, G, and K stars. Determine the mass measurement accuracy necessary to assess atmosphere retention capability of a planet; this is necessary to inform the design of future exoplanet flagship missions.
- Additional interesting science observations which ARC is well suited to do include: direct imaging of potentially habitable planets in 10 microns (with JWST); precursor observations of the Alpha Centauri system such as exozodi with GPI / SPHERE, and the galactic background to assess confusion risk.

Objective 3.6 – Determine the Measurements Required to Assess Habitability and Biosignatures

Work in the Exobiology Branch at Ames focuses on the characterization of novel gaseous and surface biosignatures in analog field settings and in laboratory simulations. Beyond identifying new biosignatures, this work is integrated into modeling activities at Ames and with other external partners to assess their remote detectability to aid in target selection, and into frameworks for biosignatures assessment for life

detection. Such frameworks will need to consider the context of the stellar and planetary environment, and provide a way to assess false positives and false negatives before arriving at a convincing interpretation of the presence of life (**Figure 3.6a**).



Experimental work centers around field and lab campaigns to measure gaseous and surface biosignatures associated with anoxic biospheres. The study of potential exoplanet biosignatures -- the global impact of life on a planetary environment -- has been informed primarily by the modern Earth, with little yet explored beyond atmospheric O₂ from oxygenic photosynthesis and its accompanying planetary surface feature, the vegetation “red edge” reflectance.

Figure 3.6a: Frameworks for biosignatures assessment (Catling et al., 2018)



However, these biosignatures have only been present for less than half the Earth's history, and recent geochemical evidence suggests that atmospheric O₂ may have been at very low - likely undetectable - levels, until 0.8 Ga (Planavsky et al., 2014). Given that our planet was inhabited for very long periods prior to the rise of oxygen, and that a similar period of anoxic life may occur on exoplanets, more studies are needed to characterize remotely detectable biosignatures associated with more evolutionarily ancient anoxygenic phototrophs and anaerobic chemotrophs. We are quantifying biogenic gas production in natural systems and in laboratory environmental chambers where we control the composition of the atmosphere and stellar irradiance. The suite of biogenic gases will then be fed into atmospheric models to assess the potential photolytic destruction and production of secondary biosignatures.

Figure 3.6b: Measuring the reflectance spectra of anoxygenic phototrophs in a variety of different ecosystems.

We are also measuring the reflectance spectra of anoxygenic phototrophs (**Fig. 3.6b**) and assessing their detectability under different atmospheric compositions and cloud coverage levels. While we focus on characterizing anoxic biosignatures, oxygen remains a key biosignature gas, so we are also assessing the productivity and detectability of oxygenic photosynthesis around cool M dwarf stars (**Figure 3.6c**). Given the low photon flux in the visible wavelengths, this may limit photosynthetic productivity and significant inhibit oxygen build-up in the atmosphere to detectable levels (Lehmer, et al., 2018).



Figure 3.6c: Ames Pathway intern Owen Lehmer measuring O₂ production in a microbial mat under (left) solar and (right) M dwarf spectral irradiance using a custom-designed LED array.

Ames Exobiology researchers plan to serve as leaders and coordinators for expanding the engagement of biologists in exoplanet biosignatures research by providing guidance on how to modify their research methodologies to make them applicable to exoplanets. Additionally, input from the 'origins of life'

exobiologists is needed in order to predict potential prebiotic chemistry and metabolisms on planets with different chemical compositions than the early Earth (e.g., a highly reducing planet).

Milestones: Exoplanet Characterization

Year 1 (2019)

- Complete K2 exoplanet follow-up and place all results in the NASA Exoplanet Archive.
- Continue validating exoplanets and star systems of newly discovered, high-value TESS exoplanets. Main effort will be on the southern sky targets.
- Finalize JWST transit GTO observation plans.
- Finish WFIRST target vetting and publish results. Place all data into NASA archive.
- Finish Kepler astrometric work leading to exoplanet host star formation scenarios and characterization of stellar orbital plane vs. exoplanet orbital plane.
- Detail Kepler and (some) K2 binary exoplanet host star physical properties such as orbital period, mass ratio, and stellar types. Compare to field stars.
- Complete development of new analytic cloud model. Select a new NASA NPP Postdoc to focus on a comparative study of exoplanet cloud models and incorporate them into retrieval framework.
- Using newly acquired experimental data, continue assessing detectability of surface biosignatures using 1-D models.

Years 2-5 (2020-2024)

- Continue validating exoplanets and star systems of high-value TESS exoplanets in the southern sky and begin to focus efforts into the northern sky.
- Begin TESS astrometric work leading to exoplanet host star formation scenarios and characterization of stellar orbital plane vs. exoplanet orbital plane.
- Finish Kepler and K2, start TESS binary exoplanet host star physical properties such as orbital period, mass ratio, and stellar types. Compare to field stars.
- Execute multi-instrument, multi-wavelength JWST GTO and GO spectroscopic observations to characterize the atmospheres of a range of warm to hot and small to large transiting planets
- Work with the community to support JWST observations. Help identify the best high value exoplanets for detailed atmospheric characterization.
- With internal and external partners, assess detectability of newly measured biosignatures using the VPL 3-D Earth model.
- Observe and analyze JWST exoplanet spectra to characterize the planets, including identification of atmosphere constituents, chemical processes, cloud properties, and potential formation mechanisms.
- Contribute to scientific planning of WFIRST Exoplanet observations.
- Provide cross-disciplinary atmosphere retrievals (astro/Earth); Complete and test exoplanet GCM.

Years 6-10 (2025+)

- Continue observational effort to characterize star systems of exoplanets- Ground-based (as needed) and JWST using high priority targets (TESS, other).
- Continue developing 3D models of disk averaged biosignatures, and flesh out and test frameworks for biosignature and life detection assessment.
- Engage in 2020 Exoplanet missions.
- Combine exoplanet atmosphere theory and JWST observational results with life detection / biosignatures.
- Participate in WFIRST, provide expertise for interpreting observations.



Radiative Transfer Research

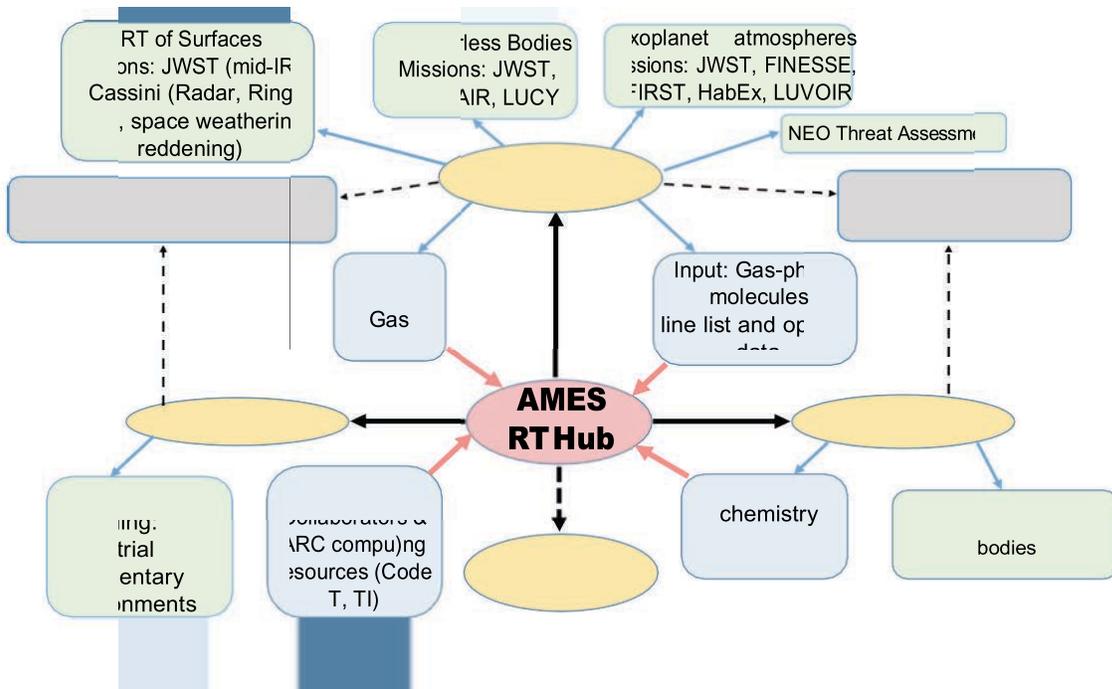
Synergies matrix: Exoplanets, Solar System Bodies, Exobiology, Astrophysics, Laboratory Astrophysics

Partner matrix: Code T, Earth Science, JPL, NASA Ames, Supercomputer

Missions supported: HST, SOFIA, JWST, WFIRST, FINESSE, 2020 missions, Europa, CORSAIR, Lucy, STARDUST, ROSETTA, OSIRIS-Rex, New Horizons, Juno, Cassini

Core Capability 4: Radiative Transfer Research

Upcoming missions such as JWST will reshape our understanding of airless solar system bodies and exoplanets. We propose to integrate the existing Ames radiative transfer teams and resources across research topics and toolsets centered on radiative transfer to form a core leading group in interpreting the vast phase space of the forthcoming observations and providing critical services to the scientific community. This effort will place Division scientists for key roles in future sample return and life finder missions, and in forging international collaborations.



disciplines.

Radiative Transfer (RT) is a fundamental topic needed to interpret all remote observations spanning airless bodies, atmospheres of exoplanets and solar system bodies, protoplanetary disks, and all other astronomical objects. These complex applications require a comprehensive toolset of custom codes and extensive databases of optical properties and atomic and molecular line data. NASA Ames Research Center has a strong and unique core competency in theoretical and computational RT studies, and a long history of applying them to solar system missions. Our expertise goes beyond using currently available models/tools to innovating new cutting-edge methodologies. We have assembled a cross-topic, "capability-focused" team to unify the existing complementary expertise, in order to facilitate progress in all individual topical areas using the same theoretical and experimental tools. The following describes the service and capability-oriented objectives that will apply both to the support and development of NASA missions and to the growth of the scientific community as a whole.

We envision a future institution where we are greater than the sum of our parts. We would like to cross fertilize our personnel and resources at Ames and make/strengthen collaborations across divisions, NASA centers, and academia. Institutions that harness interdisciplinary endeavors will be the trailblazers for future discoveries. As the scientific world becomes ever more complex and the traditional lines between disciplines fade, we need to heed the call of this future just as other institutions are, as evident at GSFC and GISS. This is attainable by facilitating interactions and implementing infrastructure geared toward cross cutting projects.

Objective 4.1 – Next Generation Radiative Transfer Methods and Tools

The Center for radiative transfer research at NASA Ames will be a cross-disciplinary collaboration focused on applied research across the following science areas (**Figure 4.1**). Detailed models of planetary atmospheres, related to the emission, absorption, and scattering of light by gases and particles should be developed. These models can then be applied to the analysis of Solar System and exoplanet observations and include complex clouds and hazes and surface-atmosphere interactions. Models of regoliths on airless bodies and implications for interpreting past, current and upcoming observations in near and mid-IR are needed as well. Such surfaces can be quite complex in terms of reflectivity and emission and also lend themselves to models for inhabited sediment ecosystems. Terrestrial regoliths harboring life interact with the atmosphere via radiative transfer mechanisms. These principles can be tested in the laboratory and prepare us for finding life elsewhere. Finally, determination and curating of optical properties of gas and solids (gas opacities, solid material refractive indices) central to all modeling calculations and derived from both theoretical and laboratory work will be housed in an archive.

We have an extensive model toolset including a world class gas opacity database, collaborators working on theoretical calculations of molecular line lists, and a material properties laboratory group capable of establishing a needed database of optical properties over a range of relevant materials. The gas and particle properties are used in state-of-the-art models of radiative transfer to model atmospheres with clouds and hazes, regoliths of planetary bodies (with or without an atmosphere), and exoplanets. These tools will be used to address the vast phase space explored by upcoming observations.

The developed expertise and tools will be turned into an interconnected hub that employs efficient pipelines, adopts best practices, and provides continuous support for community-wide users. In order to continue and expand our leadership in the development and application of radiative transfer tools we need to not only preserve the existing expertise, but also make investments to employ the newest practices and facilitate communication across teams. Expertise and tools developed in the radiative transfer group will be made available to the Agency and to the community via an archive. The technical capabilities available are outlined in Table 4.1. All these endeavors require an ecosystem of personnel ranging from current staff developing models/theory, to new staff to retain the expertise, and carry on the work of retiring staff, and expertise to adopt best code practices and algorithms on par with current developments.

Table 4.1 - Technology development, cross cutting goals, collaborations, and missions

Technical capability	
Databases	Gas opacities and material refractive indices
Cloud models for planetary atmospheres	1D A&M cloud model, microphysical models
RT in atmospheres	Atmosphere models in thermal emission, transit, and reflection, four stream, adding/doubling, DISORT
Retrieval codes	DDA – irregular aggregates, Mie/EMT - homogeneous particles, Sandy's spheroid model, Tmarix
Single particle aggregates/aerosols	codes for all wavelengths
Granular layer codes spanning UV/VIS - mid-IR, and Radar	Large grain/short λ /packed (Hapke, Spheroidal bed), Large and small grain/short λ /separated (BEAM, hybrid Tmatrix/DISORT/Conel, DDA-RRT), wavelength size grains/packed (DDA-RRT), thermal codes

Objective 4.2 – Grow Agency Capabilities

To ensure continued ARC relevance to upcoming NASA missions, Code S must make strategic investments in capabilities including opacity database development and maintenance, lab and theoretical studies of interactions of radiation with aerosols of various composition, and radiative transfer and atmospheric modeling. Example research tasks would be to interpret transit spectra of super-Earth planets in the presence of various atmospheric absorbers and photochemical and cloud layers, modeling of atmospheric structure of young Neptunes observed by JWST, modeling phase curves of warm Jupiters around M stars measured by TESS, and characterization of habitable planet candidates observed by LUVOIR or HabEx. By supporting the continuing development and integration of our radiative transfer tools and databases, the Ames group could lead the development of new mission concepts to characterize exoplanets and detect potential life markers elsewhere. Development of a cost-effective, but highly community useful public database will allow the all to greatly benefit from the work performed at ARC.

Working with other branches within the division has started, primarily with the exoplanet (SSA) and biome (SSX) groups. Planetary observations from former and upcoming spacecraft will continue to be enhanced through radiative transfer studies, especially those across other Centers. The Ames airborne program and Earth Science research are examples outside the traditional Division science work.

Objective 4.3 – Develop Smart Spectral Retrieval Tools for Complex Atmospheres & Surfaces

In addition to building physically motivated models from first principles, inverse techniques are employed to extract constraints on the model parameters from the data. This inverse problem is referred to as retrieval, following the legacy from Earth and Solar System work. Traditionally this problem was tackled by finding the best fit model in an exceedingly large grid of precomputed models. However, this is very inefficient, the grids can grow fast with more complex models and number of parameters, and the retrieved parameter constraints are limited by the grid spacings. A new generation of Bayesian methods (Monte Carlo Markov Chain, and Multinest) are now being employed to circumvent these issues, and sample the parameter space efficiently, while providing improved parameter constraints and insights into their degeneracies.

While powerful, these methods have their drawbacks, requiring increased computing power and fast, efficient, and accurate radiative transfer algorithms to compute hundreds of thousands of models for each retrieval. We are currently developing such a retrieval package to help guide the design and requirements for the coronagraph instrument onboard future WFIRST mission, and prepare to interpret its observations. The flexibility of these methods makes it appropriate for tackling other observational data, such as those of airless bodies. This is where different groups can bring their expertise together to build new and exciting

tools. This would require building a special package incorporating optical data and specific radiative transfer routines for airless bodies, but the existing expertise makes us particularly positioned to tackle it.

We expect to maximize the science return of JWST, WFIRST, FINESSE, and the 2020 exoplanet missions as well as solar system missions Cassini, New horizons, OSIRIS-ReX, Lucy, and CORSAIR. The RT Center at ARC plans to provide modular toolsets (databases & RT models) for general community applications, space missions, and earth and biological science.

Summary

The expected output from this combined effort is to help grow the agency capabilities and enable community science advances. Our capabilities in (objective 1) cloud/aerosol models and retrievals for (exo)planet observations, (objectives 2 & 3) sophisticated models of regolith surfaces applicable to thermal emission spectroscopy of airless bodies and microwave observations of Saturn's rings, (objectives 4 & 5) opacity modeling, database development and maintenance, laboratory and theoretical studies of optical and physical properties of aerosols and surfaces of various compositions will enable a wide range of community science and support current and future NASA missions. By continuing to develop and integrate our RT tools and databases, we will support the development of new mission concepts to characterize (exo)planets and detect potential life markers elsewhere. A useful, cost-effective public database will allow the community to greatly benefit from our work. We will continue to reach out widely to the community to leverage their expertise, and allow them to leverage ours, to solve problems of diverse types. We would measure success in this area by the number of other groups making use of our models or laboratory-based results, codes, or even facilities. For example, we have already had a mini-workshop for potential users of our Saturn's rings Monte Carlo code, and several users have contacted us subsequently for follow up regarding Cassini image analysis. Also, the Ames laboratory astrophysics team has a long experience with maintaining a community database on optical properties of PAHs.

Milestones: Radiative Transfer Research

Year 1 (2019)

- Nucleate cross discipline group – workshop/meetings to cross fertilize RT
 - Continually survey agency/community needs and identify new project
 - Coordinate new proposals
 - Communicate new findings/milestones – take steps to gain visibility
 - Plan for cross pollinating/integrating RT tools
 - (atmosphere/clouds → surfaces)
 - (Mars atmosphere → exoplanetary atmospheres)
- Innovate
 - New models for exoplanet clouds and hazes (theoretical forward models and retrieval methods)
 - Develop new project concepts with possible mission involvement (e.g., Lunar surface exploration)
- Develop and Apply reflectivity methods for spectra of granular surfaces (airless bodies, Saturn's Rings), Ring Radar observations. Analyze VIMS observations of Plumes of Enceladus.
- Consolidate and document surface RT models in common repository (BEAM, DDA, HAPKE)
- Lab & computational datasets:
 - Compute gas opacities for hot exoplanets
 - Measure optical constants of solids for Titan Pluto analogs
- Develop & test automated pure mineral spectral classifier on Lunar & Mars relevant rocks
- Start establishment of consolidated database facility at Ames
- Plan for Expanded staffing

Years 2-5 (2020 – 2024)

- Automate interface between models and datasets
- Establishment of unified databases facility
- Integrate new RT toolsets with new retrieval methods (JWST)
- Expand databases: gas opacities, solid optical constants, and co-registered image, IR, Raman databases of minerals, rocks, and biosignatures – cross discipline innovation
- Achieve expanded staffing & infrastructure for RT-hub
- Public repositories for code and opacity/material database
- Built co-registered image, dual or multi-probe IR instrument system
- Develop & test automated multi-mineral spectral classifier on Lunar/Mars relevant rocks
- Develop automated science analysis sensing system for co-registered instrument system
- Build interactive website and develop tools for hosting, viewing, analyzing & inter-comparing co-registered data sets for community and to support upcoming Lunar and Mars Surface missions
- Respond to requests from NASA and community

Years 6-10 (2025+)

- RT_hub enables new discoveries
- Apply RT toolset for retrieval of aerosols & habitability
- Integrated co-registered databases and science sensing algorithms onto co-registered instrument system to improve science autonomy in planetary exploration surface missions
- Field test co-registered instrument system on mobile platforms planned for future missions
- Organize RT workshops across NASA centers and academia



Laboratory Astrophysics and Astrochemistry

Synergies matrix: Radiative Transfer, Exoplanets, Astrobiology, NAI, Origins of Life

Partner matrix: GSFC, JPL

Missions supported: HST, SOFIA, JWST, WFIRST, FINESSE, 2020 missions, Europa, CORSAIR, Lucy, STARDUST, ROSETTA, OSIRIS-Rex, New Horizons, Juno, Cassini, LUVOIR

Core Capability 5: Laboratory Astrophysics and Astrochemistry

Laboratory Astrophysics plays a key and unique role in the optimization of NASA missions, both at the science conception level and at the science return level. Laboratory astrophysics is the Rosetta stone that enables translation of space mission observations into knowledge. The field of Laboratory Astrophysics and Astrochemistry consists of laboratory experiments and theoretical calculations that are key factors for the understanding of our universe by complementing astronomical observations, spacecraft missions, and modeling. Laboratory experiments and quantum calculations simulating astrophysical conditions generate the data (spectra, optical constants, opacities, line lists, etc.); necessary for the interpretation of observations returned by NASA missions while providing testable predictions to advance knowledge and guide future missions. Increasingly accurate astronomical observations provide direction for Laboratory Astrophysics and Astrochemistry measurements and calculations. Hence, the interplay between observations and experimental data is a driver for new mission concepts, development of new technologies, and mission instrumentation.

The multidisciplinary nature of the workforce at NASA Ames (astrophysicists, astrochemists, physicists, planetary scientists, theorists, astronomers) makes it a unique environment for Laboratory Astrophysics and Astrochemistry research. The expertise of the Ames Laboratory Astrophysics and Astrochemistry group, and its well-established and recognized experimental and theoretical facilities will be exploited, providing a unique capability in Molecular Universe studies (the astrophysics and astrochemistry of the interstellar medium, protoplanetary disks, etc.), Astrobiology, Solar System science, Exoplanets, and associated databases for the Agency.

2018 Highlighted Accomplishments	
<p>Lab Astro ISFM Directed Work Package (ApD/PSD): Supports Ames Lab Astro research (PAHdb, experiment, theory) as a critical asset for JWST.</p>	<p>Published results of research supporting JWST PAH research (Obj. 5.1) in 8 papers: Boersma et al. 2018, de Barros et al. 2018, Shannon et al. 2018, Ricca et al. 2018, Maltseva et al. 2018, Mackie et al. 2018a,b, Chen et al. 2018</p>
<p>Grants supporting Lab Astro research: PDART, NAI CAN 7, APRA, SSW, ADAP, EW</p>	<p>Published results of research supporting the study of exoplanetary atmospheres (Obj. 5.2) in 7 papers: Rangwala et al. 2018, Huang et al. 2018, Fortenberry et al. 2018a,b,c, Morgan et al. 2018, Dickerson et al. 2018.</p>
<p>Implementing new laboratory facilities that expand the Lab Astro capabilities at Ames:</p> <ul style="list-style-type: none"> - ICEE – new Raman microscope spectrometer + e-gun for ices, ice-grain mixtures, returned samples. - COSMIC – high resolution IR Cavity Ring Down Spectroscopy (CRDS) system. - Developing optical constant facility. New FTIR spectrometer. Improved optical constant code. - PAH lifetime measurement capability using the FLEXEMS instrument (Bramall et al. NASA-SBIR). 	<p>Published results of research supporting astrobiology (Obj. 5.3) in 5 papers: Nuevo et al. 2018, Materese et al. 2018, Cooper et al. 2018, Yabuta et al. 2018, Dworkin et al. 2018</p>
<p>Improved Ames databases: PAHdb, Ames Molecular Spectroscopic database</p>	<p>Published results of research supporting solar system exploration (Obj. 5.4) in 2 papers: Raymond et al. 2018, Ciesla et al. 2018</p>
<p>Developed new theoretical methods:</p> <ul style="list-style-type: none"> - to improve microwave prediction accuracy. - to investigate formation pathways and spectroscopic properties for astrophysical and astrobiological molecules (ab initio quantum chemical techniques). 	<p>Published results of research supporting databases (Obj. 5.5) in 1 papers: Bauschlicher et al. 2018</p>
	<p>Increased Lab Astro workforce: 1 new CS hire</p>

The Ames Laboratory Astrophysics and Astrochemistry group will continue to be an Agency leader in providing critical data that exoplanet, planetary atmosphere and protostellar disk modelers, astronomers, and astrobiologists require to conduct their research. The Ames group will focus their laboratory efforts on support of critical experiments and calculations, those based on the needs of the space science community.

In the following table (**Table 5.1**), we provide a brief listing of Laboratory Astrophysics and Astrochemistry capabilities of the Ames research group. Objectives for these applications are then provided in further detail below. In this document, we have emphasized continuity with the goals and milestones expressed in the original strategic plan. Indeed, much progress towards attaining those goals and milestones has been made in the year in review. We have also chosen to introduce a new objective in this update: the creation and expansion of databases of experimental and theoretical data and associated research-enabling tools. In our view, this objective supports the importance of providing information to the public and better supporting the science community.

Objective 5.1 – Establish a Leading Role in Supporting JWST PAH Research

Ames researchers play a critical role in formulating major scientific advances in the understanding and study of polycyclic aromatic hydrocarbon molecules (or PAHs) and carbonaceous molecules and grains. The Ames Laboratory Astrophysics and Astrochemistry group provides spectral diagnostics, theoretical calculations, and analytical tools for species ranging from free flying molecules to ices and dust particles present in interstellar, circumstellar and planetary environments. PAH research in particular has become

an interdisciplinary investigation involving Ames scientists in planetary astronomy and astrophysics as well as close collaborations with other institutions, most prominently Leiden University and the Dutch Astrochemistry Network through a Space Act agreement. This research was motivated by the desire to enable the scientific community to conduct research supporting NASA projects and missions such as the KAO (initially), IRAS, ISO, Spitzer and SOFIA, and soon JWST. The Ames Laboratory Astrophysics and Astrochemistry group is currently engaging with JWST science teams and addressing their direct needs in terms of PAH research through participation in JWST Early Release Science (ERS) projects and JWST GTO collaborations, and exploration of JWST GO proposals.

Table 5.1. List of Laboratory Astrophysics and Astrochemistry capabilities of the NASA Ames group

Science Area	Research Capabilities
Molecular Universe	PAHs and carbonaceous molecules — characterization from UV to IR, formation mechanisms (theory + experiment)
	Astrophysical ices — characterization in IR and Raman + optical constants
	Chemistry of irradiated ices — characterization in IR, Raman (lab + theory), mass spectrometry
	Ice-grain interaction — characterization in IR, Raman (lab + theory), mass spectrometry
	Cosmic grain analogs — formation mechanisms (theory + experiment) and characterization, UV-FIR, SEM, mass spectrometry
Astrobiology	Small molecules — highly accurate line lists and spectroscopic constants, opacity data, and detailed characterization of critical molecules
	Ice photolysis and irradiated ice residues, prebiotic molecule formation processes — IR, Raman, XANES, GC-MS (lab + theory)
Solar System	Evolution of organic matter in space environments — experiment (IR, XANES, GC-MS) + theory
	Comets/meteorites/asteroids/presolar materials — return sample analyses (Raman, IR) + laboratory and theoretical studies
Exoplanets	Planetary atmospheric and surface chemistry (Io, Moon, Pluto, Venus, Titan, Mars) — observations, modeling, laboratory (IR, Raman, XANES, GC-MS, TOF-MS, SEM), theory (IR line lists for remote sensing and simulation)
Databases	Exoplanetary atmospheres — spectral line lists, opacities, experimental and theoretical simulation, optical constants
	PAHdb, Ramdb, AMSD, line lists, optical constants database

A critical part of the Ames work on PAHs is the PAHdb, a comprehensive archive of thousands of laboratory measured and quantum-chemical-computed spectra of PAHs in astrophysically relevant conditions coupled to a set of innovative astronomical models and tools. An ISFM Work Package was awarded in FY19 for NASA to actively support a stable, long-term interdisciplinary Laboratory Astrophysics and Astrochemistry effort in order to increase the content of the PAHdb spectral libraries, provide advanced tools and models, and make PAHdb the go-to tool to help the scientific community interpret the wealth of information contained in the astronomical PAH bands. PAHdb (<http://www.astrochemistry.org/pahdb/>) is publicly available and offers global access to over 100 high-quality experimental and over 3500 computed PAH spectra as well as innovative tools to use those data to analyze and interpret astronomical observations.

Objective 5.2 – Provide New Theoretical and Laboratory Data for the Study of Exoplanetary Atmospheres

Reliable models of exoplanet atmospheres are in their infancy and have many laboratory data needs. These include highly-accurate rovibrational line lists with transition intensities for stable molecules that are often found in planetary and exoplanetary atmospheres (such as H₂O, CO₂, SO₂, NH₃, CH₄) and the full set of molecular spectroscopic constants for the abundant isotopologues of tracer molecules and transient species. These line lists need to be complete, consistent, and reliable for the atmosphere to be modeled. At ~500K or higher, they are often composed of hundreds of millions of lines or even more. There is a general need to combine the high-resolution experimental and ab initio quantum mechanical theoretical studies to obtain accurate rovibrational line lists for other molecules and at significantly higher temperatures and energies (for hot atmospheres). For example, laboratory data is needed for molecules such as SO₂, SiO, and ZnS to allow modeling of the atmospheres of hot rocky planets. Laboratory production and measurements of such molecules and their availability to the community via an archive or database will be important as it is expected that many of the near-term exoplanet atmospheres to be observed by JWST will be of warm to hot exoplanets.

Objective 5.3 – Investigate Astrobiological Relevance of Irradiated Ices and Ice-Grain Interactions

Molecular ices are astrophysically important as they have been shown to be ubiquitous in the universe. Cold environments allow ices to condense on the surface of grains, and are dominated by simple molecules such as H₂O, CH₃OH, NH₃, CO, CO₂, and CH₄. Once formed, ionizing radiation can break down molecules in the ices to produce reactive species that can then recombine forming new, more complex molecules. This objective investigates photochemical processes of UV and charged particle irradiation of such ices at cold, interstellar/protostellar temperatures. The results of these experiments often produce astrobiologically relevant complex molecules. The formation of organic compounds, such as amino acids, amphiphiles, quinones, nucleobases, and sugar-related compounds will be examined and investigated further in an attempt to constrain critical steps in molecular formation that played a role in the beginnings of life. The laboratory measurements and theoretical results from this work will be made available to the community in a public archive.

Objective 5.4 – Provide New Laboratory and Theoretical Data for Solar System Exploration

Laboratory measurements and quantum chemical calculations related to solar system objects will be continued and expanded, with past and new results made available to the community by being placed in a public database. Detailed comparison with returned extraterrestrial data/samples and new work aimed at surface and atmospheric chemistry of small bodies in the Solar System will be conducted. Optical constants of planetary and cometary materials will be measured and disseminated to the archive as well. With a return to the Moon, optical constants associated with lunar regolith attain renewed importance in mission planning and data interpretation. In addition, laboratory work will be carried out in support of NASA sample return missions, both through work designed to support mission development and flight and to study the extraterrestrial samples returned by these missions.

Objective 5.5 – Databases and Associated Tools

Providing publicly accessible, online databases of experimental and theoretical results along with research-enabling database tools represents an increasingly productive way for the Laboratory Astrophysics and

Astrochemistry group to interact with and fulfill scientific needs of the overall scientific community. At present, databases are organized by subject area. PAHdb (discussed above) provides infrared PAH spectral data and associated analysis tools. The Ames Molecular Spectroscopic Database (AMSD) plans to archive line lists and opacity data and the best available spectroscopic constants predicted for small molecules for astrophysical and atmospheric studies. In-progress efforts will provide new databases for Raman spectra and optical constants data along with associated theoretical calculations and subject-specific database tools. In a future stage of development, we intend to explore options for unifying current and future Laboratory Astrophysics and Astrochemistry databases.

Milestones: Laboratory Astrophysics and Astrochemistry

Year 1 (2019)

Achieve ISFM directed work package year-one milestones:

- Continue expansion of the diversity of PAH and PAH-related species in the PAHdb libraries.
- Enhance and extend the available PAHdb analytical tools, models and services.
- Install high-resolution, gas-phase IR-CRDS on COsmic Simulation Chamber (COSMIC).
- Install 100 keV electron gun for Raman, IR, UV-Vis and MS studies on Institute for Carbon Evolution Experiments (ICEE).
- Establish Ramdb (Raman spectral database of organic-ice mixtures).

Complete milestones for currently funded work:

- Theoretical + experimental research on organic matter (OSIRIS-Rex), and planetary atmosphere and surface analogs (Cassini, New Horizon).
- Ro-vibrational line lists needed to characterize exoplanets (JWST).
- Theoretical + experimental investigations of aromatic molecules and cosmic grains (JWST).

Continue astrobiological research through the transition from funding provided through the NAI to successor funding sources:

- Identify other astrophysics, astrochemistry, and astrobiology laboratory needs associated with PAHs, ices, and organics to support NASA missions (JWST, WFIRST, SOFIA, OSIRIS-Rex, ISS space exposure experiments), as well as foreign missions with significant NASA involvement (JAXA/Hayabusa2/Exocube), and connect with new funding opportunities.
- Further expand laboratory capabilities and upgrade equipment.
- Continue engagement with Division, Center, and HQ to maintain established communications, strategic direction, and progress.

Years 2- 5 (2020–2024)

- New hires to replenish the Laboratory Astrophysics and Astrochemistry workforce and retain skilled non-CS workforce.
- Provide high resolution gas-phase IR spectroscopic measurements in support of JWST.
- Theoretical calculations for all relevant PAH subpopulations and related carriers to aid the interpretation of JWST observations. Calculations on processing of organics by UV/electrons to understand degradation and chemical modifications.
- Expand optical constants capabilities (greater wavelength coverage, upgrades for better performance and sensitivity, reflectance measurements, ultra-high vacuum, etc.).
- Continue to produce rovibrational line lists needed to characterize exoplanets with JWST.
- Develop databases: line lists, optical constants, Raman measurements and calculations (Ramdb).
- Conduct laboratory simulations of the atmospheric and surface chemistry of Solar System objects (lunar regolith, Enceladus, Europa, Pluto, Titan, asteroids, meteorites) and exoplanets and theoretical calculations of reaction mechanisms involved in planetary and exoplanet atmospheres in support of missions.

- Conduct synergistic theoretical and experimental research on radiation processing of organic matter and photo-processing of ices in support of OSIRIS-REx sample return and begin laboratory analysis of actual returned samples (starting in 2023).
- Identify astrophysics, astrochemistry, and astrobiology laboratory needs of possible future sample return missions that involve NASA (i.e., New Frontiers mission concepts like CAESAR, CORSAIR, etc.).
- Continue research designed to understand the abiotic production and evolution of materials of astrobiological significance that can be used to constrain potential process and biomarkers that NASA missions can search for. Leverage international collaborations with the DAN (Dutch Astrochemistry Network), NAPA (North American PAH Alliance), through JWST-ERS, etc.

Years 6-10 (2025+)

- Continued support of JWST and other NASA IR missions (SOFIA, WFIRST, LUVOIR, etc.) through ISFM work packages and associated Laboratory Astrophysics and Astrochemistry research. Provision of mission-critical experimental and theoretical data.
- Involvement in current and future sample return missions through laboratory facility development for sample analysis (Stardust, OSIRIS-REx, Hayabusa2, CAESAR, CORSAIR).
- Study samples returned from asteroid Bennu by the OSIRIS-REx sample return mission.
- Carry out laboratory measurements designed to support mission development for future sample return missions.
- Develop a unified database capability (laboratory/theoretical data + associated tools).
- Continue support of Astrobiology through investigations regarding the formation of prebiotic molecules and their distribution throughout the Solar System.
- Extend and deepen existing collaborations with other divisions, NASA centers as well as US and international universities and institutions on laboratory astrophysics (experimental and theory) efforts, as part of science teams, and with observational work to increase the science return.



Analog Research and Instrumentation Development

Synergies matrix: SMD, HEOMD (AES, HRP), ARC Code T, R, P, NAI and SSERVI

Partner matrix: GSFC, JPL, APL

Missions supported: HST, SOFIA, JWST, WFIRST, FINESSE, Resource Prospector MSL 2020 missions, Europa, CORSAIR, Lucy, STARDUST, ROSETTA, OSIRIS-Rex, New Horizons, Juno, Cassini, OST, Human Exploration

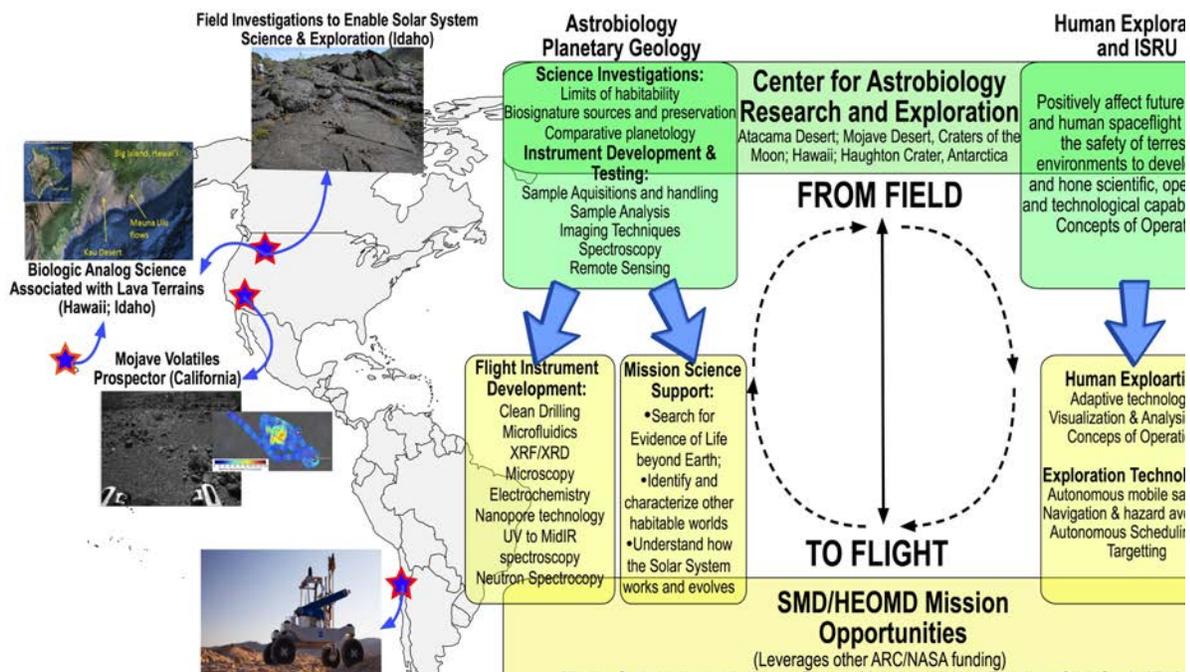
Core Capability 6: Analog Research & Instrumentation Development

The Agency core capability for Analog Research and Instrument Development will continue to lead innovation, mission design concepts for operations, and perform field tests in analog environments using low-cost, prototype instrumentation. The Instrument Development component will develop instruments for flight missions in the areas of life detection, planetary mineralogy and geochemistry, in situ atmospheric, and in situ resource identification and utilization. The teams' expertise, in partnership with other NASA Centers, will be focused in providing Agency leadership in science-driven robotic and human exploration missions as well as small mission instrumentation concepts.

This Analog Research core capability will advance science instrumentation from low to mid Technology Readiness Levels (TRL), preparing them for flight maturation through testing in relevant environments (for example, in vacuum over the range of temps encountered on the Moon, or at Mars surface pressures over the temp range found there), and then for mission insertion. Additionally, we will improve the Agency's Core Competency science expertise in Life Detection, Planetary Geology and Geochemistry, and expand on in-situ atmospheric measurements across SMD interests and leverage collaboration with STMD and HEOMD as well.

The Division capability for Analog Research will continue to focus on the following three science areas: (1) Exploration of new environments, selected on the basis of habitability and biosignature parameters; (2) Geologic investigations for understanding planetary systems; (3) Analog field work in support of human and robotic exploration; and will add a fourth area in 2019 that will focus on the creation of virtual, "Synthetic Worlds", in collaboration w/Code TI, based on analog data, to be used for planetary mission design and operations. Figure 6.1 is a summary of select on-going analog field sites, flight Instrument development, and mission science supported programs, highlighting the Division expertise available to the Agency.

Additionally, these science capabilities and mission concepts will be applied to potential mission analog field sites and a variety of spacecraft platform opportunities, including balloons and small satellites, in order to perform planning and ground truthing of mission and instrument concept operations for future robotic and exploration missions.



Based on ARC heritage and current facilities, this core competency will capitalize on in-house capabilities to bring expertise to the Agency in the following areas:

- Exobiology /Life Detection Extremophile Laboratories
- Life Detection and Planetary Protection Protocol Development Instrument Assembly
- IR Astrophysics Laboratories & Astrochemistry Laboratories
- XRD/XRF Instrumentation Laboratories
- Optical/NIR/MIR imaging technologies
- Intelligent Systems
- In situ atmospheric and resource identification and utilization
- Fabrication Machining, Measurement, and Engineering Evaluation Laboratories
- Environmental Chambers
- Planetary Geology Laboratory & Field Instrumentation
- Ocean Worlds science and exploration

Analog field-based research activities provide a lower risk and lower cost environment within which to test and refine protocols and procedures for both robotic and human planetary exploration. Within these analog settings, researchers can develop and iterate on Concepts of Operations (operational design elements that guide the organization and flow of hardware, personnel, communications, and data products through the course of a mission implementation) and supporting Capabilities (functionalities that can take the form of hardware or software) that are focused on optimizing both science return and exploration. This analog testing approach helps to increase the efficiency and efficacy of robotic and human exploration throughout the Solar System.

Objective 6.1 – Establish a Center for Analog Field Studies

Across the Agency, scientists are interested in identifying, exploring and characterizing environments for habitability and biosignatures. This is true for planetary science and astrophysics, connecting planets in our solar system with those detected orbiting alien suns. Our own solar system, which we can visit and study in detail, allows geologic investigations to understand evolution and serve as a proxy for exoplanets. Robotic and human exploration is a major goal of NASA, and the ARC analog team will maintain its leadership in analog field work to support and enhance this goal.

Objective 6.2 – Positively Affect Robotic and Human Spaceflight Utilizing Terrestrial Environments

Future robotic and human spaceflight and exploration will be positively affected by using the safety and convenience of terrestrial environments to develop, test, and hone scientific, operational, and technological capabilities. Concepts of operations that will best serve NASA's core vision and the community. Ames currently has a large cadre of field instrumentation to enable high-fidelity science-driven deployments. Analog testing of such instruments by humans or with robotic rovers and mechanisms can help demonstrate and improve concepts of operations for flight missions. The lessons learned can then be directly applied to future missions such as Resource Prospector or NASA and commercial landed missions to the Moon as well as other planetary bodies.

Objective 6.3 – Identify, Explore and Characterize Environments for Habitability & Biosignatures

Extreme environments on Earth are often proxies allowing the pursuit of information related to habitability and searching for signs of life. Astrobiology field research will continue to be held in extremely dry (hot and cold) environments as analogs to Mars (for example Earth analog volcanic craters and lava tube environments and dry desert regions around the world). Ocean worlds offer a promising habitable environment within hydrothermal systems as well. An ARC science team has begun leading analog exploration research, in connection with NOAA, focused on fluid venting at isolated seamounts in the deep ocean. The future promises to expand knowledge of possible habitable niches across the solar system and beyond.

Objective 6.4 – Develop, Test New Technologies and Instrumentation

Ames scientists are building, testing, and producing new, innovative science instrumentation and technology to support NASA's current and future space mission objectives. In both astrophysics and planetary science, we are particularly involved in exoplanet characterization and next generation planetary missions to the Moon, Mars, asteroids, as well as Europa & Enceladus. Analog mission testing has benefited from new instrument developments and studies, including ARADS and BASALT. The Resource Prospector mission has benefited from analog deployment of engineering model instruments in a field setting, reducing operational risk and increasing operational efficiency. It is expected that these direct benefits will continue to be important in both robotic and human exploration mission concepts.

Objective 6.5 – Advocate for an ARC Instrument Development Center

This instrument development center (IDC) would be similar to the Mission Design Center (MDC), and will fold in science, engineering and project management expertise (with ARC Codes R and P). For example, As NASA gives increased emphasis to lunar return, opportunities for both new missions and new instrument technologies will become available. It is critical to underpin emerging mission and instrument concepts with

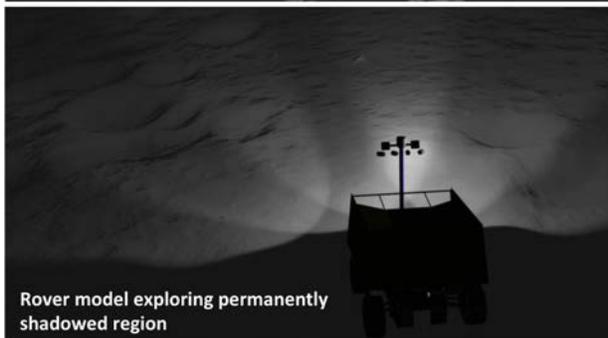
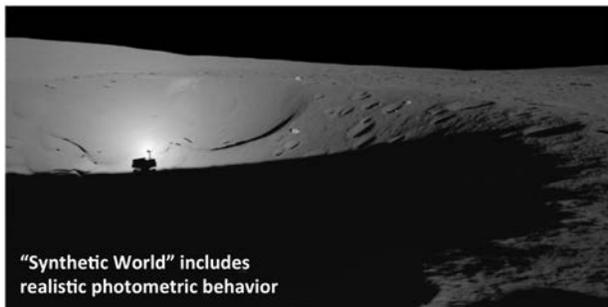
an appropriate level of engineering support to be successful, from concept, through design and into flight development. The development center would provide:

- IDC reports to Executive Council weekly - inform/educate leadership.
- Resources for engineering support for low to mid TRL instrument development stages.
- Internal peer review of instrument and mission proposals.
- A repository of documentation for past successful projects.
- Promotion of cross-center project collaboration.

Objective 6.6 – Develop Instrumentation that Responds to In situ Resource Utilization (ISRU)

By aligning with and supporting HEOMD, AES, SMD, and STMD goals and objectives, we plan to formulate new technology that advances ISRU at the Moon, asteroids, and Mars. Resource Prospector is the first landed lunar mission focused entirely on ISRU at the Moon, specifically polar volatile deposits that may offer a sea change in how Exploration is carried out. NASA's new Public Private Partnership for lunar landed services will open the door to non-governmental entities actually exploring ISRU feasibility and other commercial uses of lunar resources. We also are developing and testing IRRU for ocean worlds such as Europa. Such instruments will be used for characterizing the composition, structure, dynamics, and aerosols on/within/near solid body surfaces and atmospheres. Cutting edge instrumentation will continue to be developed in order to be ready for missions to the atmospheres of Venus, Mars, Titan and the giant planets.

Objective 6.7 – Establish a ‘virtual analog tool’ in support of NASA’s Moon to Mars initiative



In support of NASA's new “Moon to Mars” initiative, we plan to implement a “virtual analog tool” for testing mission operations concepts. In conjunction with Code TI, under the Resource Prospector mission auspices, Analog TT members have built a synthetic lunar world using real lunar topography, lighting, and optical phase functions, with realistic soil mechanics and surface features including impact craters of all sizes as well as rocks down to centimeter scales (see figure, left). We integrated rover-borne instrument models so that scientists can see virtual data, and mission operators can gauge the effects of real-time discovery, and resulting feedback on mission traverse plans. While the Mars program has created similar capabilities, Ames’ virtual lunar surface is the most realistic for lunar surface robotic operations.

While this facility was created by and for the now-cancelled Resource Prospector mission, the existing tools continue to offer significant potential for developing landed surface robotic operations on the Moon. Whether for a near-term Commercial

Lunar Payload Services opportunity, or a larger mid-term mobile robotic mission for science and/or ISRU, a virtual analog can offer significant, rapid evolution of robotic mission concepts of operations, and actual procedure development. With suitable models of spacecraft/rover battery power management, and realistic surface activity energy needs and durations, this tool can provide quantitative feedback to

mission system engineers, as well as mission operations developers. A key issue, as with the other analogs research areas, is continued support. Because this is a joint development with Code T1, ongoing resource needs would need to be coordinated at the Center level.

Milestones: Analog Research and Instrumentation

Year 1 (2019)

- Convene an Ames-led SAG to draft core competencies for the Analog Research Center for Innovation and Design.
- Define directed budgets; define CID org structure, deliverables, and milestone schedules; establish training and development plan.
- Identify personnel, designated lab space, equipment (existing and required).
- Conduct research and develop technology and instruments for identifying, exploring and characterizing environments for habitability and biosignatures.
- Increase partnering opportunities for technology developments both internally (via code R, T, P and Life Sciences), and externally with other NASA centers, academia and industry.
- Encourage Internal Peer Review (team of successful proposers) of instrument proposal concepts to SMD ROSES calls.
- Establish an internal cross directorate instrument development tiger team (See Instrument Section) to help ARC scientists develop instrument concepts for life detection and atmospheric measurements.
- Lead and Participate in STTR and SBIR opportunities to expand our core capabilities.
- Actively recruit for the instrument development NASA Postdoctoral Program (NPP).

Years 2-5 (2020-2024)

- Identify new targets for exploring and characterizing environments for habitability and biosignature.
- Continue to promote and conduct research and target technology development investments that focus on Life Detection capabilities and Geologic investigations for understanding planetary systems.
- Explore Joint Agency Goals and Objectives with SMD, STMD, HEOMD to support Analog field study objectives that enable future human and robotic exploration plans.
- Maintain significant output (publications) in three core science areas (Habitability and Biosignatures; Geological Investigations; Human and Robotic Exploration).
- Establish regular reporting structure with ARC management, SMD, and HEOMD to provide input for NASA-wide goals and mission development.

Years 6-10 (2025+)

- Flagship Mission Instruments Strategy: Ames should plan to submit proposals for the instruments developed in the near and mid-term flagship missions of the future.



Astrobiology and Life Detection

Synergies matrix: Analog field research, Laboratory Astrophysics, Instrumentation, Exoplanets, Astrobiology, Exobiology, Origins of Life, Microbial Ecology and Evolution, Habitable Environments and Biosignatures, Lunar Missions

Partner matrix: GSFC, JPL, APL, SBIR/STTR

Missions supported: Mars, Europa, Enceladus, (MSL, IceBreaker, Europa Lander, ELSAH)

Core Capability 7: Astrobiology and Life Detection

The Space Science and Astrobiology Division was instrumental in establishing Astrobiology as a field and continues to make significant advancements in Astrobiology and Life Detection. We seek to understand the processes that provide continuity from the abiotic formation of organic molecules to the transformation of planetary environments by mature biomes. We have produced multiple biomolecules in laboratory experiments that simulate astrochemical processes in multiple environments, including laboratory and theoretical modeling of molecular clouds and radiation sources. We are linking biological interactions and functions with biogeochemistry and evolutionary biology to explore the relationship between life, habitability, and the factors that constrain the production and preservation of biosignatures. We are developing bioinformatics tools for evolutionary analysis of the emergence of biosignature-relevant traits, and have studied the degradation of organic biosignatures via reactions with mineral surfaces.

In our life detection efforts, we are:

- establishing an intellectual framework to interpret the detectable products of life processes and relevant methods and instruments to detect them.
- developing the capabilities necessary to bridge the gap between the abiotic formation of organic molecules and the emergence of life
- exploring the prebiotic plausibility of chemical reaction networks
developing novel experimental systems to examine processes needed to sustain protocells and to support and shape early evolution.

We explore the boundaries of habitability on Earth by clarifying the limits of life with respect to energy, water availability, and temperature. Our research into life detection and biosignatures in the solar system and exoplanets includes field campaigns and long-term environmental monitoring focused on novel biosignatures that have potential for remote detection on exoplanets and detection in situ by Solar System surface missions. We have investigated hopanoid biomarkers relevant to interpreting evidence of microbial metabolism in Earth's early rock record. We continue to test in situ real-time life detection assay protocols for mitigating false negatives in geobiological samples from deep subsurface, hyper-arid, high elevation extreme environments. We have deployed new instrumentation (GC-IRMS, Raman microscope system) in support of these efforts.

A key component of our work is community and programmatic service: We continue to develop the Astrobiology and Habitable Environments Database (AHED), and have maintained the ongoing effort to

update “Ladder of Life Detection”. We have begun to explore opportunities to inform requirements for planetary protection and contamination control (drill, sample handling), and provide literature reviews of biosignatures and astrobiology strategies.

Objective 7.1 – Connect Abiotic Formation of Organic Molecules to Emergence of Life

To meet this objective, we must understand the relationships between the processes that support the emergence of life, the organic inventory of the Solar System, and the organic content of the interstellar medium. There is a critical gap in the field of Astrobiology that separates astrochemistry from prebiotic chemistry and Ames is well positioned, perhaps uniquely so, to address this gap. We will expand work at Ames on abiotic production of metabolites and their associated reaction networks to understand potential routes from abiotic reactions to biological metabolism. We will continue to investigate the roles of radiation and minerals in the formation of molecules used by extant biology and the formation of other molecules that may play as yet unidentified roles in driving the origin of life. To meet this objective, we will also need to address geochemical processing of organic molecules delivered to planetary surfaces and determine its prebiotic relevance.

The origin of life is defined by the emergence of a system capable of open-ended Darwinian evolution. On Earth these evolutionary processes allowed life to emerge and proliferate, establishing dynamic systems that integrate small molecule reaction networks, functional and information polymers, and selectively permeable compartments. A comprehensive understanding of the mechanisms necessary for the emergence of life requires an examination of how all of these components can evolve as a single integrated system. Ames will continue to develop novel computational and experimental systems that capture the complexities of the multicomponent, early evolutionary processes that drove the emergence of life. Work under this objective also serves our efforts to understand habitability by establishing conditions compatible with emergence of life, and it establishes a starting point for the coevolution of life and its environments.

Objective 7.2 – Biological function and Habitable Environments: Co-evolution of Life and its Environment, and Production and Preservation of Biosignatures

From the first, simplest, tenuous instances of life on Earth to the complex, global ecosystem that exists today, increasing biological complexity and the co-evolution of life and the physical environment have shaped this planet. Our understanding of biological processes, especially at the limits of life, on the early Earth or in unusual and analog conditions, is incomplete and it is therefore essential to advance our understanding of where and how life works on Earth, and the signatures that it makes and leaves behind, to inform the search for life elsewhere. Ames research seeks to understand how physical controls affect biological processes, interactions, and biological and geochemical dynamics to reveal when, why and how diagnostic biological signatures are produced and preserved.

Ames research couples’ molecular ecological tools with biogeochemistry under relevant habitability and life detection conditions and characterizes in situ biosignatures for early Earth, Mars, and exoplanets. Study of the co-evolutionary history of life and the physical environment, through theoretical and experimental studies of biological function, diversity, complexity, and the expansion of habitability, enables understanding of the nature of biological innovation at key branch points in Earth’s history in concert with studies of the geochemical record. Ames researchers will establish models for habitability and microbial metabolism on early Mars and ocean worlds. They will develop a quantitative framework for exploring the emergence of key traits and processes involved in evolution of the biosphere and the production of biosignatures through evolutionary and geologic time.

Objective 7.3 – Habitability Assessment, Biosignatures, and Life Detection in the Solar System and Exoplanets

The search for life requires an interdisciplinary approach to (1) constrain the limits or degree of habitability, (2) characterize diagnostic attributes of life (biosignatures) in the context of the environment, and (3) assess the preservation potential and in situ detectability of biosignatures on other planets and moons and in the geologic records of Earth and Mars. Ames investigators explore the boundaries of habitability on Earth by clarifying the limits of life with respect to energy, water availability, and temperature.

Division and Scientists will continue to participate in the in situ exploration of mineralogical and sedimentary indicators of ancient habitable environments on Earth and Mars. They will further enhance the application of microbial lipids and stable isotopes to identify and characterize signatures of early life and the evolution of our biosphere. They will investigate the transformation and preservation of biosignatures in Earth's rock record.

Overall, the Ames team will employ a combination of laboratory, field analog research, and theoretical investigations in order to improve our understanding of the limits of life, expand the repertoire of biosignatures, and characterize the processes that determine their preservation and detectability. Accordingly, early TRL instrumentation will be developed to characterize geochemical evidence of past environments preserved in ancient rocks.

A new facility will conduct research in planetary protection and develop instrumentation for life detection. A Discovery Program 'Icebreaker' mission will be proposed to search in situ for biosignatures in ice-cemented soils on Mars. Ultimately the Ames team will contribute to investigations of samples returned from Mars.

Objective 7.4 – Support Programmatic Efforts and Serve Research Community

Basic research at Ames provides the foundation upon which to provide key support for the astrobiology and planetary science community. The Ames team will integrate its research efforts with newly-established Research Coordination Networks (RCNs) in Astrobiology. It will provide inputs on requirements for life detection, planetary protection/contamination controls, instrument development, and the selection of landing sites that address astrobiology objectives.

The newly established Center for Life Detection will provide resources for, and points of interface between, headquarters, mission and instrument development communities, and the broader research community engaged in life detection science.

Ames will continue to develop the "Astrobiology Habitable Environments Database" (AHED) to provide a central, high-quality, long-term data repository and discussion forum for mineralogical, textural, morphological, chemical, and isotopic information pertinent to astrobiology. The Ames team will continue to publish literature reviews relevant to astrobiology.

Milestones: Astrobiology and Life Detection

Year 1 (2019)

- Expand work on abiotic production of metabolites and their associated reaction networks to understand potential routes from abiotic reactions to biological metabolism.

- Apply newly established experimental systems to model early evolution in complex multicomponent systems.
- Couple molecular ecological tools with biogeochemistry under relevant habitability and life detection conditions and characterize in situ biosignatures for early Earth, Mars, and exoplanets.
- Establish models for habitability and microbial metabolism on early Mars and ocean worlds and develop a quantitative framework for exploration of the emergence of key traits and processes involved in evolution of the biosphere and production of biosignatures through evolutionary and geologic time.
- Characterize in situ biosignatures for application to early Earth, Mars, and exoplanets.
- Publish evidence for mechanisms of biosignature preservation during sedimentary diagenesis.
- Continue early TRL development of lipid biomarker preparation technology (TRL 1-2).
- Develop Discovery proposal 'Icebreaker' to look for biomarkers in ice-cemented soil on Mars.
- Provide input on requirements for biosignature, life detection and planetary protection and contamination control for instrument development.
- Integrate efforts with newly established Research Coordination Networks in Astrobiology.

Years 2-5 (2020-2024)

- Apply systems-level approaches to research in prebiotic evolution.
- Develop ecological models to predict the potential for specific biological signatures based on environmental conditions, including for early Mars and ocean worlds.
- Model detectability of exoplanet biosignatures in disk-averaged spectra through different atmospheric compositions; input to LUVOIR STDT.
- Significantly enhance in situ biosignature characterization and provide these inputs into Mars 2020 and Europa Lander mission planning activities.
- Increase use of the AHED database for data management and collaboration in the scientific community.
- Fully implement and maintain the organizing scheme for life detection content in a community-accessible, web-based version that incorporates established community standards for life detection.
- Continue to support mission concepts, *in situ* instrumentation development and planetary protection technology, and data analysis for remote detection.
- Continue to strengthen the ties between Astrochemistry and Astrobiology via understanding the formation and degradation of biogenic molecules (biosignatures) under relevant space and planetary conditions (e.g., OREOCube, EXOCube, radiation studies, mineral surface catalysis).
- Develop a Ramdb database containing laboratory and theoretical Raman spectra of biogenic molecules obtained by the LabAstro group.
- Develop lab capabilities for sample return from Mars and elsewhere.

Years 6-10 (2025+)

- Fill in major gaps in understanding of which metabolic compounds are present in meteorites, how they are produced, and what relationship they have to the origin of life.
- Understand the underlying evolutionary mechanisms necessary for the origin and initial proliferation of life on Earth.
- Integrate biological and geological data for a predictive understanding of the limits of habitability and the processes involved in the production, preservation and detectability of biosignatures.
- Establish the Center for Life Detection as a go-to resource for program and mission planning that materially influences mission architecture and implementation.
- Ames leads and/or enables Agency instruments focused on Astrobiology and Life Detection.

Division Admin Support, Hiring, & Challenges



Synergies matrix: Ames center management other NASA Centers

Partner matrix: SSA, SST, SSX

Mission supported: All

Division administration & support provides essential professional administrative & support functions and leadership to aid in the efficient execution of Code SS technical and scientific work. NASA and ARC have been increasing administrative burdens on researchers over time, with increasingly complex administrative procedures and regulations and less technical support by other ARC organizations. This is impacting our ability to perform innovative scientific and technical work efficiently and effectively and has already significantly impeding our output and competitiveness.

Supporting the staff is the foundation and key to holding the busy workplace together. Administrative staff, carry the burden to make sure nothing falls through the cracks and must quickly shift gears to respond to immediate needs or request. Frequently, the administration personal need to respond to “urgent” actions in a limited time frame. These duties require the administrative personnel to have strong office skills, good work ethics, good communication skills, and teamwork.

As part of supporting staff, the Division administration provides guidance, assistance, reviews, and submits many forms for all types of permissions, 1676 forms, purchases, travel, lab safety, conferences, etc. The work-load is more from some and less for others as well as having periods of increased need. Effective interdisciplinary (across branch) communication, load sharing, and designated backups make the processes smoother for all. Training for procedures, cognition of who and why procedures should be done or not, and points of contact in the ARC administration also lessen the load.

The Division administrative is the backbone of the SS Division and should not be treated or thought of as only necessary for service work but an integral part of a smooth running, efficient Division. We need to work to increase the sense of importance and ownership the scientists and administrative staff feel for the Division.

Division Hiring

The acquisition of new hires is a part of the strategic plan for essentially every capability listed in this document. However, Ames hiring procedures are generally not prone to view research science hires as strategically important. However, though advocacy at the Code S level, we are likely to hire “a few” new Division scientists this year. This is not nearly enough (not even close to filling retirements) and is not strategic at all.

Without civil servant hires in specific science areas, we are at a distinct disadvantage in producing successful work packages and developing core capabilities with respect to other NASA Centers. Non-optimal solutions to this dilemma are 1) work with other NASA Centers to increase civil servant participation in research programs or 2) accept fewer, lower funded work packages. Optimal solutions are to hire critical and strategic civil servant positions at Ames. Based on the current civil servant work force, the above overlap with HQ priorities, and Ames center management interests, new hires in FY19 should start with scientists in exoplanet characterization, instrumentation, and life detection. Lower priority should be placed, at present, on other Division areas.

Division Challenges

1. The division has a number of “one deep” scientists. This is especially true in astrophysics (SSA). Such a small civil servant work force in a number of strategic areas places us at a distinct disadvantage within the Agency.
2. How does our Division and the Center realize the potential of the multidisciplinary scientific workforce available at Ames?
3. Our division suffers from a large generation gap - Older civil servants with tremendous knowledge and experience and young enthusiastic contractors. We need to define and honor a path for succession planning, internal promotion, and hiring of good, known talent.
4. Our scientists and our science suffer from a bit of cultural isolation. We need to address this through public, community, Agency engagement. We need to acknowledge and publicize our scientific achievements.

Milestones: Administrative Support

SS administration and support need to overcome a number of inefficiencies and non-compliances, which are impacting worker productivity and morale. This combined with the ever-increasing administrative burdens placed on researchers by Ames, NASA, and the Federal Government, needs modification if we are to remain competitive and solvent. We have made much progress in FY18 on the Division web site, Well-documented policies and procedures that apply uniformly across the Division are needed. These would cover travel, procurements, ARC legal interactions, technical/scientific information release, property, and likely other areas. These shall be easily accessible and tracked, perhaps via the SS Division website.

A high level, Division Administrator employee with a strong business, financial, or administrative education (e.g., MBA or equivalent) and experience (with Federal science agencies) to organize, oversee, and provide guidance and planning of Division activities is needed. This Administrator would be tasked with and held responsible for the efficient execution of the goals enumerated in the Introduction and would have considerable authority in reorganizing the support infrastructure within the Division to achieve those goals. It is expected that successful execution will require significant interaction within Ames (outside of Code SS) and with other NASA Centers and Headquarters. This person would report to the SS Division Chief. The new Division Administrator should be given considerable freedom in implementation.

Proactive management of administrative functions	Establish and enforce clear roles and responsibilities
	Resources assigned in accordance with priorities
	Communication, evaluation, feedback
Recommend Division Administrator to lead effort	Hire CS employee with strong background in enabling science in Federal agencies
	Significant proactive interaction with other divisions (travel, procurement, legal, etc.) at ARC & HQ
	Considerable authority in reorganizing Division administration & support infrastructure
	Evaluate performance based on Admin Goals and scientific / technical output.

2019 Strategic Plan

The Administrative Tiger Team suggests restructuring the existing Division Administrative support to include a designated interim point of contact (POC) for the administrative functions. This could be done ASAP by Division management and would likely have a positive impact on the Division, and to push each milestone out by one year. The milestone schedule is as follows:

Year 1 (2019)

- Establish an interim POC for administrative functions from existing staff ASAP.
- Hire a high-level administrator.
- Establish metrics for evaluating efficiency of Division's business and administrative functions.
- Accomplished partial civil servant (SSA) and hiring for 6-8 new (Division) positions.

Years 2-5 (2020-2024)

- New administration infrastructure fully implemented.
- Initial metrics tracked & evaluated, changes made.
- Expand support in functions & services related to library, graphics, computing, etc.
- Accomplish next priority civil servant hiring.

Years 6-10 (2025+)

- ARC becomes the most efficient NASA Center for performing scientific and technical work.
- Win more grants, publish more papers, and have a large quantity of technical output equal to or greater than other NASA Centers (per capita).

Appendix A: Tiger Teams and Authors

Tiger Team	Lead Authors
Radiative Transfer Capability (RT_Hub)	S. Vahidinia, J. Cuzzi, R. Lupu, S. Piorz, M. Marley, T. Roush, E. Sciamma-O'Brien, R. Freedman, L. Bebout, D. Wooden, C. Dalle Ore, A. Ricca, J. Roser, F. Salama, T. Lee, D.W. Schwenke, D. Cruikshank, D. Olson, G. Gulick, X. Huang
Origin and Evolution of Planetary Systems	J. Cuzzi, P. Estrada, U. Gorti, T. Greene, J. Lissauer, M. Marley, K. Shariff, O. Umurhan; A. Dobrovolskis, T. Hartlep, J. Simon (JSC)
Astrobiology and Life Detection Capability	J. Blank, R. Bonaccorsi, C. Dateo, D. Des Marais, M. Ditzler, D. Dubois, C. Everroad, A. Mattioda, L. Prufert-Bebout, A. Ricca, F. Salama, H. Smith, M. B. Wilhelm
Analog Research & Instrument Development	J. Blank, R. Bonaccorsi, A. Colaprete, A. Cook, A. Davila, R. Elphic, J. Heldmann, D. Lim, A. Sehlke, H. Smith, C. Stoker, M.B. Wilhelm
Exoplanet Characterization: Enabling NASA's search for Life in the Universe	R. Belikov, E. Bendek, T. Greene, S. Howell, R. Lupu, M. Marley, R. Matson, N. Parenteau, E. Sciamma-O'Brien, D. Sirbu
Laboratory Astrophysics & Astrochemistry	L. Allamandola, S. Bejaoui, P. Bera, C. Boersma, J. Bregman, G. Cruz-Diaz, D. Dubois, L. Gavilan, X. Huang, T. Lee, A. Mattioda, M. Nuevo, A. Ricca, J. Roser, F. Salama, S. Sandford, E. Sciamma-O'Brien, M. Shannon
Division Administration and Support	M. Ditzler, M.M. Hassan-Harati, C. To, C. Martinez, T. Greene
Astrophysics Research: Missions, Technology Development, Instruments, Science	T. Greene, T. Roellig, E. Quigley, C. Martinez, N. Rangwala, R. Belikov, D. Sirbu, N. Scott, S. Howell, S. Colgan, P. Temi, T. Colaprete, P. Marcum, K. Ennico-Smith
Planet Modeling: Atmospheres, Climate, and Landforms	A. Brecht, T. Bristow, D. Des Marais, E. Noe Dobra, R. Elphic, J. Heldmann, J. Hollingsworth, M. Kahre, A. Kling, J. Moore, K. Steakley, C. Stoker, O. Umurhan, O. White.

Appendix B: NRC and NASA Reports Consulted

- Vision and Voyages for Planetary Science Decade 2013- 2022” A Midterm Review
- New Worlds and New Horizons in Astronomy and Astrophysics Decade 2010-2020.
- 2018 NASA Strategic Plan
- NASA Technology Roadmap for Modeling, Information Technology, and Processing
- Space and Earth Science Core Competency of ARC
- NASA Astrobiology Program
- Astrobiology and Life Sciences: A Core Competency Deep Dive
- SMD Science Plan 2007 – 2018
- Decadal Surveys: New Worlds, New Horizons in Astronomy and Astrophysics Vision and Voyages for Planetary Science
- Exoplanet Science Strategy
- Developing Planetary Protection Requirements for Human Mars Missions: overview of recent workshops, findings and progress
- Divisional Strategic Plan Capability Gap List (internal)
- Report Series: Committee on Astrobiology and Planetary Science: Getting Ready for the Next Planetary Science Decadal Survey
- An Astrobiology Strategy for the Search for Life in the Universe
- Planetary Protection Human and Robotic Exploration COSPAR 2018 Workshop Report
- COR: Program Annual Technology Report (October 2017)
- Exoplanet Exploration Program Technology and Science Gap Lists 2018

Appendix C: Agency Science and Technology Gaps and Division Capabilities

The goal of afternoon breakout session of the Space Science and Astrobiology strategic planning retreat was to bring awareness to and discuss the overall division strategic plan core capabilities as related to four basic science theme areas: planetary systems, missions and mission support, astrobiology and life detection and human/robotic exploration. We examined how our capabilities map to the Agency science and technology gap areas of emphasis. A variety of Agency documents (see Appendix B) were consulted as part of this year's retreat. Summary science gap slides of the Exoplanet Program goals, Life Detection goals and Planetary Protection Knowledge gap areas were provided to initiate the discussion.

The Division staff were randomly broken into groups to allow good cross organizational discussion of these documents and to 1) examine our alignment with the agency's goals and priorities; 2) review our scientific capabilities; and 3) provide an open forum for discussion and reevaluation of the Division's strategic plan.

Each of the groups were to discuss where we had capability and what priorities should the division consider pursuing with its capabilities to address the Agency science and technology gap needs. Each of the groups were also tasked with adding discussion results from the retreat and directions into their final whitepapers. A summary matrix of areas of core capability within the Division is mapped to Agency Science and Technology gap areas below.

The following NASA needs and Science and Technology Gaps were extracted from the following documents:

2019 Exoplanet Exploration Program Technology List
2019 Exoplanet Exploration Program Science Gap List
NAS 2018 Astrobiology: Exoplanets and Biosignatures
NAS 2018 Exoplanet Science Strategy Study Report
Planetary Protection Human and Robotic Exploration COSPAR 2018 Workshop Report

NAS / NASA's Life Detection: Science Gaps

Division Strategic Plan Core Capability 3, 4, 5, 6, 7

- Additional incorporation of biological understanding into the field
- Improved capability to predict the expression of photosynthesis in different stellar-planetary environments
- Evaluation of potential new biosignatures, both surface and gaseous, and consideration of their false positives
- Characterize the physical and chemical properties of biogenic small volatile gases
- Model fundamental abiotic processes under planetary conditions different than our own
- Development 3-D general circulation models (GCMs) for exoplanets, esp. to simulate biosignatures
- Expansion of coupling of 1-D planetary models with different stellar inputs
- Accounting of all model uncertainties

EXPO Science Gaps: Realizing NASA's Exoplanet Program Goals

Division Strategic Plan Core Capability 2, 3, 4, 5, 7

- Spectral characterization of atmospheres of small exoplanets
- Modeling exoplanet atmospheres
- Spectral signature retrieval
- Planetary system architectures: occurrence rates for exoplanets of all sizes
- Occurrence rates and uncertainties for small planets (eta-Earth)
- Yield estimation for exoplanet direct imaging missions
- Improve target lists and compilations of stellar parameters for exoplanet missions in operation or under study
- Mitigating stellar jitter as limitation to sensitivity of dynamical methods to detect exoplanets and measure their masses and orbits
- Dynamical confirmation of exoplanet candidates and determination of their masses and orbits
- Precursor surveys of direct imaging targets
- Understanding the abundance and distribution of exozodiacal dust
- Measurements of accurate transiting planet radii

EXPO Technology Gaps: Realizing NASA's Exoplanet Program Goals

Division Strategic Plan Core Capability 2, 3, 5

- CG-2 Coronagraph Demo's and Modeling, including contrast, optics, and suppressing to $<10^{-10}$ at visible/IR wavelengths
- S-1 Controlling Scattered Light, limiting edge and diffraction suppression
- S-2 Starlight Suppression and Model validation, including starshades
- CG-3 Deformable Mirrors, including contrast and flight-qualified electronics
- CG-9 Ultra-Low Noise Near-IR Detectors, spectral detection and characterization
- M-4/CG-13 Ultra-Stable, Low-Noise Mid-IR Detectors (7-20 microns)

Science Goals: NAS Exoplanet Science Strategy

Division Strategic Plan Core Capability 2, 3, 4, 5, 7

- Understand the formation and evolution of planetary systems as a product of star formation
- Characterize and explain the diversity of planetary architectures, compositions, and environments
 - Protoplanetary disks, young planets, planet systems, and planet-star separations
 - Determine masses, radii, and (density) atmospheres of planets
- Identify potentially habitable planetary environments
 - Connect these to the planetary systems in which they reside
 - Distinguish signatures of life vs. non-biological processes
- NASA: WFIRST: microlensing & coronagraphs, JWST, RCNs (theory, lab, observations)
- NSF: TMT/GMT - high resolution optical/IR spectrographs

Near Term Planetary Protection Human and Robotic Exploration Priorities

GROUP 2: Technology & Ops for Contamination Control Opportunities in ISS, Ground and Analog Studies and Mars

Division Strategic Plan Core Capability 1, 6, 7

ISS

- Study during normal ops to understand bioburden production/degree of contamination; Assess cleanliness levels, leak rates/transport; Protocols for waste/clean up; & Microbial contamination during EVA operations.
- External & internal swabbing identified as HIGH PRIORITY to assess bioburden production & spread from vents & habitat areas.

Ground & Analogue Studies

- Bioburden levels/releases from Arctic & Antarctic field camp; levels inside-, outside- & far from habitats; Studies for indications of life in ices.
- Lab expts. on viability of microbes under extreme conditions; Modelling to assess/compare leak rates with ISS & Mars tech designs; Modelling/testing releases of Anthropogenic gasses; Testing with regolith & water ice for relevant data.
- Understand CDC/WHO protocols for biocontainment; consider MSR containment (break the chain).

Mars

- Collect data on Mars environment conditions/partitioning; modelling/weather testing.

GROUP 3: Natural Transport of Contamination on Mars

Knowledge about the natural transport of terrestrial biological contamination on Mars is essential to perform informed partitioning of the martian surface, i.e. operation zones for exploration and commercial activities.

Division Strategic Plan Objective 1, 4, 7

New measurements on Mars surface needed to acquire high frequency meteorological data over at least a full Martian year at multiple fixed sites to develop, test & validate contamination, transport models.

Appendix D: Steering Committee and HR Support Team

Steering Committee (Advisory Committee to Division Chief)

Mark Fonda
Jessie Dotson
Jaya Bajpayee
Jeff Cuzzi
Dave Des Marais
Dave Alfano
Kassandra Perlongo
Doug Hudgins (ex-officio)

Human Resources Support Team

Stacy Giffin
Sarah Guillaudeu

Appendix E: Tiger Team White Papers and Retreat Slides

The original submitted 2019 Tiger Team Core Capability White Papers and Strategic Plan Retreat Slide Presentations can be found here:

<https://spacescience.arc.nasa.gov/event/ss-division-strategic-plan-year-in-review/>

The retreat slides include a summary of work accomplished during 2018.



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