



Space Science and Astrobiology Strategic Plan 2018

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Division Vision Statement:

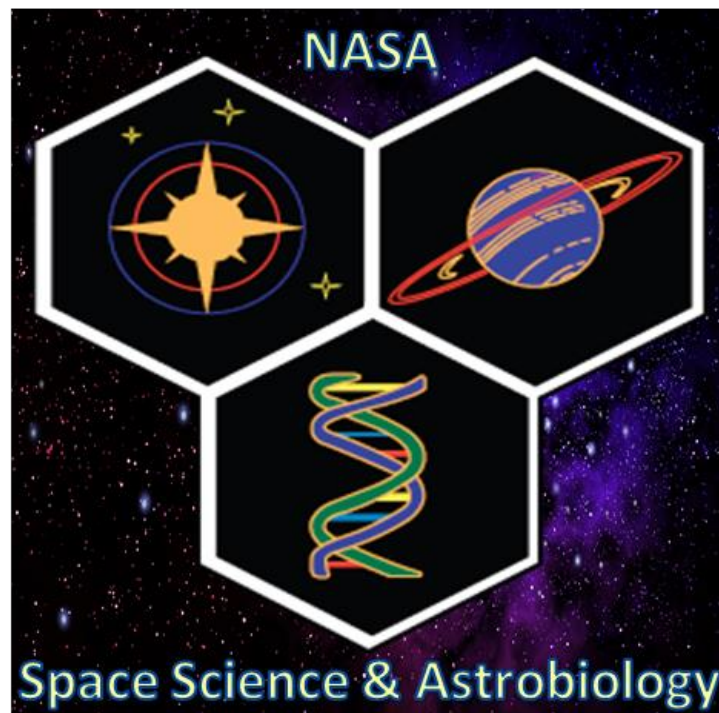
The Space Science and Astrobiology Division will continue to provide NASA and the community core interdisciplinary scientific expertise and capabilities that advance the Nation's understanding of the Molecular Evolution in the Galaxy, detail the Evolution and Formation of Planetary Systems, and expand our knowledge of the Origin and Evolution of Life in the Universe

Division Mission Statement:

The Division's strategic approach focuses on enabling long-term investments in our core capability research areas. Our unique expertise will advance the Agency's science knowledge while driving innovative technology and instrument concepts. We will provide leadership and stewardship that enhances and enables the science community to make new scientific and technical discoveries, thus assuring the success of NASA's strategic goals and space missions.

The Division will pursue Agency leadership roles, building on current core capabilities, in the following strategic focus areas:

- Planet Modeling
- Understanding Planetary Systems
- Exoplanetary Formation, Evolution, Characterization, and Technology Studies
- Radiative Transfer Research
- Laboratory Astrophysics Research
- Mission Driven Analog Research and Mission Concept Operations
- Astrobiology and Life Detection Research and Technology



The Space Science and Astrobiology Division

The Space Science and Astrobiology Division at NASA Ames Research Center provides unique interdisciplinary scientific expertise and capabilities that advance human understanding of the Molecular Evolution in the Galaxy, 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 are focused to enhance and enable the science and exploration goals of NASA and the scientific community.

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

- **Astrophysics:** Researchers study the physical and chemical properties of astronomical objects and phenomena by observing their radiation at optical, infrared and ultraviolet wavelengths.
- **Planetary Systems:** Researchers develop new, fundamental knowledge about the origins of stars and planetary systems, their evolution and formation, their environment, 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 or proposal, but a forward looking positive document capturing the ideas, goals, and objectives of the people involved.

This strategic plan has taken a bottoms-up approach. Ten "Tiger Teams" were formed and given the charter to self-organize and report on specific but broad science areas within the Division while one additional team investigated administrative support within the Division. Teams were told not to be bounded by the past but concentrate on the future, seeking to align the science research areas with NASA's goals and missions. Each team produced a white paper on their subject area which captured what the Division is currently good at, 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 82 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 (six) to present, concentrating on high level Goals and Objectives, Milestones, Core Capabilities, alignment with NASA's goals, and what missions would be supported. The bulk of this strategic plan stems from the white papers and associated presentations at the Division retreat.

Given the forward looking nature of the white papers and of this Strategic Plan, we have asked and addressed the following: What will the Agency need our Division to be good at in the future? How can

the current expertise at Ames, through new hires, Center investments, Branch, Division, and Center collaborations, Agency support, and our own vision continue to build leadership for the future?

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 research 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. The Division will continue to matrix its research scientists into key science and management positions on ARC flight projects. They 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, and define the requirements for future NASA missions.

The Division is committed to devoting its resources and expertise to ensuring a successful completion of *K2* – the Kepler extended mission – in its continued search for exoplanets and its broader astrophysics thrust. ARC will provide the experts and science oversight needed to maximize the 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. And it will provide scientific leadership (and a science payload) to *Resource Prospector*, an HEOMD-funded rover mission to ground truth the earlier results of the ARC-managed *Lunar Crater Observation and Sensing Satellite (LCROSS)*.

The Divisions' scientific and administrative visions have been collected here, with milestones by which to gauge our progress. 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. 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. 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 strategic plan for the next decade, laying out our hopes and dreams as we reach for the stars.

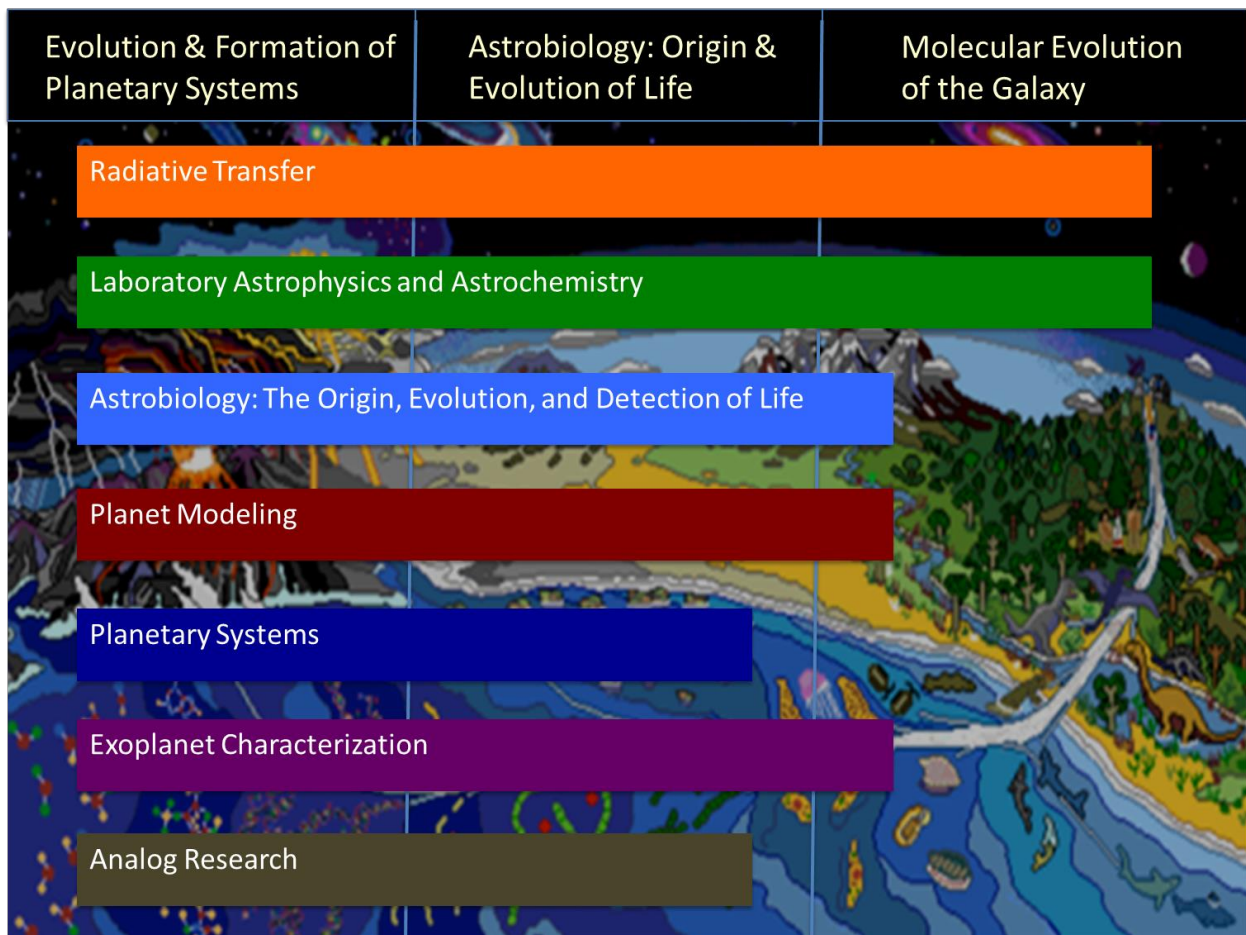
This Document is available from the Space Science and Astrobiology Division office or on our website: www.SpaceScience.arc.nasa.gov

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Graphic summary showing the Interdisciplinary Core Capabilities that exist within the Space Science and Astrobiology Division at the NASA Ames Research Center. The Core Capabilities are illustrated with their cross-cutting relationship to the three major science themes of the Division; The Evolution & Formation of Planetary Systems, Astrobiology: The Origin, Evolution, and Detection of Life, and The Molecular Evolution of the Galaxy.

Core Capability 1 - 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

Theoretical and numerical modeling of planetary atmospheres, climates, landforms, and geochemical processes fundamentally contribute to planetary systems science research at NASA Ames and to NASA's science fundamental space exploration goals and objectives. Interdisciplinary and synergistic relationships exist among planetary atmospheric, planetary landform and planetary geochemical modeling that strengthens each beyond what any one is capable separately. The following scientific goals and objectives for an Ames-based comprehensive, science-enabling planet modeling group are presented over various stages over the coming decade.

Objective 1.1 - Atmospheric and Global Climate Modeling (GCM)

The primary goals of Planetary Atmospheric and Global Climate Modeling (GCM), located at Ames, are studies to isolate, quantify, and understand physical processes (**Figure 1.1**) that control current and past (i.e., paleo-) atmospheric thermal 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 resolution 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.

Along with spacecraft measurements, these goals are most often accomplished using state-of-the-art numerical models. 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 exo-sphere. Over the next five years, the investigations will be broadened to cover newly discovered exoplanetary atmospheres and their climates.

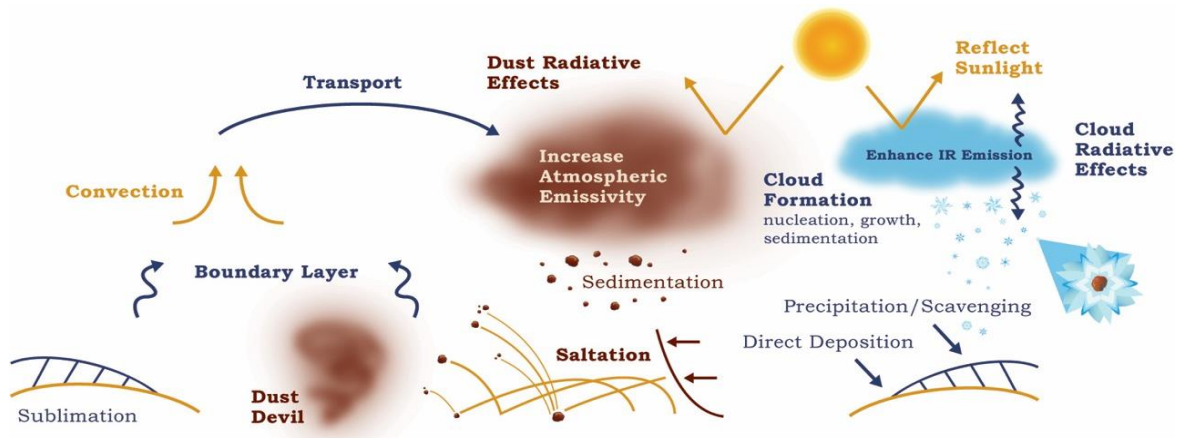


Figure 1.1. A depiction of the major processes influencing Mars' lower atmosphere. Each of these processes is handled within the NASA ARC Mars GCM. Most of these physical processes occur in other planets'/satellites' atmospheres as well.

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 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 described in separate objectives within this Planet Modeling subsection of the Strategic Goal.

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. This 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 1.2**). 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

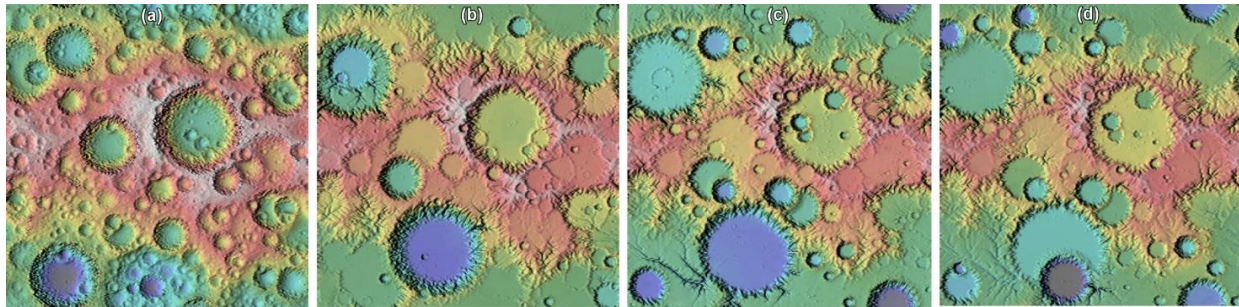


Figure 1.2. Simulated Martian landscape eroded by fluvial processes with ongoing impact cratering. Elevation range is 3000 m. Simulation domain is 102×102 km. Initial conditions, a saturation-cratered landscape, are shown in (a). Simulated elapsed times are 0.26 Myr at (b), 0.40 Myr at (c), and 0.46 Myr at (d).

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. 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. Application of state-of-the-art shape-from-shading techniques will prove to be mission-enabling for missions such as Resource Prospector.

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. Ames 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.

Objective 1.4 - Establishing an Integrated Planet Modeling Group at Ames

Planet modeling “ascertains the content, origin, and evolution of the solar system,” a key objective of the NASA strategic plan. 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.

In the search for life in the universe, the modeling performed will inform ongoing and future searches for ancient habitable environments on Mars and other bodies, and guide the hunt for organic remnants of potential inhabitants. The model results will identify the characteristics and the distribution of potentially habitable environments in the solar system and more specifically to determine their astrobiological potential.

Milestones: Planet Modeling

The NASA Ames Planet Modeling effort will provide to NASA and the community a unique and interdisciplinary team with a broad range of expertise not found elsewhere. We will continue the planet modeling core capability providing consistent support facilities and resources. The totality of which can offer science-enabling research products, codes, databases for utilization in PI-led research projects.

Year 1:

- Advance Venus upper atmosphere climate modeling capability and initiate development of a Pluto global climate model
- Develop new LEM modules that are applicable to fluid behavior (e.g., dissolution, plastic deformation, and glacial erosion) on Mars, Titan, Venus, and Pluto
- Start development of exoplanet GCM
- Start development of GCM of icy worlds and water worlds

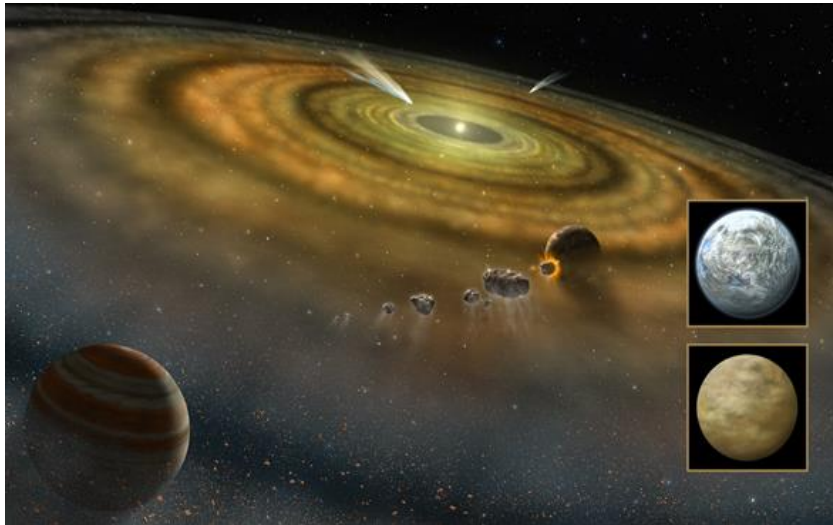
Years 2-5:

- Integrate GCM, LEM, and GSM to establish an Agency core capability for planet modeling
- Complete and test exoplanet, icy worlds, and water worlds GCM
- Establish a standing working group to engage the community
- Establish a framework and infrastructure for consolidating and publishing web-based, model-relevant databases and libraries

Years 6-10:

- Tackle complex issues related to climate history and valley formation on Mars and Titan, and atmosphere-surface interactions on Pluto
- 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

Core Capability 2 - 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

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. The importance of this effort has been catalyzed by the complete revolution in knowledge required to match the incredible diversity and surprises revealed by Kepler/K2 discoveries of planetary taxonomy. Given the many future missions (e. g., JWST, TESS, FINESSE, LUVOIR) focusing on exoplanets, 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 Ames Planetary Systems 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. 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.

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 10⁵ 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 stages hold several important long-term consequences for planet formation, including removal of angular momentum by jets or winds in the inner disk, 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.

Ultimately the diversity of exoplanetary systems must be explained in terms of 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 imminent launch of JWST, the improved sensitivity of HIRMES on SOFIA, and the full ALMA array, there will be immense amounts of observational data in the near future that will need 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 condensibles (from silicates and higher-temperature condensates such as Calcium-Aluminum rich inclusions or CAIs, through H₂O, to CO, CH₄ and other highly volatile materials) are redistributed in the disk before being accreted into planetesimals. 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, and this work continues as we incorporate subtle relative velocity effects in growth of chondrule aggregates that may now have been seen in primitive meteorites. The regimes of validity of candidate leapfrog mechanisms depend strongly on how large aggregates of solid particles can grow, in regions of different temperature, composition, and turbulent intensity, while drifting radially 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. 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, 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 will locate 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 100-200 Myr 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.

The team is actively participating in design, development and execution of missions to primitive bodies, the moon, planets, satellites and rings, and exoplanet space observatories. This work is done in a unique manner at Ames by strengthening interactions within the cross-disciplinary scientific environment in our Division (see Figure 1), within other Divisions at Ames (e.g., Code T), and across the academic community. Our theoretical work on stability in exoplanet systems will directly benefit future missions such as JWST, and produce new constraints based on future observations.

Milestones: Planetary Systems

Year 1

- Improve treatment of turbulence in protoplanetary disk models
- Ascertain role of thermal/MHD winds in gas dispersal; estimate mass outflows from protoplanetary disks
- Incorporate disk winds and mass infall; model elemental depletion seen in chondrites/planets

- Develop detailed models of the late impact flux onto potentially habitable worlds
- Produce relevant theoretical models to interpret our JWST/MIRI Guaranteed Time observations of protostars

Years 2-5

- Investigate formation/evolution of organics and their delivery to planet-forming regions. Enhance current chemical network to include PAHs/organics ice chemistry
- Predict organics & winds emission spectra for JWST/NIRSPEC, SOFIA and ALMA
- Build full, self-consistent models of evolving protoplanetary disk thermal structure and solids mass density, including turbulence, particle growth and opacity
- Model temporal variation of O-isotopes, abundances of ices in outer protoplanetary disks and Solar System objects
- Publish models of limits on orbital stability to guide searches for habitable exoplanets in single and multiple star system
- Develop dynamical instability scenario to account for Saturn's young rings

Years 6-10

- Characterize disks via their line emission and determine the chemical signature of planet formation processes
- Establish a complete picture of the turbulent state of pseudo-Keplerian 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

Core Capability 3 - Exoplanet Characterization



Synergies matrix:

- Characterization – instrumentation, exobiology, habitability, 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, STARDUST, ROSETTA, OSIRIS-Rex, New Horizons, Juno, Cassini, LUVOIR, OST

The research concentration in this area encompasses ground-based observations providing follow-up for Kepler, K2, TESS and other exoplanet discoveries, making use of high-resolution imaging to enable validation and characterization. Most small exoplanets cannot be validated in any other way and this capability provides characterization of the host star system leading to a determination of the correct exoplanet radius and density thereby identifying the most promising targets for follow-up – that is, the determination of likely rocky terrestrial-like planets capable of harboring life. These targets will then be the high priority inputs for HST, JWST and WFIRST observations as well as future space telescopes.

Detailed work with space-based observations include leading observational programs with HST, instrument teams, instrument work and (GTO, early science) observations with JWST, and technology and modeling for WFIRST, as well as tools for analysis of exoplanet observations from all of these missions. Data retrieval techniques are an active area of work at Ames, a continuing effort that will provide detailed libraries and community tools for exoplanet atmospheric analysis. Assessing the observations and measurements required to search for and identify habitability provides the final aspect in exoplanet characterization.

Objective 3.1 - Provide Unique Leadership in Exoplanet Discoveries and Characterization

Our goal in exoplanet studies is to expand the Agency capabilities to characterize exoplanets with both ground- and space-based telescopes and instrumentation to provide better understanding of exoplanet radii, mean density, atmospheric composition, planetary architecture, formation scenarios, planet occurrence rates, direct imaging technologies, and remote detection of the signatures of life. These goals are deeply interdisciplinary across the Division, especially in planet modeling, planetary systems, and astrobiology.

Agency efforts in exoplanet atmospheric characterization will begin to utilize global circulation model (GCM) expertise developed at Ames for Mars and for other solar system planets. Large missions being studied for the 2030s (LUVOIR, HabEx, OST) are focusing on characterizing the atmospheres of habitable

worlds, and Ames plans to continue work on exoplanet imaging technologies and far-IR observations allowing WFIRST and future missions the ability to obtain exoplanet science and images. We must incorporate the significant expertise of our Exobiology branch into exoplanet modeling and characterization and life detection within the next ~5 years in order to advance the requirements for future NASA missions (**Figure 3.1**) and to prepare the NASA community to fully exploit their data.

Ames is particularly well suited 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 Ames, makes a significant contribution to this work and has become the standard technique to validate exoplanet candidates; identifying false positives and detecting stellar companions that can falsify the true planetary radii. Such characterization is especially critical for small, rocky planets in long period orbits essentially not amenable to RV mass determinations or any form of direct imaging.

Exoplanet vetting is critical for TESS (with its 20 arc sec pixels) to confirm which candidates are real exoplanet detections and to set strict limits on possible companions which, if unaccounted for, can cause exoplanet radii to be incorrect (i.e., too small) by an average factor of 1.5X. Underestimating planetary radii in this way leads to improper density estimates and over-predicting the occurrence rate of Earth-sized planets, affects the classification of rocky planets, and may misidentify top-ranked candidates for follow-up studies. Proper exoplanet size and density information is also vital for modeling planet formation and evolution, as well as understanding system architectures. This type of observational work is essential for pre-screening/identifying interesting (e.g., terrestrial) planets suitable for follow-up observations with upcoming missions like JWST and WFIRST and life detection efforts by future space-based platforms.

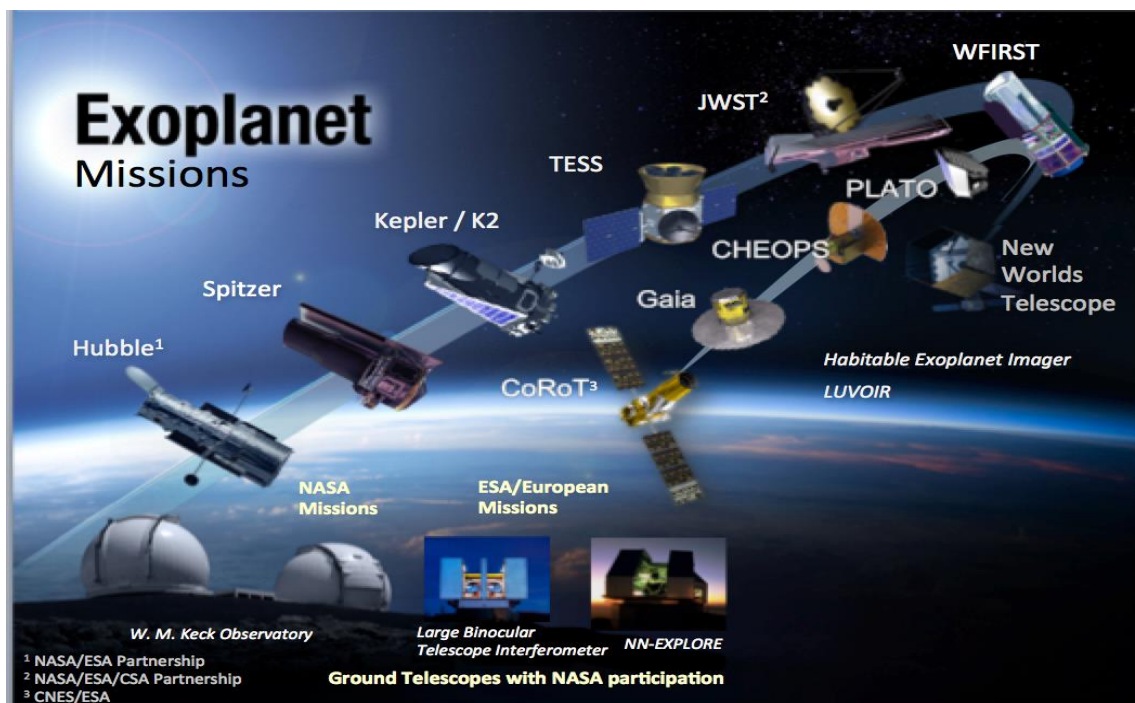


Figure 3.1. NASA's Exoplanet mission timeline.

Objective 3.2 - Develop Exoplanet Atmosphere Models

JWST will drive the field of exoplanet atmospheric studies for the next decade. HST has shown us that H₂O is common in giant planet atmospheres, and that high altitude clouds are often present 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., photo-chemical products) as can be seen in **Figure 3.2**. This will greatly inform the formation and thermo-chemical structures of these planets, and JWST's sensitivity will enable expanding these analyses to planets that are Neptune mass or below.

All of the information we receive about the composition of a planetary atmosphere comes to us from photons, which have interacted with the atmosphere. Transit and eclipse spectra for transiting planets and emitted and reflected spectra from directly imaged planets all carry the signatures of atmospheric gasses and aerosols that have interacted with the photons we receive. To interpret these signals we must understand the atmospheric structure, composition, clouds, hazes as well as the global atmospheric dynamics. 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 atmosphere codes.

In the past half dozen years 'retrieval' methodology, pioneered in the Earth sciences community, has seen a major ascendance as the latest method of choice for such studies. In this approach hundreds of thousands to millions of models are computed on a supercomputer and compared to data. Those sets of model parameters that best fit the dataset given the stated error bars provides a rigorous description of the information content of the data.

Clouds and hazes populate every solar system atmosphere and have been demonstrated to be present in exoplanet atmospheres as well. Clouds and hazes can block radiation from deeper atmospheric levels

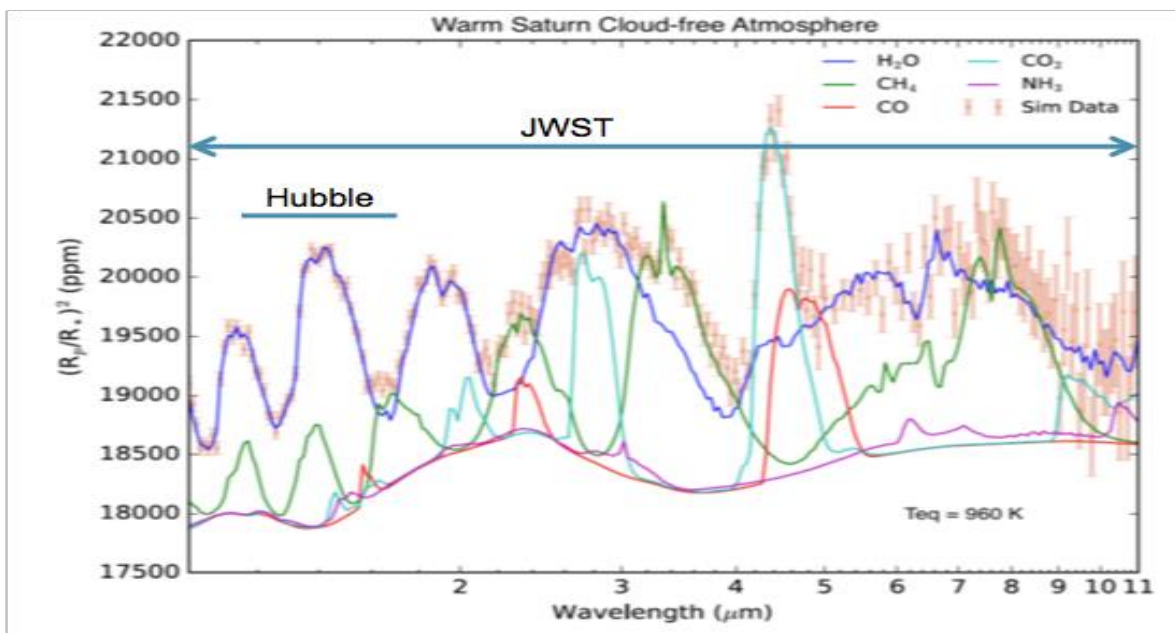


Figure 3.2 - Model atmospheric spectra of a warm, cloud-free Saturn type exoplanet showing the wavelength range covered by HST and the larger, more complete range that will be covered by JWST.

and through scattering can complicate retrievals of atmospheric abundance. They are also tracers of atmospheric dynamics. For all of these reasons exoplanet clouds must be accounted for in both retrieval and forward models of exoplanet atmospheres. There is much yet to accomplish in cloud studies and greater expertise is needed. 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 life finding telescope missions.

Objective 3.3 - 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 3.3**.

NASA's next flagship telescope after the James Webb Space Telescope (JWST) is 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.

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 $\sim 3x$ closer to the Sun than any other Sun-like star. As can be seen in Figure 3.3, Alpha Centauri is an extreme outlier and "low-hanging fruit".

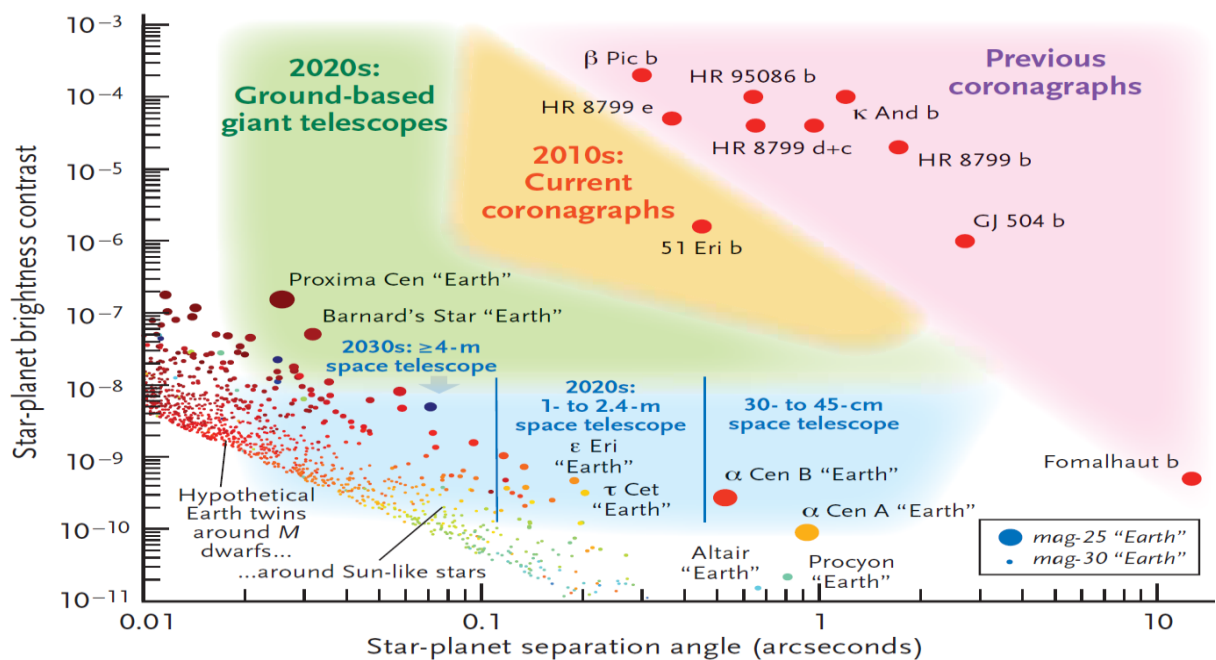


Figure 3.3. Overview of the field of exoplanet direct imaging in visible and infrared light. Capabilities of past, current, and future direct imaging instruments are shown. Red dots in the upper right are known directly imaged planets. Dots in the bottom left are our goal: hypothetical Earth twins around many nearby stars (out to 20 parsecs).

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 3.4 - Determine the Measurements Required to Assess Habitability

Current work in the Exobiology Branch focuses on measuring the surface reflectance and polarization spectra of anoxygenic phototrophs, vetting false positives and false negatives, understanding the “rules” that dictate their spectral features so that they can be predicted for different star-planet combinations, and assessing their remote detectability as a function of environmental context across a range of spatial scales: (1) local field measurements of environmental samples, (2) regional on modern Earth (continents and oceans) using airborne sensors and Earth-observing satellites, and (3) planetary-scale in exoplanetary disk-averaged spectra under various atmospheres and cloud coverage levels. Modeling partnerships include the NASA Astrobiology Institute Virtual Planetary Laboratory and University of California-Riverside teams.

The Exobiology Branch plans to serve as a leader for expanding the engagement of microbiologists and early Earth biogeochemists and advising them on how to convert their research to make it applicable to exoplanets. Additionally, input from the ‘origins of life’ Exobiology Branch researchers 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

- Investigate star systems of K2 and begin investigating TESS exoplanet candidates to identify systems with singular and binary stars. Collect, reduce and submit data to NASA archive. Document observations and analysis in refereed papers
- Develop new approaches to the interpretation of cloudy exoplanet atmospheres, especially those using retrieval techniques
- Begin cross-disciplinary modeling efforts incorporating biosignatures and model exoplanet atmospheres; Start development of exoplanet GCM
- Characterize important and / or unique biosignatures and quantify biogenic fluxes

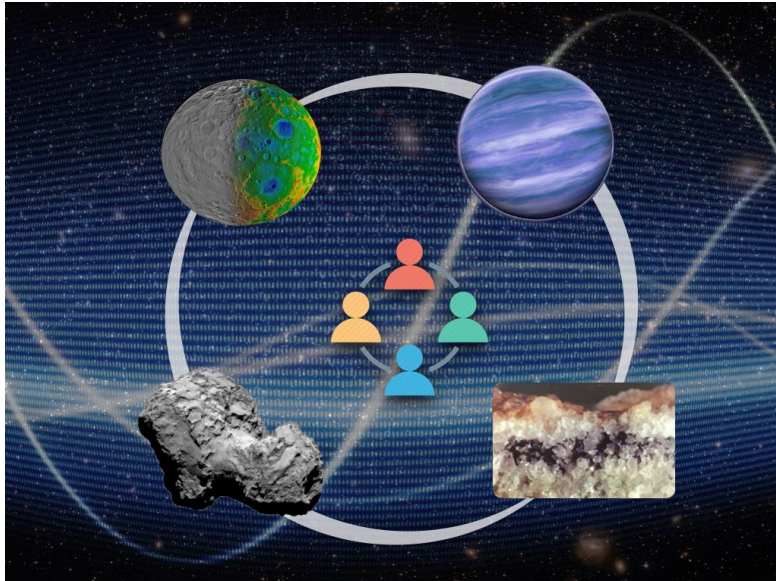
Years 2-5

- Complete K2 star system database and continue validating star systems of newly discovered TESS exoplanets to see whether they are singular and binary stars. Finish WFIRST target vetting and publish results. Place all data into NASA archive
- Analyze spectra of JWST exoplanets to characterize the planets, including identification of atmospheres and biomarkers.
- Contribute to scientific planning of WFIRST Exoplanet observations
- Test biosignature detectability and uniqueness using Earth
- Provide cross-disciplinary atmosphere retrievals (astro/Earth); Complete and test exoplanet GCM

Years 6-10

- Continue observational effort to characterize star systems of exoplanets- Ground-based (as needed) and JWST using high priority targets (TESS, other)
- Develop 3D models of disk averaged biosignatures
- 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

Core Capability 4 - Radiative Transfer Research



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

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, LUNAR

NASA Ames has a strong core competency in theoretical and computational radiative transfer studies. Initially focused on planetary astronomy and directly related to solar system missions, this science capability has grown both in number of projects and in science scope. Radiative transfer research in the Division now encompasses collaborative work not only in planetary astronomy but in astrobiology and astrophysics as well as Earth science. **Figure 4.1** shows how the radiative transfer hub at Ames has connected research efforts across science disciplines. As a part of the Division 10-year strategic plan, a core competency for Radiative Transfer studies will be developed at ARC, providing support to the Agency's scientific initiatives and space mission needs.

Radiative Transfer (RT) is an essential and unifying toolset needed to interpret all remote observations spanning airless bodies, atmospheres of exoplanets and solar system bodies, and protoplanetary disks. Modeling has included characterization of gases, atmospheric aerosols, surface components on solar system bodies, and extrasolar planets. The RT core competency will be preserved and expanded in order to provide a community resource for the Agency and an active role in the success of current and future space missions.

A core group has been formed at Ames to aid the interpretation of the vast phase space of forthcoming observations and provide innovative new RT methods for critical services to the NASA scientific community. These services will be expanded to include an agency resource across research topics and public toolsets centered on radiative transfer modeling. This work will allow the team to play a key role in leading the analysis of future sample return and life detection missions, exoplanet space missions, and in forging international collaborations.

An institute where the radiative transfer group efforts are greater than the sum of its parts is envisioned. This institute will cross-fertilize personnel and resources at Ames and make/strengthen collaborations across divisions, NASA Centers, and academia.

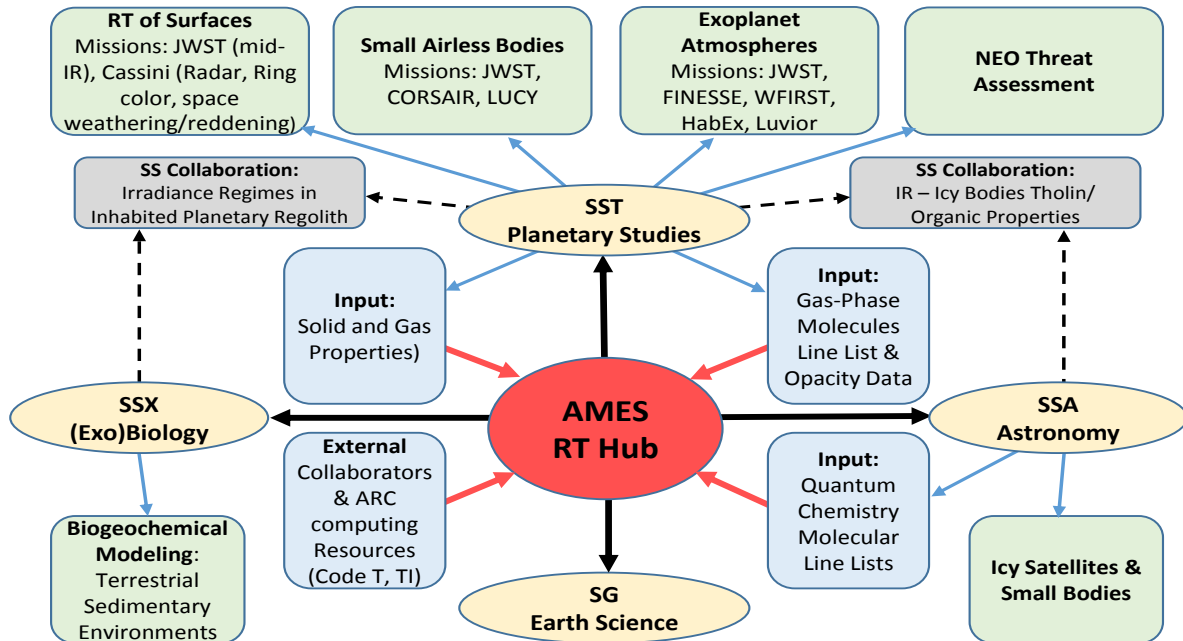


Figure 4.1. The Ames radiative transfer hub has expanded research efforts across many science disciplines.

Objective 4.1 - Next Generation Radiative Transfer Methods and Tools

Radiative Transfer research at NASA Ames is a cross-disciplinary collaboration focused on applied research across multiple science areas. Detailed models of planetary atmospheres, related to the emission, absorption, and scattering of light by gases and particles will be developed. These models will 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 ranging from near-IR to microwave and radar are needed. Such surfaces can be quite complex in terms of reflection and emission especially in the mid to far IR where regolith grains are wavelength size. This problematic regime is in critical need of the next generation models that we have under development, especially for optimizing science return from observations of airless bodies by Cassini and JWST and upcoming lunar and sample return missions. Complex surfaces 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 gases and solids (gas opacities, solid material refractive indices) central to all modeling calculations, and derived from both theoretical and laboratory work, will be maintained in an archive.

An extensive model toolset has been developed, 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 much needed database of optical properties over a range of relevant materials. The gas and particle properties will be used in state-of-the-art models of radiative transfer in model atmospheres with clouds and hazes, regoliths of planetary bodies (with or without an atmosphere), and exoplanets. The expertise and tools developed will be turned into an interconnected

hub that employs efficient pipelines, adopts best practices, and provides continuous support for community-wide users. The technical capabilities currently available are outlined in **Table 4.1**.

In order to continue and expand leadership in the development and application of radiative transfer tools, the group will not only to preserve the existing expertise, but will also make investments to employ the newest practices and facilitate communication across teams. 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	Currently in use and under development	Future development
Databases	Gas opacities and material refractive indices	
Cloud model for planetary atmospheres	1D cloud sedimentation model	Microphysical & Global Circulation Models
RT in atmospheres	RT models in thermal emission, transit, and reflection. (Ex., Discrete ordinates method, and particle opacity transit code)	Incorporate sophisticated particle scattering models
Atmospheric Retrieval codes	Bayesian methods (Monte Carlo Markov Chain, and Multinest)	Incorporate with surfaces
Aerosols/aggregate particles	Codes for particles with complex shapes, morphology, and inhomogeneous composition across all wavelengths (Ex. Discrete Dipole Approximation (DDA), Mie/Effective Medium Theory (EMT), Mie-spheroid)	Aggregate particle scattering code (T-Matirx) to compare computational efficiency with DDA.
Regolith Radiative Transfer (RRT): Granular surface layer codes spanning UV/VIS – mid-IR, and Radar	Models for surfaces: Closely packed grains of various sizes (wavelength size or smaller regolith grains - DDA RRT code; large size regolith grains – ray tracing spheroid bed, Hapke). Separated grains of various sizes (large grains with facets – Monte Carlo ray tracing; inhomogeneous aggregates of varying size – hybrid Discrete Ordinates/DDA codes.	Temperature gradients and thermal source terms in surface codes. Linking geochemical model with radiative transfer of spheroid beds.

Objective 4.2 - 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, since the grids can grow fast with more complex models and number of parameters and the retrieved parameter constraints are limited by the grid spacing. 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. A retrieval package is currently being developed to help guide the design and requirements for the coronagraph instrument onboard the future WFIRST mission, and prepare to interpret its observations. The flexibility of these methods make it appropriate for tackling other

observational data, such as those of airless bodies. Different groups can thus bring their expertise together to build new and critical tools. In order to do so, a special package incorporating optical data and specific radiative transfer routines for airless bodies will be built with ARC utilizing their expertise to lead the way.

Additionally, the team will use these tools in order 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 competency at ARC will provide modular toolsets (databases & RT models) for community involvement, space missions, and Earth and biological science.

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 groups outside the traditional Division science work which will be integrated into the cross-discipline research group.

Milestones: Radiative Transfer Research

Year 1

- Nucleate a cross discipline group, hold initial workshop to cross fertilize RT between branches, Divisions, and across the agency
- Develop new exoplanet atmospheric cloud and haze models - retrievals
- Develop reflectivity/emissivity methods for spectra of granular surfaces
- Develop models for Resource prospector; low Sun angles and challenging regolith phase relations
- Compare and utilize RT models with laboratory & computational datasets
- Compute gas opacities for hot exoplanets
- Measure optical constants of solids, especially for Titan & Pluto analogs
- Leverage Mars GCM for exoplanets

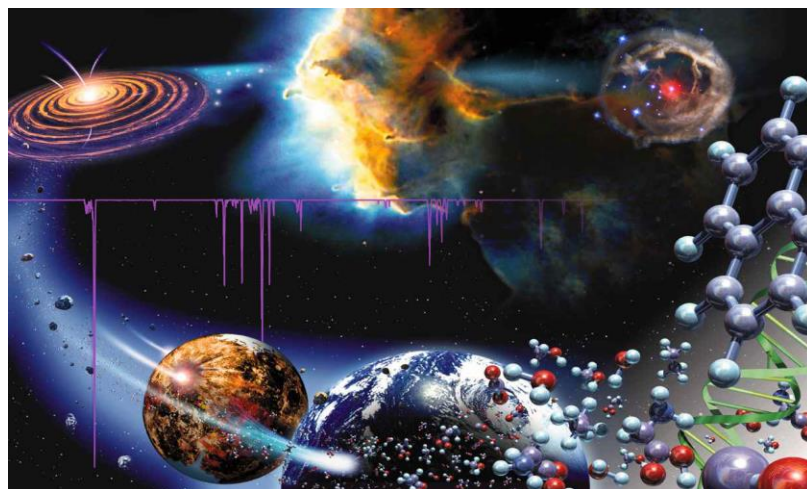
Years 2-5

- Integrate new RT toolsets with new retrieval methods for the JWST community
- Expand public databases of gas opacities and solids optical constants
- Organize yearly RT workshops across NASA Centers and academia

Years 6-10

- Enable new discoveries across NASA community via RT tools and web service
- Apply RT toolset for retrieval studies of aerosols & habitability indicators
- Enhance public repositories for code and opacity/material databases
- Respond to RT requests from NASA and community

Core Capability 5 - 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, LUNAR

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 consists of laboratory experiments and theoretical calculations that are key factors for the understanding of our universe by complementing astronomical observations and modeling. Laboratory experiment and quantum calculations simulating astrophysical conditions generate data (spectra, optical constants, opacity, line lists, etc.). These data are used to interpret the observational data returned by missions and provide testable predictions to advance knowledge and guide future observation campaigns. Increasingly accurate astronomical observations provide direction for Laboratory Astrophysics measurements and calculations. Hence, confronting observations with experimental data can be a driver for new mission proposals, development of new technologies, and mission instruments.

The multidisciplinary nature of the work force at NASA Ames (astrophysicists, astrochemists, physicists, planetary scientists, theorists, astronomers) makes it a unique environment for doing Laboratory Astrophysics research. The expertise of the Laboratory Astrophysics group at Ames, and its well-

Table 5.1. List of Laboratory Astrophysics applications investigated by the NASA Ames group

Science Area	Research Capabilities
Molecular Universe	PAHs and Carbon Molecules – characterization from UV to IR
	Astrophysical Ices – characterization in IR + optical constants
	Photochemistry of irradiated ices – characterization in IR
	Ice-grain interaction – characterization in IR
	Cosmic grain analogs – formation mechanisms and characterization
	Small molecules (highly accurate line lists) – assignment of weeds and flowers
Astrobiology	Irradiated ice residues, pre-biotic molecule formation processes
	Evolution of organic matter in space environment
Solar System	Comets/meteorites/asteroids – return sample analyses + lab studies
	Planetary atmospheric and surface chemistry – Io, Moon, Pluto, Venus, Titan
Exoplanets	Spectral lines, opacities, experimental simulation

established and recognized experimental and theoretical facilities for the study of a variety of molecules and environments, will be exploited, providing an Agency capability in Exoplanets, Astrophysics, Astrochemistry, Astrobiology, and Solar System science (**Table 5.1**).

The Ames Laboratory astrophysics/chemistry group will continue to be an Agency leader in providing critical data that exoplanet modelers, astronomers, and astrobiologists require to conduct their research. The ARC group will focus their laboratory efforts on support of critical experiments, those based on the desires of the space 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 carbon molecules and grains. Research into PAHs has become an interdisciplinary investigation involving Ames scientists in planetary astronomy and astrophysics with close collaborations at other institutions, most prominently Leiden University and the Dutch Astrochemistry Network. The NASA space telescope missions *IRAS*, *ISO*, and *Spitzer* have provided a wealth of detail on subtle variations of the band profiles and positions that can only be analyzed by comparison with laboratory data and models, which will be used and extended for JWST.

A critical part of the Ames work on PAHs is the PAHdb, a comprehensive archive of laboratory measured and quantum chemical computed spectra of PAHs in astrophysically-relevant conditions. We are currently engaging with JWST science teams as to their direct needs in terms of PAH research. PAHdb (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 Exoplanets

Reliable models of exoplanet atmospheres are in their infancy and have many laboratory data needs. These include highly-accurate rovibrational line lists that include transition intensities for stable molecules that are often found in atmospheres, such as H₂O, CO₂, SO₂, NH₃, CH₄, etc. These line lists need to be fairly complete, often being composed of hundreds of millions of lines or more if the atmosphere to be modeled is hot – approximately 500K or higher. There is a general need for high-resolution experimental and ab initio quantum mechanical theoretical studies to obtain accurate rovibrational line lists for other molecules and at significantly higher 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 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 planets.

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 silicates and grains, and are dominated by simple molecules such as H₂O, CH₃OH, NH₃, CO, CO₂, and CH₄. Once formed, ionizing radiation can

change the structures of the ices producing new, more complex molecules. This objective will investigate photochemical processes of UV irradiation of such ices at cold, interstellar temperatures. The results of these experiments often produce astrobiologically interesting complex prebiotic molecules. These organic compounds, such as amino acids and sugars, will be examined and investigated further in an attempt to determine critical steps in molecular formation resulting in macromolecules and the beginnings of life. The laboratory measurements and 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 theoretical quantum chemical model 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 archive. Detailed comparison with returned non-terrestrial 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

Milestones: Laboratory Astrophysics and Astrochemistry

Year 1

- Develop a strategic direction for the lab and prepare a step-wise plan to upgrade/replace critical experimental laboratory equipment in line with Agency direction and following community and mission needs
- Include new PAH IR spectra (calculated and experimental), anharmonic corrections, and new tools in PAH database
- Migrate PAH and other data (experimental + theoretical) to publicly accessible archive
- Work with JWST science team to identify and then provide mission critical experimental and theoretical data matched to observations
- Identify PAH and other astrophysics, astrochemistry and astrobiology needs of NASA missions including JWST, WFIRST, and SOFIA

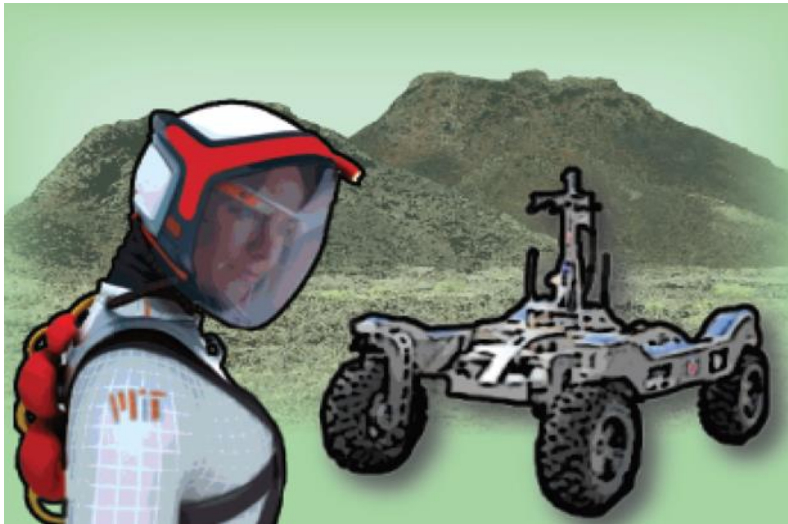
Years 2-5

- Add small molecules, theoretical spectra, and measured optical constants to archive database
- Conduct synergistic theoretical and experimental research on organic matter, in support of OSIRIS-Rex
- Provide gas-phase IR spectroscopic measurements in support of JWST
- Continue to produce rovibrational line lists needed to characterize exoplanet with JWST

Years 6-10

- Continue to work closely with science teams of JWST, SOFIA, WFIRST, and LUVOIR to provide mission critical experimental and theoretical data
- Produce laboratory measurements of available returned samples in preparation for future missions

Core Capability 6 - Analog Research & Instrument 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

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 Ames capability for Analog Research will focus on the following three science areas: (1) Identifying, exploring, and characterizing environments for habitability and biosignatures; (2) Geologic and Atmospheric investigations for understanding planetary systems; (3) Analog field work in support of human and robotic exploration. **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.

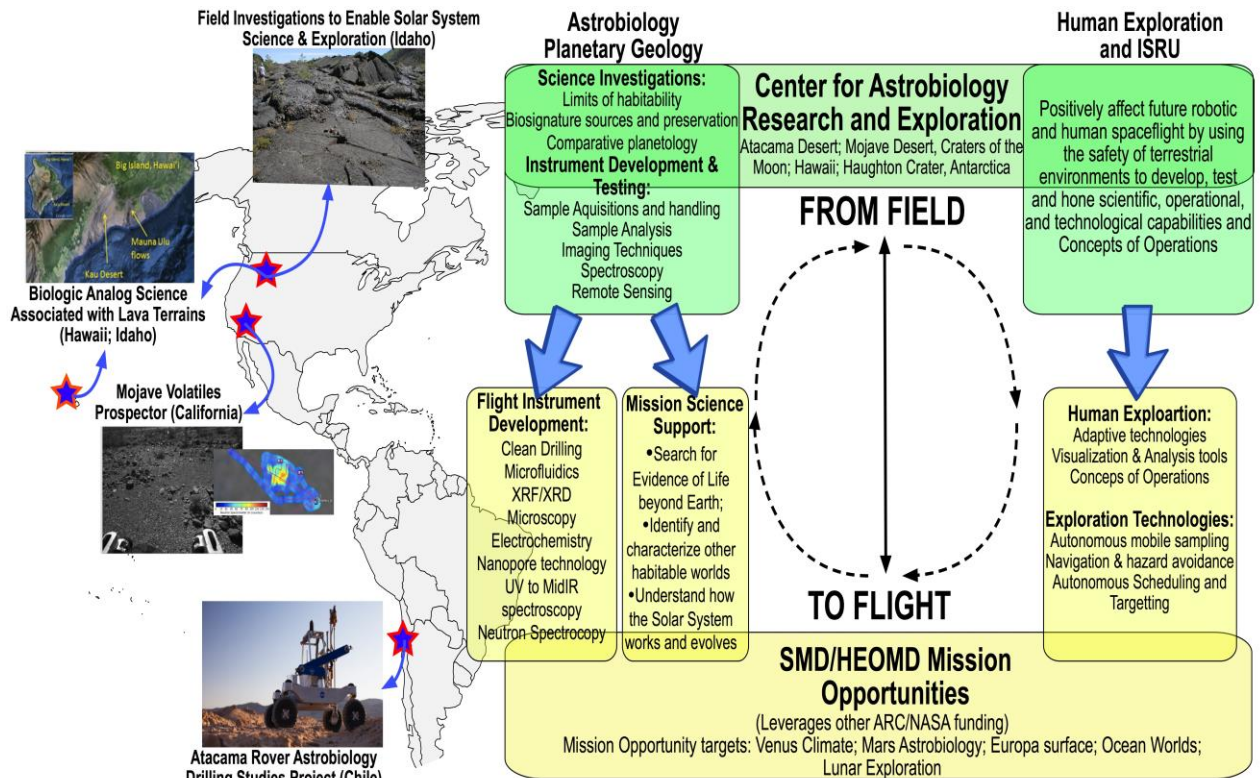


Figure 6.1. Summary of select ARC Analog activities and flight instrument development areas.

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 Science Evaluation Laboratories
- Environmental Chambers
- Planetary Geology Laboratory & Field Instrumentation

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.

Table 6.1. Science areas and instrumentation which will be developed further

Science Area	Instrumentation planned
1,2,4	End to end sample handling and processing capabilities for planetary and robotic mission exploration
1,2,3,4	Expansion of microfluidic technologies front end and sample processing devices
1,2,4	XRF and XRD technology advancements including particle induced X-ray emission imaging concepts
1,2,4	Penetrator concepts, Subsurface drill technologies
1,2,4	Immunoassay and nanopore sequencing technologies for biosignature detection
1,2,4	Fluorescence imaging microscope technologies
3,5	Electrochemical sensors, UV, NIR to MidIR spectrometer imaging and thermal radiometry technologies
1,2,4	Neutron spectrometers, Laser nephelometers
1,2,4	Micro mirror systems and handheld field portable instruments for Robotic exploration
3,5	Coronagraph and NIR spectral imaging instruments & technologies

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. **Table 6.1** lists current and near-term instrumentation that will be brought to higher TRL levels through these analog studies.

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 and 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 Incubator 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 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.

Milestones: Analog Research and Instrumentation

Year 1

- 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)

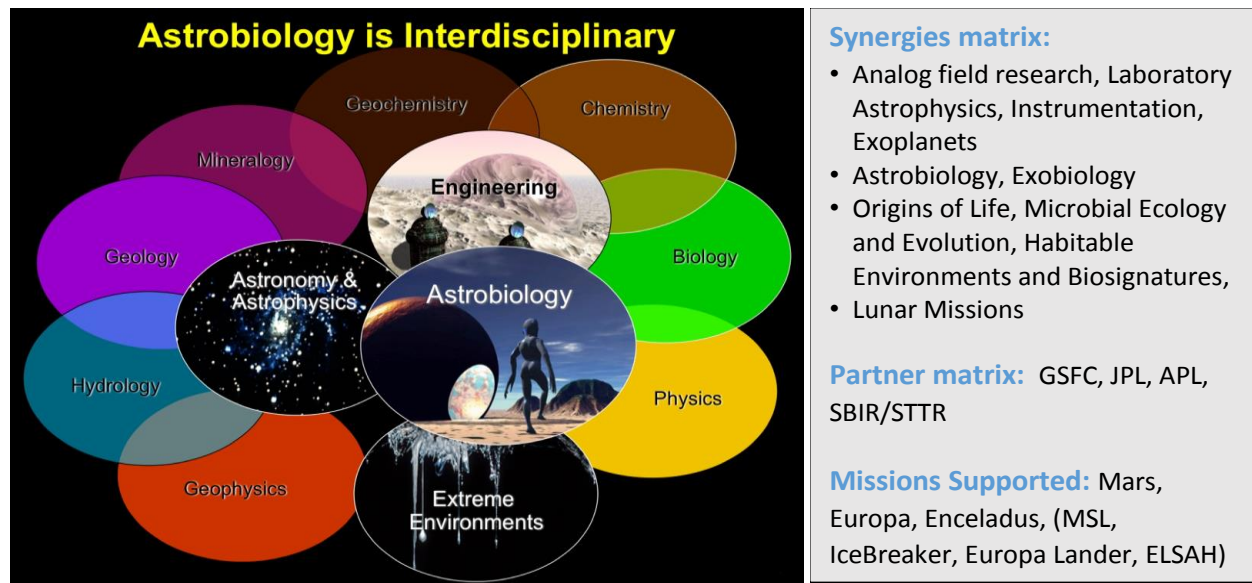
Years 3-5

- 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

Years 6-10

- 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

Core Capability 7 - Astrobiology: The Origin, Evolution, and Detection of Life



The fields of astrobiology and exobiology focus on understanding the origin, evolution, and distribution of life in the Solar System and beyond. These fields are highly interdisciplinary and involve a wide range of topics from understanding the abiotic origins of the small molecules that constitute the building blocks of life, to understanding how mature biomes are able to shape their environments to suit their needs. The interdisciplinary nature of these fields and their mutually beneficial feedback, make Ames an ideal center for the Agency's stand at the cutting edge of astrobiology and exobiology.

Objective 7.1 - Origins of Life

The origin of life research program addresses how life can emerge, persist, and proliferate on a planetary scale by connecting abiotic processes to the complex and coordinated processes of biological evolution (**Figure 7.1**). Work in small-molecule prebiotic chemistry seeks to connect the abiotic production and reactivity of small molecules with the origin of metabolism. Critical to this effort is the further exploration of the presence and production of labile metabolites and their derivatives in both meteorites and simulated prebiotic systems. Work with macromolecules combines experimental systems with modeling and simulations to identify how these molecules can acquire and improve functions. For a more complete understanding of the processes leading to the origin of life, future efforts will focus on how small molecules, macromolecule, and complex assemblies can work in concert to form systems capable of sustained open-ended evolution, i.e., systems that continually produce novel and adaptive forms. This will be accomplished through a comprehensive

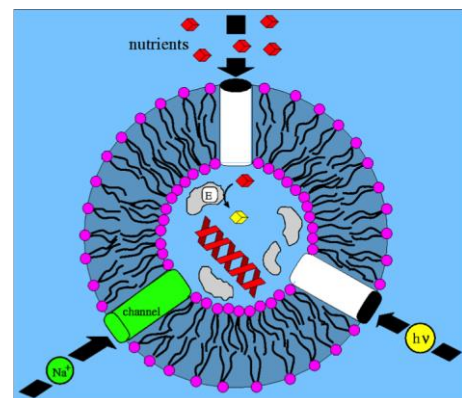


Figure 7.1. A schematic representation of a protocell illustrating the components necessary for stability, growth, replication, and evolution. In this evolving entity, all components work in concert. This feature, which is not present in past studies of the individual components, will be a focus of future work in origins research at Ames.

approach, which applies an evolutionary point of view to a broad range of protobiological processes from functions of individual polymers to the behavior of full, protocellular systems. This approach will address how evolutionary mechanism in emerging life differ from those in established biological systems and how emerging life can use these mechanisms to capture energy, replicate, and spread beyond its initial niche.

Objective 7.2 - Biological Complexity, Interactions, and Co-Evolution of Life and the Physical Environment

Life, if it exists beyond Earth, is likely to be microbial. Detecting microbial life on other worlds can be informed by understanding and cataloging the types of biomarkers that are produced here in modern day microbial ecosystems. However, a true predictive understanding of microbial detectability requires a mechanistic understanding of the way in which microbes have co-evolved with each other, and with their planets of origin, in the complex ecosystems in which they inevitably occur (**Figure 7.2**). Microbial ecological research relevant to astrobiology and the detection of biosignatures both in situ and remotely is therefore driven by questions that include: 1) How novel biological function, physiology and diversity promotes the expansion of life, 2) How evolutionary processes lead to modifications of physical and chemical environments and facilitate exchange of chemicals and energy needed to sustain life, and 3) The mechanistic ways in which community structure and complexity expands habitability.

Experimental efforts performed in on-site environmental simulation facilities, including greenhouses for photosynthetic ecosystems as well as equipment for simulating light, radiation, pressure, hydration and temperature environments, provide the basis for technology and science goals. Such facilities could also provide test standards for the development and evaluation of instruments and capabilities for in situ life detection missions. Remotely, even though individual microbial populations are small and difficult to detect, the composite activity of microbes is huge. Understanding the responses and interactions of microbes at small scales allows linkages with detectable bulk planetary processes (e.g. through modeling), as driven by bulk microbial activities and responses to environmental conditions.

Finally, we must recognize that while it may be impossible to simulate the time scales (millions to

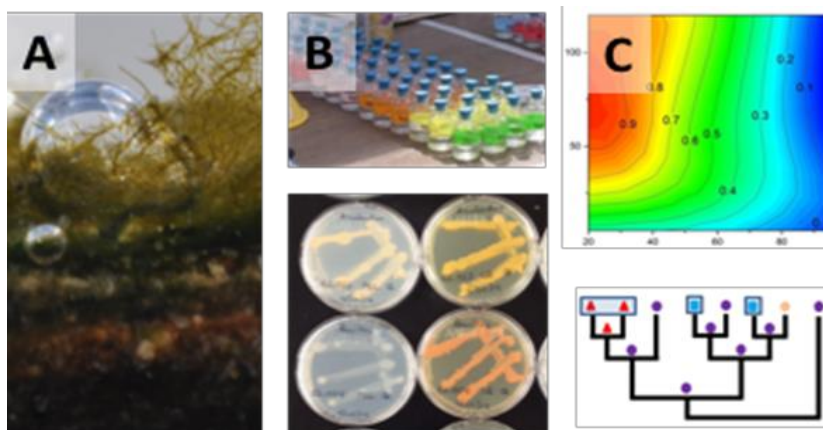


Figure 7.2. A) Complex microbial systems are the most likely form of life to be found beyond Earth. B) Understanding the mechanisms of biosignature production in microbial systems requires integration of biogeochemical, physiological, and evolutionary research. C) Science outputs from such research are essential for a predictive understanding of how, where, and why life succeeds and becomes detectable.

billions of years) of the co-evolution of life and its planet of origin using such facilities, a long-term record of microbial evolution, and innovation in response to planetary habitability and biosignature potential, is contained in the genetic material of these organisms. Efforts must be made to enhance our ability to decipher this molecular record through improved techniques in nucleic acid sequencing, molecular ecology and, especially, bioinformatics.

Objective 7.3 - Habitable Environments and Biosignatures

Interdisciplinary laboratory studies, field analog research, and theoretical investigations address the following: 1) the limits or degree of habitability of planetary environments, 2) diagnostic attributes of life in the context of the environment, 3) the preservation potential of biosignatures on early Earth and Mars, and 4) the detectability of biosignatures on icy worlds or exoplanets. The degree of habitability is being investigated in environments that are analogous to Mars and ocean worlds. The capacity of those environments to generate biosignatures is being quantified in terms of the metabolic diversity and productivity therein. These attributes in turn determine the variety and abundance of any potential biosignatures (**Figure 7.3**). Ongoing studies of life's environmental impacts could discover novel types of biosignatures, as well as assess false positives (abiotic mimics) and false negatives (a situation in which life is present, but undetectable). Environmental processes and conditions also alter and destroy biosignatures. The effects of processes that accompany the range of potentially habitable environments beyond Earth are investigated, as is the impact of long-term environmental change. This work provides the foundation for identifying the key measurements and instrumentation required for the astrobiological exploration of environments as well as life detection in deep time and space.

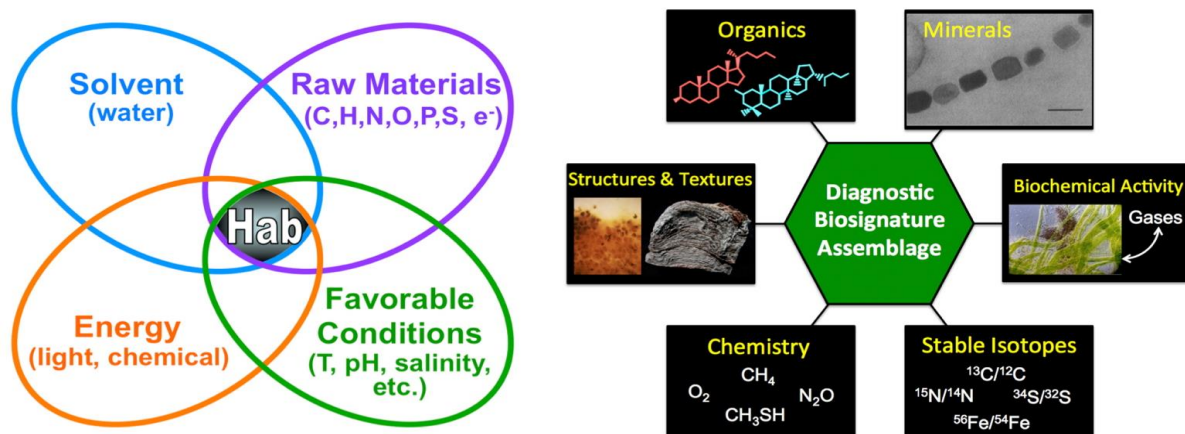


Figure 7.3. (Left) Venn diagram indicating the resources and conditions that must be available simultaneously in order to maintain a habitable environment ('HAB'). (Right) Categories of biomarkers, as follows: Organics – molecular structures from past or present biological activity; Minerals whose composition and morphology are consistent with biological activity; Structures and textures – microfossils, biological rock fabrics and structures; Biochemical activity – evidence of metabolism; Chemistry – 'anomalous' chemical assemblages, trace elements, gases indicating biological activity; Stable isotopes – Isotopic patterns created by biological activity.

Objective 7.4 - Astrobiology Habitable Environments Database

Ames will continue to develop the "Astrobiology Habitable Environments Database" (AHED) to provide a central, high-quality, long-term data repository for mineralogical, textural, morphological, inorganic and organic chemical and isotopic information pertinent to the advancement of the field of astrobiology (**Figure 7.4**). As a highly interdisciplinary field, developments in astrobiology often rely on integration of a variety of disparate data types. The aim of AHED is to go beyond simple cataloging of relevant data sets and enable NASA scientists, mission teams and the broader science community to access, visualize and analyze data on one platform. Its goals are to: (1) enable research in the areas of biosignatures, habitability and the search for life, (2) increase scientific return from past and ongoing missions, and (3) help guide planning and design of future missions.

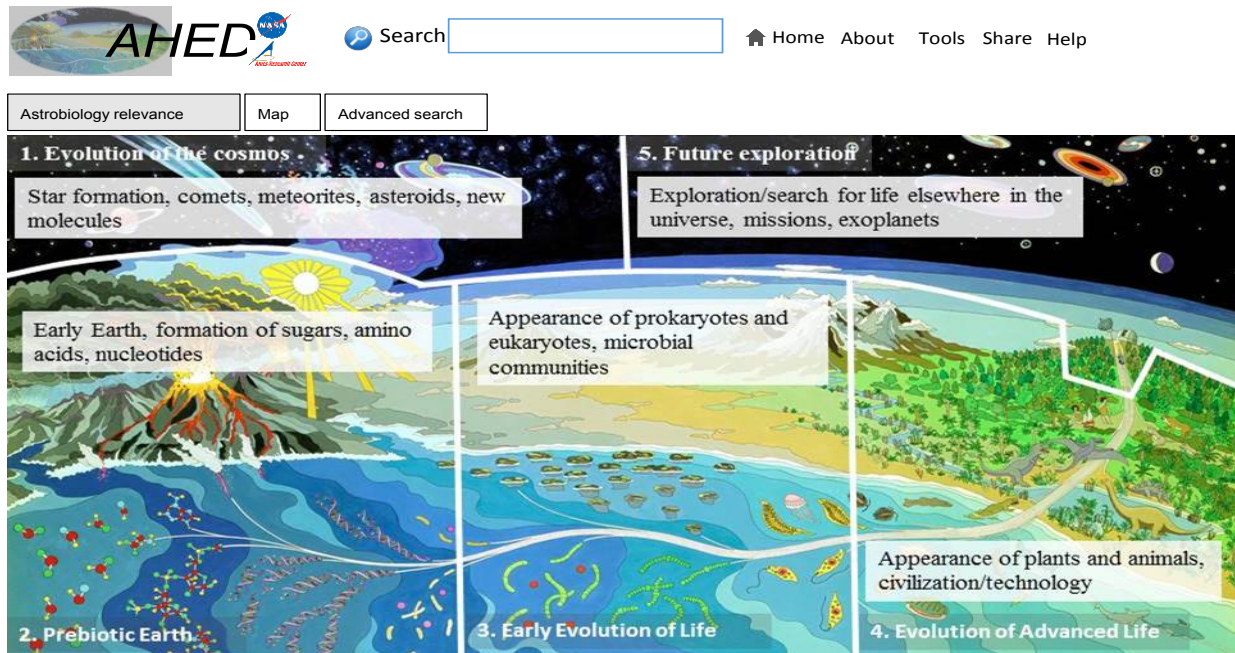


Figure 7.4. A mock up user interface for the AHED database portal in development at Ames with Science Enabling Research Activity (SERA) funding from NASA's Astrobiology Program.

Objective 7.5 - Center for Life Detection

Ames will establish a Center for Life Detection (CLD) to develop the rigorous scientific underpinning required to support NASA's search for life in the solar system and beyond. The initial focus of the CLD will be to compile, organize, and curate a "living" repository of information and community dialog relating to life detection science; and, through continuing analysis of the curated information, to identify and recommend priority areas for community engagement, research, and technology development that will best support the life detection endeavor. As the CLD becomes established, it will aid in developing community standards for life detection and provide a forum in which to bring forward and vet new approaches in life detection. Through these activities, the CLD will provide a resource for, and point of interface between, headquarters, the planetary mission and instrument development community, and the broader community of researchers engaged in life detection science (**Figure 7.5**). While based at Ames in order to leverage its breadth of scientific expertise, emerging focus on life detection instrumentation, and extensive experience in origin of life, ecology and evolution, and habitability/biosignatures research, the CLD is intended to develop as a collaborative activity that increasingly involves participants from other centers.

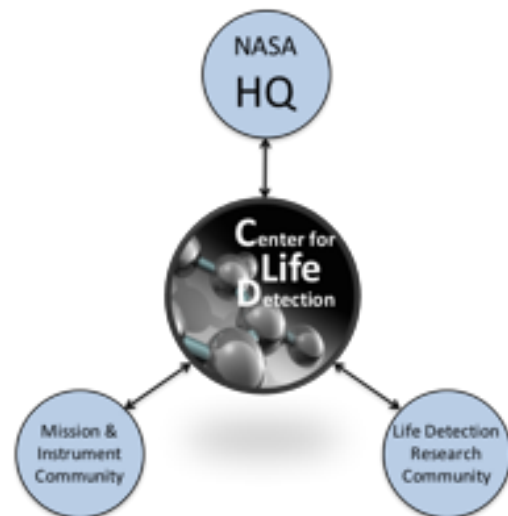


Figure 7.5. The Center for Life Detection is to be an Ames-led, multi-center collaboration that serves to connect headquarters, the planetary mission and instrument development community, and the broader community of life detection researchers to support NASA's search for life in the solar system and beyond.

Milestones: Astrobiology

Year 1

- Strengthen connections with astrochemistry
- Establish novel methods that support systems-level approaches to prebiotic evolution
- Couple molecular ecological tools with biogeochemistry under relevant habitability and life detection conditions
- Develop analysis pipelines for exploration of the emergence of key traits and processes involved in evolution of the biosphere
- Establish models for habitability and microbial metabolism on early Mars and ocean worlds
- Characterize *in situ* biosignatures for early Earth, Mars, and exoplanets
- Provide input on requirements for biosignature and life detection for instrument development
- Develop an organizing scheme for life detection content (e.g., "Ladder of Life Detection") presented for at conferences for community feedback
- Support mission concepts, *in situ* instrumentation development, and data analysis for remote detection
- Identify Mission opportunities, target Center investments in mission concepts and related instrument development
- Form collaborative relationships and partnerships with Goddard, JPL, and APL

Years 2-5

- Determine whether sugars are delivered in meteorites from space
- Apply systems-level approaches to understand key interactions in prebiotic evolution
- Develop ecological models to predict potential for specific biological signatures based on environmental conditions
- Develop a quantitative framework for studying key biological events in evolutionary and geologic history
- Finalize modeling results for microbial life on early Mars and ocean worlds
- Finalize *in situ* biosignature characterization, and provide these inputs into Mars 2020 and Europa Lander mission planning activities
- Model detectability of exoplanet biosignatures in disk-averaged spectra through different atmospheric compositions; input to LUVOIR STDT
- Increase use of the AHED database for data management and collaboration in the scientific community.
- The organizing scheme for life detection content is fully implemented and maintained in a community-accessible, web-based version with community standards for life detection established
- Continue to support mission concepts, *in situ* instrumentation development, and data analysis for remote detection

Years 6-10

- Fill in major gaps in understanding of which metabolic compounds are present in meteorites
- Understand the underlying evolutionary mechanisms necessary for initial proliferation of life on Earth
- Integrate biological and geological data over evolutionary time for a predictive understanding of the limits of habitability and detectability of microbial signatures.
- The Center for Life Detection is a go-to resource for program and mission planning and has materially influenced mission architecture and implementation
- Ames leads and/or enables Agency instruments focused on Astrobiology and Life Detection

Division Administration, Support, Hiring, and Challenges



Synergies matrix:

Ames Center
Management,
other NASA Centers

Partner matrix:

SSA, SST, SSX

Missions

Supported: All

Division Administration

Division administration provides professional administrative and 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. The inability to perform innovative scientific and technical work efficiently has impeded output and competitiveness.

Supporting the scientific staff is the foundation and key of our busy workplace. The administrative staff carry the burden to make sure nothing falls through the cracks and often need to quickly shift gears to respond to immediate requests. Frequently, the administration personnel must be aware of “urgent” actions required in a limited time frame. Such a work environment requires the administrative professionals to have strong office skills and a solid work ethics.

As part of support staff, the Division administration provides guidance, assistance, reviews, and submits many forms for all types of permissions; 1676 forms, purchase requests, travel forms, lab safety, conferences, etc. The work-load over time is more for some and less for others with periods of increased need. Effective communication, load sharing, and designated backups would make the processes smoother for all. Training for procedures, cognition of why procedures should be done or not, and points of contact in the ARC administration would also lessen the load. *In general, good communication across the branches and teamwork are the key to success.*

The Division administrative staff is the backbone of the SS Division and should not be treated or thought of as only necessary for service work but as 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 each other and for the Division.

As objectives that our Division wishes to maintain, improve, and create, the following list is provided as a guideline for the next year’s effort as well as more permanent improvements we hope to put in place.

- 1) Enable Efficient Execution of the Division’s Scientific and Technical Work
- 2) Provide Financial Services with Fiduciary Responsibilities
- 3) Comply with Ames, NASA, & Federal Policies, Procedures, Regulations, and Statutes
- 4) Community Participation of Ames Scientists
- 5) Continue Proposal Development Support at the New Opportunities Center.

Division Hiring

The acquisition of new hires is a part of the strategic plan for essentially every capability listed in this planning document. Radiative Transfer, Laboratory Astrophysics, Exoplanets (particularly planetary systems and characterization), Life Detection, and Instrumentation made particularly strong cases for new hires in order to perform and complete their 1-10 year work plan as well as to provide succession planning in order to keep specific science knowledge in-house at Ames and for the Agency.

NASA Headquarters SMD funding priorities are currently centered on life detection in our Solar System and space missions both planetary (landers and flybys) and space telescopes such as JWST, WFIRST and future exoplanet missions. Our Division's expertise aligns with Headquarters' top priorities in most of these areas but some appear to be more interesting to Headquarters as directed work. If we take the current FY18 funded work packages as a guide, the intersection of Headquarters priorities and our funded work says that life detection, habitability studies, Mars modeling, and exoplanet efforts in characterization and technology provide the overlap.

Without civil servant hires in specific science areas, we are at a distinct disadvantage in producing successful work packages with respect to other NASA Centers due to the small number of civil servant leads vs. the contractor work force. 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 fill critical civil servant positions at Ames. Strategically, based on the current civil servant work force, the above overlap with HQ priorities, and Ames Center management interests, new hires in FY18 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? How do we build a workforce in the current hiring constrained environment?
- 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. This needs to be addressed through public, community, and Agency engagement. The Center needs to acknowledge and publicize our scientific achievements.

Administrative Support

SS administration and support needs 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 research by Ames, NASA, and the Federal Government, needs modification if we are to remain competitive and solvent.

Our Division advocates, for 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.

Second, 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, office and laboratory space allocations, and likely other areas. These should be easily tracked and accessible, perhaps via the SS Division website. The new Division Administrator should be given considerable freedom in implementation. A summary of recommended actions are shown in **Table 8.1**.

Table 8.1. Summary of management actions needed

Management Task	Recommended Action
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	High-level 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 (p 2) and scientific / technical output

Milestones: Division Management and Support

Year 1

- Restructure Administration support structure and organization
- Hire high level administrator
- Establish metrics for evaluating efficiency of Division's business and administrative functions
- Accomplish civil servant hiring for 6-8 new positions

Years 2-5

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

Years 6-10

- 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)	Sanaz Vahidinia, Diane Wooden, Jeff Cuzzi, Roxana Lupu, Stuart Pilorz, Mark Marley, Ted Roush, Ella Sciamma-O'Brien, Paul Estrada, Richard Freedman, and Lee Bebout
Origin and Evolution of Planetary Systems	Jeff Cuzzi, Paul Estrada, Umi Gorti, Jack Lissauer, Anthony Dobrovolskis, Tom Greene, Thomas Hartlep, Scott Sandford, Orkan Umurhan, Diane Wooden, Kevin Zahnle
Astrobiology and Exobiology at NASA Ames Research Center	Chris Materese, Mark Ditzler, Brad Bebout, Craig Everroad, Kevin Zahnle
Ames Analog Research 10-year Strategic Plan	Alfonso Davila, Richard Elphic, Jennifer Heldmann, Darlene Lim, Heather Smith, Carol Stoker, Mary-Beth Wilhelm
Exoplanet Characterization into the 2020s	Tom Greene, Niki Parenteau, Mark Marley, Rachel Matson, Ruslan Belikov, Eduardo Bendek, Steve Howell
Laboratory Astrophysics & Astrochemistry	Farid Salama, Tim Lee, Tom Roellig, Joseph Roser, Ella Sciamma-O'Brien
Division Administration and Support	Mojgan Momeni Hassan-Harati, Caroline To, and Tom Greene
Instrumentation at ARC	Nic Scott, Naseem Rangwala, Dale Cruikshank, Yvonne Pendleton, Diane Wooden, & Pasquale Temi
The Detection of Life in the Solar System and Exoplanet Atmospheres	Mark Ditzler, Brad Bebout, Craig Everroad, Chris Materese, Kevin Zahnle
Planet Modeling: Atmospheres, Climate, and Landforms	Amanda Brecht, Thomas Bristow, David Des Marais, Eldar Noe Dobrea, Jennifer Heldmann, Jeff Hollingsworth, Melinda Kahre, Jeff Moore, Carol Stoker, Oliver White
Strategic Plan for Ames Instruments and Missions	David Blake, Karen Bywaters, Andy Colaprete, Alfonso Davilla, Rick Elphic, Jen Heldmann, Heather Smith, Carol Stoker, Richard Quinn, Mary-Beth Wilhelm

Appendix B: 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

Doug Hudgins (ex-officio)

Human Resources Support Team

Stacy Giffin

Sarah Hale

Appendix C: NRC and NASA reports consulted during the writing of this Strategic Plan

- Vision and Voyages for Planetary Science Decade 2013 to 2023
- New Worlds and New Horizons in Astronomy and Astrophysics Decade 2010-2020
- 2014 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 – 2016
- The Scientific Context for Exploration of the Moon
- NASA Human Space Exploration and Operations Mission 2015 Goals

Appendix D: Acronym List

3D	3-Dimensional	GSM	Global Science Modeling
		GTO	Guaranteed Time Observer
AES	Advanced Exploration Systems	H	Hydrogen
AHED	Astrobiology Habitable Environments Database	H ₂ O	Hydrogen Dioxide (Water)
ALMA	Atacama Large Millimeter/submillimeter Array	HabEx	Habitable Exoplanet Imaging Mission
APL	Applied Physics Laboratory	He	Helium
ARC	Ames Research Center	HEC	High-end computing
ATM	Atmosphere	HEOMD	Human Exploration and Operations Mission Directorate
		HIRMES	High Resolution Mid-Infrared Spectrometer
CH ₃ OH	Methanol	HST	Hubble Space Telescope
CH ₄	Methane	IDC	Instrument Development Center
CHEOPS	CHaracterising ExOPlanet Satellite	IR	Infrared
CIAs	Calcium-Aluminum rich inclusions	IRAS	Infrared Astronomical Satellite
CNES	Centre National D'études Spatiales (French Space Agency)	ISO	Infrared Space Observatory
CO	Carbon Monoxide	ISRU	In situ Resource Utilization
CO ₂	Carbon Dioxide	JPL	Jet Propulsion Laboratory
CoRoT	Convection, Rotation and planetary Transits Mission	JWST	James Webb Space Telescope
CORSAIR	COmet Rendezvous, Sample Acquisition, Investigation, and Return	K	Kelvin
CSA	Canadian Space Agency	K2	NASA K2 Mission
DDA	Discrete Dipole Approximation	KBOs	Kupier Belt Objects
		km	Kilometer
ELSAH	Enceladus Life Signatures and Habitability	LEM	Landform Evolution Modeling
EMT	Effective Medium Theory	LUVOIR	Large UV/Optical/IR Surveyor
ESA	European Space Agency	m	Meter
		M	Million
FINESSE	Field Investigations to Enable Solar System Science and Exploration	MCMC	Mars Climate Modeling Center
		MDC	Mission Design Center
GCM	Global Circulation Model	MHD	Magnetohydrodynamics
GFD	Geophysical Fluid Dynamics	MIR	Mid-Infrared
GPI	Gemini Planet Imager	MSL	Mars Science Lab
GSFC	Goddard Space Flight Center	Myr	Million Years
GSM	Geochemical and Spectroscopic Modeling	NAI	NASA Astrobiology Institute

NAS	NASA Ames Supercomputer	SMD	Science Mission Directorate
NASA	National Aeronautics and Space Administration	SMD	Science Mission Directorate
NEO	Near Earth Orbit	SO2	Sulfur Dioxide
NH3	Ammonia	SOFIA	Stratospheric Observatory for Infrared Astronomy
NIR	Near-Infrared	SPHERE	Spectro-Polarimetric High-contrast Exoplanet REsearch
NIRSPEC	Near-IR Spectrograph	SPICA	Space Infrared telescope for Cosmology and Astrophysics
NPP	NASA Postdoctoral Program	SSA	Astrophysics Branch
OSIRIS-Rex	Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer	SST	Planetary Astronomy Branch
OST	Origins Space Telescope	SSX	Exobiology Branch
PAHdb	Polycyclic Aromatic Hydrocarbon Molecules Database	STARDUST	NASA Comet and Sample Return Mission
PAHs	Polycyclic Aromatic Hydrocarbon Molecules	STMD	Space Technology Mission Directorate
PIAA	Phase Induced Amplitude Apodization	STTR	Small Business Technology Transfer
PIs	Principal Investigators	TESS	Transiting Exoplanet Survey Satellite
PLATO	PLANetary Transits and Oscillations Mission	TRL	Technology Readiness Level
PSD	Planetary Science Division	US	United States
RT	Radiative Transfer	USGS	United States Geologic Survey
RT_Hub	Radiative Transfer Hub	UV	Ultra-Violet
RV	Radial Velocity	VIS	Visible
SBIR	Small Business Innovation Research	WFIRST	Wide-Field Infrared Survey Telescope
SSERVI	Solar System Exploration Research Virtual Institute	XRD	X-ray Diffraction
SiO	Silicon Monoxide	XRF	X-ray Fluorescence
		ZnS	Zinc Sulfide
