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O R I G I N S

IN SEARCH OF OUR COSMIC ROOTS

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ABSTRACT

You are holding a strategic roadmap for the first two decades into the new millennium, charted by NASA's Office of Space Science to travel toward understanding and explaining the origins of galaxies, stars, planetary systems, and...life.

PRIMORDIAL QUESTIONS

Since our earliest ancestors huddled around ancient campfires until now before the cool flame of our computers we still ask the profound primal questions: Where did we come from? Are we alone?

Just 75 years ago, the "fuzzy" objects in the sky—galaxies were thought to be clouds or nebulae floating in our universe. In the 1920's, Edwin Hubble showed that they were in fact their own "island universes," receding from each other at a great rate. Now we know that even these enormous pinwheels of billions of stars are mere specks in the vast structures that comprise our universe. ...And where did *we* come from?

The advances in science and technology are allowing our generation the privilege and challenge to investigate these intriguing questions. Such is the theme of the Astronomical Search for Origins (ASO).

SEARCHING BACK TO COSMIC ORIGINS

We seek to observe the birth of the earliest galaxies in the universe, to detect all planetary systems in our solar neighborhood, to find those planets that are capable of supporting life, and to learn whether life exists beyond our solar system.

The search for our cosmic origins, as a high priority NASA enterprise, has been established as an overarching scientific program, not merely a series of missions. The Origins program is carefully engineered so that each new mission builds on science and technologies of previous ones, brings in some new enabling technology, and leaves a legacy for future missions.

Astronomical observations have begun to reveal the processes that ultimately gave rise to life several billion years after the Big Bang. Galaxies, the fundamental "building blocks" of the cosmos, have been observed as they were about a billion years or so after the origin of the Universe.

The most basic properties and processes of galactic birth await study with future telescopes with sufficient light-gathering power at mid- and near-infrared wavelengths to peer back to those critical periods of galactic formation. A goal of Origins is to discover how the first galaxies formed and transformed the featureless Universe.

Nuclear furnaces of the more-massive first stars brought forth the elements necessary for the complex chemistry of life. New generations of stars and planets are believed to form out of this seed material—planets that now contain elements necessary for life.

Stellar nurseries have been observed with increasing detail, mainly at visual wavelengths, which cannot penetrate the thick, dusty, circumstellar natal material. Besides investigating interstellar conditions, infrared and submillimeter wavelength instruments will peer into flattened disks of dust and gas surrounding young stars that may harbor newly formed planets.

How common are planets outside the Solar System? Are there any planets that resemble Earth? Although nearly 50 objects of substellar mass have been discovered orbiting stars in the solar neighborhood, observations to date show them all to be quite massive, comparable in mass to gas giants like Saturn or Jupiter. None are likely candidates for biological activity.

After indirect search for much lower-mass planets, a major goal of the Origins Theme is to search directly for warm, wet, Earth-like planets that may host biological activity. Further along, larger constellations of telescopes will search for spectroscopic signatures with unambiguous markers for biology on distant planets. We look even further to the time when we will see resolved images of other worlds.

THE SEARCH FOR LIFE

Complex organic compounds are found throughout the interstellar medium, but how does this material survive the tumultuous events of stellar birth to enrich young planets with prebiotic material? Discovering the origin of life and learning which aspects of the early terrestrial environment were essential to its emergence and survival are among the goals of the NASA's Astrobiology Program, which is managed within the structure of the Origins Theme.

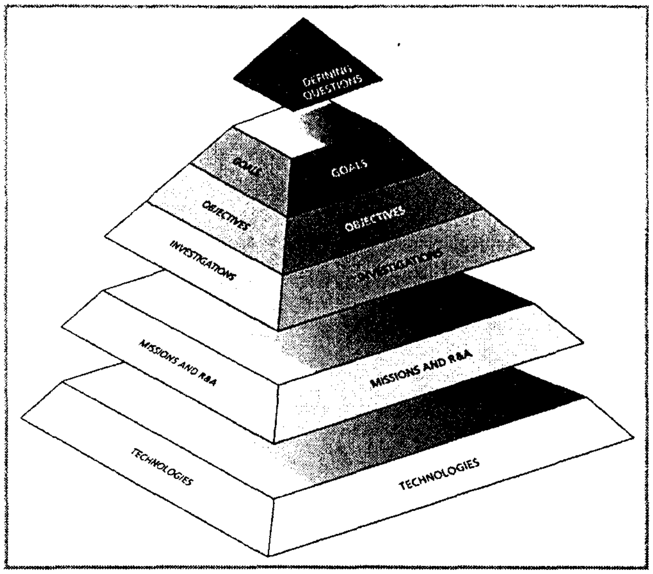
We are beginning to understand the processes that shaped the other planets in our Solar System. On Earth, we are learning about the diversity of life that exists in a wide variety of ecological niches. These advances only hint at the discoveries that await scientists working as part of the Origins Theme, as they investigate the most fundamental and intriguing of astronomical phenomena, the emergence of life in the cosmos.

JOURNEY ON THE CELESTIAL ROADMAP

Starting in the year 2000, the Roadmap for the Origins Theme charts the route of its one strategic plan for a journey of cosmic scientific investigation for the next two decades. Together with many NASA field centers and substantial input from the astronomical community, the Origins Subcommittee of NASA's Space Science Advisory Committee plotted this Roadmap. Particular emphasis is placed on activities advocated for new starts in the near-term 2003-2007 and the mid-term 2008-2013. The plan and its progress will be revisited at the five-year mark.

The Origins Roadmap presents a unified strategic plan—hierarchical in structure—aiming to answer two **Questions** that define the whole Origins Theme:

> "Where did we come from?"
> "Are we alone?"



Answers to these Questions will be found along the pathway of four long-term scientific **Goals**. Each of the four Goals has two scientific **Objectives** which are more specific and are realizable on shorter times. To accomplish the above, each Objective has one to three scientific **Investigations**. These Investigations (a total of 16) define specific scientific studies and measurements to be achieved.

Directly responsive to the identified Investigations are the activities advocated as **Missions** and as **Research and Analysis** (R&A). Some of these fact-finding requirements will require one or more space Missions.

The Missions that are envisioned will be made possible by a challenging and aggressive development program of **Technologies**.

The foundation of the Origins mission set is an extensive technology development program. The program and the mission schedules will be driven by technology readiness, not by preset launch dates.

The schedule takes into consideration the challenges; and the structure is built on an unprecedented level of precursor technology testbeds, both on ground and in space, to prepare for the major missions.

The remainder of this paper will route us along the journey planned by the Origins Roadmap.

THE TWO QUESTIONS

QUESTION ONE:

▲ "Where did we come from?"

QUESTION TWO:

▲ "Are we alone?"

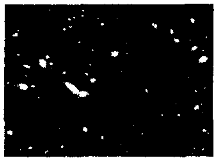
The Origins Theme is to trace our cosmic roots and to search for life outside the Solar System. We will use remote detection in our quest of the "smoking guns" indicating biological activities on extra-solar planets.

THE FOUR GOALS

To explore the two Defining Questions about origin of and company in the cosmos, the Origins Roadmap has defined four scientific Goals that will not culminate in less than a few decades.

Goal One:	To understand how galaxies formed in the early universe.
Goal Two:	To understand how stars and planetary systems form and evolve.
Goal Three:	To determine whether habitable or life-bearing planets exist around other stars in the solar neighborhood.
Goal Four:	To understand how life forms and evolves.

The Goals are the beacons that mark the path to the long-term scientific vision for the program. Each Goal has two Objectives, each of which has one or more Investigations.



GOAL ONE:

To understand how galaxies formed in the early universe.

Theoretical models of the Big Bang as well as observations of old stars demonstrate that the young Universe had no heavy chemical elements such as carbon, nitrogen, and oxygen. Over billions of years the nearly featureless Universe formed enormous galaxies such as our Milky Way. The earlier generations of stars created in their nuclear furnaces interstellar gasses with heavy chemical elements. The binding together of enormous galaxies was likely needed to manufacture vast quantities of heavy elements for the formation of Earth-like worlds to become possible. These steps are essential on the road to life.

OBJECTIVE 1: Determine the role of gravity in the emergence of galaxies from the almost perfectly smooth particle sea of the early Universe.

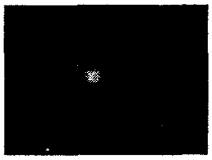
Investigation 1: Determine the fate of baryonic matter as the Universe evolves.

Investigation 2: Measure the luminosities, forms, and environment of galaxies back to the epoch of their formation.

OBJECTIVE 2: Establish how the birth and aging of a galaxy influence the chemical composition that is available to stars, planets, and living organisms.

Investigation 3: Trace the chemical evolution of the Universe from the birth of the first stars to the formation of dust, new generations of stars, and planetary systems.

Investigation 4: Determine when stars with planets could first have appeared in the Universe.



GOAL TWO:

To understand how stars and planetary systems form and evolve.

Observations using both ground- and space-based facilities have permitted us to look inside the nurseries where stars are being born. In concert with these observations, studies of the Solar System through space missions and analysis of meteorites have allowed us to formulate a theory of how stars and planetary systems form.

If this theory is correct, we would expect that most, if not all, single stars should have planetary systems. We have ample indirect evidence of planetary mass companions around other stars, based on star wobble caused by gravitational forces of orbiting companions. The nearly 50 newly discovered systems, however, are unlike our Solar System. The deduced companions have masses comparable to (or greater than) those of our most massive planets, Jupiter and Saturn, but have orbits that are closer to their central stars. We have not yet found an exact analog to our planetary system.

We must continue to use a wide variety of techniques to the search for planets and interpret the results with theoretical studies.

OBJECTIVE 3: Discover planetary systems forming around young stars and characterize their properties.

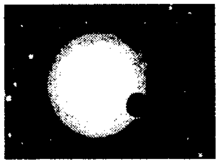
Investigation 5: Understand why molecular clouds produce mainly multiple star systems rather than single stars like the Sun.

Investigation 6: Determine how planetary system-forming disks evolve.

Investigation 7: Search for evidence of planet formation in disks around young stars.

OBJECTIVE 4: Characterize the planets and planetary systems around other stars.

Investigation 8: Search for planetary systems around a variety of stars, and determine the orbits, masses, temperatures, and atmospheric composition of their planets.



GOAL THREE:

To determine whether habitable or life-bearing planets exist around nearby stars.

The part of a planet that is most likely to carry the detectable imprint of life on the planet is its atmosphere. On Earth, life first appeared within 700 million years after Earth formed. Perhaps a billion years passed before its increasing biomass was able to alter the atmosphere with a significant amount of molecular oxygen (O_2), mainly through photosynthesis.

What would be the signatures of such primitive life in other planetary systems? How would we detect and interpret such evidence that we may obtain from telescopic observation?

OBJECTIVE 5: Determine what makes a planet habitable and determine how common habitable worlds are in the Universe.

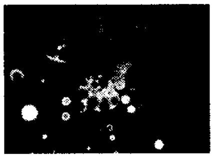
Investigation 9: Determine the ultimate outcome of the planet-forming process around other stars, especially the potentially habitable ones.

Investigation 10: Define climatological and geological effects upon the limits of habitable zones around the Sun and other stars to help define the frequency of habitable planets in the Universe.

OBJECTIVE 6: Establish how to recognize the signatures of life on other worlds.

Investigation 11: Describe the sequences of causes and effects associated with the development of Earth's early biosphere and the global environment.

Investigation 12: Define an array of astronomically detectable spectroscopic features that indicate habitable conditions and/or the presence of life on an extra-solar planet.



GOAL FOUR:

To understand how life forms and evolves.

To comprehend the nature and distribution of life in the Universe beyond Earth, we must understand the origin of habitable planetary environments. Since terrestrial life is the only form of life we know, how did it form and persist for billions of years? We seek the source and nature of the raw materials of life. We wish to understand the cosmic distribution of the environments in which liquid water existed and biogenesis occurred.

For the prebiotic Earth, we must understand the origin and chemical nature of the organic and inorganic compounds, the sources of energy, and microenvironments from which life arose. We should also consider if a viable natural mechanism exists for spreading life to Earth and throughout the Universe.

To find evidence of life on distant planets and understand its long-term survival, we must decipher the environmental and biological consequences of the formation of habitable planets and their biospheres. Scientists can combine evidence acquired from studies of gene history, microbial ecosystems, geological environments, fossils, and the limits to life imposed by environmental extremes.

OBJECTIVE 7: Determine the general principles governing the organization of matter into living systems.

> Investigation 13: Assess the relative importance of various sources of organic material for the early Earth and their respective roles in the origin of life.
>
> Investigation 14: Develop and test plausible pathways by which ancient counterparts of modern cellular components were synthesized from simpler precursors, assembled into protocells, and established replicating catalytic systems capable of evolving.

OBJECTIVE 8: Determine both the early evolution of life and its limits in environments that might provide analogs for conditions on other worlds.

> Investigation 15: Identify the environmental limits for life by examining biological adaptations to extremes in environmental conditions.
>
> Investigation 16: Define how the structure and function of microbial communities influence their adaptation and evolution, and their detection on other planets.

MISSIONS

A hallmark of the Origins architecture is that each major mission builds on the scientific and technological heritage of previous ones while providing a legacy of new capabilities for future missions. Only in this way can complex challenges of the theme be achieved at reasonable cost and acceptable risk.

New techniques developed in interferometry will be combined with infrared detectors and large-scale optics technology to look for habitable planets. A still more capable spectroscopic mission will make detailed studies of any biomarkers discovered on planets. Then filled-aperture infrared telescope technology might be used as a building block for cosmological studies with a kilometer-baseline interferometer used at far-infrared wavelengths. An ultraviolet/optical space telescope, employing large optic technology from earlier missions, will pave the way for more challenging UV/Vis telescopes.

OPERATIONAL MISSIONS

Foremost among the current Origins missions is the **Hubble Space Telescope** (HST), which was launched in April 1990, but remains NASA's most productive scientific program—thanks to regular instrument upgrades via Space Shuttle servicing missions.

This impressive achievement record will continue into the second decade of Hubble's operation, with the installation in late 2000 of the **Advanced Camera for Surveys** (ACS) and a new active cooling system for reactivating the **Near-Infrared Camera and Imaging Spectrograph** (NICMOS). The final Space Shuttle mission, planned for 2003, will install not only the highest-performance UV spectrograph ever flown in space, the **Cosmic Origins Spectrograph** (COS), but also the first truly panchromatic imaging system in space, the **Wide-Field Camera 3** (WFC3).

The most recent Origins mission to be launched is the **Far-Ultraviolet Spectroscopic Explorer** (FUSE), which is exploring the Universe at shorter wavelengths. FUSE is determining the abundance of deuterium, an isotope of hydrogen that was formed in the Big Bang. FUSE will also investigate hot interstellar gases for understanding the life cycle of matter between stars as gas cycles between stellar death and rebirth.

MISSIONS FOR OPERATION BY 2002

The **Space Infrared Telescope Facility** (SIRTF) mission will be the fourth of NASA's Great Observatories. SIRTF will have unsurpassed sensitivity throughout the infrared wavelength regime for contributing extensively to understanding formation of stars and planets and will investigate formation of luminous galaxies.

The **Stratospheric Observatory for Infrared Astronomy** (SOFIA) will have a 2.5-m telescope in a 747 aircraft that flies above almost all atmospheric water vapor that blocks most infrared radiation from reaching ground-based telescopes. SOFIA will complement SIRTF with much better spatial and spectral resolution for detailed study of bright objects. This observatory's instruments can be continually upgraded. A key scientific goal of SOFIA will be the investigation of conditions within the interstellar medium from which stars and planets form. The flying observatory will also have an ambitious Education and Public Outreach program.

The **Keck Interferometer Array** (KIA) will combine the infrared light collected by the world's two largest optical telescopes, the twin 10-m Keck telescopes in Hawaii, for a variety of astrophysical investigations. The foremost study will be the location and amount of zodiacal dust within other planetary systems. The KIA will also incorporate four smaller outrigger telescopes to detect gravitational effects of planets as small as Neptune on the positions of their parent stars. The array will also be used for the first in-depth planet census taking, to help understand planetary system formation.

MISSIONS FOR DEVELOPMENT IN 2003-2007

While the list of detected extra-solar planets is growing rapidly, space-based techniques will be required to locate objects whose mass approaches that of Earth and allow the first in-depth search for objects similar to our home planet.

The **Space Interferometry Mission** (SIM) will launch into the era of optical interferometry in space. By making highly accurate measurements of stellar positions, SIM will be the first observatory capable of detecting extra-solar planetary bodies with a few times the mass of Earth. SIM will extend the Keck census of nearby planetary systems into the range of rocky, terrestrial planets for the first time. This census will form the core of the observing programs for subsequent mission that investigate in detail the nature of these newly discovered worlds.

In addition to exploring a broad range of fundamental astrophysical phenomena, SIM will develop key technologies necessary for future missions, including constructive and destructive (nulling) interferometry and the precise, active control of optical pathlengths.

SIM's extraordinary astrometric capabilities will determine accurate positions throughout the Milky Way Galaxy. This will permit a far more precise measure of distances to major populations of stars, as well as detail the large-scale motion of the Milky Way.

After Hubble, the following step will be the **Next Generation Space Telescope** (NGST), which will have more than three times the diameter of Hubble's mirror and about an order of magnitude more light-gathering capability. NGST's greatest sensitivity will be optimized for near- and mid-infrared wavelengths, where the expansion of the Universe causes light from very young galaxies to appear most prominently. Dust which almost completely blocks observation of rapidly evolving stars can be penetrated. The Next Generation will also be a powerful general-purpose observatory for wide-ranging scientific questions, including those central to the Origins Theme.

The **Terrestrial Planet Finder** (TPF) will combine the capabilities of space interferometry from SIM and of spacecraft constellation flying demonstrated by **Space Technology-3** (ST-3) and large optics from NGST. TPF will be able to find planets around neighboring stars which may be warm with water and an oxygen-containing atmosphere. If oxygen is present in significant amounts, it is likely that some nonequilibrium process is maintaining this highly reactive substance. That process is quite likely to be life.

TPF will use spatial interferometry to make images out to distances of 50 light years of planets orbiting stars. The observatory's spectroscopic system will observe the most promising of these worlds for spectral signatures of water, carbon dioxide, oxygen (in the form of ozone), and methane.

As currently envisaged, TPF consists of four 3.5-m free-flying telescopes, each passively cooled to 35 K, and a central beam-combining facility. Angular resolution will be better than 1 milliarcsec to investigate astrophysical phenomena such as planet-forming protostellar disks and the energetic cores of active galaxies.

TECHNOLOGIES

The time has come to "pass the torch" from Hubble to a new generation of landmark observatories to lay the foundations for astrophysics in the 21st Century. The first of these new observatories are SIM, NGST, and TPF. They will introduce optical/IR space interferometry, large-aperture folded optics, and constellations of interferometrically connected large-aperture telescopes flying in formation.

The Origins Theme is investing in development of technologies focused on these enormous challenges to enable missions to new frontiers. Included are component technology development, ground testbeds, flight technology demonstration, astrobiology, detector systems, and space optics.

Today's technological investments will provide assurance of the needs for even more capable observatories in the more distant future. For this reason, the Astronomical Search for Origins (ASO) Theme proposes taking up the challenge for the mid-term development with an initiative for developing technology for very large space telescope systems on behalf of NASA and other agencies.

This **Large Telescope Systems Initiative** (LTSI) plans to develop "gossamer technologies":

- Optics mass reduced from 100s to 10s to <1 kg/m^2 for an aperture area 10 times that of NGST (> 25 m).
- Active wavefront metrology and control (25-40 m-class primary with large-format, long-stroke deformable mirrors)
- Large telescope cryocooling
- Advanced UV and FIR detector arrays.

Motivated by future need for enormous collecting areas, LTSI proposes to break the traditional optics limitations. This major technology initiative would enable a large single-telescope science mission to pave the way to the Life Finder.

MISSIONS DEVELOPMENT IN 2008-2013

For Origins to achieve its long-term goal for detailed study of life in ecosystems beyond the Solar System, spectral and spatial observations are required past those possible with TPF. Examples would be searching of distant planet atmospheres for unambiguous traces of life, such as methane and nitrous oxide; probing dusty, high z galaxies; and studying large-scale structures and dark matter. Such investigations would require spectral resolution of ~1000, using a version of TPF with 25-m telescopes.

The LTSI initiative would develop technology for the **Filled-Aperture Infrared Telescope** (FAIR), a mission using a single 15- to 25-m telescope for detecting wavelengths from 30-300 μm. FAIR would investigate critical astrophysical processes on all scales: It would study distribution of ices and minerals in the Kuiper Belts around nearby stars to learn about Earth's era of cometary bombardment; probe the epoch of energetic star formation in nearby protostellar disks; and research energetic star formation by detecting continuum and cooling-line emission from highly red-shifted, dust-enshrouded primeval galaxies. FAIR would create lighter, cooler, and more sensitive mid- and far-IR technology for the Life Finder.

The **Space Ultraviolet/Optical Telescope** (SUVO), a successor to Hubble (with a 100-times more sensitive UV spectroscopy), will produce forefront science in all areas of modern astronomy. SUVO will focus on the era from redshifts $0 < z < 3$ that occupies over 80 percent of cosmic time, beginning after the first galaxies, quasars, and stars developed into their present forms. Studies will investigate dark matter and the fate of the baryonic universe, the origin and progressive history of elements, and the major construction phase of galaxies and quasars. SUVO, with a telescope 10 times the surface accuracy of the Next Generation Space Telescope, will create technology for the Planet Imager.

MISSIONS DEVELOPMENT FOR FAR FUTURE

The **Life Finder** would follow up on discoveries made by TPF with the higher spectral resolution needed to identify unambiguously the signs of life on nearby planets. LF might consist of a TPF-like array of 25-m telescopes for the FAIR mission.

Further in the future the **Planet Imager** could actually resolve the disk of a distant planet and allow us to look for continents and oceans. Such an objective would require a constellation of ~40-m visible-light telescopes operating as an interferometer with a separation of a few hundred kilometers.

Life Finder and Planet Imager would extend the reach of biologists, geophysicists, and atmospheric chemists to ecosystems far beyond Earth. The technologies we invest in for missions like FAIR and SUVO represent a down payment on these distant dreams.

RESEARCH AND ANALYSIS

The Research and Analysis (R&A) program is the major point of contact with the scientific communities which analyze data obtained by NASA's missions as well as the scientific underpinnings and justification of future missions. The R&A program provides funding to individual scientists and their research groups to conduct necessary experimental, observational, and theoretical work in direct support of the flight programs. Principle Investigators, as resources for expert information, provide the most direct and continuing link between NASA's science programs and the public.

An active R&A program provides many essential components of the Origins Theme:

- Development of key technologies.
- Scientific analysis of the vast amounts of data expected from the space missions.
- Laboratory astrophysics to determine properties of atoms, molecules, and dust grains found in interstellar space.
- Research with ground-based and airborne telescopes to complement space observatories and develop new instrument technologies.
- Astrobiology research.

EDUCATION AND OUTREACH

The Origins Theme enjoys tremendous public interest. The Education and Public Outreach facet of Origins will continue to offer students, teachers, families, and the general public inclusion in our exploration. The resulting public enthusiasm for space science contributes solid improvements in science, mathematics, technology literacy, and their application. For us, education extends to science museums, planetariums, libraries, and other lifelong learning environments. The Origins Theme will include the public in the experience of discovery and research.

OVERVIEW OF THE ORIGINS ROADMAP

The Origins roadmap presents an exciting future for space exploration, space science and technology, astrobiology, and the understanding of our world and our Universe.

To move us along this journey of discovery, the Origins missions use all of their coordinated heritage and legacies to answer the 16 Investigations to achieve the Theme's Objectives and Goals.

May our Investigations help in understanding and explaining the origin of the Universe, galaxies, stars, planetary systems, and...life.

									
1 Fate of baryonic matter					◍			●	
2 Early galaxies			◍		●	◍	●		
3 Chemical evolution		●			●		●	●	
4 First stars with planets	◍			●	●	●			◍
5 Multi-star systems formation	◍				◍	◍	●		
6 Evolution of planetary disks	◍		◍		●	●	●		
7 Planet-forming disks around young stars		◍	●		●	●		◍	
8 Planet detection and characterization	●			●		●			◍
9 Ultimate outcome of planet-forming process	●			●	◍	●			
10 Climatological/geological effects on habitable zone				◍		◍			●
11 Early Earth biosphere development									●
12 Define bio-signatures for remote sensing									●
13 Relative importance of sources of organics on early earth		◍			◍		●		
14 Paths to the first protocell									●
15 Environmental limits for life									●
16 Detection of microbes on other planets									●