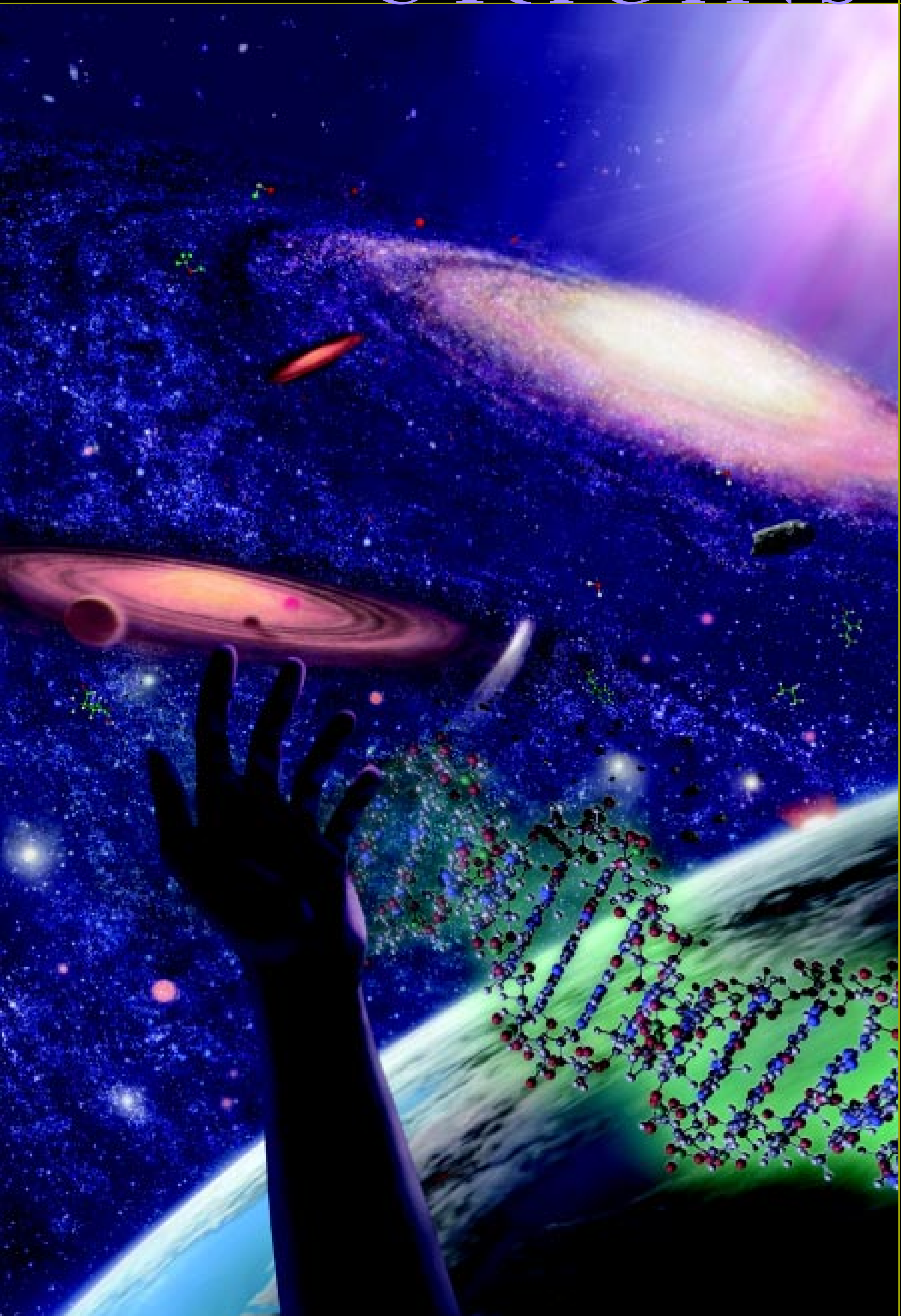
ORIGINS



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Roadmap for the Office of Space Science Origins Theme

"We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.
Through the unknown, remembered gate
When the last of earth left to discover
Is that which was the beginning…"

T. S. ELIOT
FOUR QUARTETS

ORIGINS

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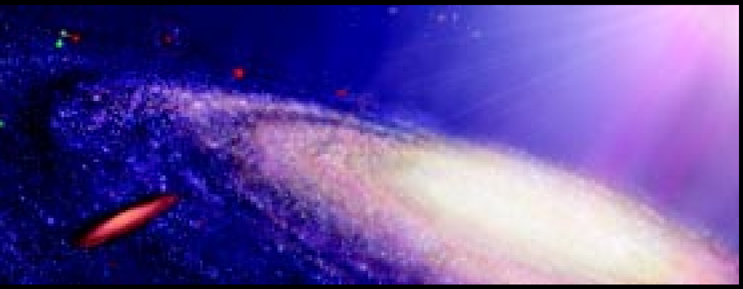
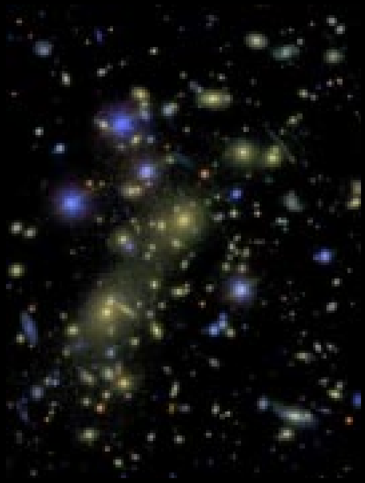




We Seek

…to observe the birth of the earliest galaxies, the formation of stars, to find all the planetary systems in our solar neighborhood, to find planets that are capable of harboring life, and to learn whether life does exist beyond our solar system. We do this to understand the origins of our world. We do this to answer two questions:

Where did we come from?

Are we alone?

As our ancient forebears huddled around their campfires might have wondered—where they came from, what lies over the hill, what lurks outside the comforting light from their own fire—so we reach out now with our minds and our technology to understand where all that we see came from, and if we are unique and alone in the cosmos, or if we are one glint among many sparks of life. These questions are profound, yet are asked by nearly all, old and young, who lie on a beach or on a meadow and embrace in their vision the spectacle of the night sky.

We are privileged to live in a time marked by scientific and technological advances so rapid and so brilliant that these elusive and intriguing questions can be pursued not only with philosophical speculation but also with scientific observation. While the questions are simple, the scientific and technical capabilities needed to answer them are challenging. In this document, we present a scientific roadmap—with an emphasis on the first two

NASA'S VISION

To improve life here,

To extend life to there,

To find life beyond

NASA'S MISSION

To understand and protect our home planet

To explore the universe and search for life

To inspire the next generation of explorers

…as only NASA can

decades of this century, followed by a vision for the far future—that will lead us to the answers that have intrigued but eluded humanity for millennia.

Where did we come from?
To answer this, we need to understand how today's universe of galaxies, stars and planets came to be, and how stars and planetary systems form and evolve.

Are we alone?
To answer this, we need to understand the building blocks of life, the conditions necessary for life to persist, and the signatures that it writes on the sky. We need to explore the diversity of other worlds and search for those that may harbor life.

The Journey So Far

Eighty years ago, we didn't know that our galaxy wasn't the entire universe, that the fuzzy "nebulae" floating in the cosmos were really neighboring "island universes" like our own galaxy. Much has been learned in these few decades that gives us a vastly expanded sense of the universe and our place in it. Five years ago, we had not observed planets around other stars. Today, over one hundred planets and planetary systems have been detected using ground observatories. We are well into the age of discovery of our origins. It is now our challenge to map the roads to future exploration and gain an understanding of how galaxies, stars, planets…and life, came to be.

About the Roadmap

This Roadmap is the product of deliberation and discussion by the Origins Subcommittee of NASA's Space Science Advisory Committee, working with representatives from NASA's field centers and with substantial input from the astronomical community. The Roadmap sets out a plan for a twenty-year period at the beginning of the millennium, with particular emphasis on activities advocated for new mission starts in the near-term (2005–2010) or mid-term (2010–2015) time frame.

The Subcommittee examined the broad scientific objectives discussed in this Roadmap, motivated by the two defining questions. For each objective, several research areas are defined to address multiple aspects of the objective. Within each research area, a number of specific investigations are called out and discussed in some technical detail. It is these investigations that give rise to the specific missions and tools that are required to make the necessary scientific observations. The Roadmap describes the Origins missions currently operating and in development, and focuses on those missions that will start in the near- and mid-term.

The universe is enormous and ancient, but life—tiny and transient—is its precious jewel.

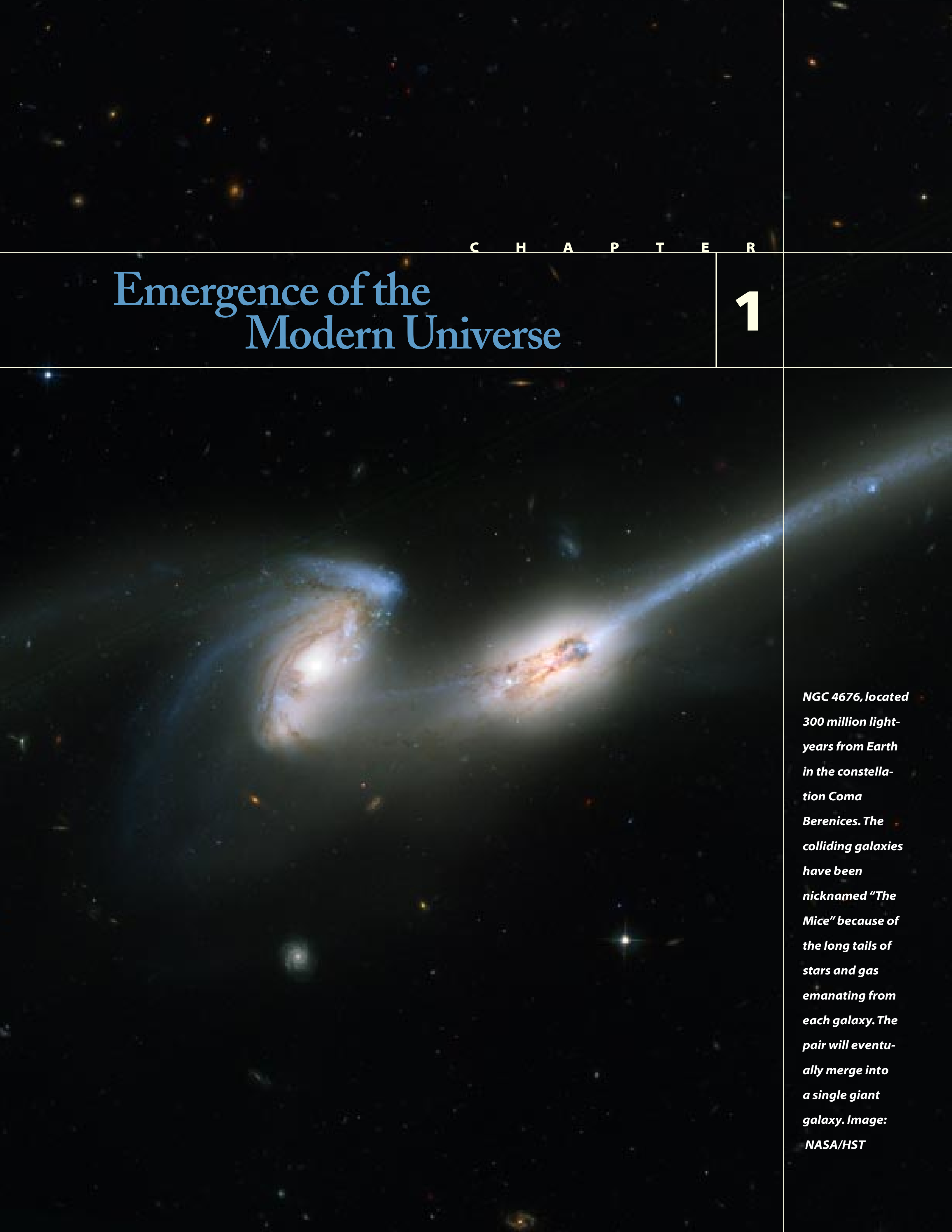
It is a key element of philosophy in the Origins theme that each major mission build upon the scientific and technical legacy of past missions, and develop new capabilities for those to follow. So, technology must be prepared and scientific theory and context must be developed to enable these missions to be defined and developed with an acceptable cost and risk. The Roadmap discusses those technology developments and research and analysis activities needed to prepare the scientific ground to conduct the investigations and to integrate and analyze the results to produce deep scientific understanding.

The two questions—"Where did we come from?" and "Are we alone?"—are simple and engaging enough to discuss with children in elementary school, yet are so profound as to challenge the scientific community and engage people in all walks of life. Therefore, the Roadmap describes a vigorous program of education and public outreach to engage all Americans and especially youth in the excitement and inspiration of this great quest.

Finally, the Roadmap concludes with a vision of the future, featuring possibilities for the kinds of investigations and missions that may be currently beyond our technological reach, but are not beyond our aspiration.

C H A P T E R

1 Emergence of the Modern Universe



NGC 4676, located 300 million light-years from Earth in the constellation Coma Berenices. The colliding galaxies have been nicknamed "The Mice" because of the long tails of stars and gas emanating from each galaxy. The pair will eventually merge into a single giant galaxy. Image: NASA/HST

OBJECTIVE ONE

...to understand how today's universe of galaxies, stars, and planets came to be.

Stars began to form even before the first galaxies, and what had been a calm, near-formless sea began to surge with the froth of complex forms of matter and energetic processes. Today the universe is full of structure, from the giant but simple galaxy to a minuscule but complex single living cell. Our objective is to understand how this came about, how stars and planets form, how the chemical elements are made, and ultimately how life originates.

In the 20th century we learned that our Milky Way Galaxy—a massive pinwheel of stars and gas bound by gravity—has been home to many generations of stars. Most of these billions of stars are likely to have "solar systems" of planets like our own—might they be home to billions of planets like Earth where life abounds? Only in the last few decades have we come to realize how closely bound our own existence is to the birth and death of these stars. Theoretical models of the Big Bang—the violent event that began the universe—describe an infant universe devoid of heavy elements such as carbon, nitrogen, oxygen, and iron that are essential ingredients of planet Earth and life itself. Where, then, did these essential heavy elements come from? It took decades of scientific research to discover how our Sun, along with every other "sun" that makes up our galaxy, manufactures heavy elements in the course of the nuclear fusion which powers it. In its death throes a star gently releases, or violently hurls, much of this material into space, where it can later collect to give rise to new stars further enriched with the building blocks of planets and life. This is the galactic ecosystem.

There is growing evidence that star formation began before there were galaxies, and that when these early stars died explosively as supernovae they produced the first spray of heavy elements. But it also appears that the birth of galaxies, by binding the stars and gas together to create these cosmic ecosystems, was crucial to the buildup of heavy elements to a level where planets and life were possible. The emergence of such enormous structures from the near-featureless universe that preceded them, and the manufacture of vast amounts of heavy elements by their stars, were key steps on the road to life.

The modern era of the universe began, then, with the birth of stars and galaxies. Even as we work to trace the origins of the universe all the way back to the Big Bang, we recognize that our origins sensibly began later, some hundreds of millions of years after the Big Bang. In the billions of years since, complex chemistry and biology have evolved from the simple beginnings of the first stars and the first galaxies. Remarkably, astronomers can travel back through time to witness these crucial steps in our origins.

Our research will focus on two areas:

- How did the cosmic web of matter organize into the first stars and galaxies?
- How do different galactic ecosystems (of stars and gas) form and which can lead to planets and living organisms?

Touch the Universe: A NASA Braille Book of Astronomy

In an effort to serve students with special needs, a scientist and a Braille book author have used funding from the Hubble Space Telescope (HST) Cycle Education and Public Outreach (E/PO) grant program to develop *Touch the Universe: A NASA Braille Book of Astronomy*. Dr. Bernhard Beck-Winchatz, an astronomer at DePaul University in Chicago, wanted visually impaired students to experience the excitement generated by HST's beautiful images of the universe. When Dr. Beck-Winchatz received an HST research grant, he took advantage of the opportunity to apply for a supplemental educational grant to work with noted Braille book author Noreen Grice in creating a book of HST images accessible to visually impaired students.

Touch the Universe contains 14 spectacular HST images, each printed in color and supplemented by a transparent tactile overlay in which the color features are represented by tactile symbols. Through these images, the reader is taken on a journey of discovery to more and more distant objects, starting with images of the telescope itself in orbit and ending with the HST Deep Field image of some of the most distant galaxies in the universe. Accompanying explanatory text is given in both Braille and large print so that readers of all visual abilities are able to view and read the book together. With plans for large-scale publication and distribution under way, the success of *Touch the Universe* indicates how a relatively small amount of money can result in a national product.

Research Area One

How did the cosmic web of matter organize into the first stars and galaxies?

Today's universe is full of structure—galaxies, stars, planets, and life. However, we now know that immediately after the Big Bang the distribution of matter and energy in the universe was almost perfectly smooth. Experiments such as BOOMERANG, COBE, and MAXIMA have measured very small irregularities—a thousandth of one percent—in the brightness of the cosmic microwave background, the vast sea of primordial radiation that shows us the universe at an age of a few hundred thousand years. Under the influence of gravity, the tiny fluctuations gradually built a weblike structure of mostly hydrogen gas and "dark matter" (whose nature remains mysterious) within which stars and galaxies would later form. A key program for the Origins theme is to provide a detailed account of how this happened.

Modern computer simulations suggest that the growth of structure advanced through the hierarchical mergers of dark matter concentrations—"halos," as they are called. Eventually the gravity of the largest halos grew strong enough to pull in and concentrate the gas needed to build an infant galaxy. However, the first generation of stars may actually have preceded galaxies. With no heavy elements the cooling of the gas would have been very inefficient. Theorists have suggested that such different conditions would have led to a generation of short-lived stars, considerably more massive, hotter, and brighter than those we observe around us today. With their violent supernova deaths these first stars would have rapidly "polluted" the gas with heavy elements, thereby dramatically changing the climate for future star formation. The remnant black holes these supernovae likely left behind may have seeded the growth of supermassive black holes that powered the first quasars.

The energy in starlight comes from nuclear fusion reactions in the stellar core. However, a comparable amount of light comes from the release of gravitational potential energy as matter falls ("accretes") into super-massive black holes at the centers of large galaxies. A quasar—the extreme manifestation of this process—can for a time outshine all the stars in its galaxy. The release of highly energetic photons from these first stars and quasars heated the gas and ionized it. We seek to understand how this happened, in detail, and how it affected the formation of later generations of stars and black holes. Ultimately, we want to know how all the relevant processes worked together to integrate gas, stars, and black holes into the dark matter halos to form the first galaxies. This means tracing the growth of dark matter halos, the distribution of gas in space and time, the synthesis of the heavy elements, and the buildup of stars and their remnants as the universe ages. A particularly important epoch lies between redshifts of 1 and 3 (from about 7 to 10 billion years ago), when the present-day universe began to take shape.

These questions lead us to pursue three investigations in this area:

- Study how pristine gas from the Big Bang condensed into the first generation of stars, and how their supernovae produced the first heavy chemical elements.
- Observe the enormous release of energy during the building of the first massive black holes that combined with energy from the first stars to change the structure of the early universe.
- Describe the assembly of galaxies and their subsequent evolution from generations of stars, leading to the diversity of galaxies in today's universe.

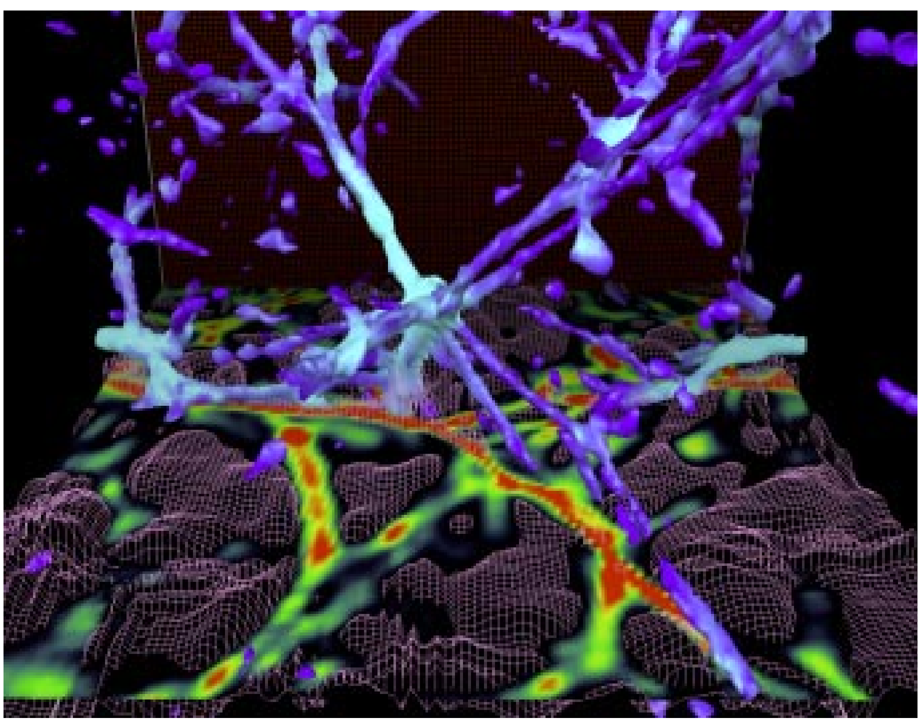
INVESTIGATION 1

Study how pristine gas from the Big Bang condensed into the first generation of stars, and how their supernovae produced the first heavy chemical elements.

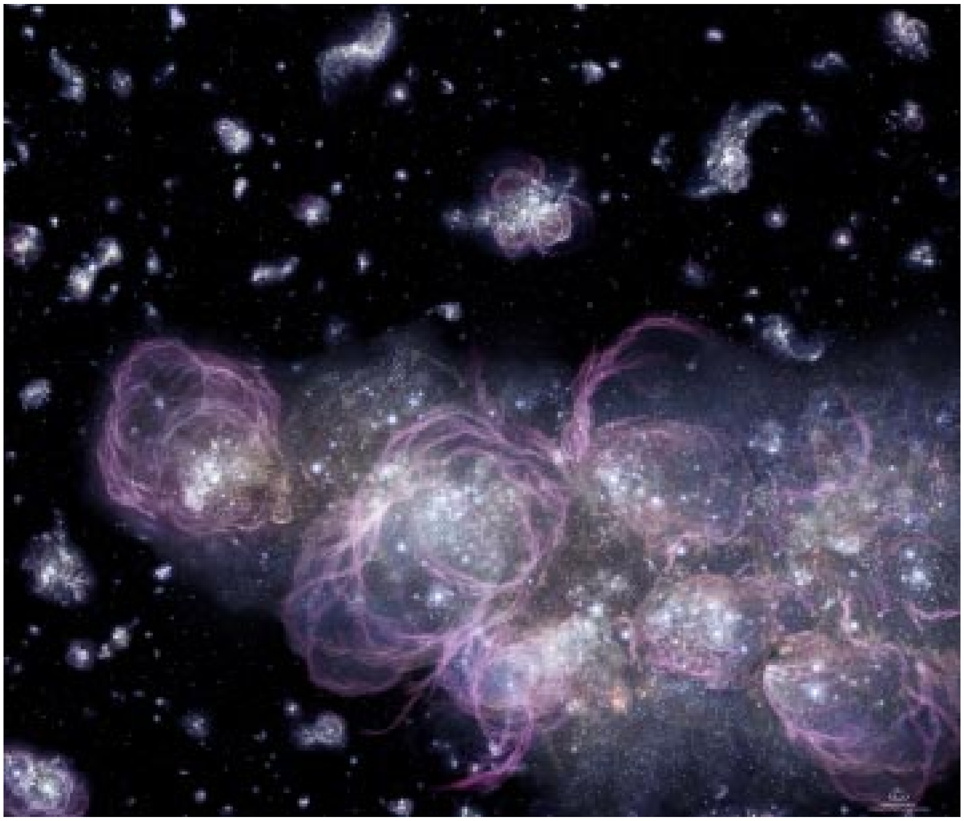
As the universe aged, gas was continually pulled into the dark matter halos. Over time, the pressure of the gas eventually came to be important and hydrodynamic effects began to compete with gravity in controlling the formation of galaxy-sized structures. The pressure in a gas depends partly on its temperature, influenced in turn by radiative cooling (depending sensitively on the history of heavy elements production by the first stars), and photoionization heating from the first stars and quasars. Shock waves would have formed in the supersonic infall of fresh gas into the dark matter gravity wells, further heating the gas. Gravitational tides exerted by neighboring structures would have applied torques to both the gas and dark matter, contributing to rotational support of the gas against gravity in these early protogalaxies. As the dark matter gravity wells coalesced and merged within the cosmic web, small protogalaxies collided and merged to form larger and larger structures—this hierarchical description of galaxy formation is strongly supported by both theory and observation.

Understanding the formation of the first generation of stars will require continued theoretical modeling of the hydrodynamics, thermodynamics, and non-equilibrium chemistry of pristine hydrogen and helium gas in the evolving cosmic web of dark matter. Trace amounts of molecular hydrogen provide the dominant coolant of the gas in the initially smaller mass dark matter gravity wells with virial temperatures below 10,000 kelvin. The formation of this molecular hydrogen depends sensitively on the free electron abundance and therefore the exact ionization state of the gas. This in turn will evolve quickly once the first stars form. Larger dark matter wells with higher virial temperatures will have mostly ionized hydrogen and be able to cool much more efficiently. Detailed theoretical modeling of these processes, supported by the Origins Research and Analysis (R&A) program, will be required to make predictions to guide observations by Origins missions.

Direct detection of the first generation of stars will almost certainly require the unprecedented sensitivity of the James Webb Space Telescope (JWST). These stars are likely to be in clusters of approximately 10^6 solar masses.



Hydrodynamic simulation of the cosmic gas density at redshift 3, for a sample box 8 million light-years on a side. These dense filaments are detected as the Lyman-alpha forest in absorption-line spectra of distant quasars.



Artist's impression of the universe at age 1 billion years. The scene is dominated by starburst galaxies with bright knots of blue stars and hot bubbles from supernova explosions.

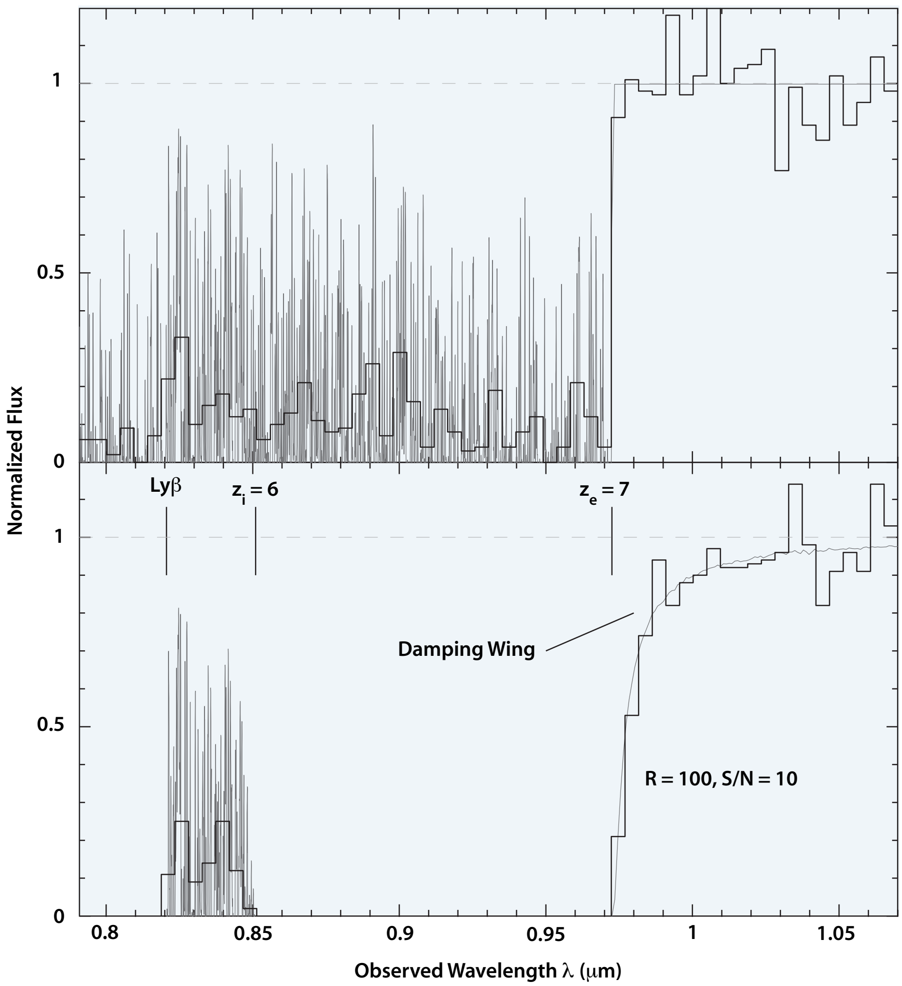
Very deep imaging of a single field with week-long exposures in multiple near-IR filters should be able to detect even modest birth rates of stars out to redshifts z = 20. Various spectral signatures will be able to test whether these are the very massive, hot, short-lived stars that theorists are now predicting, as opposed to a first generation with a full mass spectrum. JWST will also observe the first supernovae directly—these can be distinguished from starlight by their sudden appearance and slow decay. It should also be possible to investigate the dispersal of the first heavy elements by looking for the emission lines such as [OIII] predicted to be in the light from the earliest star forming regions.

The epoch of the first stars and supernovae is not likely to be uniform throughout the early universe. In the denser pockets, we may find evidence that the birth of the earliest stars lies beyond our current observational reach. In other regions, we may discover pristine, primordial gas and direct evidence of the earliest star formation. Deep surveys by JWST will provide an unbiased and statistically valid picture of the first epoch of stars and their chemical legacy.

INVESTIGATION 2

Observe the enormous release of energy during the building of the first massive black holes that combined with energy from the first stars to change the structure of the early universe.

Because they are so bright, quasars turn out to be the most distant (and therefore earliest) discrete sources of light that have been observed so far in the universe. Light from distant quasars is therefore routinely used to probe the evolution of gas between galaxies (the "intergalactic medium"). Spectroscopic observations by ground-based telescopes and the Hubble Space Telescope (HST) have used absorption by neutral hydrogen to trace the evolution of neutral gas in the cosmic web. Most of this gas is now ionized, however, whereas the very existence of the cosmic microwave background implies that electrons and hydrogen and helium



A simulated spectrum of the Lyman alpha forest in a quasar at redshift 7. The upper panel represents an extrapolation of the cloud statistics, and the lower panel shows the effect of increasing the cloud density beyond redshift 6: the reionization epoch.

nuclei combined to form neutral atoms early in the history of the universe. Something therefore reionized the intergalactic medium, almost certainly ultraviolet and/or X-ray photons from the first stars and quasars. This reionization heated the gas and altered its chemistry, thereby affecting its ability to accumulate into dark matter gravity wells and form later generations of stars and black holes. We do not yet know when this reionization epoch occurred, although there are tantalizing recent observations of the most distant quasars suggesting that the process may have been completed as late as redshift $z = 6$. We also do not know in detail how ionization occurred, and what were the relative contributions of starlight and quasars—JWST will be our primary investigative tool.

Massive black holes are now known to be ubiquitous in the nuclei of all large galaxies in the present day universe. The masses of these black holes are tightly correlated to the larger scale random motions of stars in these galaxies, providing a clear indication that the structure of galaxies and the presence of black holes are intimately related. We do not know how this observed relation arose, and resolving the mystery will require observations of black holes in the process of formation. The optical and ultraviolet light from these earliest quasars will be redshifted into the near infrared (IR), and if dust enshrouds these objects then they will also be copious sources of mid-infrared radiation. Quasars can be distinguished from star forming regions because they also produce relatively greater quantities of X-rays. Deep imaging surveys across the electromagnetic spectrum are therefore the best way to search for and interpret these early sources. This is already being done with HST and Chandra, but to push to the earlier epochs we will require high-sensitivity detections in the near-to-mid-IR. This next generation of surveys will begin with the Space Infrared Telescope Facility (SIRTF) and be carried to unprecedented depths by JWST.

Once the earliest sources are detected, JWST will use them as spectroscopic probes of the intervening intergalactic medium. Theoretical modeling of both quasar and galaxy formation, funded by the R&A program, will be crucial for interpreting this data. The exact time interval of hydrogen reionization will be determined with JWST through high signal-to-noise observations of the red damping wing of the Lyman-alpha absorption (Gunn-Peterson) trough in spectra of very high redshift sources. The shape of this damping wing can be used to directly measure the Lyman-alpha absorption optical depth and therefore the neutral hydrogen density. These and similar measurements will probe the evolutionary history of the gas, and provide a better understanding of the relative roles of stars and quasars during the reionization epoch.

This complex evolution is accompanied by ongoing star formation that illuminates the early protogalaxies. In addition, infall of gas into massive black holes produces quasars and less luminous active galactic nuclei (AGN). Observations of high redshift star formation and active galactic nuclei by HST and JWST will allow us to trace the buildup of galaxies with time. Dust formed by early generations of stars will also absorb and reradiate starlight and quasar light into the mid- and far-IR, making observations by SIRTF and JWST crucial to tracing the energy budget of galaxy formation and early evolution. Weak gravitational lensing of high redshift galaxies, observed with HST and eventually JWST, will be used to measure the mass distribution of foreground dark matter haloes. These observations can then be used to test theories of the evolution of the invisible framework of the cosmic web. JWST will be a powerful tool for the technique of gravitational lensing to chart the clustering of dark matter from galaxy halos to the much more massive galaxy-cluster halos.

The gas component of the cosmic web, for $z > 3$, would be observable in great detail with a next-generation ground-based telescope such as the Giant Segmented Mirror Telescope (GSMT). The enormous light-gathering power of such a telescope allows the use of faint galaxies as the probes of intergalactic absorption. Unlike quasars, these background galaxies are sufficiently numerous to probe the cosmic web with the required resolution to see structure growth at the correlation length. The ability to follow the gas evolution of the cosmic web from $z = 3$ down to the present day will be greatly enhanced by the Cosmic Origins Spectrograph on HST, but a larger UV-optical space telescope, with far more efficient UV detectors, will be essential for a thorough understanding.

INVESTIGATION 3

Describe the assembly of galaxies and their subsequent evolution from generations of stars, leading to the diversity of galaxies in today's universe.

The buildup of the stellar component of galaxies will be measured with present and future surveys across a wide range of wavelengths, with HST, SIRTF, and JWST playing key roles. HST and SIRTF observations of young galaxies will measure star formation rates and the accumulation of older stars in these systems. A substantial fraction of star formation may be hidden by dust, and deep mid-infrared imaging by SIRTF will be able to detect dust-enshrouded star forming regions out to $z = 2.5$, as well as possible dust-hidden AGNs. Complementary wide-field surveys in the near and mid-infrared will also be conducted by SIRTF in order to connect the evolution of galaxies with the growth of the large-scale structure that follows the evolution of the distribution of dark matter.

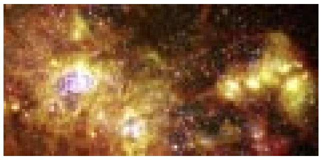
The deep JWST images designed to detect the first stars and quasars will also image large numbers of galaxies in the $z = 1 - 5$ redshift range that can be followed up with JWST and ground-based spectroscopy. Because of its much greater aperture, JWST will reach much fainter systems than HST and SIRTF, crucial for understanding the complete star formation history of the universe. JWST's spectroscopic capability will provide a powerful probe of the buildup of the heavy elements. Moderate-resolution spectroscopy ($R=1000$) in the rest-frame 3500–7000 angstrom range can be obtained for thousands of galaxies to provide a uniform sample of heavy element abundances, stellar ages, star-formation rates (from emission lines of HII regions), and measurements of the level of dust extinction. JWST spectroscopic observations of higher resolution ($R = 3000$), possible for luminous galaxies, can measure stellar and gas kinematics and provide information on galaxy masses and further detail of the process of galaxy assembly. Spatially resolved spectroscopy of bright galaxies with interesting morphologies will probe the spatial variations in physical conditions in these systems. Complementary measurements for lower-luminosity galaxies over this epoch could be done with the next generation of larger ground-based telescopes (for example, the proposed 30-meter GSMT) using laser guide star adaptive optics and sufficiently high spectral resolution to overcome night-sky emission. Imaging and spectroscopy of high redshift galaxies in rich clusters, groups, and the field will provide the data needed to describe the effects of environment on galaxy formation and evolution.

The dust content of typical galaxies at high redshift is acknowledged as a vital and largely unexplored aspect of galaxy evolution. Observations with ISO and the SCUBA instrument on the James Clerk Maxwell Telescope have partially resolved the submillimeter background discovered by COBE into galaxies, providing strong evidence that much of the light generated by high redshift star formation is reprocessed by dust. SIRTF will undoubtedly detect more of the sources contributing to the background. JWST can measure even heavily dust-enshrouded star formation out to redshift $z = 3.5$ by detecting rest-frame 3.3-micron polycyclic aromatic hydrocarbon (PAH) emission. In addition, JWST can exploit numerous mid-IR spectroscopic diagnostics to distinguish star formation from hidden AGN. These include coronal lines of silicon, sulfur and calcium as well as rotation-vibration emission of molecular hydrogen.

The goal of this part of the Origins program is to understand how the first stars and black holes began the process of assembling the galaxies we see today. It will be essential to connect what we learn with observations of nearby galaxies. Measuring the rate at which stars formed at different times in the history of the universe will allow us to account for the integral population of stars and stellar remnants (white dwarfs, neutron stars, and black holes) that we observe around us today, as well as the overall abundance of heavy elements that were produced by these stars. Detections of high redshift supernovae and the determination of the variation in supernova rate with time will provide a complementary measurement of the star-formation rate. Because certain classes of supernovae come from the most massive stars, this will also help us trace the rate at which stars of different masses form, which may help answer the question of whether the initial mass function of star formation is a function of environment and/or time. High-resolution spectral observations with ground-based telescopes of giant stars in Local Group galaxies can also provide a cross check to the yields of r- and s- process elements produced by different kinds of supernovae.

The stellar populations laid down in earlier epochs comprise the fossil record of stars in our own galaxy and its neighbors. The high spatial resolution of HST over a substantial field has been crucial for producing color-magnitude diagrams that, when combined with theory, validate the history of star formation that will be carefully charted with lookback observations of HST, SIRTF, and JWST. It will be important to extend our capabilities to larger apertures and higher spatial resolutions in order to reach other galaxies, to the main-sequence turnoff for the Milky Way's neighbors, and down to the giant and horizontal branches as far as the Virgo cluster. JWST will extend these studies beyond the reach of HST, but a larger HST descendant that images in the UV-optical would make a decisive contribution to this effort. Diffraction-limited, high-strehl-ratio imaging over modest fields would provide an essential, unique capability only achievable from space.

The morphology of today's mature galaxies is described by the Hubble sequence—a variety of distinct morphological types including irregulars, spirals and ellipticals—and these morphologies consist of basic structural components such as disks, bulges, bars, and spiral arms. There is now good evidence that the Hubble sequence arose between $1 < z < 3$, but as yet there are no observations to guide modeling of how the morphology and structures of galaxies arose and evolved. The high angular resolution and sensitivity of JWST will permit direct observations of the morphological evolution of galaxies as well as the history of galaxy collisions and mergers over this crucial epoch.



Research Area Two

How do different galactic ecosystems (of stars and gas) form and which can lead to planets and living organisms?

Earth and its solar system siblings are made of ices from the carbon-nitrogen-oxygen family of elements and rocks from the calcium, silicon, magnesium, and iron groups. Life, as we know it, depends entirely on the complex chemistry of compounds built around carbon atoms, what we call "organic" compounds. We now know that the universe was not born with these materials, but that the stars themselves are the sites of their manufacture. This discovery—that the heavy elements essential for a living being come directly from stars—ranks among the greatest human achievements in understanding the universe and our place in it.

The buildup of these heavy elements did not happen all at once. We have learned how these elements are made in stars and how they can be recycled into future generations of stars and potential planetary systems. At the ends of their lives massive stars explode and less massive stars slowly shed gas enriched with these heavy elements. In each cycle the abundance of heavy elements increases as the "ash" of nuclear burning in the centers of stars is added to the mix. We now know that this enriched gas remains bound to a galaxy by gravity, at least for giant galaxies like our own, and that this store slowly increases over time. We can even roughly chart the increase in heavy elements over the generations of stars born over the 12 billion-year lifetime of our Milky Way Galaxy and compare it with the process in other nearby galaxies.

However, we know relatively little detail of the enrichment process for interstellar gaseous material in our galaxy and others. When and how did the process of chemical enrichment begin, and what kinds of influences regulated the process? What exactly is the importance of heavy elements (in gas, molecules, and dust) for the formation of planets? Which elements are essential? For example, is there a minimum mass in long-lived radioactive elements needed for a geologically active planet such as Earth? Is there a threshold level of heavy elements necessary for planet formation? Do the abundance gradients in our own galaxy or others result in a "galactic habitable zone" where the formation of Earth-like planets is favored? Has the course of planet building changed over cosmic time as the abundance and balance of these heavy elements has grown? We can now begin to answer such questions by finding out whether the presence and character of planetary systems depends on the heavy element abundance of parent stars; for example, do stars with the lowest abundances, in the globular clusters of the Milky Way or in its outer halo, have well developed planetary systems? We can investigate whether the dust grains and complex hydrocarbons found in galactic clouds and star-forming regions survive to play a role in the formation of planets and their atmospheres, or whether instead they are vaporized in the process and remade in the later stages of planet building. Such studies will teach us how the development of giant star systems like the Milky Way is essential to the eventual emergence of life, how long our galaxy has been inhabited, and where we may look in our own galaxy to find other life.

We highlight two investigations in this area:

- Study how the lifecycles of stars in the Milky Way and other galaxies build up the chemical elements and galactic environments needed for planets and life.
- Observe when and where habitats for life emerged in the Milky Way and other galaxies.

INVESTIGATION 4

Study how the lifecycles of stars in the Milky Way and other galaxies build up the chemical elements and galactic environments needed for planets and life.

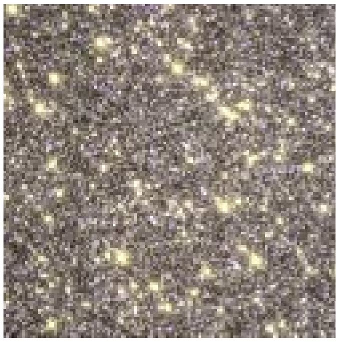
A galaxy may be thought of as a giant ecosystem containing stars, radiation, dust, gas, and planets. Much like ecosystems on Earth, the interactions among these elements are complex. As yet we know very little in detail about how galactic ecosystems work, and how they produce planets and life, but future Origins missions will shed much light on this process.

One of the least understood processes in the galactic ecosystem is the interaction between the stars and gas—massive stars and supernovae inject enormous amounts of mechanical energy through flows and shocks and by radiation into the gas. This stirs the gas and forms structures called superbubbles and fountains. Though these facts are clear, we have little understanding of the effect of this "feedback" on subsequent star formation and, hence, the buildup of heavy elements necessary for life.

The full picture of star formation in the present-day universe will emerge only when we have studied the formation of stars in a sample of galaxies with a diverse range of mass, gas density, dust content and elemental abundance. SIRTF will, for example, characterize the large-scale infrared properties of 75 nearby galaxies in order to correlate star formation rates with properties of the interstellar medium and JWST will extend such work to a far larger sample.

We also need to study how the star formation rates and elemental abundances of galaxies evolve over time, by looking at samples of galaxies at different cosmic distances (that is, at different look-back times). This will give us insight into the conditions in our own galaxy 5 billion years ago when Earth was formed. Large ground-based telescopes such as GSMT will make crucial spectroscopic studies of stars that record the fossil record of stellar birth in our galaxy and its neighbors to compare with the results of these lookback studies. The external environments of galaxies also play an important role in star formation. Galaxies rarely evolve in isolation—galactic ecosystems are not "closed boxes"—and mergers of galaxies affect their gas content, star formation rate and structural evolution. Galactic winds and the infall of clouds of gas and dust into large galaxies also act to modify the elemental abundances of the intergalactic medium and the interstellar medium in galaxies. We know that galaxies underwent many more mergers in the past, so we need to study galactic environments as a function of look-back time. This work will require large aperture telescopes and sensitive spectrographs operating from the UV to IR. These investigations will be enabled by JWST, Single Aperture Far-Infrared Observatory (SAFIR), and a HST

The nearby galaxy NGC 4214 is lit up by filigreed clouds of glowing gas surrounding bright stellar clusters. Their hot blue stars eject fast stellar winds, moving at thousands of kilometers per second, which plow out into the surrounding gas.



Hubble Space Telescope image of the center of the globular star cluster Omega Cen. The very high density of stars makes this an ideal laboratory for studying interactions among stars.

descendent. Measurements of absorption lines in the spectra of background X-ray sources by Chandra and Constellation-X will also measure heavy element abundances in the interstellar media of galaxies, independent of whether these elements exist in the gas phase or are locked up in solid dust grains.

INVESTIGATION 5

Observe when and where habitats for life emerged in the Milky Way and other galaxies.

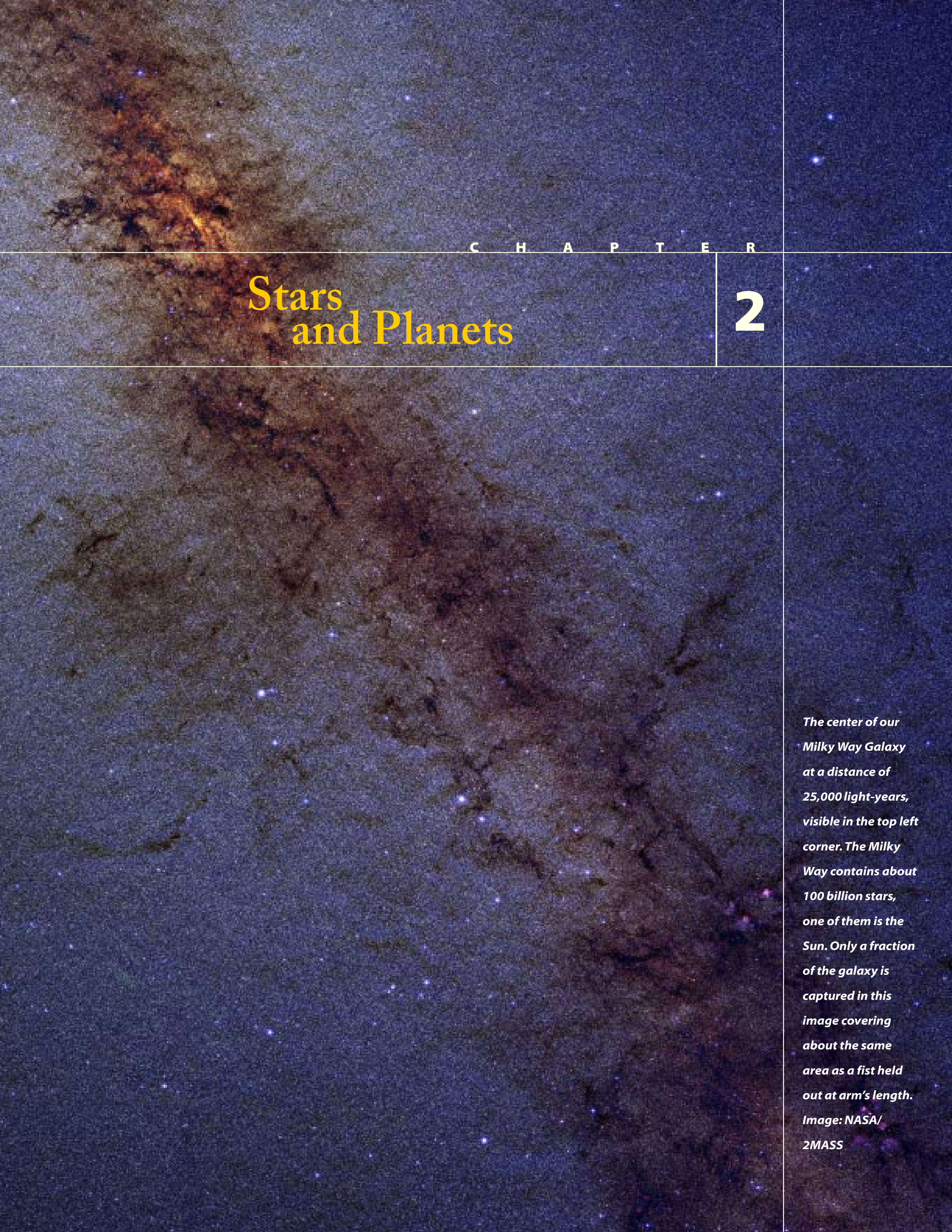
Our solar system orbits the galaxy at a distance of roughly 24,000 light-years out from the center; currently it is the only known system to contain life. Is our location a coincidence, or is this region of the galaxy more hospitable to the formation and evolution of life? In other words, is there a galactic habitable zone much as there is a habitable zone around a star? Sampling from the central regions of our galaxy to its periphery, both star formation rates and heavy element abundances are seen to decrease. It is conceivable that there is a minimum heavy element abundance necessary for the formation of both terrestrial and giant planets as well as for life, and that this abundance does not exist in the outer regions of the galaxy. It is also possible that various mixes of heavy elements, particularly radioactive ones, are important for the formation of a world with plate tectonics, and that this is important for the evolution of life. Recent studies have shown that the mix of different heavy elements has changed dramatically over the history of the Milky Way and, by implication, for other galaxies as well. By investigating the incidence of planets and, ultimately, life, in various regions of our galaxy we will be able to determine the necessary galactic environmental conditions for the formation of planets and life.

Such investigations have already begun. An extensive observational search with HST for planetary transits of stars in the ancient globular cluster 47 Tucanae turned up no planets, even though the search had considerable sensitivity. Could it be that the low heavy element abundance of globular clusters precludes the formation of planets, or might encounters between neighboring stars in such dense stellar systems disrupt planetary systems or prevent them from forming in the first place? Future observations and theoretical investigations within the Origins program will address such questions as how the presence of terrestrial and giant planets is related to stellar mass and age, magnetic activity in the star, binarity and/or the presence of surrounding stars in a cluster, and the overall galactic environment in which the star formed. For example, SIRTF, JWST, and eventually next-generation near-to-far-IR space telescopes will be able to observe planet formation in a wide range of environments.

These modest studies are only the beginning. In the far future one can imagine extending some elements of the search for planets beyond our own galaxy. For example, can observations of infrared emission from young stars in dwarf galaxies with low abundances of heavy elements tell us, by analogy to similar, higher resolution and higher sensitivity observations of Milky Way stars, whether such galaxies could have planets and life? More extensive studies of their histories of star formation and heavy element abundances will tell us, in comparison with the Milky Way, whether planet building is likely to have proceeded differently in different types of galaxies. Through exhaustive study of the relatively nearby stars and detailed studies of the stellar populations far from our neighborhood, we may eventually connect the incidence of planets and the potential for life to the global properties of galactic environments.

C H A P T E R 2

Stars and Planets



The center of our Milky Way Galaxy at a distance of 25,000 light-years, visible in the top left corner. The Milky Way contains about 100 billion stars, one of them is the Sun. Only a fraction of the galaxy is captured in this image covering about the same area as a fist held out at arm's length. Image: NASA/2MASS

O B J E C T I V E T W O

...to learn how stars and planetary systems form and evolve.

During the past three decades, we have used both ground- and space-based facilities to look inside the nurseries where stars and planets are born. Parallel studies conducted in the solar system with planetary probes and of meteorites have revealed clues to the processes that shaped the early evolution of our own planetary system. An overarching goal of science in the 21st century will be to connect what we observe elsewhere in the universe with objects and phenomena in our own solar system.

We now have strong evidence, based on the telltale wobbles measured for nearly 100 nearby stars, that they are orbited by otherwise unseen planets. One remarkable star, Upsilon Andromedae, shows evidence for three giant-planet companions. For another, HD209458, astronomers have observed the periodic decrease in its brightness due to the transit of one of its planets across the stellar disk and have thereby been able to measure the planet's radius and mass. However, these newly-discovered planetary systems are quite unlike our own solar system. The masses of the extrasolar planets span a broad range from one-eighth to more than ten Jupiter masses. Many of the planets are surprisingly close to their parent stars and the majority are on eccentric orbits. Extreme proximity and eccentricity are two characteristics not seen in the giant planets of our solar system. Although planetary systems like our own are only now becoming detectable with the techniques used to discover the new planets, the lack of a close analog to our own solar system and the striking variety of the detected systems raises a fascinating question: Is our solar system of a rare (or even unique) type?

In tandem, astronomers have now identified the basic stages of star formation. The process begins in the dense cores of cold gas clouds (so-called molecular clouds) that are on the verge of gravitational collapse. It continues with the formation of protostars, infant stellar objects with gas-rich, dusty circumstellar disks that evolve into adolescent "main-sequence" stars. These more mature stars are surrounded by tenuous disks of ice and dust that remain after most of the disk gas has dispersed. It is in the context of these last stages of star formation that planets are born.

The objective of understanding the parallel development of stars and planets and determining the prevalence and demographics of planetary systems will focus on two critical areas:

- Tracing the path from gas and dust to stars and planets.
- Detecting planetary systems around other stars and understanding their architectures and evolution.

Learning about "Invisible" Light

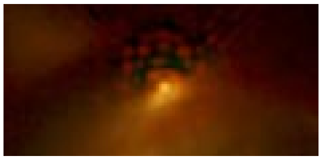
SOFIA (the Stratospheric Observatory for Infrared Astronomy) is expected to start carrying scientists and teachers into the stratosphere late in 2004. But SOFIA educators are already helping middle-school students gain a better understanding of one of the most fundamental aspects of modern astrophysics—objects in space emit a lot of energy that the human eye can't see.

"Active Astronomy: Classroom Activities for Learning About Infrared Light" engages students in four standards-based activities that help them understand that, when it comes to electromagnetic energy, there really is more out there than meets the eye.

In surveying the educational landscape, SOFIA staff discovered there were many existing classroom activities dealing with visible light and color, but very few which attempted to teach concepts of invisible light. Working with a team from Montana State University at Bozeman, they developed four activities which use common household electronics, like television remote controls and video cameras, or readily available inexpensive parts such as IR LEDs, IR-sensitive photocells, filter gels, etc.

Written drafts of the activities were submitted to the Origins Forum evaluation team, which used experienced peer reviewers-teachers to check the activities for conformance to national standards, pedagogy, and practicality. After their comments were incorporated, the SOFIA team assembled 20 sets, including kits with all the needed small electronics parts, and distributed them to volunteer teachers around the country who tested the activities in science classrooms with their students and returned valuable feedback.

Even before teachers start flying aboard SOFIA, thousands of students are learning about "invisible light," and why it is so important to our understanding of the universe.



Research Area Three

How do gas and dust become stars and planets?

The themes of this research area are the comprehensive study of the origin of stars in molecular clouds, the formation and early development of stars of all types, the formation of planets in their protostellar cradles, and the characterization of protoplanetary dust and gas disks. The goal is to trace the evolution of stars and planets from birth to maturity.

Molecular clouds both provide the raw material for production of stellar embryos and are the nurseries of newborn stars and planetary systems. The process of star formation involves a complex interplay, still poorly understood, between gravitational, turbulent, and magnetic forces within dense clouds. Upon collapse, just-formed stars produce energetic outflows and intense radiation fields which drive shocks and ionization fronts back into the surrounding medium, thereby providing feedback that can affect cloud structure and chemistry, and, hence, future generations of young stars. Moreover, the raw material from which planetary systems form contains the heavier elements in the same diverse states of molecular complexity found in the parent molecular cloud. Chemical processes at work during star and planet formation which can further modify this inventory include gas-phase reactions as well as reactions in and on coalescing planetesimals. Ultimately these compounds, including potentially important biogenic species, whether produced in the nebula or accepted unchanged from the interstellar medium, are incorporated into the material that becomes the planets, satellites, asteroids, and comets. Thus, the compounds that emerge from the interstellar/protostellar crucible provide the seeds from which life must spring. A central question is: How did the chemistry reach a complexity that made life possible?

By fragmentation and possibly also through merging, the objects formed from molecular clouds exhibit a wide variety of masses and multiplicities. These range from single stars and low-order multiples formed in relative isolation, for example, the T Tauri triple star system, to dense clusters of stars and brown dwarfs spanning four orders of magnitude in mass such as the Orion Nebula Cluster. Our stellar system (the Sun) has only one average-mass star, though it is strongly suspected that the Sun was born—like most stars—in a sizable cluster. An important goal in this research area is to understand how the mass distribution of stars (the "initial mass function") emerged and how the number, mass, and environment of stars figures into the formation of planets and, ultimately, life.

To understand planet birth and growth requires the protoplanetary disks that encircle protostars.There is observational evidence for two disk constituents: gas, primarily molecular hydrogen, and dust, including grains of interstellar origin and those formed in situ. A natural question is: How does dust and gas accumulate into mature planetary systems?

The Origins theme will:

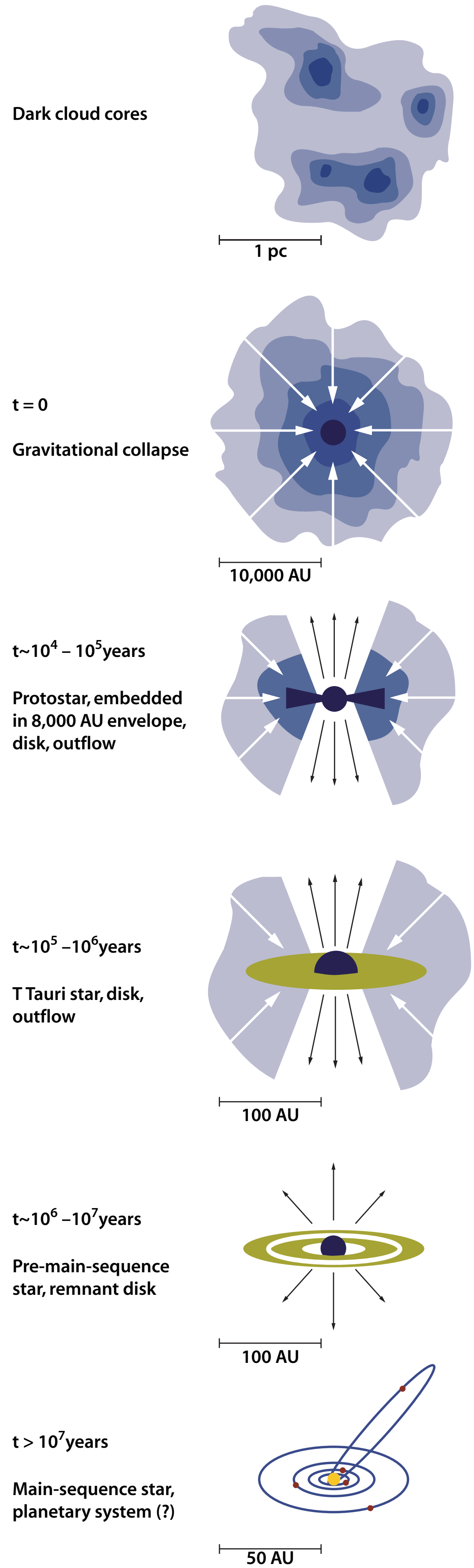
- Investigate molecular clouds as cradles for star and planet formation.
- Study the emergence of stellar systems.
- Determine how protoplanetary dust and gas disks mature into planetary systems.

INVESTIGATION 6

Investigate molecular clouds as cradles for star and planet formation.

Opaque to optical photons, molecular clouds achieve densities much higher than those of the diffuse interstellar medium. Deep within these "dark" clouds a rich range of chemical reactions is supported, including the creation and depletion of heavy elements onto dust grains and into ices. We know relatively little of the overall enrichment process for interstellar gaseous material in the universe, whereas explanation of how stars synthesize new elements through nuclear reactions was one of the great triumphs of science in the 20th century. Comprehensive understanding of heavy element creation and depletion and the important role of dusty material in star and planetary system formation is required in order to understand the chemical conditions from which life on our planet later arose. We must study dust formation and destruction, dust content in our own and other galaxies spanning a wide range of heavy element abundances, the influence of recently formed stars on the ambient cloud, and the effects of varying molecular cloud chemistry on star and planetary system formation.

The above investigations can be pursued with spectroscopic studies of the interstellar medium that probe molecular cloud chemistry. Also, observations of dust, either directly via its thermal infrared emission or indirectly through the extinction of background sources, and dust spectroscopy are required. A large-aperture ultraviolet/optical telescope will permit spectroscopy of the interstellar medium, cloud extinction maps, and detailed



Major stages in the formation of stars and planetary systems from the densest cores of molecular clouds, based on an original sketch by Frank Shu. Each of these transitional states yields characteristic signatures that can be observed.

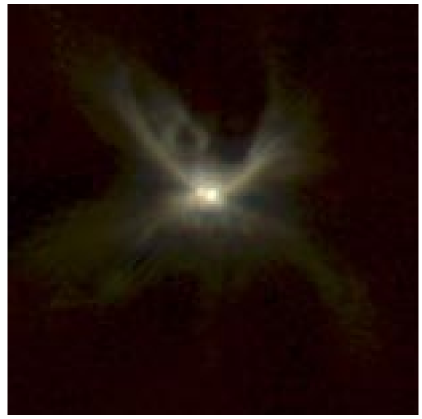
study of jets and outflows. In the mid- to far-infrared (30–300 micrometers), first SOFIA and Space Infrared Telescope Facility (SIRTF), and later a large-aperture space-borne telescope will be able to determine the temperature, density, and velocity structure of molecular clouds and collapsing cloud cores by mapping the emission from the dominant gas coolants (OI, H_2O, C^+, high-J CO lines) as well as the dust-generated continuum. At longer wavelengths, high spectral resolution submillimeter (300–650 micrometers) investigations with SOFIA will reveal infall kinematics and protostellar chemistry. ALMA will elucidate molecular cloud characteristics through high-J CO and more complex molecules. In order to provide clues concerning the earliest phases of star formation, these continuum and spectral line observations must be conducted at angular resolutions of 0.1–1 arcsec (10–100 astronomical units in the nearest star-forming regions). JWST will be able to probe the most central regions of protostars.

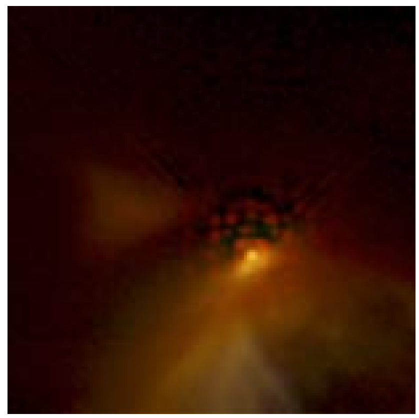
Where, when, and for how long do stars form in molecular clouds? Is star formation a fast process as recent evidence suggests, or one that occurs on the slow pace of particle drift along the magnetic field lines that thread molecular clouds, as theory has long predicted? Why do certain regions or neighborhoods in clouds produce stars, while others do not? Understanding these different modes of star formation will require the continuation of a vigorous R&A program that investigates the chemistry, physical structure, turbulent and magnetic effects, and fragmentation processes of molecular clouds. Furthermore, the chemistry in molecular clouds is quite exotic by terrestrial standards and targeted laboratory studies of materials under conditions that mimic—as much as possible—the appropriate cosmic environment are essential.

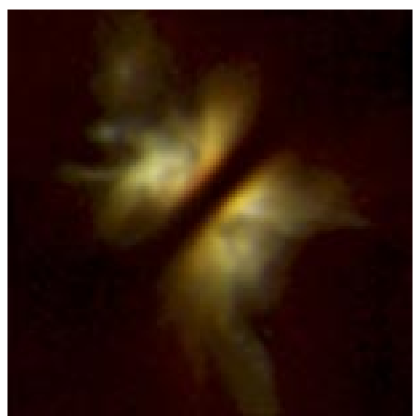
INVESTIGATION 7

Study the emergence of stellar systems.

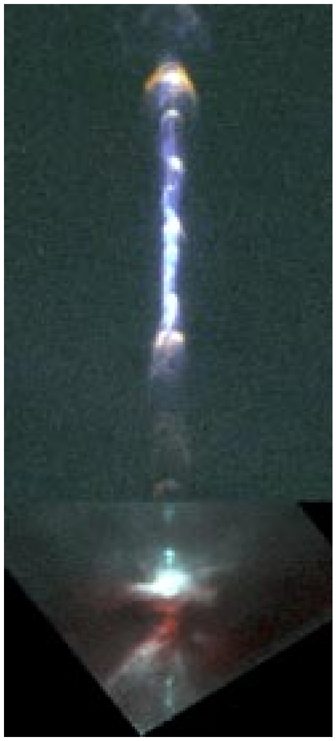
Gravitationally bound multiple star systems (e.g., binaries) are thought to form by fragmentation, induced by rotational effects during the collapse of a single molecular cloud core. In order to explain the diversity in orbital periods, eccentricities, and mass ratios observed in binary star







Disks of dust encircling young stars provide a view of the formative stages of the building of planetary systems. Images of disks seen in various orientations allow estimates of the disks' size, shape, and thickness.



Hubble finds young stars in a cosmic dance. One star of a trio of newborn stars emits oppositely directed streams of glowing gas 12 light-years long. Pulses in the gas flow create the fine structures in this IR image.

systems, an understanding of the physics of fragmentation is needed. Fragmentation at even earlier stages is responsible for star cluster formation. Observations show that the result of this process can be small groups or aggregates of 10–30 stars, ranging to large clusters of up to 10,000 or even 100,000 stars. The relationship between the stars and star clusters that are formed and the initial conditions in the parent cloud is not at all understood.

In order to achieve the scientific goals listed in this investigation, deep imaging and spectroscopic surveys from the ground, in the air with SOFIA, and from space with SIRTF and the James Webb Space Telescope (JWST) will be crucial. These missions will quantify the statistical properties of star clusters and lead us to an understanding of the star formation environment most likely to have hosted our own protosun. Moreover, advances in laboratory astrophysics are needed to understand chemical evolution in the circumstellar environment. A strong R&A program is essential to investigate the formation and properties of circumstellar disks around both single and multiple star systems.

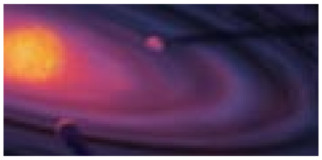
INVESTIGATION 8

Determine how protoplanetary dust and gas disks mature into planetary systems.

It has been determined observationally that stars accrete material from disks and that disks around young stars have finite lifetimes that range from perhaps one to several tens of millions of years. However, many aspects of this schematic picture remain unclear and the history of the gas content in disks, though critical, is insufficiently understood. Moreover, the flow of material during stellar accretion is inward toward the star. This flow would naturally carry any nascent planets with it. How then do the planets survive? Crucially, the timescale for the disappearance of gas may determine whether planets can form and survive at all. The most abundant species in protostellar disks is molecular hydrogen. However, its quantity until now has largely been inferred from trace species such as carbon monoxide, which may not be a proper tracer of total gas throughout the lifetime of the disk. Hence, direct measurements of molecular hydrogen, via infrared spectroscopy with SIRTF, SOFIA, and Single Aperture Far-Infrared Observatory (SAFIR), are needed to directly probe gas disks.

Furthermore, evidence from our own solar system suggests that the chemical composition varies with location in the disk. High angular resolution studies in the near-infrared (SIRTF, JWST) and far-infrared (SIRTF, SOFIA) are necessary to trace the distribution of important planetary constituents such as water ice, silicates, and complex carbon molecules.

Near the end of the evolution of a mature disk-planet system, the remnant disk gas is dispersed, leaving behind planets and the rubble of many smaller bodies. Dust produced in collisions of asteroid-like debris is thought to form the low-mass disks that have been detected around more mature stars, such as Vega. SIRTF will give us our first hints concerning gas and dust dispersal, but follow-on large space-based telescopes such as JWST and SAFIR are ideally suited to track the evolution and map the structure of vestigial debris disks around nearby main-sequence stars.



Research Area Four

Are there planetary systems around other stars and how do their architectures and evolution compare with our own solar system?

A cornerstone of the Origins program is the discovery of planets and planetary systems. Along with their discovery comes the determination of the numbers, distributions, and orbits of planets in the solar neighborhood. How many planets are there and around what types of stars are they found? Are other planetary systems similar to our own? This research area is an ambitious one for both observation and theory. Our efforts have begun with indirect detection of planets by measuring the radial velocity perturbations conferred by their gravitational pull on their parent stars. Soon, ground-based and space-based interferometers will add an important dimension to indirect detection by measuring the periodic shift in position of a star on the sky (astrometry) induced by its planets. With this additional information, the orbits of planets can be deduced—even those of complex systems with multiple planets—leading to accurate measurements of the planetary masses.

The large star-planet brightness ratios—a million in the mid-IR and a billion in the visible—make their direct detection a technical challenge beyond anything attempted to date in astronomy. Astronomers will need to build high-precision telescopes to accomplish the separation of the light from star and planet for even the nearest few hundred stars, at distances of no more than 20 parsecs. Eventually, statistically valid samples will require extending to many times that distance, meaning that the challenge of exploring the solar neighborhood for other worlds—already daunting—has just begun.

As we plan, test, and build instrumentation capable of detecting planets as small as Earth around nearby stars, there is much work that can be done now to improve our scant knowledge of other planetary systems. It is now possible to survey for the largest planets, down to the masses of Jupiter and Uranus by both indirect and direct means. Hence, an inventory of neighboring stars for such giant planets is a key goal of the Origins initiative. A related goal is to find "solar-system analogs," planetary systems with giant planets on near-circular orbits many astronomical units (AU) in size. Another crucial study will be to determine how common are smaller planets such as Earth, something that can be done, surprisingly, more easily for stars at considerably greater orbital distances than the Earth-like worlds we eventually hope to find and study in detail.

To accomplish these goals, present and future, the research in this area is sectioned into two investigations:

- The search for evidence of planets in disks around young stars.
- The census of planetary systems around stars of all ages.

INVESTIGATION 9

Search for evidence of planets in disks around young stars.

The initial steps toward planet formation occur in the surrounding disk of material that avoids either falling into a forming star or being ejected in outflows. These steps are now occurring around young stars in nearby molecular clouds. They should be apparent through their effects on the structures of the disks, but are hidden from view by a combination of obscuration due to the surrounding dust and limitations in resolution that mask the details in those young disks we can observe. Over time these observational limitations will be overcome through larger aperture telescopes and interferometers.

The most likely chemical constituents of the disks, including simple organic compounds that are the raw material for life, have characteristic absorption features accessible to JWST. In the near infrared, JWST will penetrate the obscuration to image these disks and map the distribution of disk materials on scales down to about 6 AU. With these images, we will fit disk model parameters, such as disk scale height (flaring), outer radius, and grain optical properties. These constraints provide the initial conditions necessary for studying the origin of planetary systems.

As planets form from the dust disk, they can interact gravitationally with the remaining gas. For relatively small planetary masses (10–100 Earth masses), this interaction results in density waves; for masses comparable to that of Jupiter, it results in the opening of gaps in the disk, with a radial extent of a few tenths of an astronomical unit or greater. These disk signatures may serve as proxies for the underlying planet, which may be much more difficult to detect directly. The resolution of JWST will allow an initial survey for large gaps in young disks. However, the detection of a gap associated with a proto-Jupiter, 1 AU width at a distance of 5 AU from a star in a nearby star-forming region, will require an angular resolution better than 0.01 arcsecond. The gap and planet will be separated from the star by only 0.05 arcsecond, and for typical disk and planetary temperatures of a few hundred kelvin, most of the energy is radiated in the 10-micrometer spectral region. Interferometric or coronagraphic imaging of disks in nearby star-forming regions by the Terrestrial Planet Finder (TPF), will be able to map and characterize these disk structures and give us an unprecedented view of the planet-formation process.

Another promising way of studying planet formation in disks is to find evidence that small dust grains are being depleted by coagulation into larger grains and eventually into planetesimals. Observations must distinguish grain growth from effects caused by radiation blowout and Poynting-Robertson drag. Spectral and photometric studies, using JWST and SAFIR, of the temporal development of the IR spectral energy distributions of the disks around young stars play central roles in this investigation.

It may also be possible to image young protoplanets directly, since some theoretical models predict that they achieve a brightness of 1/1000 to 1/100 that of the central star during a relatively brief phase of rapid accretion of gas. A Jupiter-like protoplanet at 5 AU from its star will be separated from the star by 0.05 arcsecond at distances of 100 parsecs. The starlight nulling or advanced coronagraphic ability of TPF will be essential to separate the planetary radiation from that of the surrounding disk and the star, but the precursor interferometry that will soon be done from the ground with the Keck Interferometer (KI) might give us our first tentative glimpse of such an embedded planet.

INVESTIGATION 10

Conduct the census of planetary systems around stars of all ages.

We must follow-up the initial epoch of giant planet discoveries with an extensive dynamical, photometric, transit, and imaging exploration of main-sequence stars to determine the orbital characteristics and gross physical properties of their planets. A multi-pronged strategy of dynamical, photometric-transit, and imaging techniques should be pursued in series and in parallel. These should be implemented in three chronological phases.

In the first (reconnaissance) phase, astronomers must make a complete inventory of giant and Neptune-mass planets around all stars within 10 parsecs and around a statistically significant sample of more distant stars. Such a census, carried out with ground-based radial-velocity and astrometric techniques, will determine the abundance of planets and the correlation of stellar properties (such as mass, metallicity, and binarity) with giant planet properties (such as mass and orbital parameters). Importantly, giant planets dynamically constrain the orbits left available to terrestrial planets, influencing later searches for Earth-like worlds. In this sense, the study of giant planets is an important stepping stone to the more demanding study of the smaller terrestrial planets.

The above Doppler and astrometric surveys are challenging, requiring velocity precision of 1 m/s and astrometric precision of 20 microarcseconds (for example, the Keck Interferometer). Nonetheless, these efforts are relatively inexpensive and the technology is already relatively mature. Note that the planets detected in this first reconnaissance phase have intrinsic brightnesses of a millionth to a billionth that of the host star and many will be separated by an arcsecond or less.

A second phase employs the space-telescopes Kepler—a new Discovery-class mission designed to photometrically search for terrestrial and giant planet transits around tens of thousands of nearby stars—and the Space Interferometry Mission (SIM), an interferometer with an astrometric precision for terrestrial and giant planet detection of 1–10 microarcseconds. Kepler will have a photometric precision of one part in 100,000 and should discover hundreds of terrestrial and giant planets, while SIM will discover and astrometrically measure planet masses down to a few Earth-masses. SIM will survey the youngest stars close to the Sun to study the formation and evolution of Jupiter-size planets. To obtain a secure mass for a terrestrial planet requires a dynamical technique such as only SIM will employ. The complementarity between the photometric-transit technique of Kepler and the astrometric-interferometric technique of SIM provides NASA with a powerful program for pioneering terrestrial planet discovery and preliminary terrestrial and giant planet characterization.

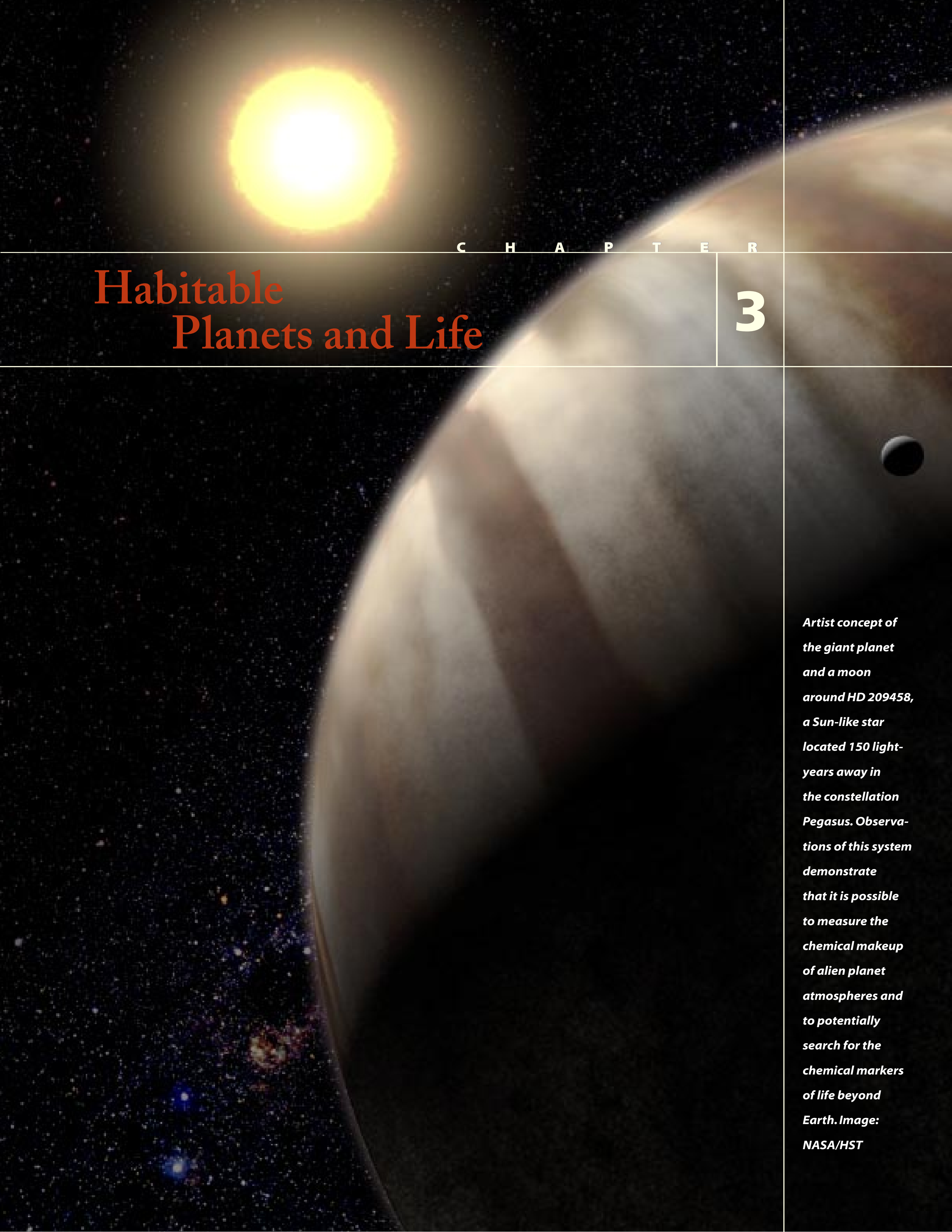
The first and second phases of dynamical and transit surveys must be followed by a third phase of direct space-based detection of the reflection and/or intrinsic light of the planets themselves. For giant planets, the logical technological and scientific precursor to a Terrestrial Planet Finder (TPF) and the more difficult problem of direct terrestrial planet imaging and spectroscopy is a space-based "giant planet finder." Using high-contrast imaging and low-resolution spectroscopy, such a mission would be capable of both discovery and analysis of the dynamically dominant and brighter components of planetary systems, while the later TPF will be able to observe at even larger star-planet flux contrasts the spectral features of the water, carbon dioxide, methane, and ammonia thought to reside in the atmospheres of the terrestrial planets. The technology, management structure, and discoveries of a giant planet finder program would provide NASA with valuable experience and guidance as it embarks upon the more challenging TPF initiative.

Though the direct photometric and spectroscopic detection of extrasolar giant planets will be a milestone in planetary research, the discovery and study of Earth-like planets that would be enabled by TPF is the ultimate goal of this first era of extrasolar planetary exploration.

Radial-velocity programs are unlikely to detect extrasolar planets with masses below a Uranus mass. Astrometric searches with an accuracy of 10 microarcseconds (KI) to 1 microarcsecond (SIM) can push the limit down to a few times the Earth's mass and survey a volume out to 5–10 parsecs. A space-based photometric-transit survey such as Kepler will extend to much larger volumes of space and provide an initial estimate of the frequency of terrestrial planets. However, direct imaging and spectroscopy of Earth-like planets will require TPF, an infrared interferometer or an optical coronagraph that can suppress the light of the central star to unprecedented levels, to reveal for the first time the atmospheres of planets like our own outside the solar system.

C H A P T E R 3

Habitable Planets and Life



Artist concept of the giant planet and a moon around HD 209458, a Sun-like star located 150 light-years away in the constellation Pegasus. Observations of this system demonstrate that it is possible to measure the chemical makeup of alien planet atmospheres and to potentially search for the chemical markers of life beyond Earth. Image: NASA/HST

OBJECTIVE THREE

...to explore the diversity of other worlds and search for those that might harbor life.

We have now found many extrasolar planets. Most are unlike those in our own solar system. But might there be near-twins of our solar system as well? Are there Earth-like planets? What are their characteristics? Could they support life? Do some actually show signs of past or present life?

After centuries of speculation, we finally know that there are indeed planets orbiting other stars. The extrasolar planets discovered so far seem to be gas giants like Jupiter. Earth-like worlds may also orbit other stars, but to this point our measurements lack the precision to detect a world as small as Earth. This could happen before the end of the decade through a NASA Discovery mission called Kepler, but even before then, detailed study of giant planets will tell us much about the formation and history of planetary systems, including our own. We have already made a first reconnaissance of the atmospheric properties of one such giant planet, which fortuitously passes directly in front of its star, allowing us to probe its atmosphere even if we can't see the planet directly. Beyond this, new techniques under development will actually provide images of these distant solar systems. With direct imaging we can make more detailed studies of giant extrasolar planets, helping us to learn whether other Jupiter-sized planets are near-twins of our Jupiter.

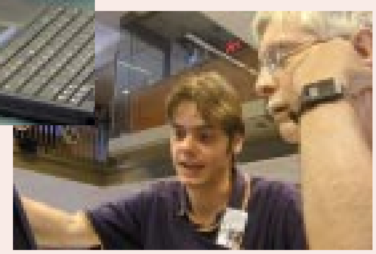
The Kepler mission, focusing on a myriad of distant stars, will be our first opportunity to find out how common it is for a star to have an orbiting Earth-like planet, how big those planets are, and where they are located in relation to the "habitable zone" where life as we know it is possible. This information will shape the follow-on search for Earth-like planets orbiting stars closer to us. The flagship mission to carry forward the search for Earth-like worlds will be the Terrestrial Planet Finder (TPF), which will image nearby planetary systems and separate out the extremely faint light of a terrestrial planet from its parent star. It will be difficult to see Earth-like planets, because they are even fainter than their giant planet siblings and because they must orbit much closer to the glare of their parent stars for life-giving liquid water to exist. Daunting as this may be, TPF's goal is to do just that, to find Earth-like worlds orbiting any one of about 150 nearby stars.

Once we have found terrestrial planets orbiting nearby stars, we can then tackle two even more ambitious objectives: first, to determine which of these planets actually have conditions suitable for life, and second to find which, if any, among those actually show signs of past or present life. Studies are already under way to learn which "biosignatures" —identifiable features in the spectrum of the planet's light—can reveal past or present life on a planet, and to plan future telescopes capable of making such observations.

Toward the ultimate goal of finding life on other Earths, Origins will address a sequence of questions:

- What are the properties of giant planets orbiting other stars?
- How common are terrestrial planets? What are their properties? Which of them might be habitable?
- Is there life on planets outside the solar system?

Future Researchers Prepare for NASA Missions

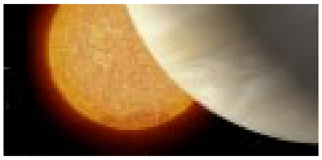


An excited hum of voices fills the Phillips Auditorium at the Harvard Smithsonian Center for Astrophysics in Cambridge, Massachusetts. It is Tuesday, June 25, 2002. Sixty-five students and young researchers from around the country are huddled over laptop computers trying to make sense of sample data from the Palomar Testbed Interferometer. It is the second day of a weeklong summer school on the practical application of optical interferometry in astronomy.

This year, the summer school runs for the fourth time as part of the Michelson Fellowship Program to encourage and support the next generation of researchers in becoming familiar with interferometry, a powerful technique considered for a series of NASA missions.

The program is sponsored by NASA's Navigator Program and also offers fellowships for graduate students and postdoctoral scholars.

One of the 21 instructors of the week is Dr. Michelle Creech-Eakman, a researcher on the team that took the original data the people at the laptops are discussing. Dr. Creech-Eakman and Dr. Peter Lawson, the organizer of the scientific program of this and the preceding summer schools, are two examples of how experienced researchers can inspire their future colleagues in sharing their expertise and using their numerous contacts with colleagues in the field. They are looking forward to meeting some of today's students in the years to come as collaborators on some of the missions currently on the drawing board.



Research Area Five

What are the properties of giants orbiting other stars?

Our solar system contains both distant gas-giant planets (notably Jupiter, Saturn) and much smaller terrestrial (rocky) planets in or close to the Sun's habitable zone—Venus, Earth, and Mars. Studies of planet-induced velocity "wobbles" of other stars have already found more than 100 giant planets, some in near-circular orbits as far from their parent stars as Jupiter is from our Sun. These few are quite reminiscent of our own solar system. Although we cannot with this method detect terrestrial planets in these systems, we can learn a great deal about the degree to which they resemble our own solar system by studying the giant planets themselves. Also, by perfecting new observational tools to study the properties of these giant planets we will take a big step toward developing the more advanced tools that will later be required for finding and studying terrestrial planets.

A first characterization of the properties of one giant planet has already been achieved, by careful study of the combined light of the planet and its parent star. This would normally be extremely difficult because a planet's light is typically between a million and a billion times fainter than its star and the planet is so close to the star that its faint light is lost in the star's glare. This first characterization was possible because the orbit of the planet just happens to be aligned so that the planet passes directly in front of the star during its orbital path. The exact amount of the starlight the planet blocks tells the size of the planet, which, interestingly, is about the same as our own Jupiter. A tiny fraction of the star's light is absorbed by the planet's atmosphere while it transits the star; detailed analysis of its spectrum tells us something about the chemical composition of the planet's atmosphere, and even about the possible presence of opaque clouds high in the atmosphere. These observations require extraordinary precision—best attainable only from space by large telescopes such as the Hubble Space Telescope (HST) or the James Webb Space Telescope (JWST), or possibly by giant ground-based telescopes equipped with large spectrographs. Future observations of this sort may even reveal circulation patterns in the giant planet's atmosphere, and day/night side variations.

If we are lucky, we may discover more such transiting giant planets passing in front of their stars. But a more powerful tool for understanding the properties of giant planets requires the development of instruments that can actually make an image of the planetary system, so that the light of planets is separated from that of the parent star. Though difficult, direct imaging of giant planets has powerful diagnostic potential, by enabling the direct observation of orbital motions, measuring planetary rotation and seasonal effects, and undertaking detailed studies of the composition of their atmospheres. Direct imaging of the giant planets in extrasolar planetary systems will mark a major milestone in our search to understand the nature and origins of our own solar system. The techniques developed in the process will lay the foundation for a later generation of instruments with the greater sensitivity necessary to image terrestrial planets and to search for signs of life.

Research aimed toward understanding the physical properties of giant extrasolar planets incorporates two investigations:

- Study the properties of giant extrasolar planets using the combined light of the planet and the parent star.
- Detect giant planets by direct imaging, and study their properties.

INVESTIGATION 11

Study the properties of giant extrasolar planets using the combined light of planet and parent star.

The information derived from the one transiting planet presently known suggests that observations of others will become increasingly valuable in coming years—extensive ground-based surveys are beginning that should detect many more. Follow-up studies using both space telescopes (e.g., JWST) and large ground-based telescopes can then yield detailed information of the sort described above.

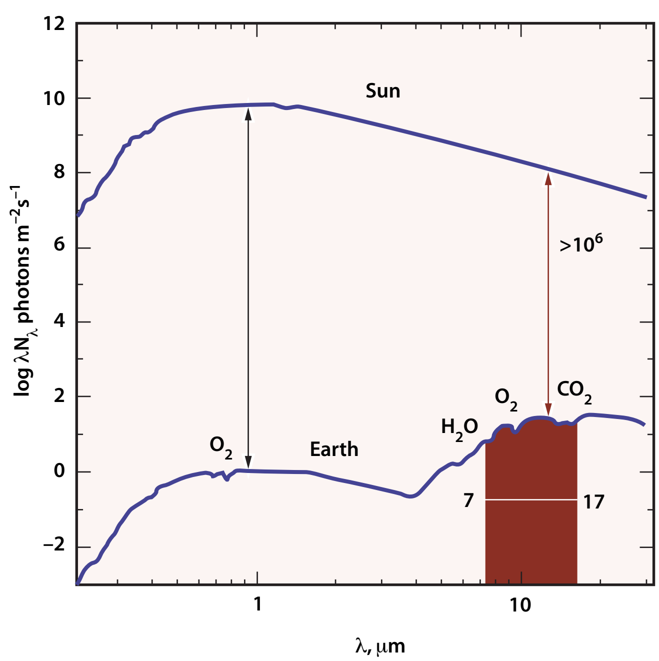
Most extrasolar planets, of course, do not have orbits fortuitously tilted so that they transit directly in front of their stars. But even for non-transiting planets we may tease some information about the composition of their atmospheres from the combined light of star and planet. Specialized techniques at very large ground-based telescopes (for example differential phase interferometry, and Doppler deconvolution) may reveal some atmospheric constituents of giant planets close to their parent star. And from space, the Kepler mission and others like it can measure the tiny change of the system's total brightness as the planet orbits from "new moon" phase to "full moon" phase. Information gleaned in this way from the combined light of planet and star, together with theoretical analysis, will tell us a great deal about the atmospheres and interiors of giant planets. For example, the combination of observations and theory may help us determine whether the central cores of giant planets are made up of heavy "rocky" elements or lighter gases. Calculations of atmospheric circulation and winds in strongly heated close-in giant planets may be tested by high-precision observations from Kepler or other spacecraft through measurements of how much the light and heat emitted toward Earth from such a planet varies over its orbit.

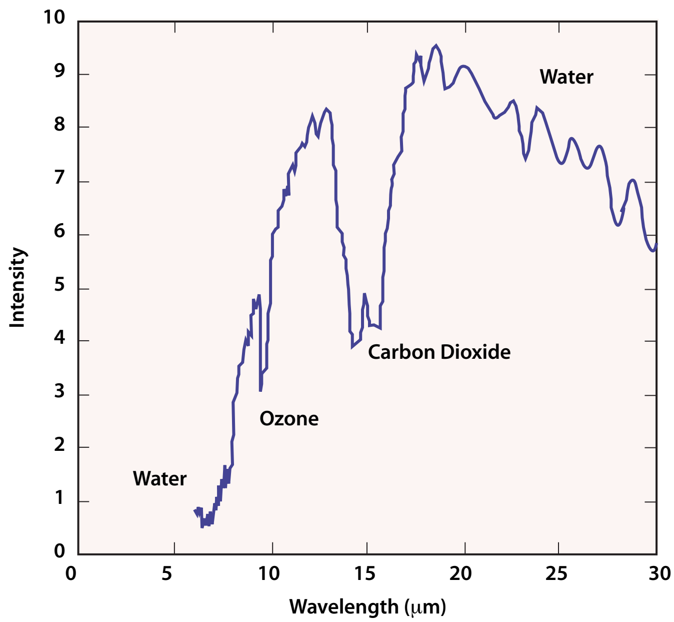
INVESTIGATION 12

Detect giant planets by direct imaging, and study their properties.

While much can be learned by studying the combined light from a star and its planets, the ability to make an image of the system, and thereby separate the planet's light from that of the central star, will open up far greater opportunities. Making such an image is a significant technical challenge, even for giant planets that, like our own Jupiter, are relatively bright because of their huge size and also lie relatively far (several astronomical units) from their parent stars. Nevertheless, telescopes and instruments are now being developed to provide the huge dynamic range

Detection of the faint light from an Earth-like planet in the glare of its parent star. Instruments are being studied which will suppress most of the starlight and will provide low-resolution spectra of the planet.





Mars Global Surveyor looks back at Earth. This would be the spectrum of an extrasolar planet which is truly Earth-like.

necessary to separate the faint light of an orbiting planet from its parent star. Such a capability will enable us to follow the planet in its orbit, and, together with radial velocity measurements, determine the mass of the planet directly. Furthermore, the relative brightness of the planet and star will give information on its size and reflectivity. Near- or mid-infrared spectra, even at low spectral resolution (R ~ 20–50) will yield the abundance of key chemical species like water, methane or ammonia in giant planet atmospheres. The time variation of the planet's brightness will tell us its rotation period. The variation of brightness and polarization with phase angle can provide information about atmospheric composition and clouds—this is in fact how the clouds on Venus were first identified and characterized. Higher-resolution spectra will yield information on the winds and circulation patterns of its atmosphere.

Ground-based interferometers, for example, the Keck Interferometer (KI) and the Large Binocular Telescope Interferometer (LBTI), will make early attempts to separate faint planetary light from the host star. Although ground-based observations are hampered by the smearing effects of Earth's atmosphere, rapidly maturing adaptive optics systems can correct for much of the damage due to the atmosphere. Beyond that, nulling interferometry (in which two or more widely-spaced telescopes work in tandem to null out most of the light from the star while leaving the planet's light undiminished) holds great promise. These techniques will be vigorously pursued during the next 5–10 years.

Taking such techniques to space avoids the smearing of Earth's atmosphere. A moderate-sized telescope in space could do the job, if equipped with one or more of several promising technologies. Examples are coronagraphic techniques, which directly block most of the light from the central star; adaptive optics, which correct for the miniscule imperfections and flexures of even the most perfect mirror in space, and shaped or apodized apertures, which minimize the starlight diffracted into certain parts of the image. A complementary approach is nulling interferometry in the mid-infrared, which will detect the heat radiated by a giant planet rather than its reflected light. Infrared observations must contend with the bright infrared emission from zodiacal dust surrounding the star (as well as the emission from the dust that surrounds our own Sun). However, infrared observations have an advantage because the planet's infrared radiation will be only about a million times fainter the parent star's, rather than a billion times fainter as is the case for reflected light.

NASA is studying several such approaches that would allow study of a planet's light separated from that of its parent star and hence direct characterization of the planet's properties. These approaches include both coronagraphic and interferometric techniques. While studying these approaches will ultimately lead to an advanced mission—the Terrestrial Planet Finder—to image much smaller Earth-sized planets, they also are applicable to the easier problem of imaging giant planets. Indeed, the time is at hand for a mid-sized space mission to apply such an approach to imaging giant planets. Such a mission, carried out during the present decade, would lead to a major near-term advance in understanding the nature of gas-giants, including the formation and evolution of these planets and of the planetary systems in which they occur. At the same time such a mission will help solidify the technical base for pursuing the next, eagerly anticipated step of searching for the rocky terrestrial planets that could harbor life.

Research Area Six

How common are terrestrial planets? What are their properties? Which of them might be habitable?

Extrapolating from our own solar system, the most reasonable home for life elsewhere in the universe is a terrestrial planet (or rocky satellite of a giant planet) that lies within its star's "habitable zone" (HZ), so that liquid water can flow on its surface. Such planets will of course be much harder to detect than the Jupiter-like planets, because of their small size and relative closeness to their parent star.

For terrestrial planets, just as has been the case for giant planets, observations of transits will give us important early information. As noted in Chapter 2, the Kepler mission later in this decade will use transit measurements to answer the question of whether rocky planets in stellar planetary systems are common or rare in the extended solar neighborhood (within 200–600 parsecs of the Sun). But Kepler will detect Earth-like planets through their very uncommon transits, which means it must monitor hundreds of thousands of relatively distant stars to reap a significant number of detections. While the individual Earth-like planets Kepler will discover will be too distant for detailed follow-up study, the frequency of their occurrence will be crucial for planning later missions that can directly detect and characterize terrestrial planets orbiting closer stars.

Another very important precursor mission will be the Space Interferometry Mission (SIM). By measuring the astrometric (that is, positional) wobble of nearby stars, SIM will be able to detect planets as small as a few Earth masses, in the habitable zone surrounding a number of nearby stars. The data will also yield the mass of the planet directly. This will be an important prelude to actual imaging of terrestrial planets, which will be carried out by the Terrestrial Planet Finder (TPF) mission.

TPF will use coronagraphic or interferometric techniques to actually image terrestrial planets orbiting nearby stars (although each planet will appear only as a single point of light). This will yield important information on the physical properties of extrasolar terrestrial planets, including their size, temperature, and location within the habitable zone. From our knowledge of the solar system we can then make a fair estimate of their mass, which determines how well the planet can retain an atmosphere, and also whether it is likely to have a history of active volcanism and plate tectonics. All of these considerations enter into the question whether the planet is able to support life.

Another important role for the TPF mission will be to create a census of those terrestrial planets orbiting nearby stars that appear to meet the basic requirements for habitability, as determined by their mass, location with respect to the habitable zone, properties of the parent star, etc. Such a census will provide the observing list for the much more intensive studies, carried out first by TPF and perhaps later by a Life Finder (LF) mission, to actually detect evidence for past or present life on such planets.

Research toward characterizing terrestrial planets and identifying those that might be habitable is divided into two investigations:

- Which nearby stars host terrestrial planets that might be suitable for life?
- What are the compositions of the atmospheres of terrestrial planets orbiting nearby stars? Which of these planets are suitable abodes for life?

INVESTIGATION 13

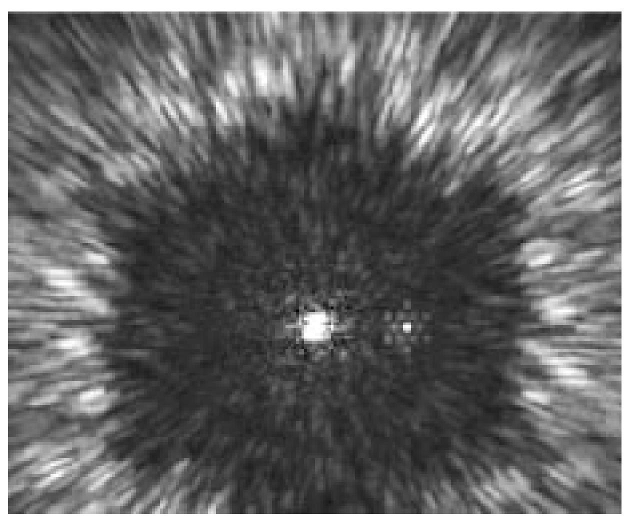
Which nearby stars host terrestrial planets that might be suitable for life?

In order for us to assess the habitability of an extrasolar terrestrial planet, it must be close enough to us for detailed investigation. Ongoing precise radial velocity surveys are beginning to uncover relatively nearby planetary systems that are good candidates for having terrestrial planets in their habitable zones. At the end of this decade SIM should be able to detect a few terrestrial planets if they exist in orbit around nearby stars, and measure their masses. These activities will set the stage for a comprehensive search for terrestrial planets orbiting nearby stars, to be carried out by TPF.

The goal of TPF is to image nearby solar systems, with such precision and sensitivity that it can separate out the light from a rocky planet in orbit within or near the star's habitable zone, from the parent star itself. Direct detection of such planets is extremely difficult, both because of their intrinsic faintness and their closeness to the parent star. It is expected that TPF, when it is launched sometime in the next decade, will be able to find terrestrial planets (if they exist) around any of about 150 stars closer than about 15 parsecs to Earth. (The nearest star is about 1.3 parsecs from Earth.) How many terrestrial planets might there be in the habitable zone around those 150 stars? Unfortunately, we may not know the answer to this important question until nearly the end of this decade, when the first data from Kepler and SIM are returned. However, unless terrestrial planets are rare indeed, TPF should locate dozens of terrestrial planets in the habitable zones surrounding those 150 stars.

The exact architecture of the TPF mission is still to be selected, from among two contending approaches. One is a coronagraphic telescope, which makes use of large and very precise optics to obtain images at visual wavelengths of a planetary system after the brilliant light from the central star has been blocked out by internal blockers within the telescope. The other is an infrared interferometer, which combines the light from several moderate sized telescopes distributed over a long baseline. The telescopes might all be mounted on a single long boom, or alternatively they might be separated in space and steered relative to each other to maintain their separation to exquisite accuracy. Either the visual light coronagraph or the infrared interferometer could in principle do the job of detecting terrestrial planets closer than about 15 parsecs, so the choice will probably come down to technical feasibility and cost.

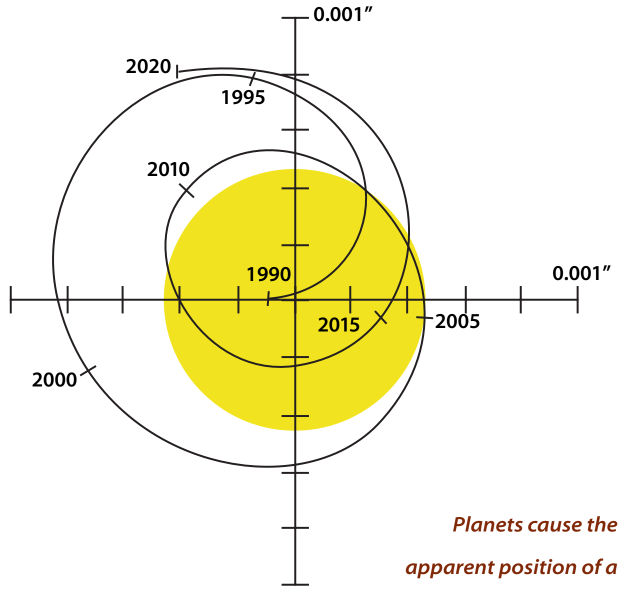
Once a planet has been detected, repeat observations over its "year" will determine its orbital period and distance from the parent star. This already will give an important first clue to its temperature, i.e., whether it does indeed lie



Simulation of a mid-IR image from a space-based coronagraphic telescope of an Earth-like planet orbiting a Sun-like star at a distance of 8 light-years.

within the star's habitable zone. Another key characteristic is the planet's size, and hence its mass. Even if the planet is located in a stellar HZ, too small a mass means that any atmosphere will be quickly lost, whereas too large a mass could mean an atmosphere so thick so that sunlight does not reach its surface. Mass also determines the likelihood of plate tectonics; in turn this may be important in cycling surface material and hence affecting the conditions conducive for life.

If Earth-like planets are found orbiting the closest stars, their masses may be determined directly by SIM. Otherwise, planet size can be estimated at least crudely either from data in the mid-infrared, such as can be obtained by the infrared interferometer version of TPF, or from the amount of visible reflected light as can be obtained by the visual coronagraphic version of TPF. Then, from the planet's size, together with knowledge of the relation between size, mass, and thermal environment of solar system rocky planets, one can make a reasonable estimate of the planet's mass.



Planets cause the apparent position of a star to wobble. Viewed from a distance of 30 light-years, our Sun would move by its own diameter (yellow circle), due mainly to the pull of Jupiter and Saturn.

INVESTIGATION 14

What are the compositions of the atmospheres of terrestrial planets orbiting nearby stars? Which of these planets are suitable abodes for life?

To determine whether a planet is likely to be habitable, many other properties of the planet must be investigated in addition to whether the planet lies within or near its star's habitable zone. Many of these properties can be revealed by the spectroscopic capability of TPF, which can explore the composition of the atmosphere and in some cases the surface of the planet.

TPF will have sufficient spectroscopic capability (resolution R ~ 20–50) to measure the composition of the atmosphere of the planet. Spectra of this resolution can be used to detect evidence for gases such as carbon dioxide or water vapor. The visible and infrared spectrum, in conjunction with theoretical and empirical models, can tell us about the amount of atmosphere, the gases present in the atmosphere, the presence of clouds, the degree and variability of cloud cover or airborne dust, and the presence of a greenhouse effect. The concentration of greenhouse gases can determine whether the surface is warm enough to maintain liquid water, even if (as for Earth) the equilibrium temperature without such gases would result in a frozen surface. Clouds and dust aerosols can determine the amount of light absorbed and reflected, and thus the surface temperature. Spectra can also tell us about the surface, whether it is rock-like with little or no overlying atmosphere, or whether it has strong surface biosignatures, such as the red-edge spectral feature of photosynthesizing vegetation on Earth.

The issue of habitability also involves the properties of the planetary system, including the star itself. A shield of outer giant planets, their presence gleaned from the missions discussed earlier, may be a crucial ingredient for protecting a terrestrial planet from bombardment from outlying belts of comets and asteroids. Conversely the presence of asteroids and comets, at least early in the history of the stellar system, may be important if these are the delivery vehicles for water and complex organics to an inner terrestrial planet, as may have been the case during the early evolution of Earth. As for the star itself, what must its age be so that life might reasonably be expected to have arisen by now, given what we know of the evolution of life on Earth? How low must its early magnetic activity level have been to allow life to evolve without damage by high-energy radiation from stellar flares? Does it matter if the galactic orbit of the star has carried the system out of the galactic plane or through regions of strong star formation (and hence strong UV flux), also exposing any nascent life to unhealthy radiation environments? What other hazards to habitability are there? These questions are appropriate for Earth-based telescopes and will require a continuing, vigorous research and analysis program for understanding the varied and complex data.

TPF will make at least several observations of each star which is a candidate for hosting a terrestrial planet. If a terrestrial planet is found in or close to the star's habitable zone, the mission will make intensive observations of the system, not only to verify the discovery but also to explore the planet's spectrum in detail, including its time variability. The latter will give information on the diurnal rotation period, and also seasonal variations of the atmosphere and surface, as well as on the presence of transient clouds and dust aerosols.

TPF will thus not only find terrestrial planets around nearby stars, but will also explore their suitability for hosting life. This work will phase directly into the next and most exciting step in the Roadmap—the search for actual signs of present or past life on the most promising candidates.

Research Area Seven

Is there life on planets outside the solar system?

The ultimate goal of the Origins program is of course not just to discover which extrasolar planets might be conducive for life, but rather to detect actual evidence for life on one or more of those planets, in order to answer the age-old question, "Are we alone?"

The search for life on extrasolar planets is founded upon the premise that signatures of life (biosignatures) in astronomical observations will be recognizable. We already know from observations of our own planet that surface biosignatures could be detected. Potential biosignatures include the characteristic spectra of life-related compounds like oxygen and water vapor, but care must be taken because they are not uniquely signs of the existence of life. It is very important to explore possible biosignatures in great detail, both theoretically and in the laboratory, so as to identify the key spectroscopic capabilities that TPF must have, and the extent to which observations are required at optical wavelengths, infrared wavelengths, or both. These findings will be a very significant determinant in shaping the architecture of the TPF mission.

While it would be very exciting to discover a near-twin of Earth orbiting a close-by star, and then study it carefully for signs of life, we should cast a broader net. For example, a planet as remote from its star as Mars is from the Sun, if it is massive enough to retain a "greenhouse" atmosphere, may be warm enough and wet enough to sustain life at its surface. The key requirement that a planet have a surface temperature permitting liquid water depends on many factors beyond its mean distance from its star, including its reflectivity and the composition of its atmosphere, which determines the extent of greenhouse warming and hence the planet's surface temperature. In addition, it is important to determine the temperature difference between the "day" side and "night" side of the planet, for example through infrared observations of the planet at different portions of its orbit, and optical observations of the diurnal change in its optical reflectivity.

After TPF is developed and deployed, it will use its capabilities not only to make a first reconnaissance of the nearby terrestrial planets, but also to go further and study in detail those planets which have the greatest likelihood for habitability—searching for the tell-tale biosignatures uniquely indicating the existence of present or past life on those planets. This search will not be easy, and may well require a larger and more advanced follow-on Life Finder mission using technologies yet to be defined.

To make progress in this challenging research area, we must proceed in two steps:

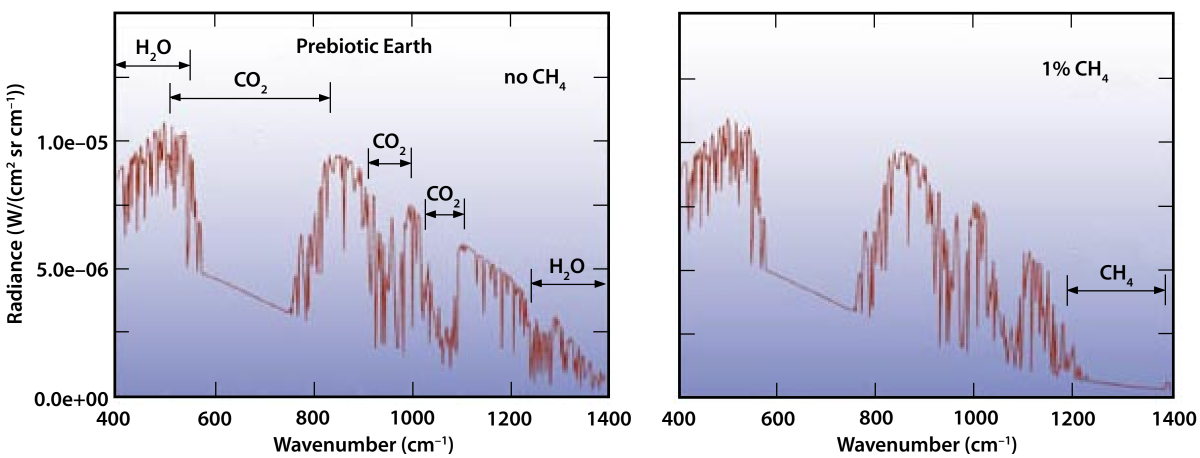
- Determine the optimal biosignatures for life on other worlds.
- Search for these biosignatures as evidence of life on habitable planets orbiting other stars.

INVESTIGATION 15

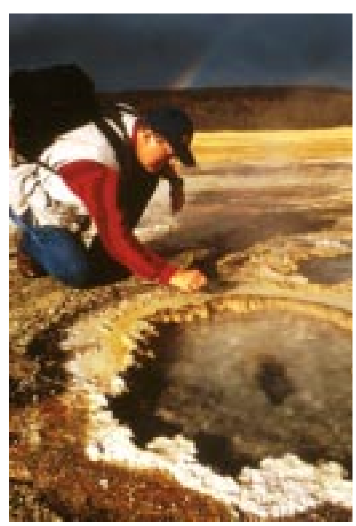
Determine optimal biosignatures for life on other worlds.

An astronomical biosignature is a spectral, photometric or temporal signal whose origin specifically requires a biological agent. To find past or present life beyond the solar system, we must identify robust biosignatures and learn how to measure them on extrasolar terrestrial planets. Planets can create non-biological features that mimic biosignatures, and these must be thoroughly understood to avoid false detections. At the same time our compilation of biosignatures and non-biological imitations must embrace a broad diversity of possible biota and habitable conditions in the universe, probably exceeding the diversity of such features on Earth. Having determined the best signatures of life on other worlds, we must then use them to detect present or past life on planets orbiting nearby stars.

An important biosignature is oxygen. In Earth's atmosphere, oxygen is produced during photosynthesis, the process by which green plants use sunlight to convert carbon dioxide and water into carbohydrates. Once created, molecular oxygen may combine with other molecules in the process of oxidation, and thus disappear as a spectral signature unless it is continually replenished by further photosynthesis. Thus a significant presence of oxygen, as well as water vapor and carbon dioxide, would



Methane-producing bacteria could have a profound effect on the atmosphere of the early Earth, producing strong absorption in the mid-infrared at a wave number of 1300 cm^{-1} (7.6 micrometers).



suggest that life is present. Molecular oxygen is detectable in the red part of the visual spectrum, and its photolytic product ozone is detectable in both the visible and infrared. The search for biosignatures of oxygen or ozone is a key part of the TPF mission.

A potential biosignature is methane, which is produced by life but also has many non-biological sources. Another biosignature is nitrous oxide, which is produced only by biological sources. Unfortunately, these gases are not very abundant in the Earth's atmosphere—their spectral signatures are weak—so their detection on another Earth-like planet will probably require a later-generation successor to TPF, such as Life Finder.

To identify the key biosignatures, both field and laboratory observations as well as theoretical simulations must be conducted in order to examine the relationships between the structure and function of microbial ecosystems and the gaseous products they produce. Ecosystems that are analogs of our ancient biosphere (e.g., based upon chemosynthesis or upon non-oxygen-producing photosynthesis, in heat-loving and subsurface communities, etc.) should be included. The effects of key environmental parameters such as temperature and abundance of H_2, CO_2 and O_2 should be evaluated, because these parameters probably varied during planetary evolution. Ecological processes that have been affected by oxygen-producing photosynthesis are centrally important, not only because they determine the net flux of oxygen (a key biosignature) to the atmosphere, but also because photosynthesis potentially sustains high rates of production of other biosignature gases, including reduced species.

Habitable planets are geologically active and therefore can create non-biological features that mimic biosignatures. For example, hydrothermal processes on a planet that exhibits a more reduced crustal composition than that of Earth might produce methane at rates comparable to biological rates on Earth. To cite another example, non-biological processes of oxygen production might be able to sustain detectable levels of atmospheric oxygen on a planet that is less geologically active than Earth. Accordingly, it is imperative to characterize the environmental conditions of any planet for which potential biosignatures have been identified.

Biosignatures in atmospheres and surfaces can be altered chemically by photochemical and other reactions that occur in atmospheric gases and also in clouds in the lower atmosphere. These species can also be transported to the upper atmosphere and encounter additional reactions. Which biosignatures survive these atmospheric processes? In what chemical form do they survive? How does their survival and/or transformation vary as a function of atmospheric vertical structure, composition, temperature, circulation and cloud content? Both laboratory and theoretical simulations are required to investigate atmospheres of habitable planets that differ from our own modern atmosphere. Examples include atmospheres that lack O_2 and/or include clouds of varying composition, including compositions that occur near the limits of habitable zones (e.g., dense H_2O clouds, CO_2 clouds) or on a young planet.

Based on our knowledge of the history of life on Earth, we can expect that the spectral signatures of life on other planets will depend significantly on the age of the planet. NASA's astrobiology research will help expand our knowledge of how these signs of life would appear at various stages in the planet's history, including for a planet whose properties and history are not exactly the same as our own.

Research on understanding the optimum spectral signatures of life is urgent, and already well under way. The results of this research will be key in determining the design of TPF and its Life Finder successor, for example to what extent it stresses optical spectroscopy (which may be possible using coronagraphic techniques) or infrared spectroscopy (which may require an interferometer with widely separated apertures).

INVESTIGATION 16

Search for evidence of life on habitable planets orbiting other stars.

The knowledge of which spectral features are unambiguous indicators of the presence of life on a planet, and which of those are technologically the easiest to measure, will be very important for the final design of TPF. According to present plans, TPF should have enough spectroscopic capability to

The development of life on the early Earth provides clues to the possible evolution of life elsewhere

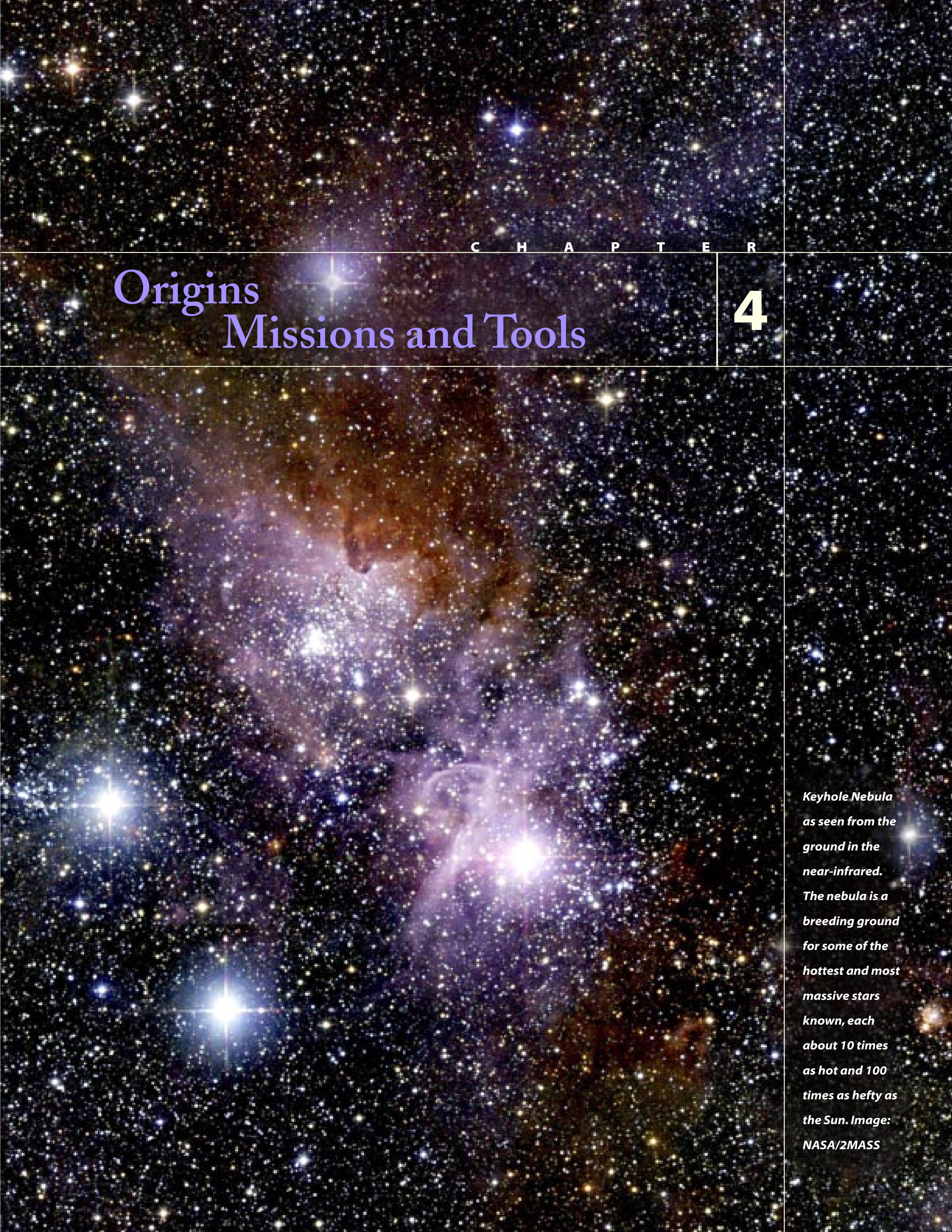
search for the more abundant atmospheric species that would indicate life on those planets. A current plan calls for finding and studying those terrestrial planets that may orbit any of about 150 Sun-like stars within about 15 parsecs of the Sun. However, the size of the search space will be refined as we learn more about how rare or common terrestrial planets really are orbiting other stars—for example, from the Kepler mission. While detecting even one life-bearing planet in orbit around another star would be a tremendous milestone, the converse—learning of the absence or near-absence of life on other worlds, would require a large number of examples to draw a statistically meaningful conclusion. The distance to which one must search to find that number of examples, and hence the limits on apparent brightness of the planet and its angular separation from the parent star, will become well determined only over the next half decade.

Already it can be guessed, however, that unless planets showing very robust signatures of life are very common orbiting Sun-like stars, the search will ultimately require the most advanced tools we can marshal, probably going beyond the capabilities of the TPF mission as it is presently conceived. Conceptual studies are already beginning to define a follow-on Life Finder mission dedicated to this goal. With greater collecting area offering greater spectral resolution, Life Finder will make possible the search for additional biosignatures, especially those gases that have unambiguously out-of-equilibrium abundance—incontrovertible evidence for life. Life Finder would also provide greater spatial resolution that, together with its greater light grasp, would allow us to extend our search for Earth-like worlds beyond the limits of our first exploration with TPF to perhaps thousands of stars. The dual goals of extending our search to further planetary systems and providing greater, time-resolved, spectral information will challenge our imagination and technical prowess for decades to come.

Ultimately, and beyond the scope of this roadmap, lies the question of whether there is life in the wider universe, for example on planets orbiting stars so far away that there can be no hope of detecting life by studying biosignatures in the spectra of those planets. We can only extrapolate outward, from our knowledge of life in the solar system and around relatively nearby stars, to ascertain the likelihood of life throughout our galaxy, or our sister Andromeda Galaxy, or even beyond out into the distant universe. If life is found anywhere within our stellar "neighborhood," then we can conclude it to be highly probable that life is common in our galaxy, and surely so in the wider universe. Conversely, if present or past life is found to be absent from our stellar neighborhood except for here at home, then this information surely will inform our view of how rare life is anywhere in the universe, and how precious it is on Earth.

CHAPTER 4

Origins Missions and Tools



Keyhole Nebula as seen from the ground in the near-infrared. The nebula is a breeding ground for some of the hottest and most massive stars known, each about 10 times as hot and 100 times as hefty as the Sun. Image: NASA/2MASS

...to build on the past, and leave a legacy for future missions.

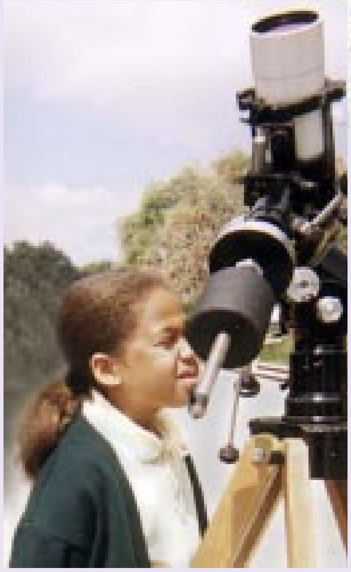
The central principle of the Origins mission architecture has been that each major mission builds on the scientific and technological legacy of previous missions, while providing new capabilities for the future. In this way, the complex challenges of the theme can be achieved with reasonable cost and acceptable risk. For example, the techniques of interferometry developed for the Keck Interferometer, the Large Binocular Telescope Interferometer and the Space Interferometry Mission, along with the infrared detector technology from the Space Infrared Telescope Facility and the large optics technology needed for the James Webb Space Telescope will enable the Terrestrial Planet Finder to search out and characterize habitable planets.

Inspired by bold vision, this philosophy has allowed the Origins theme to navigate through many daunting scientific and technological questions, toward a set of specific scientific missions, and toward scientific goals that stretch even beyond the missions we now know how to define. Six years down the path from the first Origins Roadmap, much has been learned about the technological difficulty and the scientific framework for this scientific theme, which brings into play another feature of a robust strategic plan: flexibility and adaptability. Origins has a policy of ensuring that all major technological problems have been solved prior to embarking on the expensive construction phase of its challenging missions. Even so, the challenges to achieving the scientific goals of Origins are so great, that in addition to mission-oriented enabling technology developments, additional options for gaining precursor scientific knowledge through observations from the ground, work in scientific theory, and more modest precursor missions must be added to the future investigative agenda. While the vision remains, the path and the pace must be what the nation will afford.

At the publication of the *Origins 2000 Roadmap*, less than half the extrasolar planets now known had been discovered. Today, we see increasing pace of discovery through ground observations of radial velocity Doppler shifts and photometric transits as data sets are filled in. Technology development and mission architecture studies conducted in the previous decade did not suggest that large single-aperture visible-light coronagraphs would be viable for a terrestrial planet finding mission. Today, Terrestrial Planet Finder (TPF) architecture studies and technology development do include coronagraphs, and also precursor mission options of reduced scope. The recently selected Kepler mission in the Discovery Program will provide valuable planetary system statistics, and exemplifies the kind of alternate approaches Origins must embrace. The dynamic state of this emergent scientific field suggests strongly that the program undertaken to achieve the Origins goals must remain flexible, and must adapt to and make use of evolving technical and scientific knowledge and capability. The Origins roadmap for 2003 elaborates on the previous plan, adding "off-ramps" from some endeavors that may prove too difficult

Girls Inspired to Imagine New Worlds

A few hundred participants and their families gathered in May 2002 at Pasadena City College to learn about Origins science and celebrate the winners of the "Imagine a New World" art and essay contests, sponsored by Girls Inc. and NASA's Navigator Program.



Taking an interdisciplinary approach, the contests were provided through the Operation SMART program, an age-appropriate curriculum that builds girls' skills in math, science, and technology. Co-sponsor Girls Inc. is a national nonprofit youth organization dedicated to inspiring all girls to be strong, smart, and bold.

Elementary and middle school-age girls in the Los Angeles area were asked to imagine life on a distant planet, using Navigator educational materials as background. A diverse panel of judges graded the entries based on creativity, literacy, and incorporation of Navigator themes.

The contest was capped off with a celebration at which the winners were presented with awards and certificates. All participants were treated to a half-day of fun learning activities, including "Ask a Scientist," "Taking the Measure of the Universe," and planetarium tours.

or too costly to maintain, and finding "alternate routes" to arrive at the same objectives, while reflecting realistic assessments of the cost and risk inherent in scientific discovery and exploration.

Origins will solicit new ideas for technology developments and scientific missions of moderate scale that hold promise for facilitating the Origins goals. Solicitations through NASA Research Announcements will provide a science and technology incubator to obtain and support proposals for technology development and mission concept definition studies. The most promising of these may be pursued as possible flight missions through the Explorer or Discovery Programs or even a future competed mid-size Origins mission program. Complementing the missions described below, the Research and Analysis (R&A) program provides three essential components of the Origins theme: (1) development of key technologies that will be necessary for Origins missions; (2) development of alternate mission concepts which could lead to smaller-scale intermediate missions exploring aspects of the Origins scientific agenda; and (3) a broad program of scientific theory and analysis that helps frame the scientific questions, provides models to define the science requirements for key missions, and is critical for the understanding of the vast amounts of data expected from space missions in the coming decade. Increasingly, the development of strategic missions will invoke, and fund, targeted application of R&A programs to help draw in a broad constituency in developing new scientific knowledge and technology. The Origins R&A program is described in Chapter 6.

Even as we work to develop the missions for this and the next decade, we must start now to envision where our explorations will lead us afterwards, as developing the needed technologies can easily take a decade or more before they are ready to be applied. Our focus will be placed not on specific missions, but on the compelling scientific questions and the technologies that will enable the missions and tools to find the answers. Beyond TPF, scientific attention will turn to detailed studies of any indications of life found on the planets that TPF discovers. This will require a still more capable spectroscopic mission, a Life Finder (LF), which will probe the infrared spectrum with great sensitivity and resolution. Both Origins and the Structure and Evolution of the Universe Theme call for advanced investigations in galaxy and planetary system formation and cosmology that require a high resolution IR telescope such as the Single Aperture Far-Infrared Observatory (SAFIR), an 8-meter space-based telescope recommended in the National Research Council decadal survey. Such a telescope might launch and operate between TPF and LF to carry out its own science program, and to lead to the 25-meter telescopes needed for LF. The technology developed for such a mission might also be used as a building block for a kilometer-baseline interferometer used at far-infrared wavelengths for cosmological studies. Investigations in distribution of matter in the universe (including dark matter) will require a large-scale UV/optical observatory that will build on the technology developments of the James Webb Space Telescope (JWST) and of the Space Interferometry Mission (SIM), and pave the way for more challenging UV/optical telescopes of the future. The technology developments necessary to enable these missions are described in Chapter 5, Enabling Technologies.

While the Astronomical Search for Origins and Planetary Systems remains inspired by a far reaching vision, the rules of the road will be those of clearly focused waypoints and sound management practices.

Operational Missions

Foremost among the current Origins missions is the Hubble Space Telescope (HST), which was launched in April 1990, and—thanks to regular upgrades of its instruments via Shuttle servicing missions—remains NASA's most productive scientific program. This impressive record of achievement continued into the second decade of HST's operation, with the installation in early 2002 of the Advanced Camera for Surveys (ACS) and a new active cooling system to reactivate the Near Infrared Camera and Multi-Object Spectrometer (NICMOS). The subsequent and probably final Shuttle servicing mission, planned for 2004, will install both the highest performance ultraviolet spectrograph ever flown in space, the Cosmic Origins Spectrograph (COS), as well as the first truly panchromatic imaging system ever flown in space, the Wide-Field Camera 3 (WFC 3). This mission will also install a number of engineering system replacements to enable the observatory to operate through 2010, at which time it is planned to retrieve the telescope in the Space Shuttle.

The importance of HST to the scientific community is matched by the positive role that the mission has played in educating the public about science. The observatory may be the best-known scientific facility in the world, with its results used in classrooms globally.

The most recent Origins mission to be launched is the Far-Ultraviolet Spectroscopic Explorer (FUSE), which explores the universe at wavelengths that are inaccessible by HST. In particular, FUSE is determining the abundance of deuterium, an isotope of hydrogen that was formed in the Big Bang. Determination of its abundance is essential to constraining conditions in the Big Bang. Beyond this, FUSE will also investigate the hot interstellar gas, in order to understand the life cycle of matter between the stars, as gas cycles between stellar death and rebirth. A highlight of the education and public outreach program of the FUSE mission is its highly visible role in the Maryland Science Center, in Baltimore, which is visited by over 600,000 persons per year.

The Space Infrared Telescope Facility will contribute extensively to the understanding of the formation of stars and planets and will investigate the formation and early evolution of galaxies.

Ground Observatories

The Origins theme supports a broad science program in conjunction with the W.M. Keck Observatory in Hawaii. This program has two main thrust areas: first the sponsorship of community-accessible time on single Keck telescopes to pursue Origins science goals; and second, the development and operations of the Keck Interferometer (KI). The single-Keck program has been in place since 1996, and has been extremely successful in producing important scientific results such as radial velocity exo-planet detections, spectral characterizations of L and T-dwarfs, and mid-infrared imaging of planetary debris disks. KI has combined the infrared light collected by the two 10-meter Keck telescopes to undertake a variety of Origins astrophysical investigations. Among the issues addressed by KI will be the location and amount of zodiacal dust in other planetary systems and the astrometric detection and characterization of exo-planetary systems around stars in the solar neighborhood. This first in-depth and long-term census of planets will be an important contribution to our understanding of the architecture and evolution of planetary systems, and will be key in helping to define the requirements and the architecture for TPF.

The Large Binocular Telescope Interferometer (LBTI) will further a variety of Origins goals in

The Stratospheric Observatory for Infrared Astronomy, flying on a modified Boeing 747 aircraft, will study sites of star formation, the cold interstellar medium, and the center of our galaxy at high spatial resolution.

star, planet, and galaxy formation through both nulling and wide-field imaging interferometry. Primary among these goals is a planned systematic survey of nearby stars to understand the prevalence of zodiacal dust and gas giant planets and to determine a system's suitability for terrestrial planets. The modest baseline and common mount design of the dual 8.4-meter LBTI allows uniquely sensitive infrared observations of candidate planetary systems through nulling interferometry. The development of nulling technology and observing techniques will help create a mature technological basis for a TPF mission. The LBTI also allows wide-field, high-resolution imaging of objects down to brightness levels similar to filled aperture telescopes. This is applicable to a wide variety of Origins-related imaging and astrometric observations.

The National Virtual Observatory (NVO) will build on developments in computing and information technology and will have a major impact on Origins missions and science. For the most part, essential technologies will emerge from academia and industry and will be usable without Origins-specific development initiatives. The NVO will federate digital sky surveys, observatory and mission archives, and astronomy data and literature services, and provide a framework that will reduce the cost of developing and maintaining future archives and data services. The NVO will be able to address research topics of particular relevance to the Origins program, such as:

- Star formation rates in galaxies
- The environments of clusters of galaxies, e.g, through systematic searches for gravitational lenses
- The galaxy merger rate as a function of look-back time
- The population of brown dwarfs, through cross-correlation of survey catalogs
- Cosmological models, through confrontation of simulations with observations
- A complete census of Kuiper-Belt objects, and a compositional atlas of the solar system, as a means to understanding the formation process and dynamics of the solar system

The NVO will also be an unprecedented venue for science and technology education and public outreach.

Missions Targeted for Operation by 2005

The Space Infrared Telescope Facility (SIRTF) will be the fourth of NASA's Great Observatories and will use imaging and spectroscopy at infrared wavelengths from 3–180 micrometers to investigate Origins scientific goals. In particular, SIRTF will contribute extensively to the understanding of the formation of stars and planets and will investigate the formation and early evolution of galaxies. SIRTF will provide key information on the dust environments TPF will need to penetrate to find and characterize planets. A very important component of SIRTF science will be the Legacy Programs, in which very large and scientifically important data sets will be made available rapidly to the entire scientific community. Six teams with broad community participation have been competitively selected to execute Legacy Programs. SIRTF is a cryogenic mission with an expected cryogenic lifetime of up to 5 years. The wide applicability of infrared technology is highlighted in the mission's extensive eduction and public outreach program.

The Stratospheric Observatory for Infrared Astronomy (SOFIA) will study sites of star formation, the cold interstellar medium, and the center of our galaxy at high spatial resolution at far-infrared wavelengths. It is a joint U.S. (80%) and German (20%) observatory which consists of a 747 aircraft with a telescope as large as HST. SOFIA will also function as a unique platform for developing, testing, and reducing risk of new instrument technologies, particularly detectors for future missions such as SAFIR. It will have a prominent education and public outreach program, including involving high school teachers and students in its flights and observations. SOFIA will be making observations by 2005.

The Kepler mission will complete a photometric survey of the extended solar neighborhood to detect and characterize hundreds of terrestrial and larger planets in or near the habitable zone.

Missions Targeted to Enter Development Phase in 2005–2010

Extrasolar planets are a reality: more than one hundred planet-sized objects have been indirectly detected around neighboring stars and their number is growing rapidly. But the techniques available from the ground today are capable of detecting only the most massive such objects, perhaps a few times the mass of Saturn. The Keck Interferometer will push this mass limit significantly lower, possibly to the mass of Neptune. However, it will require space-based techniques to detect objects that approach the mass of Earth and allow the first in-depth search for objects in space like our own home planet.

Kepler is a new mission in the Origins firmament, selected through the Discovery Program and scheduled for launch in 2007. This provides an excellent example of the kind of moderate scale missions that can contribute to Origins in important ways. The Kepler mission is specifically designed to photometrically survey the extended solar neighborhood to detect and characterize hundreds of terrestrial and larger planets in or near the habitable zone and provide fundamental progress in our understanding of planetary systems. The results will yield a broad understanding of planetary formation, the frequency of formation, the structure of individual planetary systems, and the generic characteristics of stars with terrestrial planets. These results will be instrumental in determining how deep TPF will have to look to find an adequate sample of planetary systems to find and characterize habitable planets.

The Space Interferometry Mission will be the first observatory capable of detecting and measuring

The Space Interferometry Mission will extend the Keck census of nearby planetary systems into the range of rocky, terrestrial planets.

the mass of planetary bodies with a few times the mass of Earth in orbit around nearby stars. Thus, the Origins theme will take a major step forward in answering one of its defining questions: "Are we alone?" Are there other worlds like our own home planet, existing within planetary systems like our own solar system? SIM will extend the Keck census of nearby planetary systems into the range of the rocky, terrestrial planets for the first time, permitting scientists to refine their theories of the formation and evolution of planets like Earth. This census will form the core of the observing programs for subsequent missions that will investigate in detail the nature of these newly discovered worlds. It will provide the "target list" for TPF.

SIM Technologies

Technology	*Builds on past missions*	*Leaves legacy for future missions*
Interferometric techniques	Keck Interferometer	TPF (interferometer options), Life Finder, Far-IR Interferometer
Nanometer stabilization techniques	HST, Chandra	TPF, SAFIR, Large UV/Optical Telescope, Life Finder
Picometer sensing techniques	New	TPF, Life Finder

In addition to its scientific goals, SIM will develop key technologies that will be necessary for future missions, including precision location of optical elements to a fraction of the diameter of a hydrogen atom (picometers) and the precise, active control of optical pathlengths to less than a thousandth the diameter of a human hair.

Beyond the detection of planets, SIM's extraordinary astrometric capabilities will permit determination of accurate positions throughout the Milky Way Galaxy. This will permit studies of the dynamics and evolution of stars and star clusters in our galaxy in order to better understand how our galaxy was formed and how it will evolve. Accurate knowledge of stellar positions within our own galaxy will allow us to calibrate luminosities of important stars and cosmological distance indicators enabling us to improve our understanding of stellar processes and to measure precise distances throughout the universe.

The next step beyond the Hubble Space Telescope will be the James Webb Space Telescope,

JWST Technologies

Technology	*Builds on past missions*	*Leaves legacy for future missions*
Large, passively cooled optics	SIRTF for passive cooling	TPF, Life Finder, Large UV/Optical Telescope, SAFIR
Cryogenic coolers	HST-NICMOS, Planck, TPF Technology	SAFIR, Life Finder
IR detectors	SIRTF, SOFIA	TPF, SAFIR

Each Origins mission builds on the scientific and technological legacy of the previous mission, while providing new capabilities for the future.

which will have three times the diameter of HST's mirror and about an order of magnitude more light-gathering capability. Because the prime science goals for JWST are to observe the formation and early evolution of galaxies, JWST's greatest sensitivity will be at mid- and near-infrared wavelengths, where the expansion of the universe causes the light from very young galaxies to appear most prominently. JWST will be a powerful general-purpose observatory capable of undertaking important scientific investigations into a very wide range of astronomical questions, including those that are central to the Origins theme.

JWST is expected to have a telescope diameter of at least 6 meters and be celestial-background-limited between 0.6 and 10 micrometers, with imaging and spectroscopic instruments that will cover this entire wavelength regime. JWST has a requirement to be diffraction-limited at 2 micrometers. With these capabilities, JWST will be a particularly powerful tool for investigating fundamental processes of stellar formation and early evolution, as well as the later stages of evolution. In both cases, dust almost completely blocks our ability to observe the light from rapidly evolving stars, so that detailed observations have to be carried out at longer wavelengths.

The European Space Agency and the Canadian Space Agency have agreed to contribute significantly to the JWST project. These contributions will be important in significantly enhancing the overall capabilities of the observatory.

Missions Targeted to Enter Development Phase in 2010–2015

The Terrestrial Planet Finder will directly detect and study planets outside our solar system from their formation and development in disks of dust and gas around newly forming stars to their evolution and even potential suitability as an abode for life. By combining the high sensitivity of space telescopes with revolutionary imaging technologies, TPF will measure the size, temperature, and placement of terrestrial planets as small as Earth in the habitable zones of distant solar systems as well as their gas giant companions. In addition, TPF spectroscopic capability will allow atmospheric chemists and biologists to use the relative amounts of gases like carbon dioxide, water vapor, ozone and methane to find whether a planet someday could or even now does support life. Our understanding of the properties of terrestrial planets will be scientifically most valuable within a broader framework that includes the properties of all planetary system constituents, including gas giants, terrestrial planets and debris disks. TPF's ability to carry out a program of comparative planet studies across a range of planetary masses and orbital locations in a large number of new solar systems is an important scientific motivation for the mission. However, TPF's mission will not be limited to the detection and study of distant planets. An observatory with the power to detect an Earth orbiting a nearby star will also be able to collect important new data on many targets of general astrophysical interest.

The TPF observatory will likely take the form of either a coronagraph operating at visible wavelengths or a large-baseline interferometer operating in the infrared. The visible-light coronagraph concepts would use a single telescope with an effective diameter of 8–10 meters, operating at room temperature, but required to achieve a billion-to-one

TPF Technologies

Technology	*Builds on past missions*	*Leaves legacy for future missions*
Large, passively cooled optics	JWST	SAFIR, Life Finder
Formation flying	StarLight ground demo	LISA, Far-IR Interferometer, Life Finder
Interferometry and nulling	SIM, LBTI, Keck Interferometer	Far-IR Interferometer, Life Finder
IR detectors and cryocoolers	JWST, Planck	SAFIR, Far-IR Interferometer, Life Finder
Coronagraph	Precursor mid-size mission	Future filled-aperture observatories

The James Webb Space Telescope will be a powerful general-purpose observatory capable of undertaking important scientific investigations into a wide range of astronomical questions.

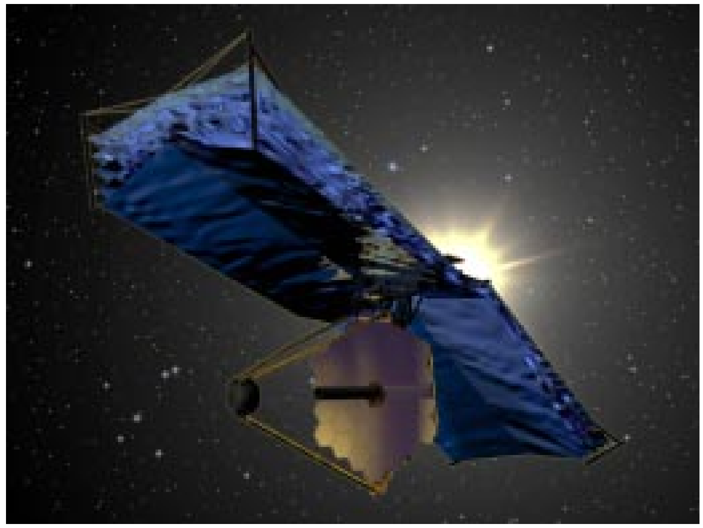


image contrast. Very precise, stable control of the telescope optical quality would be required. The infrared interferometer concepts would use multiple (≈4), smaller, 3–4-meter-diameter telescopes configured as an array and spread out over a large boom of up to 40 meters or operated on separated spacecraft over distances of a few hundred meters. The telescopes would operate at extremely low temperatures of ≈40 kelvin, and the observatory would necessarily be large. However, the image contrast requirement, "only" a million to one, and thus the required system optical quality, would be much easier to achieve at infrared wavelengths.

TPF will perform system studies, science investigations, and technology development for both architecture classes over the next several years. Final selection of a TPF architecture will occur about 2006, based on the science and technology progress of the next four years. Also, multimission architectures that take smaller steps toward the ultimate scientific goal will be investigated.

The European Space Agency (ESA) has been actively studying an infrared interferometer with essentially the same science goals as TPF, usually referred to as either Darwin or the Infrared Space Interferometer (IRSI). Under a NASA/ESA Letter of Agreement, scientists and technologists in both agencies are discussing ways in which the preliminary architecture studies can lead to effective collaboration on a joint mission.

Missions Targeted to Enter Development Phase in 2015–2020

A long-term Origins goal is the detailed study of life and its evolution in ecosystems beyond the solar system. Achieving that goal will require observations beyond those possible with TPF. For example, searching the atmospheres of distant planets for unambiguous tracers of life such as methane (in terrestrial concentrations) and nitrous oxide would require a spectral resolution of ~1,000, utilizing a version of TPF with 25-meter telescopes. While a Life Finder interferometer is beyond the horizon of this strategic plan, except as a beacon for the technologists' vision, the Single Aperture Far-Infrared mission consisting of a single 8–10-meter telescope operating in the far-IR could serve as a building block for the Life Finder while carrying out a broad range of scientific programs beyond JWST and SIRTF. These include probing the epoch of energetic star formation in the redshift range $1<z<10$ at a wavelength regime that can easily detect continuum and cooling-line emission from dust-

SAFIR Technologies

Technology	*Builds on past missions*	*Leaves legacy for future missions*
Large, passively cooled optics	JWST, TPF	Life Finder
IR detectors and cryocoolers	JWST, Herschel, Planck, TPF	Life Finder, Far-IR Interferometer

enshrouded primeval galaxies with an angular resolution capable of isolating individual objects at or below the limits of the Hubble Deep Field; investigating the physical processes that control the collapse and fragmentation of molecular clouds to produce stars of various masses by mapping of cold, dense cores at <100 AU resolution at the peak of their dust emission and using gas phase tracers such as H_2, H_2O, CO, OI, NII; learning about the era of cometary bombardment that may have determined the early habitability of Earth by making high spatial resolution maps of the distribution of ices and minerals in the Kuiper Belts surrounding nearby stars; and, studying the nature of the recently discovered objects in the Kuiper Belt of our own solar system which may be remnants of our own planet formation process.

Large UV/Optical Telescope Technologies

Technology	*Builds on past missions*	*Leaves legacy for future missions*
Large optics	JWST, Coronagraphic TPF	Visible light complement to Life Finder
UV detectors	HST, FUSE, Galex	

A successor to HST operating at ultraviolet and optical wavelengths, a large UV/optical telescope, would produce forefront science in all areas of modern astronomy and would be focused on the era from redshifts, $0<z<3$, which occupies over 80% of cosmic time, beginning after the first galaxies, quasars, and stars emerged into their present form. The science to be addressed in the post-HST era includes studies of dark matter and baryons, the origin and evolution of the elements, and the major construction phase of galaxies and quasars. Key questions include: Where is the rest of the unseen universe? What is the interplay of the dark and luminous universe? How did the intergalactic medium collapse to form the galaxies and clusters? When were galaxies, clusters, and stellar populations assembled into their current form? What is the history of star formation and chemical evolution? Are massive black holes a natural part of most galaxies? A large-aperture UV/optical telescope in space will provide a major facility in the second quarter of the century for solving these scientific problems.

The Far Future: Beyond 2020

Two missions still far in the future because of their demanding technologies have strong relevance to Origins goals. The first is the Life Finder, which as described above would provide high-resolution spectroscopy on habitable planets identified by TPF. This information would extend the reach of biologists, geophysicists, and atmospheric chemists to ecosystems far beyond Earth.

A second mission concept that appears promising is an interferometer capable of detecting the far infrared and submillimeter light from the youngest galaxies. JWST will study the visible starlight from forming galaxies that has been red-shifted into the near infrared by the expansion of the universe. However, typically half, and sometimes more than 99% of the starlight of a galaxy is absorbed by dust in that galaxy and re-radiated in the far infrared. This emission is red-shifted further into infrared or into the submillimeter bands. An interferometer consisting of three 15–25-meter telescopes with a 1-kilometer baseline would have the sensitivity and angular resolution (0.02 arcseconds at 100 micrometers) needed to study the physical conditions in these young galaxies. In addition to cosmological studies, the interferometer would be able to observe collapsing protostars deeply embedded in their parental molecular clouds, providing valuable constraints on models for star formation.

C H A P T E R 5

Enabling Technologies

Abell 2218, a rich galaxy cluster and a spectacular example of gravitational lensing. Light passing through the cluster is deflected by its enormous gravitational field, much as an optical lens bends light. This causes the arc-like pattern spread across the picture like a spider web. Image: NASA/HST

...to invent tools for

a new age of discovery.

The Origins technology program will develop the means to achieve the most ambitious and technically challenging measurements ever made. These developments envisage new methods to gather signals from distant sources, precise control of optical elements to a precision of one-thousandth of a human hair, and measurements of distances between optical elements to the width of a hydrogen atom. Such exquisite techniques require methods and tools that do not exist today. Building spacecraft of the future incorporating these technologies will exploit the creative inventiveness of our scientists as well as the care and precision of our engineers.

The technology plan has two strategic objectives. In the near term, the maturing technologies for observatories such as the Space Interferometry Mission (SIM), the James Webb Space Telescope (JWST), and the Terrestrial Planet Finder (TPF) must be completed and tested. It is also critical to begin establishing the new technological building blocks for the very large space observatories described elsewhere in this roadmap that are envisioned to follow our current missions. Remarkable progress has been made toward the near term objectives. However, the longer term objectives are not yet within our grasp. Creating the technological capabilities to realize the observatories of the future will require a new technology initiative. This initiative will develop advanced detector arrays to convert the light into electrical signals; build large, lightweight mirrors; actively control the surface errors of the mirrors and optical elements to produce an almost perfect aperture; and provide cooling techniques to eliminate the infrared emission from the optical surfaces of a warm telescope. These four areas of focused technology development will provide the basic capabilities for a broad range of future space observatory architectures.

Accomplishments Following the Previous Roadmap

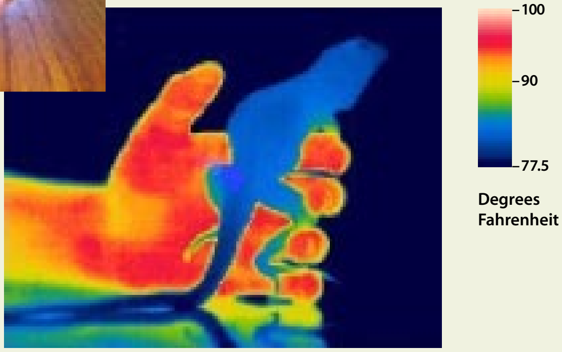
Over the past five years, technology developments leading towards the Origins missions have been remarkably successful. The successes have been both technical and institutional. Not only have new space observatory components and capabilities been developed, but also a number of valuable new partnerships with other government interests have emerged.

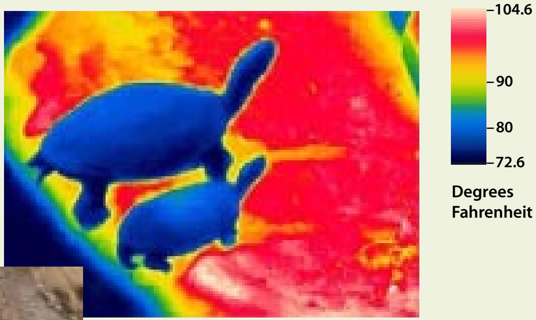
HST is now the beneficiary of cryocooler advances that have allowed the reactivation of the NICMOS instrument and large format CCD detectors that have increased the useable field of view of the telescope. The Space Infrared Telescope Facility (SIRTF) mirror is fabricated from a form of beryllium metal that is optimized for cryogenic optical system applications. This is a technology that was initially studied and developed with the help of NASA's Aerospace Technology Enterprise. SIRTF will carry improved infrared detector arrays that are derived from technology originally developed by the Department of Defense (DoD).

Do Animals Glow in the Dark?

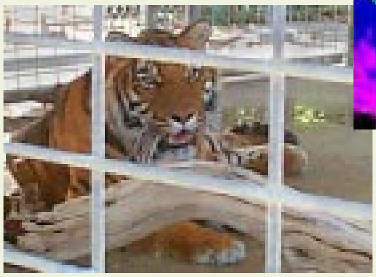
Have you ever wondered what animals look like in the dark? The Education and Public Outreach Office of NASA's SIRTF mission has created an infrared zoo on the web. This website has received numerous awards and the seal of Good Housekeeping magazine.

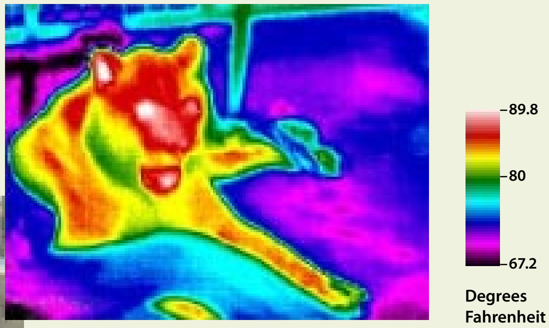
Infrared light shows us the heat radiated by the world around us. By viewing animals with a thermal infrared camera, we can actually "see" the differences between warm- and cold-blooded animals. Infrared also allows us to study how well feathers, fur, and blubber insulate animals. Visitors to the "Infrared Zoo" see what new information you can gather about the animals here that you would not get from a visible light picture.





Through its inventive use of technology SIRTF involves students in science and encourages conversations that span discipline boundaries. This is just one example of the multidisciplinary educational materials that are produced with the goal of engaging the young minds of the future scientists.





JWST has sponsored significant work on demonstrating an array of 2,000 by 2,000 near-infrared detectors which will benefit other IR missions.

Recent achievements in precision metrology and reduction of microdynamic disturbances will enable the SIM mission to achieve its goal of measuring ultra precise stellar positions.

Progress towards the primary mirror for JWST has come on two fronts. The Advanced Mirror System Demonstrator project, a partnership between NASA and DoD, has produced a number of options for rapid fabrication of lightweight, 2-meter mirror panels. These are the building blocks for large apertures, such as JWST, that must be folded to fit into the payload space of affordable rockets. In parallel, techniques have been demonstrated to deploy a folded mirror and align panels automatically in space to the accuracy desired for JWST.

Until recently, the TPF mission was envisioned to be a starlight nulling interferometric instrument that would operate at infrared wavelengths and have a baseline of about 80 meters. Additional examination of extrasolar planet detection strategies and technological alternatives has lead to a number of architectural options that are now under study. The options now range from the original separated spacecraft infrared interferometer to structurally connected interferometers and visible light coronagraphic telescopes.

We have also seen real progress toward an architectural breakthrough in space optical systems. With sufficiently accurate measurement and control, it will be possible to place the elements of a single large aperture on individual separated spacecraft. The requirement is to be able to control a constellation of spacecraft as if they were connected by a rigid structure. It then becomes possible to construct interferometers and sparse aperture telescopes with dimensions that exceed hundreds of meters. These capabilities are being developed by the StarLight portion of the TPF project.

These examples demonstrate the substantial progress made in the technology areas envisaged in our earlier roadmap. Nevertheless, our future technology needs have not yet been met. Staying on the present course is clearly the most likely route to success. We have also had success in identifying common technology needs with other government agencies and developing partnerships and shared resources to find technological solutions.

Innovative, lightweight mirrors and support structures will make large optical apertures in space possible while keeping the total mass constant.

Building Future Very Large Observatories

Detector Technologies

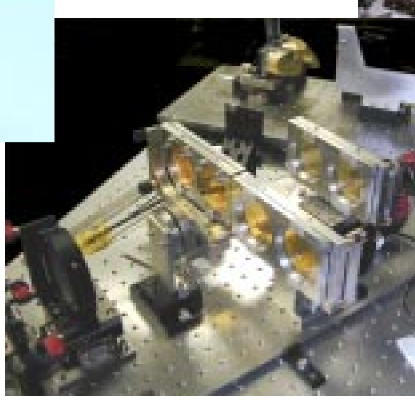
Detectors, the devices which convert light energy to electrical signals, are the single most important technology which determines the ultimate performance of our observatories. If the detectors fail to do their job, the entire observatory system is seriously compromised. Technologies are poised to make dramatic gains in detector performance at far-infrared wavelengths and in the ultraviolet. In the infrared, devices have not yet reached fundamental limits, and large format imaging arrays (10^3–10^4 pixels) have yet to be perfected. In the ultraviolet, new solid state devices allow simultaneous detection of the both the intensity and wavelength of the light. Several technologies should be explored, including semiconducting and superconducting devices, such as impurity band detectors and transition edge sensors for imaging in the 40–600 micrometer band. In addition, very sensitive detectors are needed for spectroscopy, including coherent detectors at the longest wavelengths. It is also in the more extreme domains that productive partnerships with non-astronomical users of detector technology have not developed because there is minimal commercial or military application for the technologies needed by astronomers at long wavelengths.

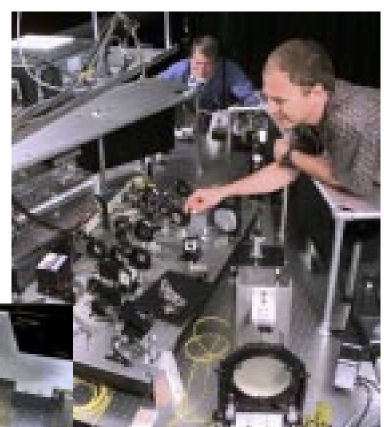
Detector technologies, while critically important for the large visionary missions of the mid-century, will also enable highly productive, smaller-scale space investigations that might be developed in the Explorer or Discovery programs.

To achieve their ultimate performance, these new detectors will require improvements in small, very low temperature, cryocoolers. In fact, the detector and its cryocooler should be viewed as an inseparable technological pair. The TPF mission is undertaking development of the next level of cryocooler capability; however, the missions of the far future will require further advances to enable detector operation with sufficient sensitivity.

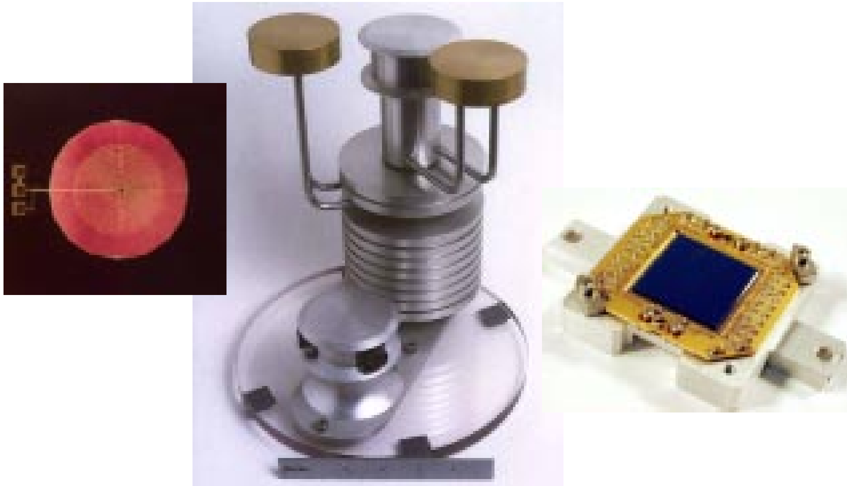
Space Optics Technologies

Usually, the largest and most massive component of a telescope is its primary mirror. In order to launch larger and larger telescopes into space with our current launch vehicles, we must find a way to keep the mass constant as the size increases. This requires new precision materials and structures that allow the mass per unit area, the areal density, of the large optical elements to be reduced. The JWST mirror technology program hopes to achieve 20 kg/m^2 over a 33-square-meter aperture. A 10-meter mirror that has the same total mass requires an areal density about 8 kg/m^2. Ultimately, areal densities as low as 1 kg/m^2 may be required.





Active wavefront control and ultra-precision laser metrology under development will be key components of future instruments.



Component development of high-performance detectors and cryocoolers lays the foundation for the next generation of observatories.

Active Wavefront Error Control

As the areal density of the optical elements is reduced, they become more flexible and prone to distortions induced from external disturbances. However, the performance requirement on the overall optical system will remain close to perfect in order to achieve the benefits of going to space. This is true even for JWST. As the telescope size increases, there will be a growing need to actively sense and control the shape of the optical surfaces. This will be the only way to ensure the required optical performance as the thermal, gravitational, and mechanical disturbance environment changes in orbit.

Full Aperture Cryocooling

The largest of the Origins observatories will operate at infrared wavelengths. In order to achieve the highest possible performance, the telescope's optics must be cooled to prevent them from being a brighter source of infrared energy than the astronomical targets. Cooling huge telescopes to temperatures close to absolute zero represents an enormous challenge. Observatories that are located at the Earth's distance from the Sun require some form of active cooling to reach the desired temperature of below 15 kelvin. If the telescope could be placed beyond the orbit of Mars, it could be made to naturally cool to the required temperature. NASA's new nuclear power and propulsion initiative may produce new flight options that will allow space observatories to operate successfully in the outer solar system, eliminating the need for a separate large aperture cooling technology.

Preserving Unique Space Science Technologies

As new technologies appear, we often lose sight of the important and continuing role of the older ones. It is easy to assume that reliable devices will always be there—reality has proven to be different. For example, scientific CCD detectors are no longer always available, optical filter technology was recently threatened by competing pressure for the same manufacturing capabilities, and other spacecraft components are no longer made. And, capabilities required for scientific research are not always of commercial or military interest, as we see in the far-infrared detector case. Where mature technologies exist that are still a critical component of space science missions, NASA must take active steps to ensure that the manufacturing and testing capabilities are preserved. The single most import area is preservation of the technology base for high performance detectors that operate in the visible and infrared. These devices are near their theoretical limits and that capability must be retained.

CHAPTER 6

Research and Analysis

Keyhole Nebula, approximately 8,000 light-years from Earth. The vantage point of space reveals details of the nebula invisible from the ground. Image: NASA/HST

...to develop new experiment concepts,

and to create and to test theories of our Origins.

The Origins Research and Analysis program provides scientists with the opportunity to explore innovative ideas and technologies that lead to better understanding of astrophysical concepts and methods. This fundamental research is crucial to achieving the scientific goals of the Origins program, and provides the basis for many future mission concepts.

The goal of the Origins Research and Analysis (R&A) program is to provide the seed opportunities for scientists to investigate innovative ideas and to do the fundamental research required to enable the scientific objectives of the Origins theme. Theoretical research and laboratory astrophysics, combined with analysis of data from ground and space observations leads to increased understanding of astrophysical phenomena and forms the basis for mission concepts. Innovative technology development begins in the R&A program through laboratory proof-of-concept demonstrations and the flight of instrumentation on suborbital platforms such as sounding rockets or balloons. The R&A program also offers strong connections to universities and is the breeding ground for future space scientists and engineers. Finally, the loop is closed in the R&A program where the return on investment in flight missions is reaped through the analysis and interpretation of data.

Creating the Tools of Investigation

High-resolution imaging and spectroscopy at wavelengths ranging from the ultraviolet to the submillimeter is required for a variety of studies, including those addressing the inflow and outflow of gases, the structure of the cosmic web, radial and vertical disk structure, grain growth chemistry, chemical composition of the interstellar and intergalactic medium, and the characteristics of planets around other stars. In order to develop the required knowledge and technical capabilities, R&A efforts need to be focused in the areas of detector development, mission supporting technology, suborbital payloads, laboratory astrophysics, and origins of solar systems.

Detector Development

The study of star and planet formation, interstellar dust, and very distant and dusty objects calls for innovative detectors in the infrared and submillimeter portion of the spectrum. Impurity band conduction arrays, such as those aboard the Space Infrared Telescope Facility (SIRTF), have proven remarkably successful, but must be further improved for the Stratospheric Observatory for Infrared Astronomy (SOFIA), the James Webb Space Telescope (JWST), and the next generation of infrared missions. New large format low read-noise and low dark current, near-infrared arrays are vital to the success of JWST. For other large infrared missions of the future, including the Terrestrial Planet Finder (TPF), a new generation of true photoconductor arrays, gapless bolometer arrays, or altogether new sensing technologies will be required. For the far-infrared/submillimeter bands, further developments in coherent detectors will be required. In addition to advancing the state of the art of the

Amazing Space is a set of web-based activities developed for the classroom. The program was designed to enhance students' science, mathematics and technology skills using recent data and results from NASA's Hubble Space Telescope. The resulting online multimedia resources are the culmination of five-week summer workshops that partnered teachers with scientists, graphic artists, writers, and multimedia developers.

Each activity is a fun, interactive way to explore a topic that adheres to National Education Standards for the target age group. All activities include a teacher guide that helps prepare educators to present the lesson in the classroom. In the guide, teachers find "science background" information, vocabulary, and detailed topic information.

In the future, the Amazing Space website will be updated with additional downloadable materials. The materials developed for educators and learners of all ages are accurate, classroom-friendly, visually appealing, as well as carefully crafted to adhere to National Educational Standards. By producing and sharing classroom resources based on the Hubble Space Telescope's discoveries, the Formal Education Group hopes that visitors, young and old, will enjoy learning about the universe.

detectors themselves it will be important to improve upon the readout technology used by infrared and submillimeter detectors.

In the ultraviolet range, a multifaceted approach is needed to develop more efficient detectors. New circuit designs, backside treatments, mosaicing, multiple device packing, and charge injection techniques are needed to improve the performance of CCDs in the ultraviolet. Research on superconducting devices (such as superconducting tunnel junctions and transition edge sensors) suggests that they have good sensitivity over the entire UV range and provide broadband imaging, time tagging, and low-resolution, high-efficiency spectroscopy. Looking ahead to space astrophysics missions of the future, complementary metal-oxide semiconductor (CMOS) active pixel sensors (APS) technology offers extraordinary advantages over current CCDs.

An emphasis on early detector research is crucial to the scientific success of a new mission. Concepts for detectors on several missions including the Hubble Space Telescope (HST), the Far-Ultraviolet Spectroscopic Explorer (FUSE), and SOFIA were initiated in the R&A program and brought to fruition in the focused technology program described earlier.

Mission Supporting Technology

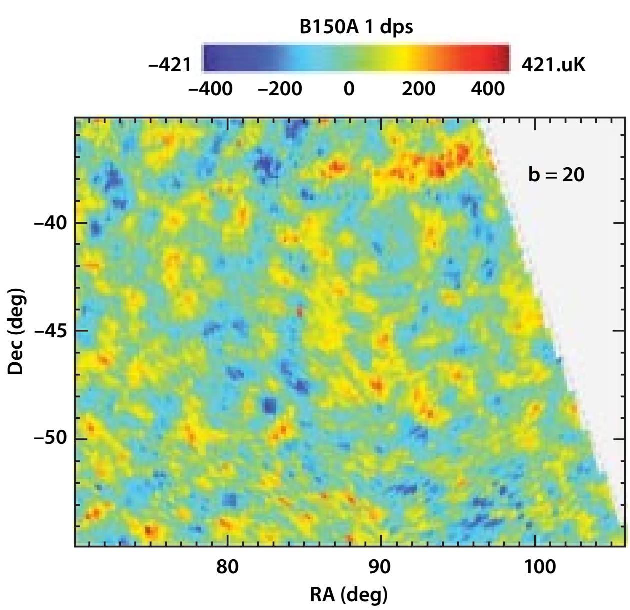
The R&A supporting technology program supports the development of innovative proof-of-concept ideas in a broad range of technologies that are relevant to the theme's objectives.

In the UV, the development of anti-reflective coatings for mirrors and gratings is an important area. Efficient grating designs, solar blind filters, grid filters, UV calibration lamps, focal plane shutters, interferometers, holographic gratings, and visible coronagraphs are some of the supporting technologies in need of further development.

Improved filter technologies which deliver larger diameters and extend spectral coverage to longer wavelengths are needed in the IR regime. In addition, cold analog-to-digital converters and improved support electronics are ripe for development.

Suborbital Payloads

The R&A program offers an excellent opportunity to develop small payloads for suborbital flights. In particular, balloon or Shuttle-borne payloads produce cutting-edge science. Sounding rockets can also be used as technological testbeds. Such flights not only help to develop state-of-the-art technol-



Sound waves in the embryonic universe are revealed for the first time in this image captured by the BOOMERANG balloon-borne telescope during its maiden voyage around the Antarctic. The patterns visible in the image are consistent with those that would result from sound waves racing through the early universe, creating the structures that by now have evolved into giant clusters and super-clusters of galaxies.

The National Virtual Observatory will connect digital sky surveys, observatory and mission archives, and astronomy data and literature services into a single framework, enabling investigations otherwise too resource intensive to undertake.

ogy, but also constitute a high yield investment in human capital. Investigators that come through the program have gone on to become principal investigators of flight missions, major instrument builders, and astronauts.

Laboratory Astrophysics

By utilizing a combination of laboratory experiments, modeling, and theoretical calculations, the laboratory astrophysics program provides the fundamental knowledge needed to make sense of data collected by space missions or to plan them. Laboratory measurements are often an essential link between observations and scientific conclusions. The program explores a tremendous breadth of topics, from the very coldest regions deep in molecular clouds to the extraordinary environments around super-massive black holes. It supports NASA's space missions from conception to completion, defining mission parameters and providing post-flight analysis.

Ultraviolet laboratory spectroscopy supports observations which test cosmological models and provide a better understanding of the processes that created the elements during the Big Bang. Spectroscopic data are key to interpreting visible and UV spectra of important interstellar molecules, such as the large organic species and diffuse interstellar bands (DIBs) that may be connected to the origin of life. Finally, combining laboratory results with space data provides insight into the ages and metallicities of galaxies, the sequence of galaxy formation, as well as the energetics of interstellar dust in a variety of environments.

Fine structure transitions of atoms and atomic ions in the far-IR/submillimeter are the main cooling lines of the non-ionized interstellar medium. This makes them key contributors to gravitational collapse, and as such they are critical to understanding the formation of stars and planets. IR/submillimeter transmissions of interstellar dust grains indicate specific mineral and carbonaceous composition, leading to grain opacities in various environments. These opacities, uncertain now by an order of magnitude, are key to estimating the temperature and mass of the interstellar medium within entire galaxies.

Perhaps most importantly, future missions will study Earth-like planets and search for signs of life. Laboratory experiments have shown that some of the raw materials for life on these planets can be created in interstellar grains of ice and dust. It is vital to continue these experiments, as well as others aimed at understanding the potential biosignatures observable spectroscopically on these planets from space missions.

Origins of Solar Systems

The search for new solar systems by ground-based techniques has been extraordinarily successful in the last several years. These searches can be expected to be increasingly successful in the next several years and represent crucial inputs to the design of the TPF mission. The R&A program will continue to support these searches and will broaden the range of techniques and opportunities.

However, the TPF program will require more than just an inventory of the nearby planets. We need to understand how planetary systems formed, what determines their stability, and what determines the size of planets. These are research topics to be pursued in the Origins R&A programs.

If the answer to "Are we alone?" is yes, we need to have the background theoretical basis to understand why we are unique.

Theory and Data Analysis

Before a space mission can be designed, the scientific objectives of the program must be firmly supported by observation and theoretical calculation. Recognizing this, the Origins program includes important support for theory and archival research.

Theory

Theory provides the fundamental quests for our programs, predicts observable and measurable phenomena, and drives mission and payload design requirements. Theoretical tools are required for the extraction and interpretation of essential science from observational data.

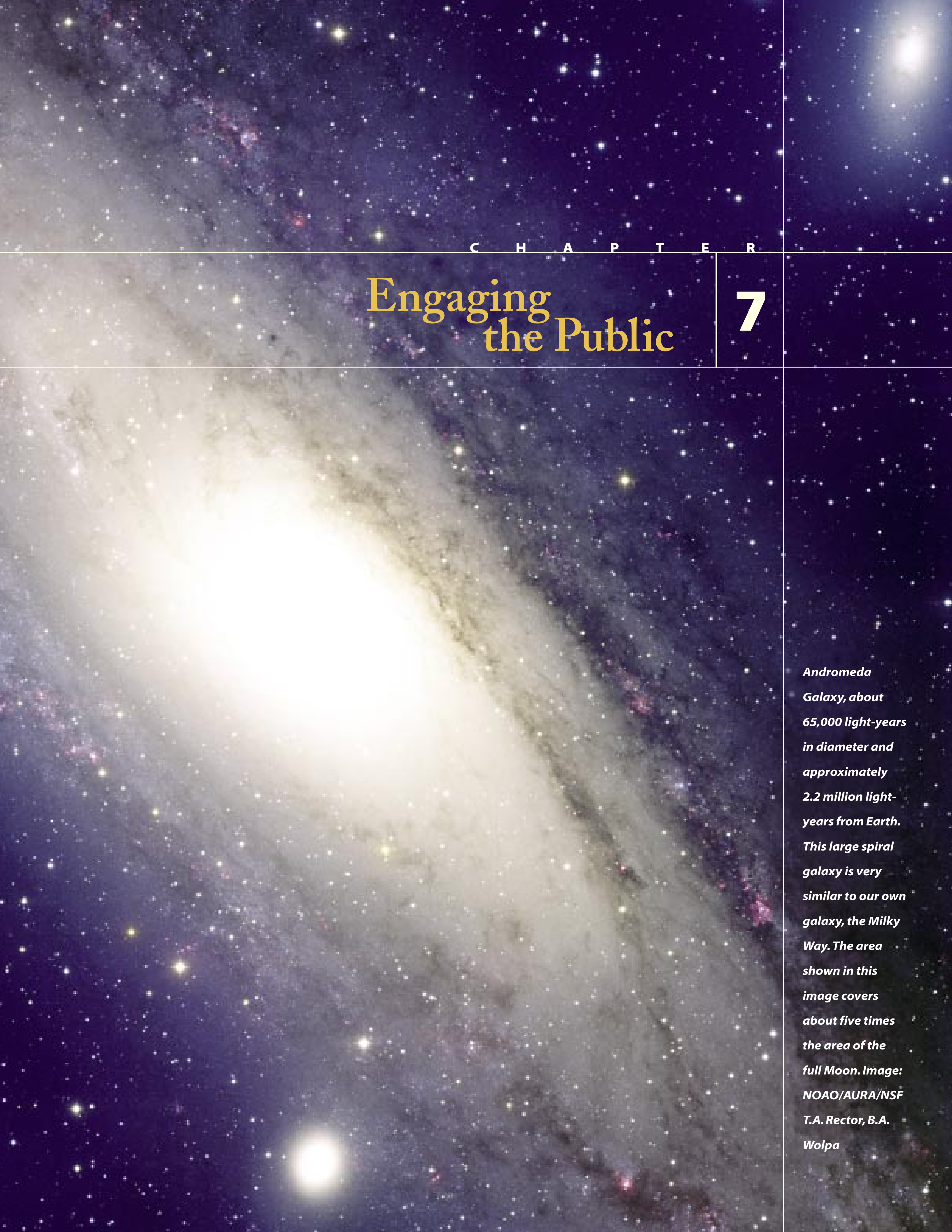
Theoretical studies of early stars, galaxy formation processes, the physical processes of star, planet, and disk formation and evolution, and models in direct support of the search for extrasolar planets are all essential to the Origins program.

Archival Research

As data from previous and ongoing NASA missions accumulate, the value of archival research mounts. Through the multi-wavelength data already available, researchers have gained a much better understanding of a variety of important and interesting astrophysical phenomena without ever using a telescope. Such gains range from establishing universal relations between disparate emission phenomena such as the radio-infrared correlation in star-forming galaxies, to the identification of rare "Rosetta-Stone" objects by comparing multimillion lists of sources from different wavelengths. Though current wavelength-specific archives are readily available, their contents are growing exponentially in both content and diversity. The development of more sophisticated software tools permitting queries spanning all available archives would prove invaluable to scientists. Such a collection of tools would constitute a National Virtual Observatory, a powerful new research capability enabling investigations otherwise too resource intensive to undertake.

CHAPTER

Engaging the Public 7



Andromeda Galaxy, about 65,000 light-years in diameter and approximately 2.2 million light-years from Earth. This large spiral galaxy is very similar to our own galaxy, the Milky Way. The area shown in this image covers about five times the area of the full Moon. Image: NOAO/AURA/NSF T.A. Rector, B.A. Wolpa

...to share, to inspire, to educate all Americans in the adventure of discovering our origins.

The goal of the Origins public engagement program is to share our stirring quests and findings with people of all ages and backgrounds, conveying the thrill of scientific discovery and technological accomplishment in space. We strive to inspire Americans, to enhance scientific literacy nationwide, and to improve science, mathematics, and technology education at all levels.

The Origins program seeks to answer questions that have endured since humans looked into the night sky from the first campfires. The age-old questions "Where did we come from?" and "Are we alone?" have always been part of humanity's need to understand our existence and place in the universe. People have considered these questions in the realms of religion, myth, the arts, and the pop culture interest in the unknown.

Origins scientists use methods that integrate a wide range of scientific disciplines from astronomy, physics, and chemistry, to geology and paleontology, as well as micro- and evolutionary-biology. Sharing the results of the Origins quest will require as diverse a set of tools in public engagement as in science. The ideas and discoveries of the Origins program will expand people's intellectual reach through the tools of science and the unique vantage point of space. We can accomplish this by seeking answers to fundamental questions and sharing what we learn with all humanity.

Missions Create Opportunities

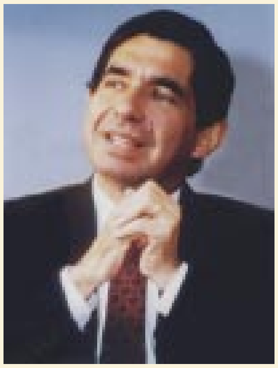
Each mission of the Origins program provides unique opportunities to engage the public in the journey of discovery.

The excitement of the launch, and the ongoing drama of astronauts repairing and upgrading the Hubble Space Telescope (HST) have been of immense public interest during the first 12 years of HST's life. Images from HST have become iconic, stimulating public excitement about space science in ways never dreamed of at the time the telescope was conceived. The future servicing mission in 2004, and the proposed return to Earth in 2010 to become a permanent exhibit at the National Air and Space Museum, will provide opportunities for public inspiration well into HST's second decade. The James Webb Space Telescope will continue this tradition of including the public in our explorations of the farthest regions of space and time.

After its launch in early 2003, the Space Infrared Telescope Facility (SIRTF) will further open the infrared window on the universe, permitting observations in a region of the spectrum not fully visible from beneath Earth's obscuring atmosphere. This mission provides an opportunity to engage both students and the general public in perceiving the otherwise invisible world of the infrared. Together with SIRTF, the Stratospheric Observatory for Infrared Astronomy (SOFIA) is uniquely poised to demonstrate the strength of partnerships between missions with similar goals.

The Seed of Peace

Dr. Oscar Arias Sanchez, Nobel Peace Prize laureate and former President of Costa Rica, on whether the search for origins can bridge science, religion, and spirituality and hence contribute to world peace.



"In the past century and a half, a tragic divide has developed and grown between science and religion with regard to the origins of life, specifically human life. This division is all the sadder because it is unnecessary, and fails to take account of the best in both traditions. As Albert Einstein once said, 'In every true searcher of Nature there is a kind of religious reverence, for he finds it impossible to imagine that he is the first to have thought out the exceedingly delicate threads that connect his perceptions.'

If each of us were to become a 'true searcher', in realms both scientific and spiritual, then I believe that we would all draw closer not only to our origins, but also to our destiny: our destiny as enlightened beings able to live in peace with each other, because we have reached a state of respect, tolerance and love that can only come with the recognition that we are more alike than unalike, and that all humanity is bound together by our very life on this planet.

Exploring the marvels of science—both on Earth and in space—is one of the best ways to tap into the wonder of the universe and, consequently, the great potential of humankind to create societies worthy of the tremendous physical gifts of creation. For when we contemplate the fact that this grand universe is somehow at our disposal, that its beauty, immensity, and mysteries touch our hearts in the deepest way, then we come to understand that though a small part of the cosmos, we are, in fact, in touch with the infinite—and therefore infinitely connected with each other. This realization is the seed of peace."

Dr. Oscar Arias Sanchez was born in 1941. After studying in the United States, he read law and economics at the University of Costa Rica in the capital, San Jose. As a student he engaged actively in the work of the National Liberation Party. Having completed his degree, he went on to take a doctorate in England, with a thesis on the subject of "Who rules Costa Rica?" Dr. Arias embarked on his political career in earnest in 1970 and was elected President in 1986. As President, he was instrumental in forging an accord between Costa Rica, Guatemala, El Salvador, Honduras, and Nicaragua to bring peace to this region of Central America long torn by strife and civil war. For this achievement, Dr. Arias was awarded the Nobel Peace Prize for 1987.

SOFIA is also an infrared observatory, but one that uses a Boeing 747 aircraft to get above most of Earth's atmosphere. Teachers will work side by side with scientists during observing flights, providing thousands of dedicated educators a chance to participate in scientific research and discovery.

The Space Interferometry Mission will take breakthrough technology into space to detect Earth-size planets around distant stars. This search for other Earths has the potential to ignite public excitement and stimulate the public imagination akin to the greatest scientific discoveries in the history of humankind.

An even more ambitious step in the search for life outside our own solar system is the Terrestrial Planet Finder. The direct detection of an Earth-like planet, including indications of a warm, wet atmosphere will bring the search for life from the realm of speculation and science fiction to the workbench of scientific investigation. We will need to be prepared to respond to the likely tremendous worldwide interest such a discovery will cause.

Engaging a Broad Audience

The Origins public engagement program aims to include all of the diverse members of the American public, with their varied backgrounds, wide range of experience, and different ages. We will reach them by forming a wide spectrum of partnerships, adopting a multimedia approach, integrating the perspectives of varying disciplines, and strategically guiding such activities through the Origins Education and Public Outreach Forum.

The involvement of scientists and engineers will be critical to present the scientific goals and results of Origins missions in greater depth, and with a broader perspective, than their images and discoveries alone provide. We recognize the skill of making scientific results accessible for general audiences while preserving intellectual authenticity as a quality that needs to be continually nurtured in interested scientists. These individuals will help us build bridges between the science realm and the lives of our audiences to extend the missions into the classrooms and living rooms of

We engage the public, teachers, and students to implement NASA's vision to inspire the next generation of explorers.

Education and Public Outreach

All of the activities of NASA's Office of Space Science engage the public at various levels. In the context of a science program such as Origins, these levels fit broadly into the following categories:

Formal Education
K–14 curriculum materials, teacher training and professional development, distance learning programs.

Informal Education
Museum programs, planetarium shows, traveling science exhibits and associated take-home materials.

Public Outreach
Public lectures, classroom visits, educational videos, interactive/educational websites and software.

Each of these categories interacts with every other category. Typically, however, public engagement activities for science programs are contained within one or two categories.

America. The public at large has a long-held fascination with space. We will capitalize on this fascination by showcasing the people behind the discoveries and the technological breakthroughs that enable them, thereby providing a human element to the missions.

We will work with the existing public affairs infrastructure of NASA to make scientific discoveries and results gathered by the missions promptly available in a news-oriented format. We will involve in our planning members of the communities we are aiming to serve, and we will draw on teams of writers, producers, and education specialists who have experience with our audiences to make this information understandable and relevant to the public. Wherever possible we will create opportunities for teachers and students to immerse themselves in the authentic process of discovery, thereby showing them how scientists work and how we progress from observations to scientific knowledge.

An important element in achieving these goals will be collaborative activities involving diverse communities. To reach these diverse communities we will need to use diverse means of communication.

The partnerships we seek to forge will connect:

- Science and education departments at colleges and universities
- Scientists at colleges, universities, and government agencies
- Museums, science centers, and planetaria
- Organizations serving traditionally underserved groups
- School districts
- Libraries
- Community-based organizations
- Youth club organizations

Strategic Leadership

Strategic leadership will be provided by the Origins Education Forum, operated at Space Telescope Science Institute. The Forum will help determine how the various mission outreach efforts fit into the broader educational context. It will be proactive in seeking high-leverage opportunities to maximize the usefulness and effectiveness of material, programs and services created by the Origins missions. The Forum will work with missions to enhance activities targeted at formal (K–14) education, informal education (e.g., exhibits), news, and online audiences in a manner that minimizes duplication of effort and utilizes limited resources for maximum effectiveness. The Forum will coordinate distributed activities, and will serve as an information resource for measuring the impact of education and public outreach efforts conducted by the Origins missions and research programs.

Science Summary

GROUND-BASED

		R&A	Keck	KI	LBTI
	EMERGENCE OF THE MODERN UNIVERSE				
Research Area One	**How did the cosmic web of matter organize into the first stars and galaxies?**				
INVESTIGATIONS	1 Pristine gas, the first stars, and the first heavy elements				
	2 Black holes and structure in the early universe				
	3 Formation and evolution of galaxies				
Research Area Two	**How do different galactic ecosystems (of stars and gas) form and which can lead to planets and living organisms?**				
INVESTIGATIONS	4 Lifecycle of stars in the Milky Way and other galaxies				
	5 Habitats for life in the Milky Way and other galaxies			○	○
	STARS AND PLANETS				
Research Area Three	**How do gas and dust become stars and planets?**				
INVESTIGATIONS	6 Molecular clouds as cradles for star and planet formation	●			
	7 Emergence of stellar systems	●	●		
	8 Evolution of protoplanetary dust and gas disks into planetary systems	●	●	●	●
Research Area Four	**Are there planetary systems around other stars and how do their architectures and evolution compare with our own solar system?**				
INVESTIGATIONS	9 Evidence of planets in disks around young stars	●	●	●	●
	10 Census of planetary systems around stars of all ages	●	●	●	●
	HABITABLE PLANETS AND LIFE				
Research Area Five	**What are the properties of giant planets orbiting other stars?**				
INVESTIGATIONS	11 Chemical and physical properties of giant extrasolar planets			●	●
	12 Detect giant planets by direct imaging, and study their properties			●	●
Research Area Six	**How common are terrestrial planets? What are their properties? Which of them might be habitable?**				
INVESTIGATIONS	13 Which nearby stars host terrestrial planets that might be suitable for life?				
	14 Atmospheric compositions of terrestrial planets orbiting nearby stars				
Research Area Seven	**Is there life on planets outside the solar system?**				
INVESTIGATIONS	15 Optimal biosignatures for life on other worlds	●			
	16 Evidence for life on planets orbiting nearby stars	●			

● Major Contribution ○ Contribution

Origins missions flow from the research areas and investigations in this roadmap.

S P A C E - B A S E D

HST	FUSE	SIRTF	SOFIA	Opt/IR Coronagraph Mission	Kepler	SIM	JWST	TPF	SAFIR	Large UV/OPT Mission
●	●						●			●
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Glossary

ACS	Advanced Camera for Surveys
AGN	Active Galactic Nuclei
APS	Active Pixel Sensors
AU	Astronomical Unit
ALMA	Atacama Large Millimeter Array
BOOMERANG	Balloon Observations of Millimetric Extragalactic Radiation and Geophysics
CMOS	Complementary Metal Oxide Semiconductor
COBE	Cosmic Background Explorer
CCD	Charged-Coupled Device
COS	Cosmic Origins Spectrograph
CSA	Canadian Space Agency
DIBS	Diffuse Interstellar Bands
DoD	Department of Defense
E/PO	Education/Public Outreach
ESA	European Space Agency
FUSE	Far-Ultraviolet Spectroscopic Explorer
GMST	Giant Segmented Mirror Telescope
HST	Hubble Space Telescope
HZ	Habitable Zone
IGM	Intergalactic Medium
IR	Infrared
IRSI	Infrared Space Interferometer

ISM	Interstellar Medium
ISO	Infrared Space Observatory
JCMT	James Clerk Maxwell Telescope
JWST	James Webb Space Telescope
KI	Keck Interferometer
LBT	Large Binocular Telescope
LBTI	Large Binocular Telescope Interferometer
LF	Life Finder
LISA	Laser Interferometer Space Antenna
MAXIMA	Millimeter Anisotropy eXperiment IMaging Array
NASA	National Aeronautics and Space Administration
NICMOS	Near-Infrared Camera and Multi-Object Spectrometer
NVO	National Virtual Observatory
PAH	Polycyclic Aromatic Hydrocarbon
R&A	Research and Analysis
SAFIR	Single Aperture Far-Infrared Observatory
SCUBA	Submillimeter Common-User Bolometer Array
SIM	Space Interferometry Mission
SIRTF	Space Infrared Telescope Facility
SOFIA	Stratospheric Observatory for Infrared Astronomy
TPF	Terrestrial Planet Finder
UV	Ultraviolet
WFC 3	Wide-Field Camera 3

EPILOGUE

Where do we come from?

Are we alone?

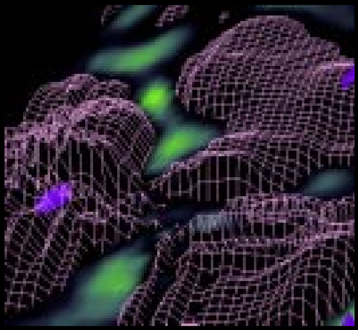
When the answers to these questions are known, our civilizations will evolve new visions of who we are and what our futures might be.

Origins Horizon

Born of the extraordinary accomplishments of 20th century physics, astronomy, geology, and biology, the Origins program takes up the challenge of answering questions as old as our species. When Galileo first turned his tiny telescope to the night sky, he saw the Milky Way resolved into millions of stars, in one stroke expanding our grasp of the universe to a scale that had not been imagined from the sight of eyes alone. The growth of scientific culture and tools over the next three centuries revealed a vast realm, each at-first-incomprehensible discovery assimilated into an increasingly uncomfortable reality. The eruptive growth of 20th century astronomy has brought us an appreciation of how vast, old, and unearthly the universe is, and has left humanity struggling for a sense of our own significance consistent with the reality of who and what we are. But science has also given us something that will help, by promising answers to our ancient questions: Where do we come from? Are we alone? When the answers to these questions are known, our civilizations will evolve new visions of who we are and what our futures might be. Already we have learned enough to appreciate that the universe is enormous and ancient, but life—tiny and transient—is its precious jewel.

In the first few decades of this new century astronomers will largely complete the study of cosmology: the description of the universe on the largest scales and how it works. With the Space Infrared Telescope Facility (SIRTF) and the James Webb Space Telescope (JWST) we will also begin to write the final chapter of the story of galaxies, witnessing the actual birth of these continents of stars. In particular we will chart the13-billion-year history of the Milky Way Galaxy we inhabit, understanding how the materials for new stars, planets, and life were generated and distributed. SIRTF and JWST will also lead the way in studying the birth of stars with their families of planets, moons, comets, and asteroids, the cosmic Petri dish of life. Led by the Terrestrial Planet Finder, we will peer one-by-one at our hundreds of nearest neighbor stars and inventory their planets, searching for solar systems resembling our own with a balmy, wet planet like Earth. It will require much more ambitious telescopes such as Life Finder to detail the conditions of such a world, gathering far more light from a distant world, enough to see the signatures of life in the atmospheres of planets, evidence for seas and continents, for seasonal variations. We cannot yet know whether the worlds we seek are common or exceedingly rare, so our journey may eventually involve great flotillas of large telescopes that can

EPILOGUE



extend the search to thousands or tens of thousands of stars. By the middle of the 21st century, the Origins program could be compiling a vast catalog of tens of thousands of solar systems and monitoring the weather, climates, seasons, and biochemistry on hundreds of inhabited worlds. Machines almost beyond today's imaginings will be needed to scrutinize and perhaps even image the worlds we humans might someday visit, but if the will and spirit hold, physics says it can be done.

Will we humans leave our home in the solar system and begin to migrate over the Milky Way as we once spread over the Earth? From our view at the beginning of this new century it seems both inevitable and impossible. But, whether we make these future settlements in body or only in mind, our journey has surely now begun, and when we first find, in the orbit of a neighboring star, a planet resembling Earth, one where human beings might conceivably live, the quest could become an obsession. Perhaps our descendants will praise us for our initiative, perhaps they will curse the relentless curiosity that propels humans into greater accomplishments and greater peril, but our part in this drama is preordained, its resolution beyond our time and imagination, barely within our dreams. We go on.

— Alan Dressler

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