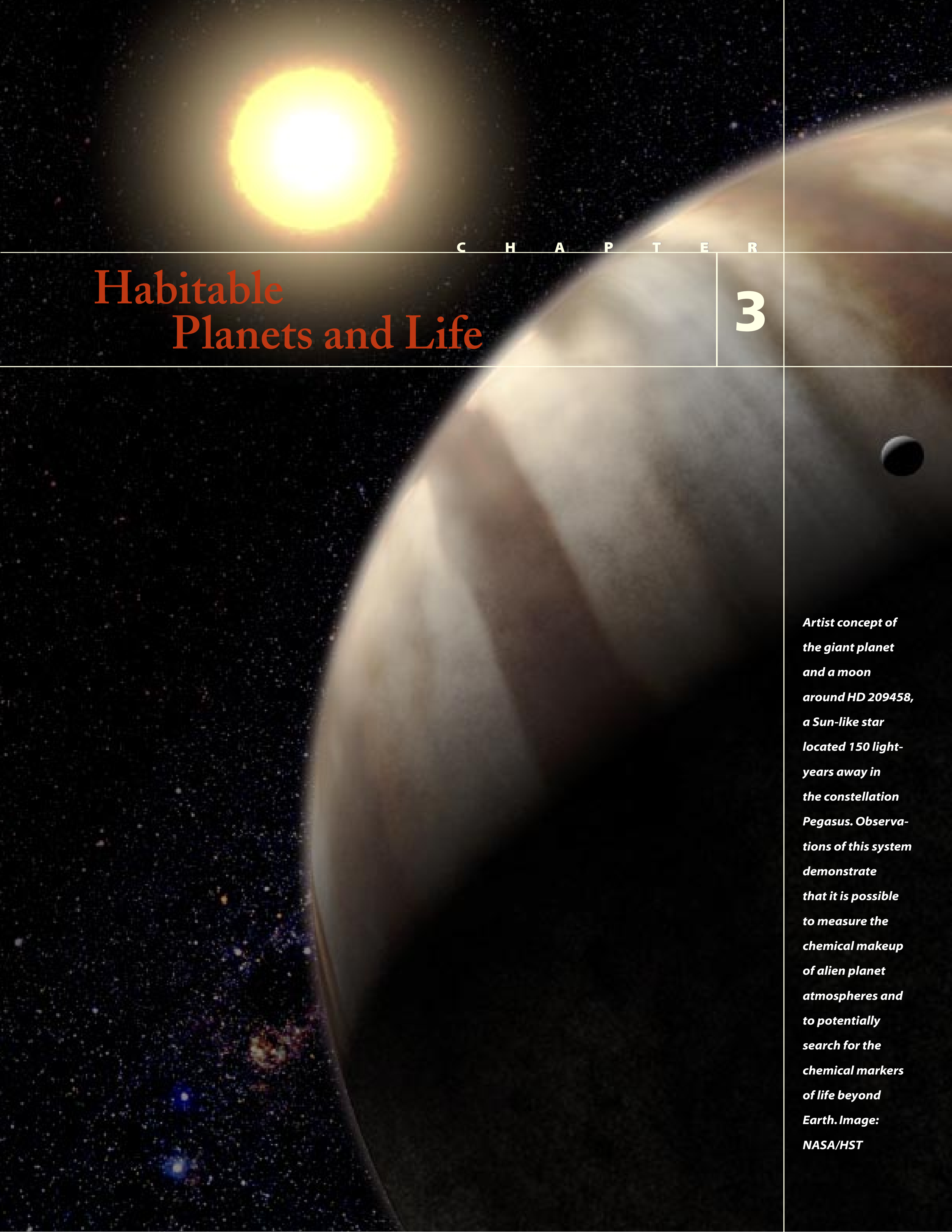
CHAPTER 3

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.

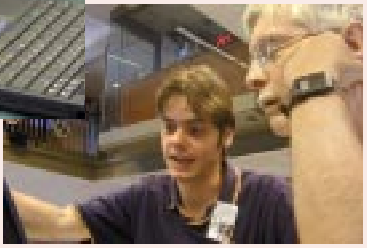
The Kepler mission, focusing on a myriad of distant stars, will be our first opportunity to find out how common it is for a star to have an orbiting Earth-like planet, how big those planets are, and where they are located in relation to the "habitable zone" where life as we know it is possible. This 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

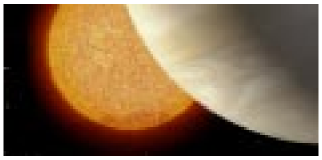


An excited hum of voices fills the Phillips Auditorium at the Harvard Smithsonian Center for Astrophysics in Cambridge, Massachusetts. It is Tuesday, June 25, 2002. Sixty-five students and young researchers from around the country are huddled over laptop computers trying to make sense of sample data 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.

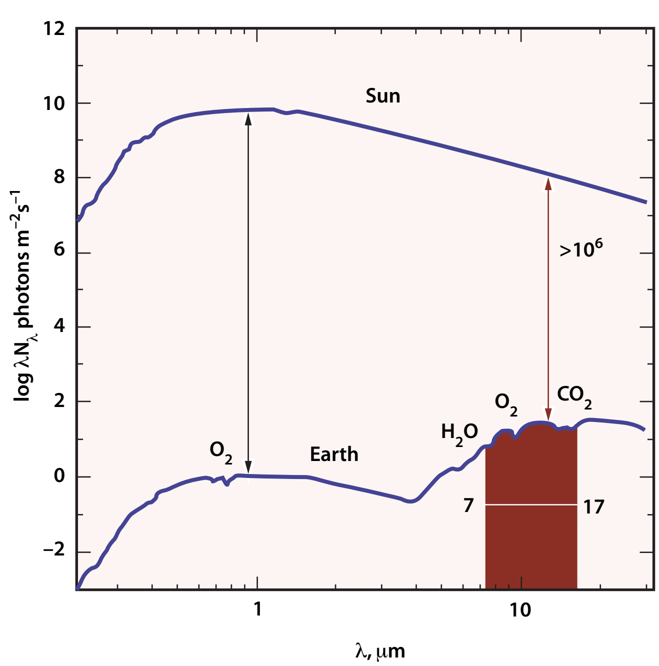
Most extrasolar planets, of course, do not have orbits fortuitously tilted so that they transit directly in front of their stars. But even for non-transiting planets we may tease some information about the composition of their atmospheres from the combined light of star and planet. Specialized techniques 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.

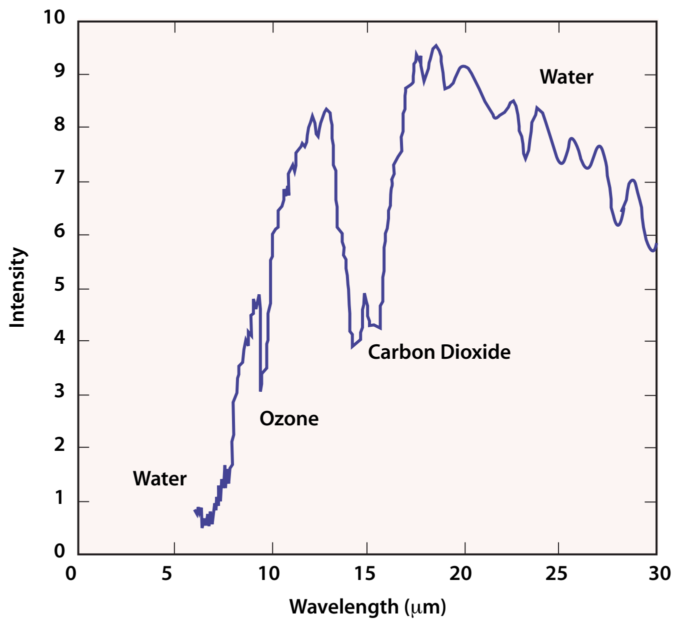
INVESTIGATION 12

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

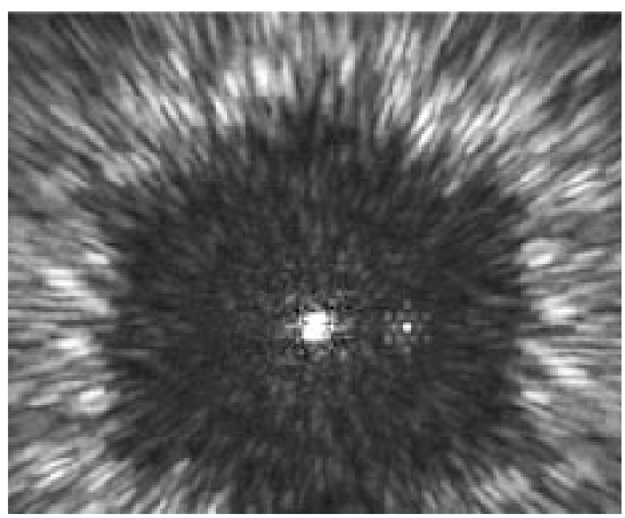
Which nearby stars host terrestrial planets that might be suitable for life?

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.

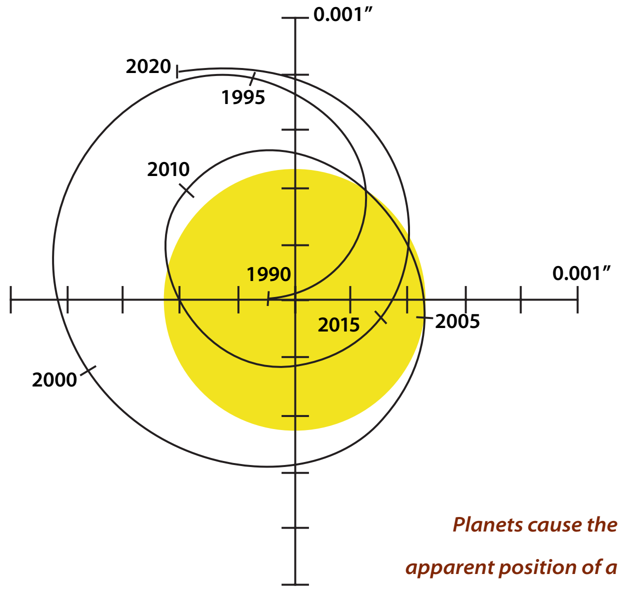
Once a planet has been detected, repeat observations over its "year" will determine its orbital period and distance from the parent star. This already will give an important first clue to its temperature, i.e., whether it does indeed lie



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:

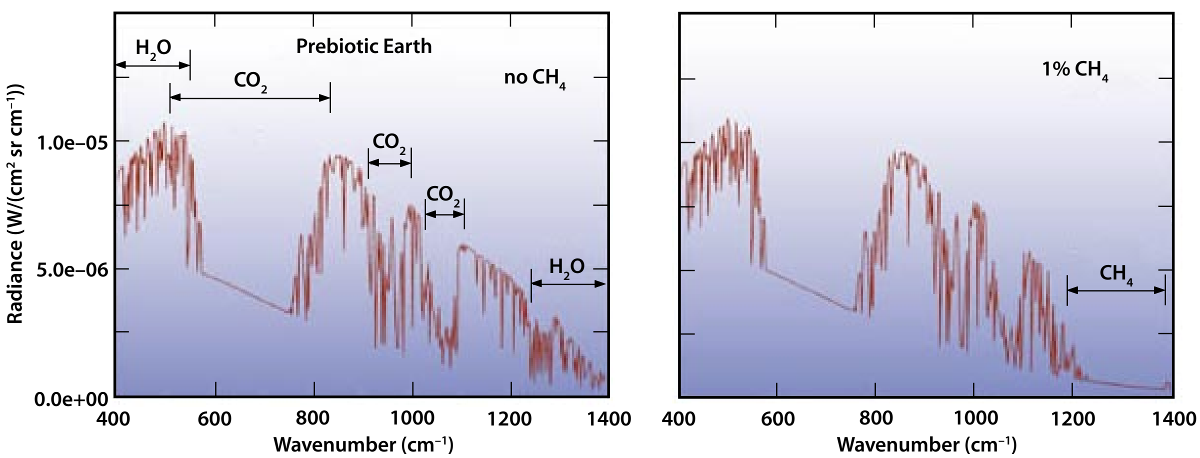
- Determine the optimal biosignatures for life on other worlds.
- Search for these biosignatures as evidence of life on habitable planets orbiting other stars.

INVESTIGATION 15

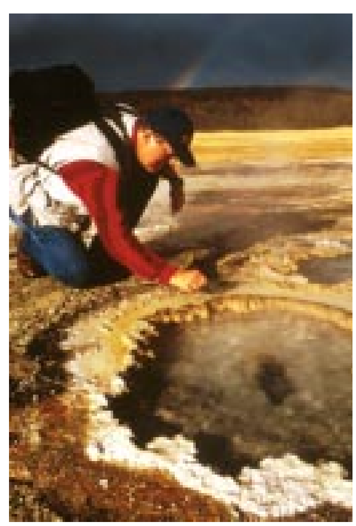
Determine optimal biosignatures for life on other worlds.

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 bio-signatures 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.