A Road Map for the Exploration of Neighboring Planetary Systems (ExNPS)

August 1996

A brown dwarf star having only 20–50 times the mass of Jupiter is located below and to the left of the bright star GL 229 in this image from the Hubble Space Telescope. At the 19 light year distance to GL 229, the 7.7-arcsec separation between the star and the brown dwarf corresponds to roughly the separation between Pluto and the Sun in our Solar System. The goal of the program described in this report is to detect and characterize Earth-like planets around nearby stars where conditions suitable for life might be found. For a star like the Sun located 30 light years away, the appropriate star-planet separation would be almost 100 times closer than seen here for GL 229B.

A Road Map for the Exploration of Neighboring Planetary Systems

The ExNPS Team

edited by C. A. Beichman

August 1996

http://jpl-origins.jpl.nasa.gov/ExNPS

Prepared by The ExNPS Integration Team

Charles Elachi (chair)	JPL
Roger Angel	University of Arizona
Charles Beichman	Infrared Processing and Analysis Center
Alan Boss	Carnegie Institution
Robert Brown	Space Telescope Science Institute
Alan Dressler	Carnegie Institution
Freeman Dyson	Institute for Advanced Study
James Fanson	JPL
Chris Ftaclas	Hughes Danbury Optical Systems
Lawrence Goad	Itek Optical Systems
Mike Klein	JPL
Alain Léger	University of Paris
Charles Lillie	TRW
Stanton Peale	University of California, Santa Barbara
Deane Petersen	State University of New York, Stonybrook
Bob Reasenberg	Center for Astrophysics
David Sandler	Thermo Trex
Mike Shao	JPL
Richard Simon	NRAO
Domenick Tenerelli	Lockheed Martin
David Tytler	University of California, San Diego

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1
EXECUTIVE SUMMARY

Within the next 20 years, a space-based observatory could detect the radiation from any Earth-like planets orbiting the closest 1,000 stars. This same observatory could also characterize the atmospheres of the brightest of these planets. This is the consensus conclusion of a group of 135 scientists from 53 institutions chartered by NASA to lay out a Road Map for the Exploration of Neighboring Planetary Systems (ExNPS). The ExNPS Road Map promises a continuing stream of results and will culminate in the flight of an infrared interferometer with enough sensitivity to make "family portraits" of planets orbiting nearby stars and to detect CO_2, O_3 and H_2O in the atmosphere of an Earth-like planet up to 13 pc away. Figure 1-1 shows schematically a discovery timeline for the ExNPS program. The Road Map consists of a variety of ground-based and space-based initiatives:

- A program of the indirect detection that would reveal planets with masses as small as that of Uranus. This program involves both ground-based and space-based platforms to make radial-velocity, astrometric, and micro-lensing observations. The goal of this program is to learn as much as possible about the larger planets in the sample of the nearest thousand stars of spectral types F, G, K, and M.

- A space-based optical interferometer for astrometry that would both carry out astrophysical investigations and prove key technologies, as well as have the precision to detect the wobbles in a star's position due to the presence of planets less massive than Uranus, and possibly as small as the Earth.

- An ambitious program for directly seeing planets with masses as small as Uranus. The program would use adaptive optics on large ground-
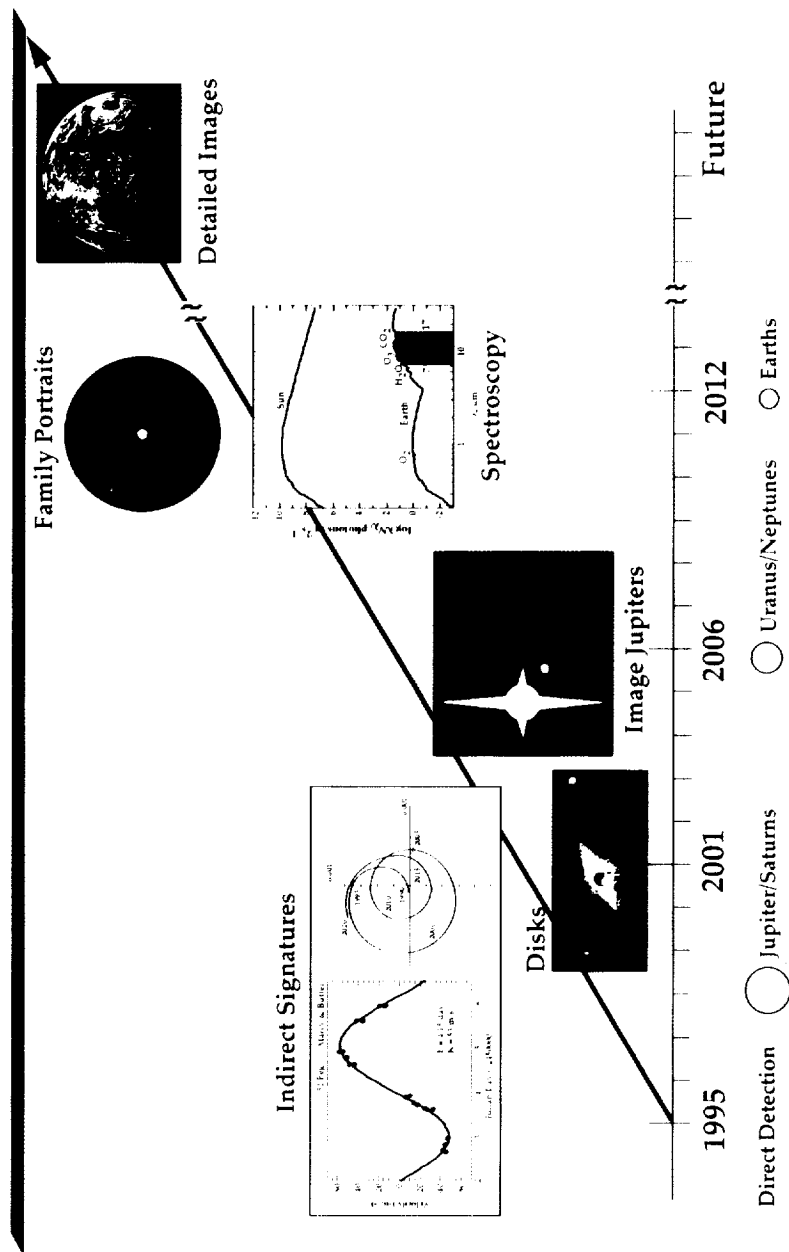
Figure 1-1. Discovery Timeline for the ExNPS Road Map

based telescopes (6–10 m), an adaptive optics coronagraph on the Hubble Space Telescope (HST), or a scattering-compensated mirror on a balloon-borne telescope.

- Characterization of the dust clouds around stars like our Sun using space telescopes (ISO and SIRTF) to probe the outer regions of the cloud (>30 AU), as well as large ground-based telescopes joined together as an interferometer to study the inner parts of the clouds (<10 AU).

- An infrared interferometer consisting of four or more ~1.5-m telescopes linked together on a ~75-m baseline and operating in a deep-space orbit 5 AU from the Sun for maximum sensitivity, will have the capability to detect and characterize Earth-like planets out to 13 pc. In addition to its planet-finding mission, this space infrared interferometer could be an important tool for a wide variety of other astrophysical investigations.

The recent discoveries of objects of planetary mass around several nearby stars through radial velocity and astrometric measurements highlights the timeliness of the ExNPS program and its potential for broad public support. Determining whether or not these first objects are giant planets like Jupiter or brown dwarf stars will be part of the exciting observational and theoretical quest laid out in this Road Map.

In addition to recommending specific programs, the Road Map calls out critical technologies that must be supported to make these facilities possible in a timely, but low-cost fashion, and points out where decisions will have to be made in response to future discoveries.

- Identification of key technologies for this program, including inflatable structures, precision station-keeping, manufacture of large, high-precision optical surfaces, ultra-low-noise infrared detectors, interferometric nulling, etc.

- Identification of important observations and theoretical investigations that should be carried out to support the ExNPS goals.

- Identification of key decision points in the Road Map that affect the direction of the program; e.g., how do we proceed if most stars are surrounded by zodiacal dust clouds brighter than our own?

Finally, the Road Map acknowledges that making resolved images of planets, obtaining very high resolution spectra, and studying more distant

stars requires breakthroughs in key technologies, including on-orbit deployment of large, precise, lightweight telescopes operating as a multi-spacecraft constellation thousands of kilometers across. These difficult observations remain long term goals for a program that has a near-term potential for exciting scientific returns and enormous popular appeal.

The above conclusions were originally reported to NASA in November, 1995. Since that time, NASA established the Origins program within its Office of Space Science with the express goals of finding and detecting other planetary systems and of understanding the origins of planets, stars, and galaxies. The recommendations of the ExNPS Road Map presented herein are presently being integrated with the recommendations of a group of scientists, chaired by Dr. Alan Dressler, who studied the potential of a 4- to 8-m telescope for a broad range of "Origins" science.

Chapter 2

Introduction

2.1 The Search for Other Planets

Twenty-five years ago the Apollo astronauts looked back from the Moon and took now-famous photographs depicting the Earth as an island of life in space. These photographs highlighted the Earth as a sanctuary of life in the blackness of space and gave a new perspective on the age old question of whether life exists elsewhere in the Universe. In the intervening years since these historic photographs were obtained, advanced astronomical techniques have enabled us to identify the first planets outside our Solar System that revolve around other stars. In the not-too-distant future, we may find Earth-like, habitable planets. Discovering these "other worlds" will require a new generation of space observatories utilizing advanced technologies. While, today, we have the technology to find only indirect evidence of giant planets like Jupiter around other stars, we know how to develop the instruments needed to discover and study smaller planets like the Earth. When we have achieved this, when we find these other worlds, it will mean knowing better how our Earth, our Solar System, and we ourselves came about. We will better understand our "origins."

This Road Map lays out a plan that will take us from our present-day capabilities to a future where we can discover and characterize distant, *habitable* worlds. The search for planets around other stars is a quest on the cutting edge of science and technology, and it draws upon all we know of Earth, the Solar System, the formation of stars, and the remarkable phenomenon of life on Earth. In addition, the search for other worlds will have a broad cultural impact. Since ancient times, humans have wondered on the uniqueness of Earth and the life it bears. People from all walks of life

perceive the deep significance of the question of whether there are planets around other stars and whether these planets might harbor life. For the first time since these questions were first posed, thousands of years ago, we have the potential to provide unambiguous answers.

2.2 THE ROAD MAP CHARTER AND PROCESS

In March, 1995, NASA chartered a group of scientists and engineers to lay out a Road Map for the Exploration of Neighboring Planetary Systems (ExNPS). The Road Map activity, organized by NASA's Jet Propulsion Laboratory (JPL) was organized into three teams: one established and led jointly by JPL and the Space Telescope Science Institute (STScI) and two selected competitively by peer-review (Appendix A). All three teams were asked to propose complete Road Maps addressing all aspects of the challenge: science rationale, indirect detection of planetary systems, direct detection and characterization of planets, and multi-pixel imaging of planets. The resulting Road Maps were completed in September, 1995, and then synthesized into a single plan by an Integration Team consisting of members of each of the individual Road Map teams. This report represents the consensus view of the Integration Team.

The ExNPS Road Map was presented to a Blue Ribbon Review Panel headed by Professor Charles Townes on October 5–6, 1995, and subsequently to the NASA Administrator, Mr. Dan Goldin, on November 7, 1995, after incorporating comments from the Townes panel. The response of the Townes Panel is included in this document as Appendix B. Appendix C discusses some of the broad cultural implications of the ExNPS programs.

The Road Map was largely completed before the recent discoveries of planet-mass companions to nearby stars. The Road Map explicitly recommended vigorous support for precisely those areas of indirect detection of planets that have been so recently successful. The fact that some of the first systems discovered have turned out to be quite different from the Solar System provides an important caution that the Road Map must always be ready to adapt to new discoveries.

Information on NASA's overall Origins Program is available at:
http://www.hq.nasa.gov/office/oss/origins/Origins.html

The text of this report plus a synopsis, with additional figures, can be found via the JPL Origins Home Page:

http://jpl-origins.jpl.nasa.gov/ExNPS

2.3 RULES OF THE ROAD

The Road Map teams imposed a number of philosophical and scientific constraints on the definition and scope of their plans to ensure the scientific rigor, technical feasibility, and public support of its recommendations.

SCIENTIFIC RIGOR

The proposed program has to be able to withstand critical scientific scrutiny in light of the fundamental importance of the results and because of the intense competition for scarce budgetary resources. Part of this rigor is the recognition that the failure to find planets is an important result that must be statistically meaningful. The requirement that a negative result be meaningful implies that a relatively large sample of stars be observed. This requirement in turn implies developing instruments capable of reaching over 1,000 stars at a limiting distance of at least 13 pc from the Sun.

SCIENTIFIC ROBUSTNESS

The Road Map must provide multiple techniques to achieve key goals so that results can be rapidly confirmed and so that the program is robust against the failure of some technique to meet expectations.

FREQUENT RESULTS, CONTINUING PROGRESS

To generate and maintain scientific and public enthusiasm, the program must produce a steady output of scientifically important results.

IMPORTANCE OF SPECTROSCOPY

Direct detection methods have to be sensitive enough to make high signal-to-noise detections of planets in just a few hours so that a large number of sources can be surveyed to a meaningful level, and so that crude spectroscopy can be carried out with the same apparatus to provide an initial characterization of the detected planets.

Ground-Based Astronomy is Faster and Cheaper

The Road Map teams looked explicitly at a unified program of ground- and space-based observations. If a ground-based technique came close (within a factor of 3) of the performance of a space-based technique, it was felt that the ground-based technique would probably be more timely and cost-effective and should be adopted.

Expect the Unexpected

To the extent possible, the program should avoid assumptions based on the structure of our own Solar System. The recent discovery of a Jupiter-mass object located only 0.05 AU from a nearby star, far closer than predicted by current theoretical considerations, confirms the importance of this precept.

Chapter 3

The Formation of Stars and Planets

A dramatic breakthrough in the study of extra-solar planets occurred during the final stages of the Road Map process when two groups (Mayor and Queloz in Europe; Marcy and Butler in the US) reported the indirect detection of Jupiter-sized planets orbiting three nearby stars from measurements of radial velocity perturbations. These discoveries galvanized the public imagination, provided obvious confirmation of the potential of the ground-based program proposed as part of this Road Map, and gave theoreticians new data to guide their investigations into the formation of planets.

The dominant theory on the formation of the Solar System is based on one of the oldest surviving scientific hypotheses. In the 18th century, Immanuel Kant (1724–1804) and Marquis Pierre Simon de Laplace (1749–1827) independently suggested that planets in the Solar System accumulated from material in a revolving disk of gas and dust around the young Sun. This hypothesis was inspired by two sets of observations: the mapping of the orbits of the planets in three-dimensional space, (which were found to be circular, lying in a common plane, and rotating in the same sense—an apparent vestige of an earlier disk structure); and the discovery and cataloging of the shapes of astrophysical nebulae by Charles Messier (1730–1817); these nebulae appeared to be disks around stars in which new planets might be forming. Even though these nebulae turned out to be galaxies—that is, whole hosts of stars—the Kant-Laplace hypothesis still survives as the basic paradigm of planet formation. The co-planarity and co-revolution of planetary orbits is still regarded as the definitive signature of planet formation by accretion in a circumstellar disk.

Planet formation is an aspect of star formation. Scientists believe the process begins with the gravitational collapse of a vast cloud of gas and dust (Figures 3-1 and 3-2). The central condensation accretes infalling material, shrinks, and later becomes a star. Material that does not fall on the star forms a disk. The rotation of the original cloud is preserved in the revolution of the disk and the rotation of the star. After a few tens of thousands of years, the dust sinks to the midplane of the disk, forming a dense sheet. Within this sheet, the dust clumps together and agglomerates into larger objects, called planetesimals, which collide and build up to Earth-size planets and the cores of giant planets like Jupiter, Saturn, Neptune, and Uranus. Next, these bodies can accrete atmospheres. Finally, the disk's residual gas and dust dissipate by being either blown away by stellar winds or accreted onto the planets (Figure 3-3).
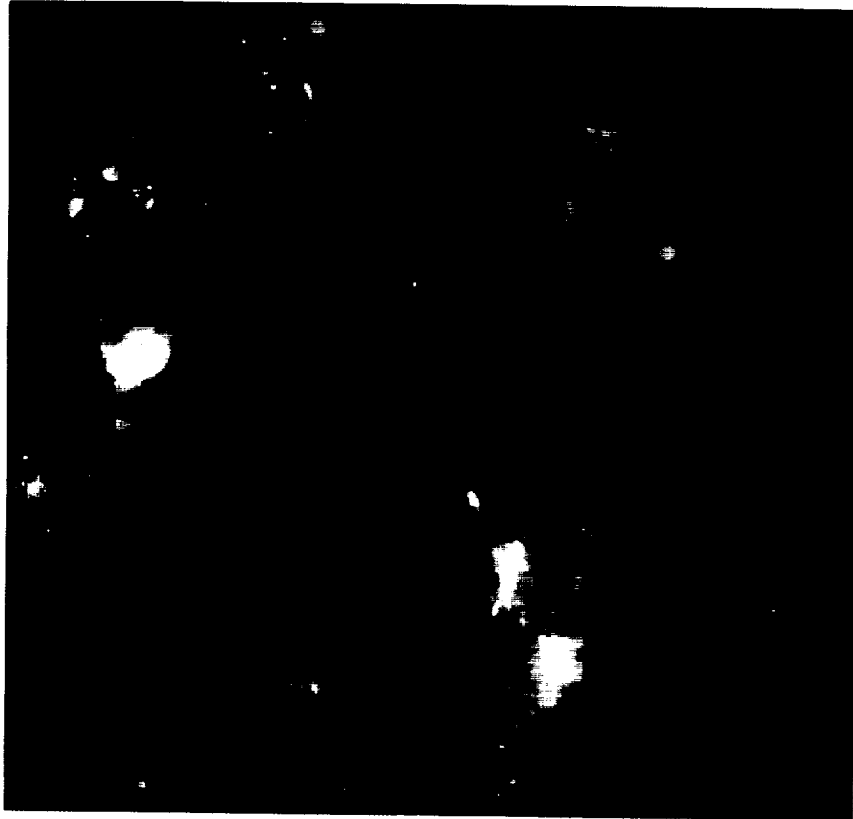
Figure 3-1. IRAS image of the Orion star-forming cloud shows hundreds of new stars forming out of dense interstellar clouds.
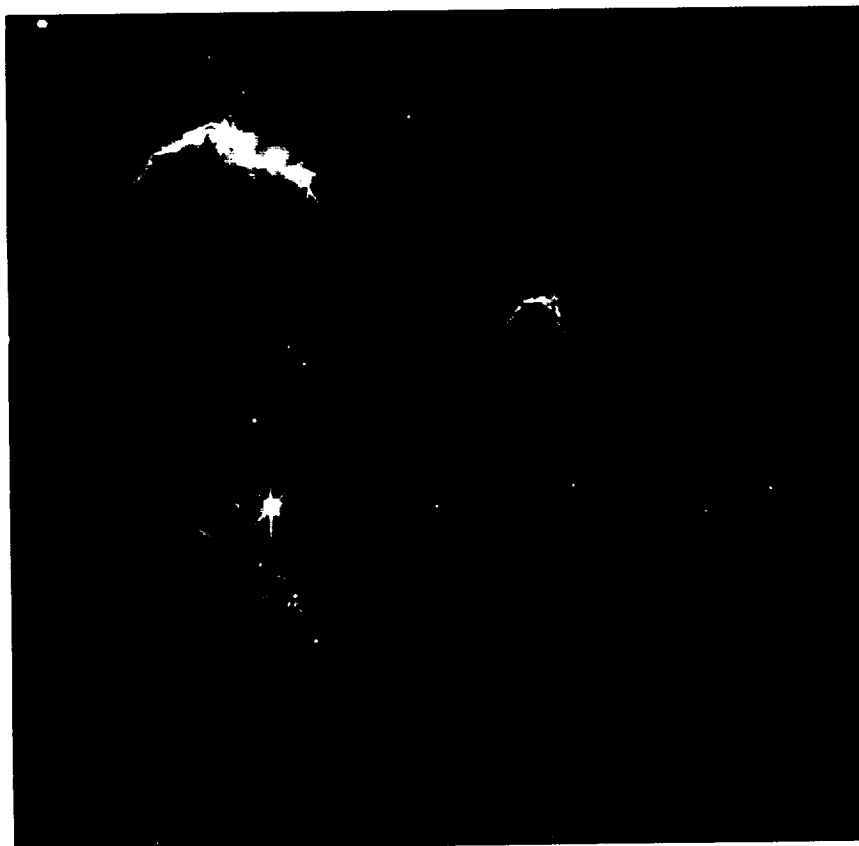
Figure 3-2. An HST image showing a region of star formation around the nebula M16.

In the 1980s and '90s, new astronomical discoveries, including those from the Infrared Astronomical Satellite (IRAS) documented stages in this scenario of how stars and planets form (Figure 3-1). These examples include newborn stars surrounded by embryonic material, youthful stars with flattened disks in which planets may be forming, and older stars with diffuse dusty envelopes that may harbor mature planets.

We have only recently developed the tools to find planets themselves. The planets detected around HD114762, the pulsar planets, 51 Pegasi, 47 Ursa Majoris, 70 Virginis, and Lalande 21185, are just the first in a series of planets that will be found by ground- and space-based techniques. The detection
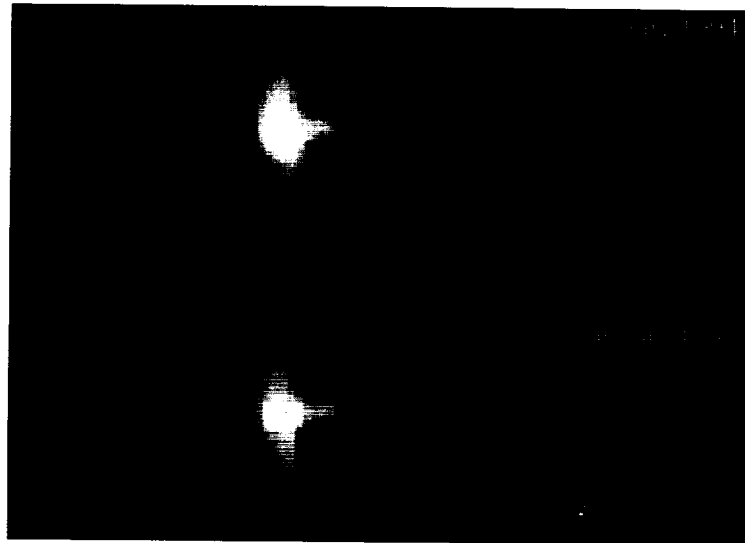
Figure 3-3. Jets of material streaming out from a young star (Herbig-Haro 30) show structures on the size scale of our Solar System.
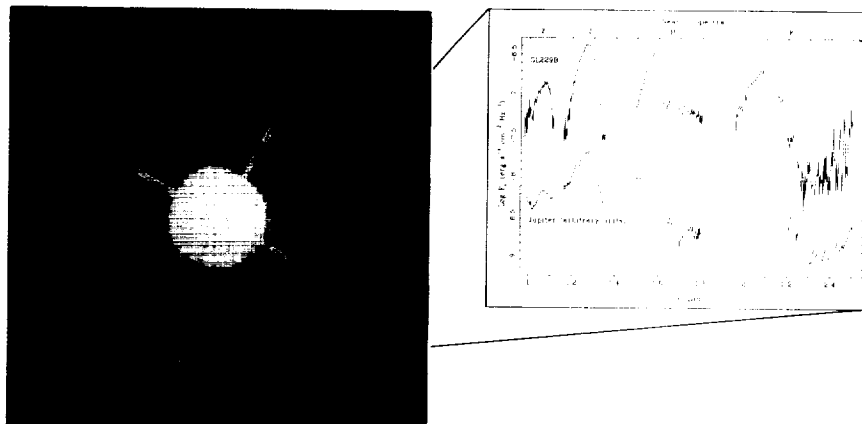
Figure 3-4. An HST image of the brown dwarf star, or "super-planet," GL 229 B located 7.7 arcsec away from the star GL 229. A spectrum (inset) of GL229 B taken with the Keck telescope (Oppenheimer et al. 1995) shows deep absorption bands of methane, similar to those seen in the gas giant planets of our Solar System.

and spectral characterization of a brown dwarf with 50 times the mass of Jupiter orbiting 44 AU from the nearby star GL 229 (Nakajima et al. 1995; Figure 3-4) points the way to finding fainter, lower mass planets close to their parent stars.

Because of the wealth of circumstantial evidence, most astronomers today believe that planetary systems are common occurrences around other stars. The next few years will provide quantitative information on the distribution of planetary masses and distances from parent stars for planets with sizes between Jupiter and Uranus and, with micro-lensing measurements, down to Earth size. With these data in hand, theoreticians will begin to form a coherent picture of the entire process of planet formation. Answering the ultimate question of whether Earth-sized planets are common or rare will require many of the instruments described in this Road Map.

CHAPTER 4
THE INSTRUMENTAL CHALLENGE

4.1 ROAD MAP ASSUMPTIONS ABOUT OTHER SOLAR SYSTEMS

A number of questions had to be answered to help define the instrumental challenges for the ExNPS Road Map. The answers were used to determine the required sensitivity or precision needed for various direct and indirect detection techniques.

WHAT SHOULD WE LOOK FOR?

The first goal of the Road Map is to characterize other solar systems, encompassing planets of Jupiter mass down to less than the mass of the Earth. The goal of imaging a terrestrial planet is taken to mean making an image—a family portrait or an *orrery*—of the planet(s) in a planetary system around a nearby star and identifying whether any of these planets are habitable. For the purposes of the Road Map, a habitable or Earth-like planet is defined as a solid body with a mass between ~0.5 and ~10 Earth masses at a distance from its parent star such that the planet's surface temperature and atmospheric pressure are consistent with the presence of liquid water, 250–300 K.

WHERE SHOULD WE LOOK?

The distribution of spectral types with distance is skewed so that most nearby stars are low-mass, low-luminosity M and K stars. We interpret the mandate to examine the ~1,000 closest stars to include the closest stars spanning a variety of relevant spectral types, from F to M. The minimum distance over which the ExNPS facilities must operate extends

to about 13 pc to ensure that about 100 of the most promising stars are examined.

WHAT WAVELENGTHS SHOULD WE EXAMINE?

The visible, near-infrared, and thermal wavelengths each offer distinct advantages and disadvantages. A key consideration in choosing a wavelength region apart from pure technical feasibility should be the existence of atmospheric spectral signatures to characterize planetary conditions.

WHAT IS THE ENVIRONMENT OF PLANETARY SYSTEMS?

IRAS demonstrated that >15% of all nearby main sequence A–K stars have excess far-infrared emission, indicating the presence of orbiting dust clouds. These clouds must be continually replenished in the face of dynamic dust destruction mechanisms and have size scales ranging from less than 10 AU to beyond 500 AU. The presence of a zodiacal cloud is a fundamental source of photon-noise and of fixed-pattern interference against which planets must be detected. The fact that both our own Solar System and the solar systems we wish to study have dust clouds will prove to have a major influence in the course of the Road Map.

4.2   THE STELLAR POPULATION

The closest stars offer a number of unique advantages, including the largest astrometric displacements for a given planet mass, the greatest separation for direct detection, the most light for direct measurements, and the best chance for spectroscopic follow-up observations. There are roughly 1,000 stars within 13 pc. Of these there are 12 A stars, 20 F stars, and only 70 G stars like our Sun; the remainder are stars less massive than our Sun, K stars and the much smaller M stars. Getting a statistically meaningful sample of stars over a range of spectral types implies being able to make measurements of stars at least as far away as 13 pc. The nearest 1,000 stars have a privileged position in the ExNPS program simply because they are the closest to us, thereby enabling detailed studies of their intrinsic properties (§7.8).

4.3 THE HABITABLE ZONE

A primary purpose of the ExNPS program is to find and characterize *habitable* planets. However, the very concept of habitability is fraught with perils of making anthropocentric decisions about what one wants to find. The topic has a long history in the often interchangeable literatures of science fact and fiction. For the purposes of the Road Map, the *Habitable Zone* is simply taken to be the region around a star at which liquid water, an excellent facilitator of complex chemical reactions, might plausibly be present. The inner and outer radii of the Habitable Zone are defined by surface temperatures below the boiling point and above the freezing point of water at one atmosphere of pressure. The planet-star separation at which these temperatures occur depends on such straightforward factors as the stellar temperature and luminosity, and on such hard to quantify effects as the strength of the greenhouse effect and the distribution of clouds. Kasting et al. (1993) have made calculations of the size of the habitable zone under a number of plausible assumptions (Figure 4-1).
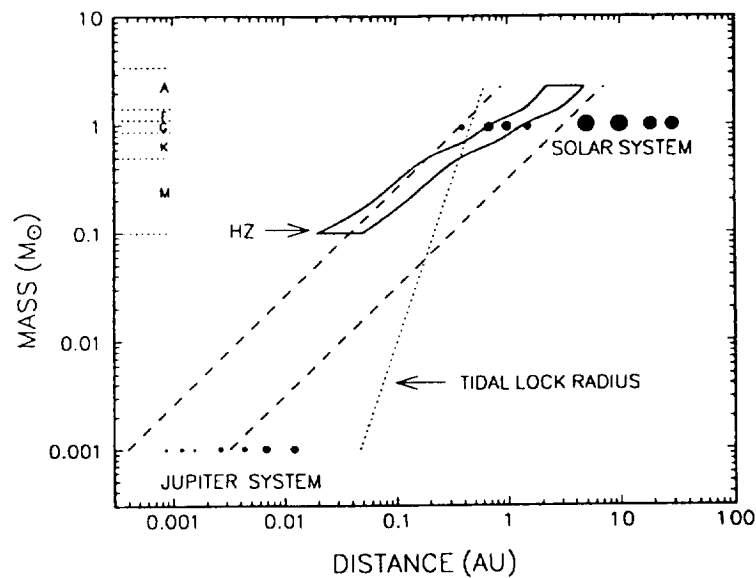
Figure 4-1. The Habitable Zone is defined by the presence of liquid water and varies with stellar luminosity and planet-star distance, among many other factors.

4.4 Techniques for Finding Planets

The Road Map describes both direct and indirect methods of finding extrasolar planets. A *direct method* implies the detection of either starlight reflected from or thermal radiation emitted by the planet. An *indirect method* uses some effect of the planet on the parent star as a signpost of the presence of the planet. This section outlines briefly the major methods that have been advanced for planet detection. The detailed discussion of those methods recommended as part of the Road Map is presented in Chapters 5 through 7.

4.4.1 Direct Detection of Thermal Radiation

The ultimate challenge of the Road Map is to detect directly the photons from a planet itself. This radiation could be either visible starlight reflected from the planet's surface or infrared radiation emitted from a planet heated by its own internal energy and by the light of its parent star.

A direct measurement is exciting because it offers the prospect of learning about the planet by dissecting the planet's light spectroscopically. Direct measurements are difficult because a planet's radiation is overwhelmed by the radiation from the parent star located only a fraction of an arcsec away. Figure 4-2 shows the spectral energy distribution of objects in the Solar System as seen from 10 pc away. The contrast between the Sun and the Earth or Jupiter is about a billion to one at visible wavelengths and about one million to one around 10 μm.
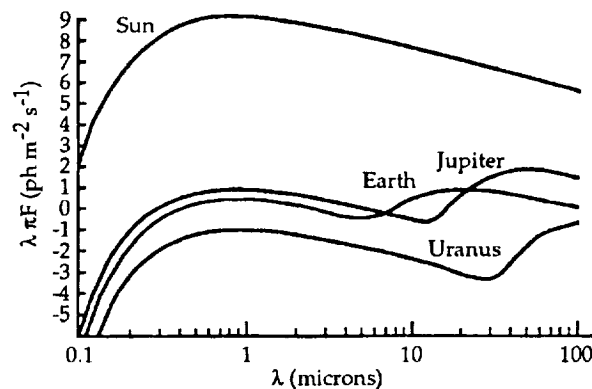
Figure 4-2. The spectral energy distribution of the Sun and planets in the Solar System as seen from a distance of 10 pc.

The flux of photons from either the Earth or Jupiter at 10 μm as seen from 10 pc away is $\nu\phi_\nu$ ~2 photons m^{-2} s^{-1}. The two planets are of comparable brightness because the Earth, although much smaller than Jupiter, is far hotter than the distant gas giant. As will become evident in Chapter 5, the signal from an Earth-like planet is detectable even with today's telescopes. The difficult problem is one of contrast; i.e., it's like trying to find a firefly in the glare of a brilliant searchlight. The existence of an exo-zodiacal dust cloud heated by the star creates an additional hazy background against which a planet must be detected.

From the simple direct detection at a number of wavelengths plus the star-planet separation, one can estimate the radius, albedo, and temperature of a planet. But the greatest diagnostic capabilities come from molecular tracers that probe physical conditions in a planet's atmosphere. The infrared portion of the spectrum between 7 and 17 μm offers strong transitions of chemically important species (Angel et al. 1986). Table 4-1 and Figures 4-3 and 4-4 show that Carbon Dioxide (CO_2), Ozone (O_3), and Water Vapor (H_2O) can have deep and broad absorption features in the planetary spectra. Methane, CH_4, at 7 μm is much weaker in the terrestrial spectrum.

Table 4-1. Key Tracers in Earth's Atmosphere

Atmospheric Constituent	Terrestrial Abundance (ppm)	Wavelength (μm)	Equiv. Width (μm)
Water	4700 (seasonal)	5–8	2.5
Carbon Dioxide	330	17	1.7
Ozone	0.23	9.8	0.17
Methane	1.6	7.6	0.016

While even the basic details of the chemistry of planetary atmospheres are matters of great debate, there are arguments that suggest that the presence of O_3 is a strong indicator for the presence of O_2 and that primitive life is the most plausible source of O_2 (Owen 1980). One atmospheric model (Figure 4-5) shows that the abundance of O_3 changes by a factor of 2–3, while the O_2 abundance changes by a factor of 100, so that the detection of O_3 can indicate the presence of even small amounts of O_2. The logarithmic change in ozone abundance implies that one can use O_3 to trace O_2 over more than 2 billion years of the Earth's history (Figure 4-6; Kasting et al. 1985; Léger et al. 1993). Methane, CH_4, when seen in conjunction with O_2 is thought be an even stronger indicator of the presence of life. Unfortunately, CH_4 absorption in the terrestrial atmosphere is much weaker than the signatures of the other species mentioned above (Table 4-1; Figure 4-3).
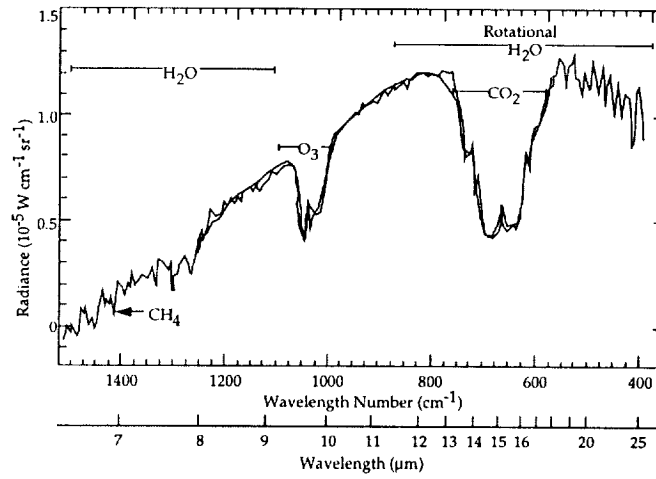
Figure 4-3. The infrared spectrum of the Earth as observed from an orbiting Nimbus satellite shows a variety of spectral features.
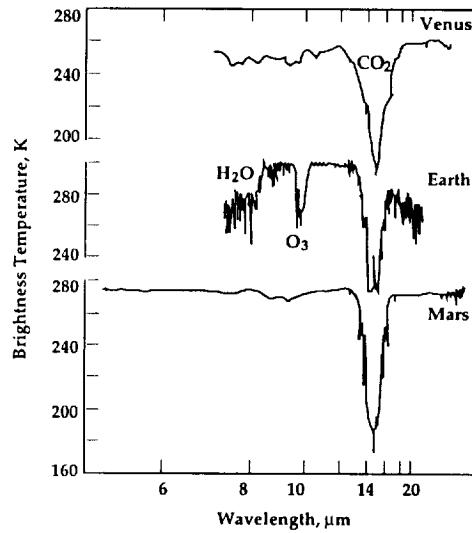
Figure 4-4. The spectrum of the Earth is contrasted with that of Venus and Mars.
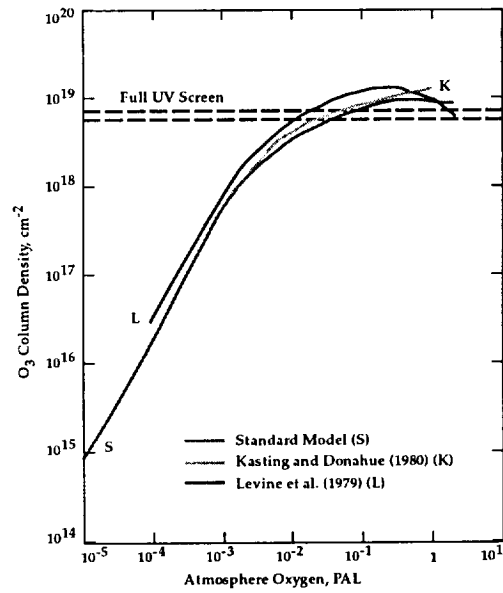
Figure 4-5. A model showing the relative abundances of oxygen and ozone demonstrates that O_3 is a good tracer of O_2 for even small amounts of O_2.
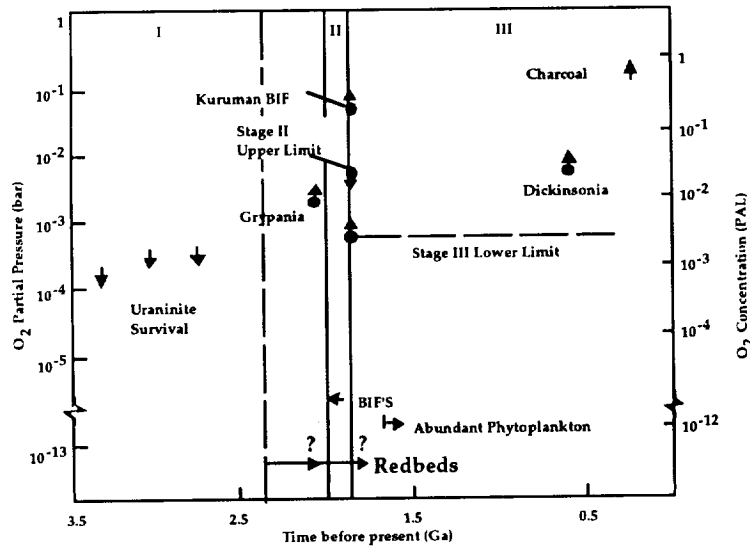
Figure 4-6. The evolution of O_2 in the Earth's primitive atmosphere can be attributed to the effects of photosynthesis.

MERCURY   VENUS   EARTH   MARS

2.4 M$_{JUP}$

0.6 M$_{JUP}$

0.8 M$_{JUP}$

6.6 M$_{JUP}$

10 M$_{JUP}$

0   1   2

ORBITAL SEMIMAJOR AXIS (AU)
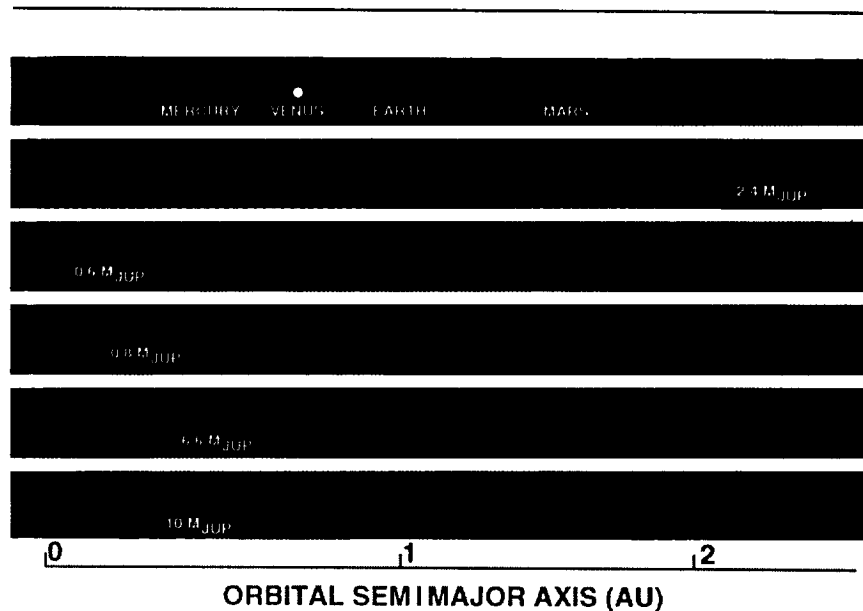
Figure 4-7. Distribution of planets found around nearby stars through radial velocity measurements (courtesy G. Marcy).

Figures 4-5 and 4-6 represent, of course, only one of many possible models. Atmospheric chemistry is complex and mechanisms unrelated to life might create O_3. One example is photolysis of H_2O and the subsequent escape of hydrogen to leave an excess of oxygen that creates ozone. But the mere detection of water, carbon dioxide and ozone in the atmosphere of a planet in the habitable zone would be an exciting discovery that would motivate further searches for rarer, but more certain tracers of life.

4.4.2 RADIAL VELOCITY TECHNIQUES

A technique already successfully proven for finding planets around nearby stars involves the detection of slight perturbations in the line-of-sight velocity of the parent star due to the effect of an unseen companion. Mayor and Queloz (1995) and Marcy and Butler (1996) recently discovered objects of planetary mass around nearby stars using radial velocity techniques (Figure 4-7). It is not yet known whether these objects are planets, i.e., they formed out of their parent star's protostellar disk, or some low mass brown dwarfs formed independently and subsequently captured by the larger star. Nevertheless, this success highlights the conclusions of the Road Map teams that planetary searches by indirect techniques are an essential first
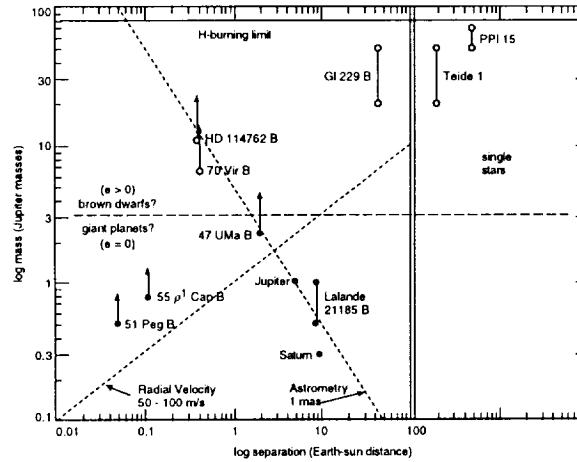
Figure 4-8. The range of planet-masses and star-planet distances which radial velocity and astrometric techniques can probe. Objects in the region above and to the left of the dashed line can be detected by radial velocity techniques with a precision of ~50 m s⁻¹. Objects above and to the right of the dot-dashed line can be detected by astrometric techniques with a precision of ~1 mas. A number of giant planets detected recently using these techniques are indicated. (Boss 1996).

step in the Road Map, for they will indicate definitively whether major planets are common or rare about nearby solar-like stars.

The strength of a radial velocity perturbation is given by

$$Amplitude \sim 30 \frac{M_{planet} \times \sin(i)}{\sqrt{a_{planet} M_*}} m\ s^{-1}$$

where M_{planet} and M_* are the planet and stellar masses, in Jovian and solar units, respectively, and a_{planet} is the star-planet separation in AU. Note that the distance to the star enters only as a limit to observability set by the number of stellar photons detectable in a certain time. Radial velocity measurements favor finding large planets located close to their parent star. Figure 4-8 shows the range of planet-masses and star-planet distances which radial velocity techniques are likely to probe.

Radial velocity searches have been underway for several years at the 5–10 m s⁻¹ precision level, which is barely sufficient to detect Jupiter-size planets around solar-type stars. Three planets of roughly Jupiter-mass have

now been found by this technique (around 51 Peg, 70 Vir, 47 UMa), and more detections are likely to be announced in the next few months. Recently, it has been shown that a precision of 3 m s^{-1}, and perhaps better, is attainable with the use of an iodine absorption cell and very careful modeling of changing point-spread-function and instrumental effects. This would bring detection of Saturn-size planets around a solar-type star within reach.

Ideally, one would like to reach an accuracy substantially better than 3 m s^{-1}, or even 1 m s^{-1}. It would take 0.1 m s^{-1} accuracy to detect an Earth-like planet around a solar-like star. The situation is somewhat more favorable for lower-mass stars. For example, for an Earth-mass planet at an orbital distance around a K5 or M5 main sequence star such that water is in liquid form, the reflex velocity induced in the parent star is 0.17 or 0.63 m s^{-1}, respectively. The orbital period in these two cases would be 115 and 25 days, respectively; so if a detection were made, it would happen quickly. Thus, reaching an accuracy below 1 m s^{-1} could open the possibility of detection of habitable planets by radial velocity techniques.

The limits to planetary detection by the radial velocities are unknown. A measurement accuracy of 1 m s^{-1} or better is allowed by photon flux, given large telescopes, bright stars, and practical observing times. An accuracy of even 0.1 m s^{-1} cannot be ruled out in principle for a few very bright stars. The ultimate limit may be imposed by stellar surface Doppler velocity "noise" from short period atmospheric oscillations, from sunspots rotating into and out of view, and to long period effects tied to magnetic cycles.

4.4.3 ASTROMETRIC TECHNIQUES

An unseen planet causes the position of the star projected onto the sky to shift as the star orbits around the barycenter of the star-planet system. The amplitude of this wobble is given by

$$Amplitude \sim 1000 \frac{M_{planet} / M_{Jupiter}}{M_* / M} \times \frac{a_{planet} / 1AU}{D_* / 1pc} \mu arcsec$$

where M_{planet} and M_* are the planet and stellar masses, in Jovian and solar units, respectively, a_{planet} is the star-planet separation in AU, and D is the distance to the star in pc. The inclination of the orbit is not a factor. Figure 4-9 shows the wobble of the Sun due to the planets in our Solar System as seen from 10 pc.
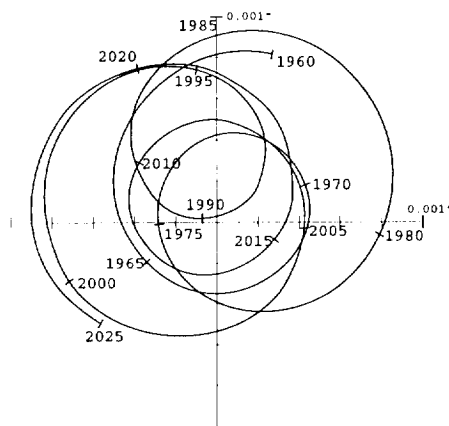
Figure 4-9. The wobble of the Sun's projected position due to influence of all the planets in the Solar System as it would appear from 10 pc.

A *major difference* between this report and the earlier report TOPS report is that ground-based interferometers have now been shown to be capable of detecting planets with masses as small as Uranus. What previously was thought to require a space mission can in great part be accomplished from the ground using differential astrometry (Shao and Colavita 1992). In this technique, the position of a target star is measured relative to the positions of reference stars observed simultaneously with a dual-feed interferometer operating in the near infrared. The ultimate limits of this technique are as yet unknown, but may be as low as 10 µas. The recent detection of a Jupiter-mass planet around the nearby (2.5 pc), M2 V star Lalande 21185 (Gatewood 1996) is an indicator of the potential of astrometric techniques. There is also recent evidence that astrometry of certain classes of radio emitting stars may reveal the presence of planets as well.

The astrometric signature of the Sun–Jupiter system at 10 pc is 500 µas (Figure 4-9), readily detectable by astrometric techniques using single large telescopes or small interferometers. The Sun–Uranus signal of ~100 µas would be detectable by ground-based interferometers consisting of four 2-m telescopes operating over a 100-m baseline. Only the detection of the Sun–Earth system with an astrometric signature of 0.3 µas is beyond detection from the ground. Below ~1 µas there is probably a limit set by star-noise to the precision with which astrometric motions can be measured. While multicolor measurements may reduce the effects of star-spots on the location of the photo-center of the star, the degree to which one can reduce

these effects is at present unknown, and so it is not clear that Earth-like planets can be detected indirectly.

Table 4-2 indicates the number of planets of various mass that would be found around stars within 25 pc for a given astrometric accuracy if these planets are at the same separations from their parent stars as they are in our own Solar System. Figure 4-10 indicates the number of stars that could be searched with various facilities discussed in the Road Map.

4.4.4 PHOTOMETRIC TECHNIQUES

The passage of a planet close to its parent star affects the brightness of the star in two different, but physically well-founded ways. The first is the simple geometrical passage of a planet across the face of a star. The transit of the planet *reduces* the apparent brightness of the star by an amount proportional to the relative areas of the two objects, roughly 10^{-4} for an Earth–Sun system. A second, less intuitive, effect involves a well-observed effect of general relativity, micro-lensing, which can *increase* the apparent brightness of the star for a few hours by a large factor sometimes exceeding 100%.

Both techniques present formidable challenges, but also offer the enticing prospect of detecting Earth-like planets around ordinary stars. In neither case are the stars nearby suitable for further study, but both techniques offer

Table 4-2. Number of Planets vs. Astrometric Accuracy

Accuracy (μas)	Instrument	Number[1] Jupiters	Number Uranus	Number Earths
0.20		3802	3734	303
0.50	20-m SIM[2]	3802	3659	17
1.00	7-m SIM	3802	3607	4
2.0		3795	3455	2
5.0		3723	1825	0
10.	100-m Interferometer	3664	656	0
20.		3612	108	0
50.	Palomar Testbed	3325	8	0
100.	8- to 10-m Telescope	2000	3	0
200.		759	0	0
500.		63	0	0
1000.	1-m Telescope	10	0	0

[1]Out to the 25-pc limit for stars in the Gliese Catalog.
[2]Space Interferometry Mission (Section 8.2).
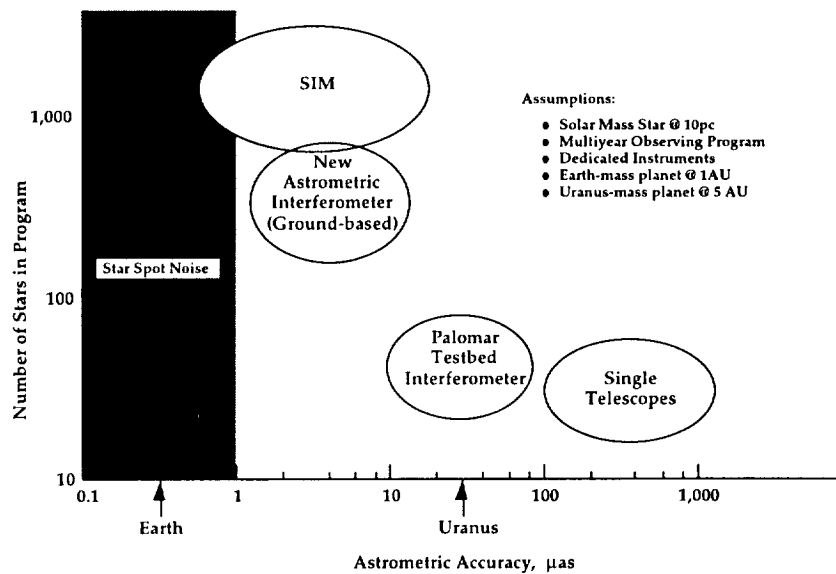
Figure 4-10. The number of stars that can be searched for planets with various masses depends on the astrometric accuracy of the observing system. The power of various facilities mentioned in the Road Map are shown schematically.

fundamental statistical information on the frequency of Earth-like planets impossible from almost any other technique.

Planetary Transits

The effect of a planetary transit is well-understood. When a planet passes in front of its parent star, it blocks out a fraction of the light from the star. Unfortunately, the effect is difficult to measure since it is small (1 part in >10^4 and subject to the star's intrinsic fluctuations), rare (only ~1% of star-planet systems, if analogous to our Solar System, are properly aligned with the line of sight to the Earth), short (lasting only 12 hr for an Earth–Sun analog), and infrequent (occurring only once per year for an Earth–Sun analog). The limiting sensitivity for this technique has been investigated by groups in the US and Europe who suggest that a ~1-m space telescope continuously monitoring ~5,000 stars for a period of 4–6 years might detect 10's of Earths. Whether photon statistics, instrumental effects, or noise due to star-spots sets the ultimate noise floor for this technique, and whether the noise floor is consistent with the detection of a significant number of Earth-like planets is presently being actively debated.

Microlensing

Microlensing offers an new technique for determining the frequency of planets, down to Earth masses, around ordinary distant stars. Existing microlensing surveys are now finding dozens of star-star microlensing events per year, and could discover a planet around an ordinary low-mass star in the near future. An expanded survey could find hundreds of planets, of all masses, around hundreds of distant stars in a decade. Microlensing can determine the frequency of planets, the star-planet mass ratios, and the star-planet separations using standard photometry.

Microlensing events occur when two distant stars align by chance: a "source" star at ~8 kpc and a "lens" star at 1–7 kpc (Figure 4-11). The lens star focuses the light from the source producing a typical magnification of 2–5 times which varies smoothly and predictably as the lens moves across the line connecting the source and the Earth (Figure 4-12).

Planets orbiting the lens star can produce additional magnifications sometimes exceeding 100% which last 1.5–50 hours, depending on the planet's mass and other parameters (Gould and Loeb, 1992; Mao and Paczyński, 1991). In the absence of a planet, and ignoring parallax from the Earth's motion, the light curve for a single source star is smooth and symmetric, with a simple analytic shape. Planets are most likely to be
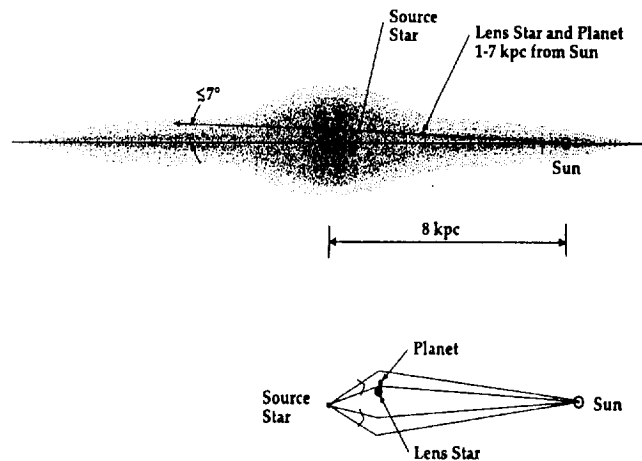
Figure 4-11. Geometry of microlensing of a star in the Galactic Bulge by a star with a planet at intermediate distance.
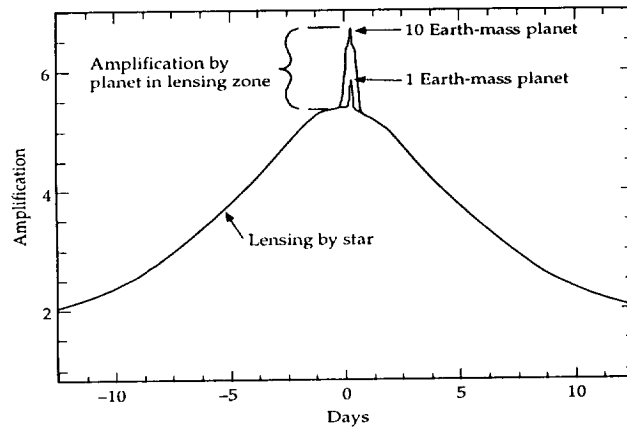
Figure 4-12. The expected signature of a star-planet combination serving as a lens for the light of a more distant star.

detected when they are in the "lensing zone" which extends from about 3–6 AU around a $M_\odot$ lens star. The size of the lensing zone scales as $M_{lens\ star}^{0.5}$, and planets can also be detected outside the zone, but less often. The probability of detecting a planet scales as $M_{planet}^{0.5}$ implying that a wide variety of masses might be detected, including those with the mass of the Earth. Averaged over inclinations and orbits, the probability of detecting a Jupiter-mass planet in the lensing zone is 18% per lensing event, and an Earth-mass planet 1–3%, depending on the size of the source star (see §7.3).

The probability of a lensing event is highest in the direction toward the center of our Galaxy where there are the most stars. Toward the Galactic Bulge, the probability that any individual star is lensed at an arbitrary time has recently been measured to be $\sim 2 \times 10^{-6}$ (Alcock et al. 1996; Bennett et al. 1995). If we observe N_* source stars for 200 days, (when the Sun is far from the bulge in the sky), we will detect $10^{-5}N_*$ lensing events each lasting about 40 days. Over 100 events (C. Stubbs, private communication 1996) have now been found by two international collaborations: MACHO (Alcock et al. 1995) and OGLE (Udalski et al. 1994).

4.4.5 DIRECT DETECTION OF REFLECTED LIGHT

As discussed in section 4.4.1, direct detection of thermal radiation from space will be a very powerful technique, with the capability to image Earth-like planets and determine their atmospheric composition through spectroscopy. An important precursor to such observations will be the

direct imaging of larger planets in light reflected at visible and near infrared wavelengths. The planet/star contrast is weak compared to that in infrared thermal emission. Nevertheless, such observations should be possible, by the addition of special correcting optics to large ground-based telescopes or to the Hubble Space Telescope. Direct detection offers the opportunity not only to detect and confirm the existence of extra-solar planets early on, but also the take the first step toward their characterization.

By their very nature, the techniques of direct detection must isolate the planetary photons from the background associated with the parent star. Once direct detections are made, the same observing systems can then be used in a concentrated campaign to begin spectral characterization of the planets. Generally, for integration times 10 to 100 times longer than the initial detection times, atmospheric constituents like methane and water could be detected, as in the thermal emission spectrum of GL 229B and reflected light spectrum of Jupiter (Figure 3-4). Direct detection offers still another unique characteristic, a picture of the planetary system, and over time, a movie of it. Such images will make an important step in advancing the overall program, both by resolving multiple components which are confused in astrometric detection, and through their public appeal value.

Given a contrast ratio of about a billion to one and a very close angular separation, the key requirement for direct detection of starlight reflected by planets is a telescope system corrected to yield a near perfect optical wavefront. Wavefront distortions cause a halo of scattered light about the star, which takes the form of faint but sharp speckles, a host of spurious planets. But it is possible to correct the images of telescopes both below and above the atmosphere. Ground-based telescopes suffer from atmospheric wavefront distortion that is continually changing. Most of this distortion could be removed with a fast acting adaptive optics system, in which the aberration of the starlight is measured and corrected in real time. The residual aberration leaves speckles that are still brighter than a planet, but which continually change, while the planet remains constant. Angel (1994) has shown that with "super" adaptive optics an integration of several hours with a corrected 6.5-m telescope should be sufficient to average out the residual speckles and bring out a Jupiter-like planet, as shown in the accompanying computer simulation by Stahl and Sandler (1995; Figure 4-13). Images formed by the 2.4-m Hubble telescope also suffer from a speckle halo from irregularities in the polished mirror surface. Malbet, Yu and Shao (1995) have described a wavefront sensor and deformable mirror system that could be added in a new instrument package to improve the near static
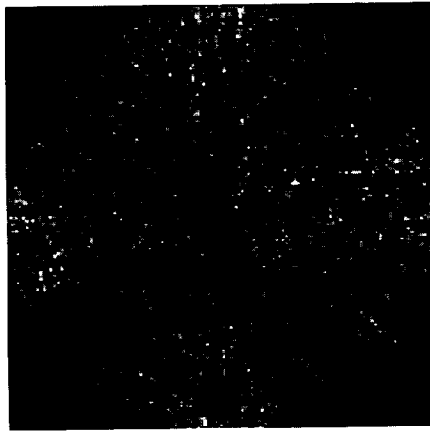
Figure 4-13. A simulated image from a super AO system on a 6.5-m telescope shows a Jupiter-like planet around a star 8 pc away. The planet is at the "2 o'clock position," 0.6 arcsec from the occulted star.

aberrations and allow planet detection. Another platform that could be largely free of optical and atmospheric aberrations be a balloon telescope with new optics of very high precision. In this case diffraction from the small aperture would place a burden on extremely precise coronographic techniques.

CHAPTER 5

THE SPACE INFRARED INTERFEROMETER

5.1 INSTRUMENT PERFORMANCE

As described in previous sections, the fundamental goal of the ExNPS program is the detection and characterization of terrestrial planets in the habitable zone around the nearest ~1,000 stars, or roughly to a minimum distance of ~13 pc. This challenge immediately sets constraints on the required sensitivity and spatial resolution of an appropriate instrument. The desire to detect atmospheric tracers and to minimize the star-planet brightness contrast argues for operation in the thermal infrared where there are strong spectral features, for a modest spectroscopic capability, and exceptional sensitivity.

5.1.1 SPATIAL RESOLUTION

The first constraint on spatial resolution is that one must be able to isolate the planet from the parent star at the limiting distance of the survey, 13 pc. This size scale depends on the luminosity of the star and ranges from 2 AU (0.15 arcsec) for a habitable zone around an F2 star, 1 AU (0.077 arcsec) around a G2 star, and 0.5 AU (0.038 arcsec) around a K2 star. The second constraint on spatial resolution comes from the brightness of the exo-zodiacal cloud around the star. The 10-μm emission from an exo-zodiacal cloud like our own comes from an area of ~12 $(AU)^2$ and has an integrated brightness 300 times brighter than the light from an Earth-twin. To reduce the flux in a pixel to equal that of an Earth, requires a resolution of roughly

0.1 AU, or 0.01 arcsec at 13 pc. If the dust emission is smooth, less resolution might suffice. These constraints imply a spatial resolution of at least a few hundredths of an arcsec.

In addition to providing adequate spatial resolution, the observing system must suppress the light from the parent star to one part in a million, avoid systematic errors due to zodiacal cloud asymmetries, and be able to distinguish multiple planets orbiting a star.

5.1.2 AREAL COVERAGE

The system must be able to search the Habitable Zone around a star. This star-planet separation is roughly 3 AU for a planet orbiting an F0 star and corresponds to a minimum field of view of 1 arcsec for an F0 star at 3 pc.

5.1.3 SPECTRAL REGION AND RESOLUTION

The requirement for spectroscopy of key molecular tracers, coupled with the desire for good contrast relative to the star, suggest a wavelength band from 7 to 17 µm, which includes lines of CO_2, O_3, and H_2O (Table 4-1). A spectral resolution of $\lambda/\Delta\lambda$ ~20 suffices to resolve these broad features. Detecting the CH_4 line at 7 µm would require a factor of 10 greater resolution.

The wavelength region and spatial resolution together define the overall size of the instrument, roughly $\lambda/(0.038$ arcsec), to resolve the habitable zone around a K2 star, or 40–90 m for $\lambda=7$–17 µm. *The scale of this instrument is clearly too large for a single filled aperture and implies that a interferometer is required for this application.*

5.1.4 SENSITIVITY

The basic requirements for the sensitivity of this instrument are to detect a planet in a few hours and to perform low resolution spectroscopy to the 5-σ level in less than a thousand hours on the weakest lines. While the desired signals are not ridiculously small, there is background noise from various sources that must be mitigated against (Table 5-1).

Table 5-1. Signal and Background Levels

Source of Signal @ 10μm	Signal Strength photons m^{-2} sec^{-1} in octave bandwidth
Earth Twin at 13 pc	2.25
Exo-Zodiacal emission	600
Sun Twin	8,000,000
Telescope background	<100 (T=35 K)
Solar System zodiacal emission	60,000 (1AU)

The background levels from a ground-based telescope would be impossibly high for this experiment, necessitating a space mission using cryogenic telescopes (T<35 K) for low background operation. However, even the local zodiacal background at a distance of 1 AU from the Sun is bright for this experiment. One must either use very large apertures (~4–6 m), or operate at larger distances from the Sun, where the zodiacal emission is reduced due to lower temperatures and lower dust density (Bracewell and McPhie 1979). Figure 5-1 shows the variation of zodiacal emission with wavelength and with distance from the Sun based on models derived from Infrared Astronomical Satellite (IRAS) and Cosmic Background Explorer (COBE) data (Good 1988; Reach et al. 1995). Operation at 5 AU, the distance of Jupiter, results in a 200×reduction in the brightness of the 10 μm sky, which for background limited observations corresponds to a 200$^{1/4}$ = 3.8-fold
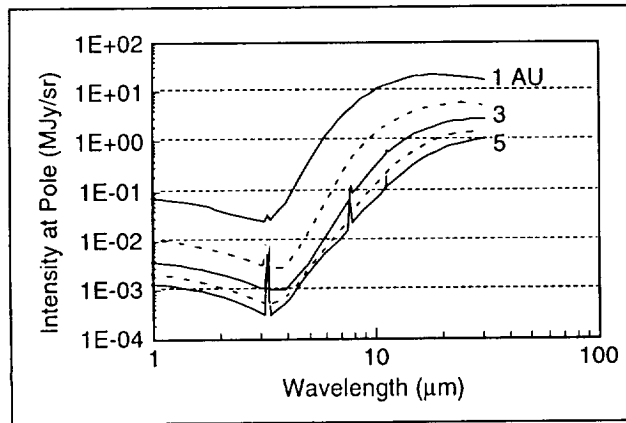
Figure 5-1. Variation of the zodiacal brightness in our Solar System with distance from the Sun. Emission from Galactic dust sets a lower limit to the sky brightness at some wavelengths.

reduction in the telescope aperture needed to attain a given sensitivity level in a given time. Faint emission from dust in the Galaxy sets a lower limit to the sky brightness, particularly in certain spectral bands.

It should be noted that the use of larger telescopes operating around 1 AU does not offer the same capability as a system operating at 5 AU, since the field-of-view of an interferometer is limited to the diffraction-limited beam of one of its component telescopes, $r \sim 0.7\lambda/Diam = 0.15\ \lambda(\mu m)/D\ (m)$ arcsec at half power. Thus, an interferometer consisting of 6-m telescopes would be able to search only $r \sim 0.25$ arcsec (1 AU at 4 pc) at 10 μm, while an interferometer using 1.5-m telescopes would be able to search ~1 arcsec (4 AU at 4 pc).

The instrument can be limited by irreducible astrophysical limits if the three controllable sources of photon noise (leakage from the star, local zodiacal emission, and telescope background) all lie below the level of the exo-zodiacal emission around the target star. In the case of a system operating at 5 AU, about 7 m² of collecting area, corresponding to four 1.5-m telescopes, suffices to measure an Earth-twin at 13 pc. Detector performance about 10 times better than current technology will be required to achieve this low level of background-limited performance.

5.2 INSTRUMENT CONCEPT

The idea of using an interferometer to null out the stellar signal in the search for a weak planetary signal originated with Bracewell (1978), who demonstrated that an interferometer used with a π-phase delay between the two arms of the interferometer would cause the Airy pattern for a source seen on-axis to vanish, whereas the signal for a planet, seen off-axis, would be transmitted. Conceptually, one can imagine an interferometer of baseline B imposing a fringe pattern of spacing λ/B onto the Airy pattern of width λ/D of a component telescope with diameter D. By rotating the interferometer around the line of sight to the star, one rotates the fringe pattern on the sky; the star remains nulled while a planet moves in and out of the fringe pattern (Figure 5-2). Both Angel (1990) and Shao (1990) suggested the use of a Bracewell interferometer for the detection of Earth-like planets.

There are two problems with the classical Bracewell interferometer. First, the null is neither deep nor broad enough for this application. The finite size of the stellar disk results in incomplete suppression of star light ($\sim 10^{-3}$).
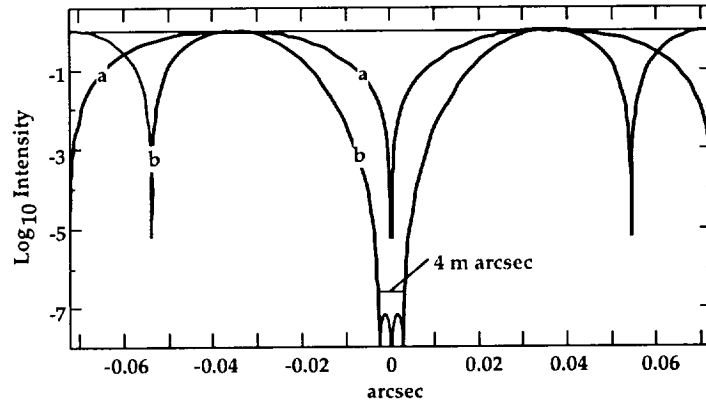
Figure 5-2. Intensity pattern from a Bracewell interferometer (curve a) suppresses the star light and transmits the planet signal. The breadth and depth of the null for the four-telescope OASES system (curve b) provides more than 10^6 suppression.
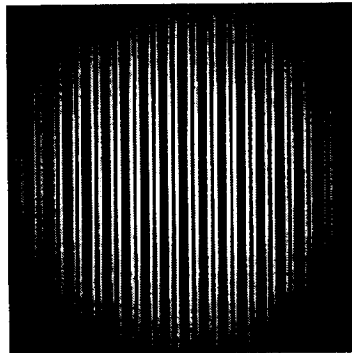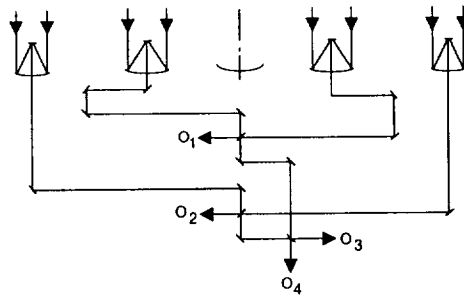
Figure 5-3. A linear nulling interferometer brings light from the four telescopes to a central beam combiner to null the light from a central star.

Second, as the interferometer rotates, the exo-zodiacal emission in the beam has the same 2θ modulation as the planet. Angel (1990) suggested a modified Bracewell interferometer with four telescopes. Léger et al. (1996) suggested that much smaller mirrors could be used in an interferometer operated far from the Sun because of reduced zodiacal emission. Finally, Angel and Woolf (1996) developed a scheme for the OASES mission concept (Figure 5-3) which gives a deep, broad null that results in suppression of starlight by a factor of 10^6 and a 2θ modulation of the exo-zodiacal cloud, which can be distinguished from the 4θ signals due to a planet.

Extracting information from the interferometer data is conceptually straightforward (Figure 5-4). Data are recorded in 10 to 20 wavelength bands as the interferometer rotates every 1 to 2 hours around the line of sight to the star. Planets at different radii produce unique signatures as they move in and out of the rotating fringe pattern. Since the fringe pattern is different at each wavelength, the instrument provides good uv-plane coverage for broad-band sources. This data set can be inverted to give a sequence of images showing planet motion, i.e., an orrery, of the planetary system. Figure 5-4 shows the simulated raw data; Figure 5-5 shows the derived image of an illustrative planetary system. The data represent a 10-hr integration with an interferometer consisting of four 1.5-m telescopes on a 75-m baseline. The instrument efficiency has been assumed to be 20%.
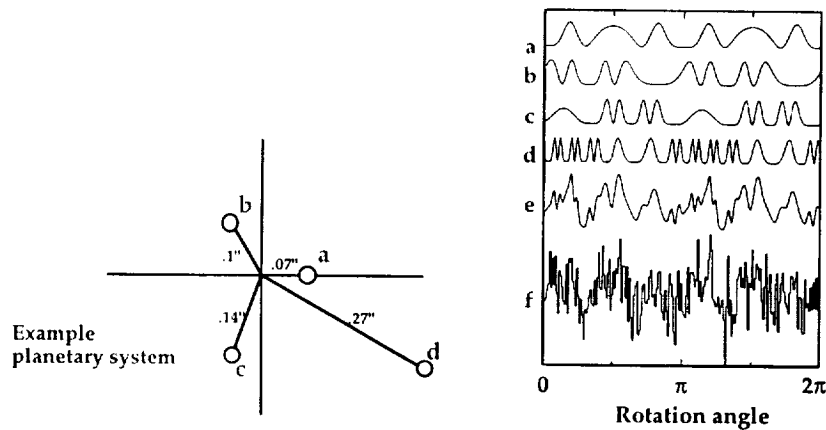
Figure 5-4. An illustrative planetary system laid out as shown at left results in the signals shown at right as the interferometer rotates around the line of sight to the star. The planets labelled 'a–d' produce the corresponding signals on the right. The sum of these signals is denoted 'e'. The interferometer measures the sum of 'a–d,' plus noise, labelled 'f'.
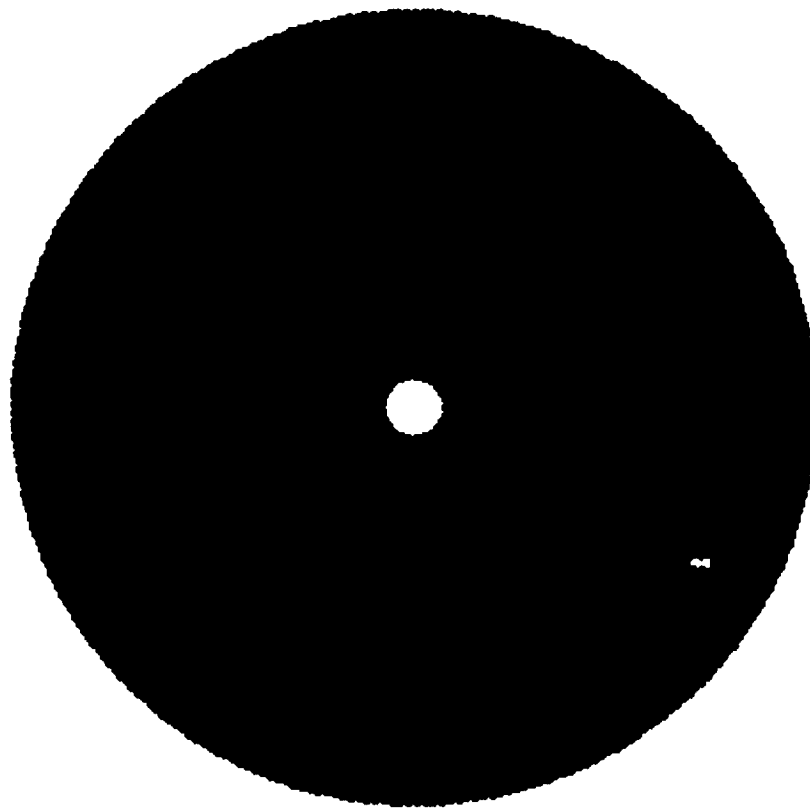
Figure 5-5. An image of the planetary system can be reconstructed from the data shown in Fig. 5-4 (Angel and Woolf, 1996).

The image doubling resulting from the symmetry of the instrument has been removed by offsetting the star relative to the optical axis. The inner radius of the image corresponds to 0.06 arcsec, implying that the habitable zone around a G2 star would be resolvable out to 15 pc and that of a K2 star out to 7.5 pc. The spectroscopic performance of the system is such that the broad CO_2 line could be detected to the 5-σ level in a week of observing, while the weaker O_3 and H_2O lines would require 6 weeks of integration (Figure 5-6).
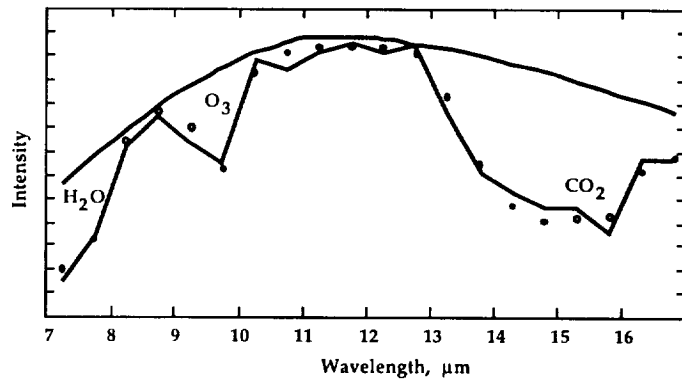
Figure 5-6. The spectrum of an Earth-twin after 6 weeks of integration.

5.2.1 ILLUSTRATIVE OBSERVING PROGRAM

After 1 year of observation, one would be able to perform a broadband survey of approximately 50% of the sky and study 100 to 200 objects in the search for planetary candidates. In the subsequent 3 years, one would make follow-up spectroscopic observations of promising candidates. For example, one could look for CO_2 toward 50 stars for one week each, and for H_2O and O_3 toward 10 to 15 stars for 6 weeks each.

5.3 ILLUSTRATIVE ExNPS DESIGN AND ALTERNATIVES

The baseline space IR instrument consists of four 1.5-m telescopes operating in a linear array with a 75-m baseline (Figure 5-7). From its vantage point at around 5 AU to take advantage of the dark sky, this system would be able to detect and characterize Earth-like systems out to 13 pc from the Sun. However, this configuration is not unique. The Darwin concept (Léger et al. 1995) proposed to the European Space Agency (ESA) for a similar planet-finding purpose uses a circular array of five 1-m telescopes on a 50-m-diameter circle. This arrangement produces a sharp distinction between the exo-zodiacal cloud and the planet signals. A six-element system proposed by JPL is arranged as three two-element arrays and allows for good suppression of star light and good rejection of smooth exo-zodiacal emission. Each configuration has its own strengths, which must be studied carefully over the next few years.
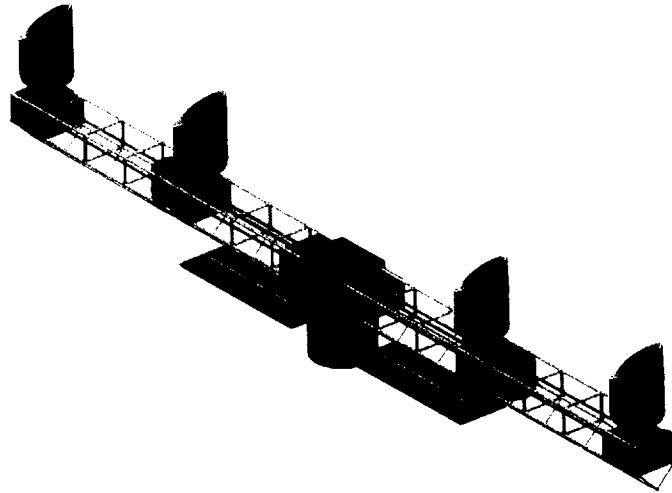
Figure 5-7. The nominal space IR interferometer consists of four 1.5-m telescopes in a linear 75-m baseline array.

5.4 KEY INTERFEROMETRIC REQUIREMENTS

The nulling performance of one part in 10^6 will be difficult, but not impossible to achieve. First, the interfering wavefronts must match in phase to $\lambda/6000$, or roughly 1.5 nm, and the amplitudes in the two arms of the interferometer must match to one part in 10^3. In addition, the null must be achromatic. These requirements can be achieved by using a fully reflecting phase shifter and single-mode spatial filters (optical fiber or waveguide) to clean up the wavefront to the required accuracy. Other requirements, such as precision pointing and path-length control, are possible because of the copious number of short-wavelength photons from the parent star. The λ <5 μm radiation will be used to close the telescope pointing and interferometer servo systems with kHz bandwidths.

CHAPTER 6
TECHNOLOGY CHALLENGES FOR A SPACE INFRARED INTERFEROMETER

The space IR interferometer poses technological challenges in areas from precision structures to infrared detectors. In addition to requiring excellent performance from a lightweight spacecraft operating at 5 AU, the space IR interferometer will demand advances in the state of the art in many areas of optical and mechanical engineering. It should be pointed out that no new inventions are required to carry out this experiment. A steady progression from laboratory innovation, to field-testing, and to space qualification can make all the necessary components available for a mission slated for the middle of the next decade. This section briefly highlights some of the technological "tall poles" and suggests a plan for achieving the appropriate level of technological readiness. Figure 6-1 shows the different technologies that will be important for the space IR interferometer.

The ExNPS program will benefit from advances in spacecraft design already underway in industry and in technologies being developed for the Space Infrared Telescope Facility (SIRTF), the Space Interferometry Mission (SIM), the New Millennium program, and the NSTAR solar-electric propulsion program. Dedicated flight demonstrations using simple experiments may be needed to validate key technologies and simplify integration and test of more complex instruments.

ExNPS Interferometer

Cryogenic
Optics

Beam Control
and Nulling

Advanced
Propulsion

Vibration
Isolation and
Structural
Quieting

Metering
Structure

Science Focal Plane
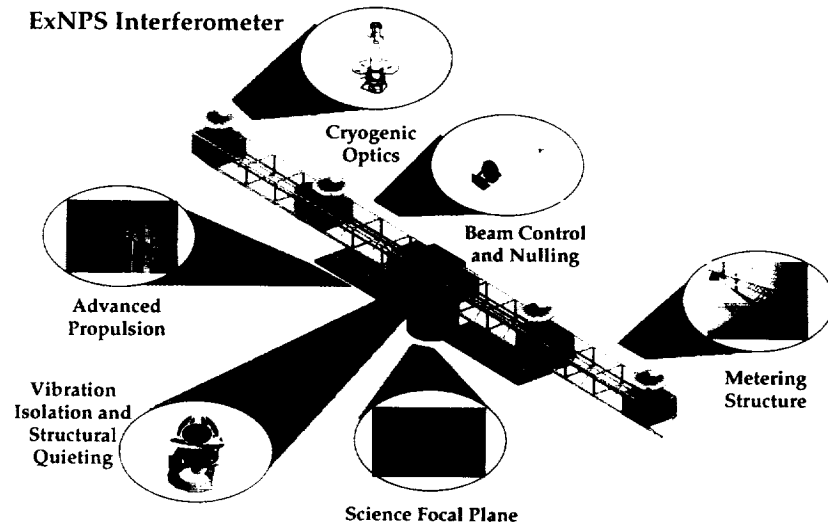
Figure 6-1. The ExNPS space interferometer will push the state of the art in a broad range of space technologies.

6.1   METERING STRUCTURE

The nanometer precision needed for a 75-m interferometer appears initially daunting. Fortunately, a series of nested structures tied together with laser metrology can span the range from meters to nanometers. Progressively smaller and faster optical delay lines and steering mirrors, all operating cyrogenically and introducing no background, correct the residual errors in the larger, coarser systems, with the final delay line operating over only a few tens of centimeters and correcting nanometer errors at 0.1 to 1 kHz (Figure 6-2).

Although the 75-m assembly needs to be no more precise than a few centimeters, exactly how this structure is to be achieved remains a matter for further study and development. A number of options exist:

- The most conservative approach would be a deployed system, such as the 30-m space station structures (FASTMast), that has already flown in space. Two FASTMasts deployed back-to-back come close to meeting the nominal requirements for the ExNPS interferometer.

- Inflatable structures offer advantages of reduced weight and packaging flexibility. However, the structure would have to be rigidified for long-
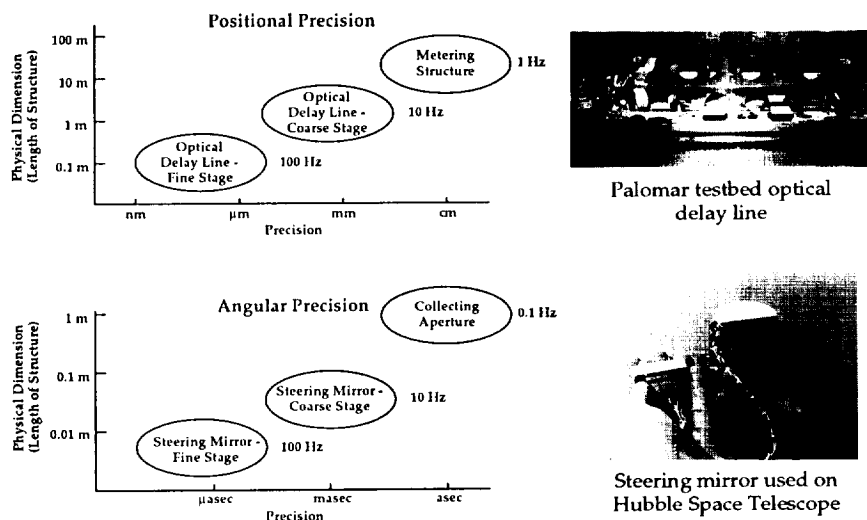
Figure 6-2. A series of nested servo systems delivers the necessary precision for the optical system.

term, cryogenic operation. A significant amount of technology development is needed to bring this technology to the appropriate level.

• Assembly of the interferometer by astronauts at the Space Station has a number of attractive features, including a reduced risk of deployment failures and the opportunity for limited on-orbit testing before launching the system to its final orbit. Disadvantages include the costs associated with man-rating the space IR instrument, operating in the hostile thermal environment of low Earth orbit (LEO), and the need for efficient propulsion of the deployed interferometer from LEO.

• Finally, there exists the option of having no metering structure at all. For some baseline greater than 75 m, it will become cheaper to operate each telescope as an independent spacecraft flying in precise formation to produce the desired array configuration. This approach has the obvious advantage of operation of the interferometer over a wide variety of baselines to obtain good uv-plane coverage for general astrophysical imaging. The disadvantage of this approach is that one must provide five independent spacecraft (four telescopes plus a central beam combining station). Detailed studies will be required to establish the cross-over baseline length at which a multi-spacecraft design becomes more cost effective than a deployed or inflatable approach.
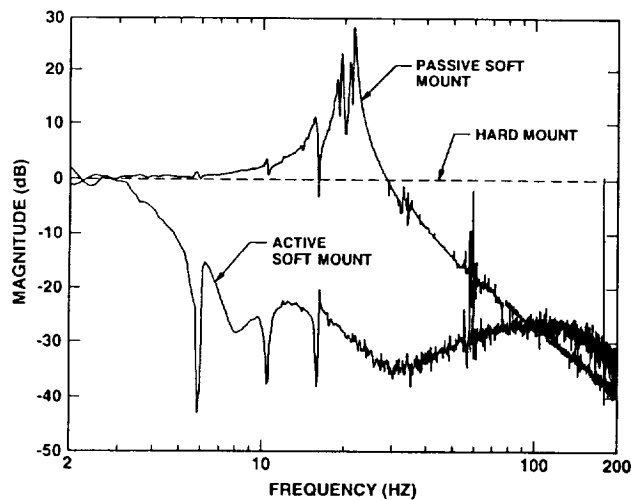
Figure 6-3. Vibration isolation systems for the optical system will make the interferometer immune to disturbances from the spacecraft.

6.2 VIBRATION ISOLATION

The interferometer and telescope assemblies must be carefully isolated from the reaction wheel vibrations, solar array torques, and other spacecraft disturbances. The key technologies of active vibration isolation and structural damping have been demonstrated at room temperature with 40 to 50dB of damping possible over 5 to 1000 Hz (Figure 6-3). This level of isolation coupled with the active systems within the interferometer will be adequate for the ExNPS application.

6.3 BEAM CONTROL AND NULLING

The key to suppressing the light of the parent star is the quality of the interferometric null. Breadboard laboratory systems have demonstrated a 10^{-3} null, and a concerted laboratory effort could demonstrate a 10^{-6} null in a few years. Technology development is required to identify materials for the single-mode 10-μm optical fibers or waveguides needed to clean up the wavefront to achieve the desired 1.5-nm wavefront error.

The laser metrology needed for the ExNPS application is well within the state of the art. Systems capable of long-term stability less than 1 picometer

(pm) have been demonstrated in the laboratory; the ExNPS application requires only 10 to 30 pm.

6.4 CRYOGENIC OPTICS

The 1.5-m telescopes envisioned for the space IR interferometer must operate at 35 K with diffraction-limited performance at 2 μm. Although these requirements are a significant advance in the state of the art defined by the 0.85-m SIRTF mirror, which is diffraction limited at 6 μm (Figure 6-4), the ExNPS application seems a reasonable extension of the current technology. Beryllium or silicon carbide are seen as attractive materials.

6.5 SCIENCE FOCAL PLANE

The greatest demands on the science instrument are in detector performance and cooling. Achieving background limited sensitivity in the spectroscopic mode at 7 to 17 μm will require dark currents less than $2e^-s^{-1}$ and read noises less than $8e^-$. While this level of performance has been achieved with optical CCDs and with short-wavelength infrared arrays (HgCdTe and InSb), long-wavelength systems such as Si:xx Impurity Band Conduction (IBC) detectors are about a factor of 10 worse than required for spectroscopic performance. One advantage of the space IR interferometer is that large-format arrays are not required. All the light from the interferometer is detected in just a few pixels, i.e., a few times the number
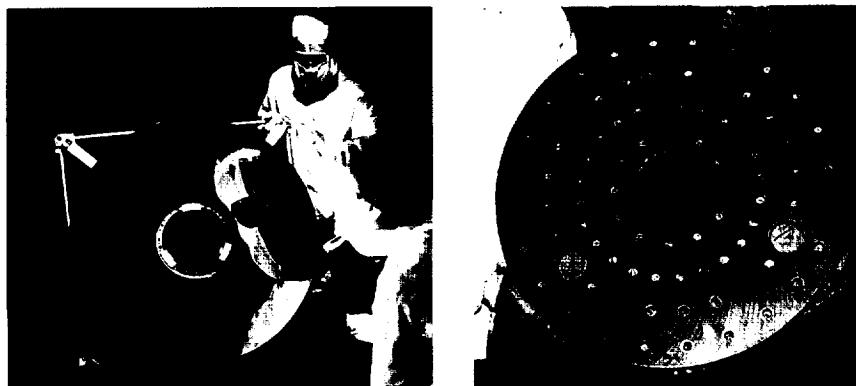
Figure 6-4. A full-scale 0.85-m Beryllium mirror has been fabricated and tested for use on SIRTF.

of spectral elements. Thus, a lot of effort can be expended to make a "few good pixels." It is important not to minimize the importance of good progress in the area of detector performance. With the decline in defense budgets for low-background space applications, NASA will have to play a much larger role in defining industry's efforts in this area. Extrapolations of existing IBC devices or wholly new devices such as Solid State Photomultipliers or Quantum Well Infrared Photodetectors (QWIPS) may be required to meet the ExNPS requirements.

There is a critical interplay between detector performance, operating temperature, and focal-plane cooling requirements. Vibrationless, low-power sorption coolers have been flight-qualified for temperatures of 10 K and above. Although mechanical coolers have also been operated down to 4 K, stored cryogen provides the most assured way of achieving temperatures down to 2 K. The requirement for a long mission lifetime, 5 to 10 yr, makes active systems attractive if their operating temperatures can be lowered, or if the operating temperatures of the detectors can be raised without affecting performance. *The interplay between detectors and cooling is a critical aspect of the system design where technological advances can have very high rewards in the cost and performance of the ultimate instrument.*

6.6   ADVANCED PROPULSION

The nominal orbit for the space IR interferometer is highly elliptical with a perihelion of 5 AU. This is achieved with a combined Atlas II rocket launch, a series of Venus-Earth gravity assists, and, possibly, solar-electric propulsion (SEP) during the part of the orbit close to the Sun when the spacecraft has excess electrical power (Figure 6-5). A perihelion-raising maneuver could be carried out using Jupiter's gravity, although the energetic-particle environment of Jupiter could pose a hazard to the infrared detectors and other sensitive electronics. Advances in SEP could have an enabling effect on the design of the ExNPS interferometer.

6.7   ADVANCED SPACECRAFT COMPONENTS

New technologies developed over the last 10 years have dramatically reduced the mass, power, and cost of key spacecraft components. For example, the electrical power required for systems (such as communications, computers, instruments, momentum control, data storage, and power
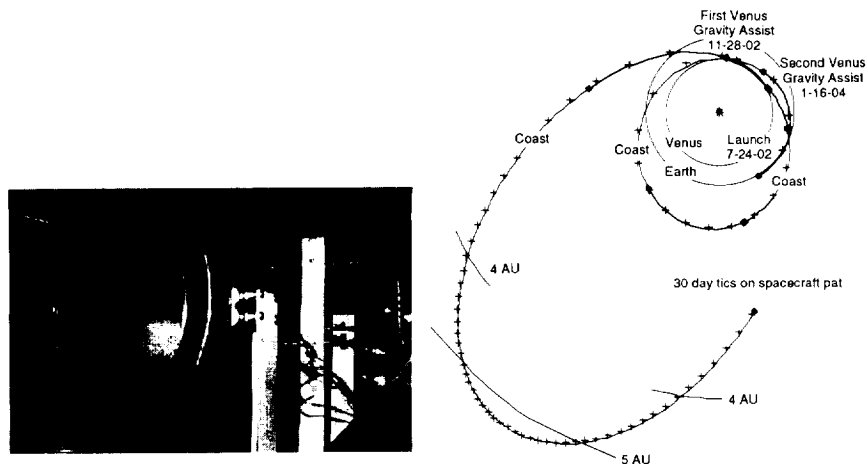
Figure 6-5. A series of Earth-Venus-Venus gravity assists plus low-thrust solar electric power propulsion can bring the space IR interferometer out to 5 AU in 4 years using an Atlas II-A launch vehicle.

management) far more capable than those on Hubble Space Telescope (HST) would require less than 300 W, instead of the nearly 3 kW now being consumed.

ExNPS will take of advantage of continuing advances in technology coming from commercial satellites or NASA's New Millennium program for such components as powerful, lightweight computers; lightweight X-band transponders; high-output, deep-space solar arrays; ultra-lightweight structural materials; advanced lithium batteries; solid-state data recorders; autonomous star trackers; and solid-state gyros.

6.8 QUALIFICATION OF KEY TECHNOLOGIES, SYSTEM INTEGRATION, AND TEST

The space IR interferometer will be a very complex instrument involving one or more spacecraft, one or more major deployments, dozens of cryogenic mechanisms, and many precision optical surfaces with critical alignments. There are many questions about how to integrate and test such systems, and how to reduce the risk of failure to a manageable level. One of the most important aspects of the ExNPS program is its evolutionary nature with an

emphasis on development, testing, and operating instruments (either on the ground or in flight) in incremental steps to build confidence in the underlying concepts, components, software, and integrated systems.

During the ExNPS Integration process there were many discussions about the appropriate type and number of precursor missions needed to build confidence in the ExNPS interferometer. An integrated approach was developed that uses a variety of planned missions, ground-based tests, and small-flight demonstrations to validate key aspects of the ExNPS design.

- The SIRTF mission will demonstrate cryogenic optics, passive cooling (50-K outer shell temperature at 1 AU), and advanced detectors.

- The SIM mission, an optical interferometer operated primarily for astrometry, will space-qualify many ExNPS technologies such as laser metrology, active delay lines, and optical nulling.

- The New Millennium and NSTAR programs will demonstrate key spacecraft components and advanced propulsion concepts.

- Ground-based demonstrations will qualify cryogenic mechanisms, focal-plane assemblies, interferometer software, and some aspects of system integration.

- A space mission to test the deployment and microdynamics of a metering structure in a cryogenic environment could be an important step in demonstrating ExNPS technology.

Finally, a number of members of the Integration Team felt that a scaled-down version of the space IR interferometer itself, perhaps two small cryogenic telescopes (40 cm) on a 10- to 20-m baseline, could be used to detect and map the exo-zodiacal emission around nearby stars. This instrument, operated for just a few months, would be an intermediate technological and scientific step on the way to the 75-m space IR interferometer. Considerably more study will be required to assess the costs and benefits of such precursors.

CHAPTER 7
SUPPORTING GROUND-BASED PROGRAMS

The goals of these ground-based studies include improved understanding of planet and star formation and the level of zodiacal dust emission in other stellar systems, and the detection of massive planets to help develop a target list for the space interferometer. In addition to expanding our scientific understanding of extra-solar planets, these observations are critical to the design and efficient operation of the space interferometer needed for the final goals of detection and characterization of Earth-like planets.

Figures 7-1 and 7-2 summarize the roles of various programs in determining the masses and orbits of planets around the large number of stars needed for the ExNPS program. Table 7-1 illustrates an observing program for large 6- to 10-m telescopes. Table 7-2 outlines a hypothetical and admittedly optimistic timeline of discoveries using ground-based telescopes.
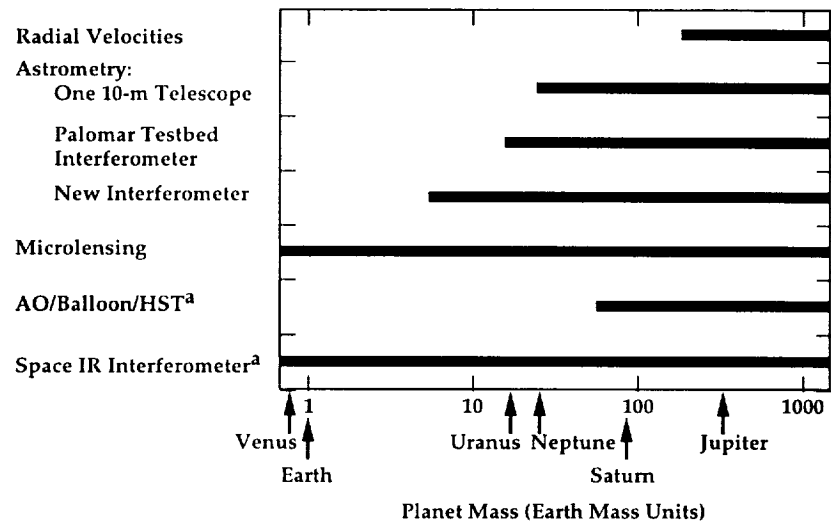
[a] The direct imaging methods are sensitive to planet size, albedo and temperature, rather than mass. The relative merits of these different techniques remain to be quantified.
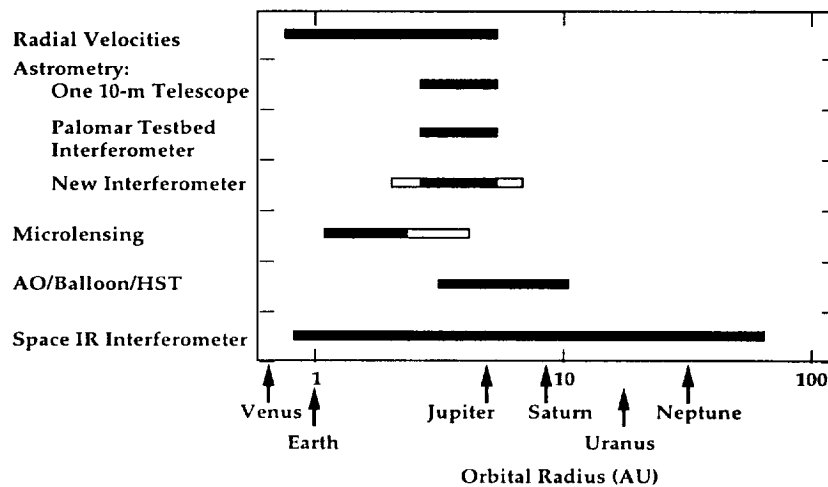
⬚ Reduced Sensitivity

Figure 7-1. Different techniques yield information on the masses and orbital separations of planets around stars.

Radial Velocities ████████████████████████ 1000

Astrometry:
    One 10-m Telescope █ 40
    Palomar Testbed ██ 60
    Interferometer
    New Interferometer ███████████ 500

Microlensing[a] ████████████████████████████████ 3500 →

AO/Balloon/HST ██ 50

Space IR Interferometer[b] ███████ 250

0	100	500	1000
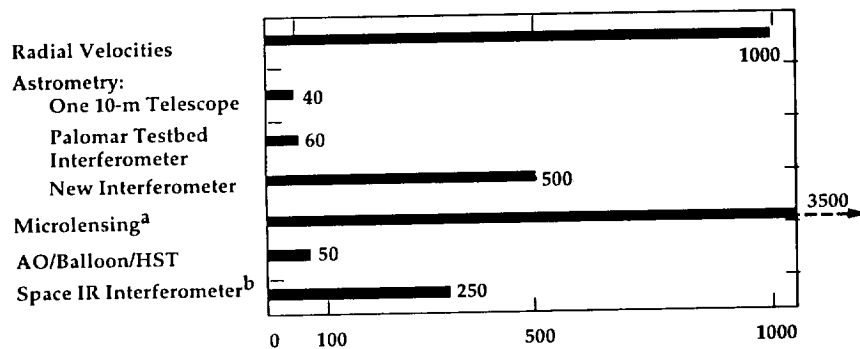
[a] Efficiency depends on planet mass - 1% for Earth mass, 18% for Jupiter mass.
Microlensing alone uses distant stars.

[b] Includes spectroscopy of detected planets.

Figure 7-2. Different techniques can survey different numbers of stars for information on planetary systems.

Table 7-1. Illustrative Large Telescope (6- to 10-m class) Program

Program	Nights/yr	Years
Velocities of 200 stars to detect Jupiters	35	1 to 10
Astrometry of 50 stars to detect Uranus	35	1 to 5
Microlensing stars (images and spectra)	5	1 to 10
Disks around Young Stellar Objects (YSO); hot young planets	5	1 to 10
Direct detection of Jupiters (advanced AO)	15	2 to 5
Direct detection of Jupiters advanced AO on two-element interferometer	2x15	6 to 10
Exo-zodiacal detection with two-element interferometer	2x5	6 to 7
YSO disk absorption	5	7 to 8
Total	75 to 95	

Table 7-2. A Decade of Ground-Based Observations

Year	Possible Milestones
1995[1]	First planets discovered through radial velocities
1996[1]	High-mass planets on short-period orbits, detected by astrometric wobble with single telescope and interferometers
1997	Microlensing detects first Earth-like planets
1998	Microlensing detects 10 more planets with first follow-up
1998	Radial velocities find Uranus-mass planets in a 1-year orbit
1999	Five more planets from radial velocity (year three of data)
1999	Microlensing detects 50 planets
1999	Keck or other interferometer detects exo-zodiacal emission
2000	Direct detection of Jupiter-mass planets on 6- to 10-m telescopes in near-IR
2000	High-mass planets on short-period orbits
2002	Earth-mass planets in habitable zone around M stars detected by improved (<1 m s^{-1}) radial velocities
2003	Large ground-based interferometer finds hundreds of Jupiters around nearby stars in about 3 years
2006	Microlensing search finds 30 Earth-, 50 Neptune-, 80 Saturn- and 100 Jupiter-mass planets
2006	Radial-velocity search complete. 200 Saturn- and Jupiter-mass planets around 1,000 nearby stars

[1]Already achieved!

7.1 RADIAL VELOCITY PLANETARY SEARCHES

Radial-velocity studies have already detected the first objects of planetary mass orbiting nearby stars, finding Jupiter-sized objects through low-cost programs on telescopes of modest aperture (<4 m). An enhanced program of radial-velocity searches would have dramatic rewards in terms of identifying planetary systems around hundreds of stars. A program examining ~1,000 stars will determine unambiguously the frequency of planets of different masses (>Uranus) and separations (<few AU) as a function of stellar spectral type. The sample will consist mainly of F, G, K, and M main-sequence stars. Stars at the low-mass end produce the highest Doppler signal, even if their faintness makes high precision observations very time consuming. Conversely, stars at the high-mass end have high relative brightness, even if the Doppler signal is small. A natural cutoff occurs for stars earlier than F because they have fewer spectral lines, which also tend to be broad due to relatively high rotational velocities. We also

note that most of the stars that will be monitored astrometrically will be nearby F, G, K, and M stars.

The search should last at least 10 years. At current and anticipated levels of accuracy, i.e., 3 m s^{-1} and possibly 1 m s^{-1} for the brighter stars, Jupiter- or Saturn-size planets might be detected in a fraction of an orbital period, but 10 years is a minimum for detection of a large fraction of such planets around solar-like stars.

In principle, the Keck telescope with the HIRES spectrograph is ideal for this purpose because of its large aperture. The Keck, with reasonable time allotted to radial velocity studies, cannot survey the entire sample of 1,000 stars with the minimum number of observations of three per year. However, in 35 nights per year, the Keck could study the faintest 200 stars (mainly late K stars within 15 pc and M stars within 7 pc). Then, a complementary program utilizing existing telescopes in the north and in the south could monitor about 400 of the brighter F, G, and early K main-sequence stars in each hemisphere.

Finally, one or more research groups should work to develop and test new instrumental, observational, or analytical approaches to improve radial velocity accuracy (including dealing with the minimization of stellar-noise effects), with the goal of moving beyond the 1-m s^{-1} level.

7.2 ASTROMETRIC DETECTION OF PLANETS

The astrometry program suggested in Table 7-3 could result in the discovery of high-mass planets on short-period orbits in 3 years with the Palomar Testbed Interferometer or large, single-telescope observations. A large interferometer at a site with good seeing could search for Jupiters around hundreds of nearby stars in about 3 years (1/4 orbit). Finally, a space interferometer could search for Earth-mass planets around 100 stars in 2 to 3 years. It would also determine the limit to astrometry arising from stellar fluctuations. The astrometric detection of a planet around Lalande 21185 using a single telescope (Gatewood 1996) is an exciting first step along this path.

Table 7-3. Summary of Astrometry Program

Single Keck, 40 nights/year, 10 years[1]
Select from the following programs

100 stars mixed types F, G, K, M	for Jupiters
586 mostly M stars	for Jupiters
43 stars (mostly M)	for Saturns
5 M stars	for Uranus to 3.2 AU

Palomar Test-bed Interferometer[2]
(B=100 m, 0.4-m telescopes)

50 to 100 stars (F,G,K)	for Jupiters to 7 AU
50 to 100 stars (F,G,K)	for Saturns to 5 AU
3 stars	for Uranus

Astrometric Interferometer[3]
(four 2-m telescopes B=100 m for 10 years)

500 stars (60% M, 40% FGK)	for Jupiters to 5 AU
250 stars (60% M, 40% FGK)	for Uranus to 5 AU

Space Interferometer[4] *(B=20 m)*

100 stars	for Earth

[1] 107 μarcsec/star; [2] 25 μarcsec/star; [3] 10 μarcsec/star; [4] 0.5 μarcsec/star

7.2.1 GROUND-BASED SINGLE-APERTURE ASTROMETRY

A large-aperture ground-based telescope could survey hundreds of nearby stars for gas-giant planets. This survey could begin within 1 year of the allocation of telescope time and the construction of an astrometric camera. Astrometry at visible wavelengths could measure the motions of target stars around their centers of mass. Stars within 2 arcmin of the target stars form inertial reference frames from which the relative target star motions are detected (Gatewood 1987).

Large telescopes improve the quality of the reference frames in three ways: (1) the atmospheric noise between the target and reference stars decreases as $D^{2/3}$ (Shao & Colavita 1992) where D is the aperture diameter; (2) the number of reference stars with adequate photons increases for a fixed reference-field diameter because of the large collecting area—this is important since the model of the reference field and of the target-star motion has a number of degrees of freedom that require a minimum number of reference stars (e.g., four reference stars for a linear field model and target-star

parallax, proper motion, acceleration, orbital amplitude and phase); and (3) for a fixed photon flux, the reference-field size decreases with a corresponding linear improvement in astrometric accuracy.

7.2.2 Ground-Based Astrometric Interferometer

In addition to providing important scientific results, large ground based interferometers are a test-bed for technology that will be essential to the ultimate goals of direct detection, characterization, and imaging of Earth-mass planets.

Using interferometric techniques, a ground-based search can be conducted for Uranus-mass planets around hundreds of nearby stars. As with single-aperture astrometry, indirect planet detection from the ground using interferometry involves measurement of the perturbations in the position of a target star relative to nearby reference stars. The characteristics of atmospheric turbulence favor narrow-angle measurements made with a large instrument. For a long baseline B (larger than the atmospheric outer scale) and small field θ, astrometric accuracy improves as θ/B (Figure 7-3).
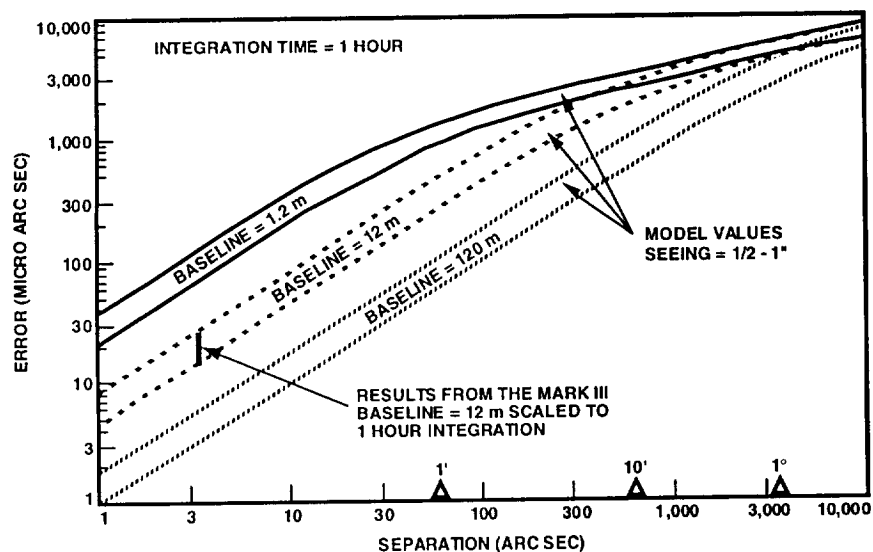
Figure 7-3. The precision of ground-based, differential astrometry improves with longer baselines and better seeing (Shao and Colavita 1992).

Infrared interferometers designed for planet detection can provide the long baselines and narrow fields required for high accuracy (Shao & Colavita 1992). The essence of the tracking technique is to co-phase the interferometer within the infrared isoplanatic patch of the bright, nearby target star. The increase in sensitivity provided by co-phasing allows the detection of faint reference stars located close in angle to the target star. A multiple-star feed routes the light from the target and reference stars to optical beam combiners, which measure the relative fringe positions to perform the astrometric measurements. This technique requires two nearby reference stars to provide high accuracy and uses several more widely spaced reference stars to solve for the interferometric equivalent of plate scale and rotation. Laser metrology is used to control systematic errors.

We recommend development of a new long-baseline interferometer optimized to perform a comprehensive planet-detection program. The nominal parameters of such an instrument would be a 100-m baseline using four 2-m telescopes in a two-dimensional array to provide simultaneous right ascension and declination measurements. A multiple-star feed and detector system would allow simultaneous observation of the target star and two reference stars. Situated at a site with excellent seeing and a small outer turbulence scale, an astrometric accuracy of <10 μas in 1 hour of integration time will be achievable for most target stars. The availability of the Keck site for this task and the potential for later combining the 2-m mirrors with the 10-m apertures for imaging suggests this would be an optimum location for this work.

At the level of precision of this ground-based interferometer, which is 10 times that achieved with a single large telescope, a deep search for Jupiter- and Uranus-mass planets can be conducted. A sample 10-year, 500-star program, using targets of various spectral types selected from the Gliese catalog (Gliese & Jahreiss 1993), would be able to detect Jupiters out to a semi-major axis of 8 AU on all of the stars, and be able to detect Uranus's out to 5 AU on about 250 stars.

7.2.3 PRECURSOR INTERFEROMETERS

As part of the Astronomical Studies for Extra-Solar Planetary Systems (ASEPS) program, NASA funded the ASEPS-0 Testbed Interferometer, currently in operation at Palomar Mountain. The instrument was conceived as a test-bed for the narrow-angle interferometric technique described above. The specific objective is an end-to-end demonstration of the dual-star narrow-angle astrometric technique, demonstrating co-phasing to

increase sensitivity by a factor of 1,000 over non-co-phased measurements, and demonstrating total system astrometric accuracy to <60 μarcsec in one hour—within a factor of two of the expected atmospheric limit at Palomar. As a test-bed, the system incorporates modest 40-cm apertures, so not all potential targets are available. However, a program of 50 to 100 stars, covering spectral types F, G, and K, with a few M, could do a deep survey for Jupiter- and Saturn-mass planets. Jupiters could be detected out to 7 AU, while Saturns could be detected out to 5 AU in a nominal 10-year program. Approximately three stars could give Uranus detections. These results assume an atmospheric and photon-noise error of 25 μarcsec/star/year. Thus, while a search as complete as that provided by the large interferometer above (which would also detect Uranus-mass planets) would not be achieved, a test-bed would permit a limited search with the possibility of providing scientific results prior to completion of the large interferometer. It will also provide the observation, calibration, and data-reduction experience to enable rapid and efficient use of the large interferometer, as well as acting as verification of key components of a large interferometer.

7.3   MICROLENSING PLANET SEARCH

An intensive gravitational microlensing survey can determine whether Earth-like planets are common, rare, or very rare. This basic information is required for the detailed design of space missions that will directly detect Earth-like planets. We normally assume that most other stars have planetary systems similar to that of our Solar System. Since many of the recent discoveries are of systems *unlike* the Solar System, the frequency of Earth-size planets in ~1 AU orbits is quite uncertain.

7.3.1   PREDICTED NUMBERS OF PLANETS

The number of planets one might expect to detect in any microlensing program is quite dependent on the assumptions about the planetary systems, e.g., Gould and Loeb (1992). We indicate sample results from a hypothetical microlensing survey where 3000 events are assumed to have been followed with high time resolution, 1% photometry, and with 50% average coverage (Peale, 1996, in preparation). A 5% perturbation of the otherwise smooth light curve of the source sometime during the lensing event will be assumed detectable. About half of these events will have lenses that are members of binary or higher order systems, although only a fraction will reveal their binary nature. It is arbitrarily assumed that none of the binary systems have

planets, but all of the remaining 1500 lenses have planetary systems qualitatively similar to the Solar System. A stellar mass function like that of nearby stars is assumed, for which the distribution is heavily weighted toward stars of spectral type M. A microlensing survey might then find 0 to 1 Venus's at 0.7AU, 1 to 2 Earths at 1.0 AU, 2 to 3 Earths at 2.5 AU, 6 to 7 Uranus's at 5AU, 1 to 2 Uranus's at 10 AU, 24 to 25 Jupiters at 5 AU and 3 to 4 Saturns at 10 AU, if the mean distance of the lenses toward the galactic bulge is 4 kpc. The lensed stars are all assumed to be at 8 kpc in the galactic bulge. Different assumptions, all equally plausible at this stage of our ignorance, move these numbers up or down by a factor of 2 to 3. These numbers would be increased if we allowed planets in the binary systems. The Gould and Loeb (1992) probabilities are based on the assumption of point sources, whereas the probabilities of detection of the smaller Earth-size planets is significantly increased when the finite angular size of the source stars is taken into account (Bennett and Rhie 1996).

7.3.2   A POSSIBLE MICROLENSING PROGRAM

The observational program has three parts: 1) measure the brightness of 35 million stars to an accuracy of a few percent once every night to find 350 lensing events each year; 2) at any one time, about 70 lensing events are taking place. We measure their brightness with about 1% accuracy every 1 to 4 hours, almost continuously for about 40 days; 3) each night the few stars which show signs of a planet are monitored frequently for about 50 hours to improve the sampling and accuracy.

This program uses standard technology to produce a larger (more stars), more frequent (once per hour), and more accurate (better seeing and deeper exposures) version of ongoing searches. The microlensing planet survey has five strong points: 1) it provides a simple and reliable survey, which is guaranteed to work because it uses standard ground-based techniques; 2) it is fast and efficient, and will detect hundreds of planets in a few years; 3) it is the only ground-based indirect detection method that is sensitive to the full range of planet masses, including Earth-mass planets; 4) it gives measurements of the masses of the planets and their distances from their stars; 5) it surveys the frequency of planets around the most common ordinary stars. These stars have low mass, and because they are also the majority of our nearest neighbors, they will be targets for most programs that directly detect light from planets. Three dedicated southern hemisphere telescopes of 2-m aperture appear to be needed for this task.

7.4 Tests of Precision Photometry

Modest amounts of time on a large telescope and careful modeling of atmospheric effects could be used to investigate the limits of photometry on thousands of stars observed simultaneously with large format CCDs. While a space mission to detect planetary transits might be a long-term goal of this program, a great deal could be learned about stellar noise sources, the realities of CCD artifacts, and many other systematic errors by taking repeated images toward a number of fields. This program should be coupled to a program of modeling of photometric performance in a realistic space environment.

7.5 Detection of Zodiacal Clouds around Other Stars

One characteristic of stars that will affect our ability to detect planets is the amount of circumstellar dust near the star in the target system, the analog of the zodiacal dust in our own Solar System. The exo-zodiacal emission creates both photon noise and a background against which planets must be detected. Finding an Earth-like planet in the presence of exo-zodiacal emission 1 to 10 times brighter than our Solar System's requires a space interferometer consisting of four 1.5-m telescopes on a 75-m baseline. A brighter exo-zodiacal cloud would require a correspondingly larger, more widely separated system.

Our knowledge of the exo-zodiacal emission comes predominantly from IRAS observations, augmented by ground-based observations of the brightest of these systems, β Pictoris. While new observations of this phenomenon will come from the recently launched Infrared Space Observatory (ISO) satellite, these data are not yet available and the picture described here comes from earlier observations. The combined IRAS, optical coronagraphic, and ground-based mid-IR data for β Pictoris show that this disk is seen nearly edge-on and consists of an outer region beyond ~80 AU that emits primarily at far-IR wavelengths and an inner region detectable at shorter wavelengths. Interior to 80 AU that the amount of emitting material falls by more than a factor of 10 below an extrapolation of the outer disk profile (Backman, Gillett, and Witteborn 1992; Lagage and Pantin 1994; Burrows et al. 1996). Similarly sharp density discontinuities inside a radius of ~100 AU are inferred toward other stars on the basis of the

IRAS spectral energy distributions. Apart from the Sun, nothing is known directly of the dust content of any disks within a few AU of the star, the region of interest for the detection of extra-solar planets!

β Pic is among the brightest of IRAS disks, with a surface brightness roughly 10^4 times that of our Solar System. The faintest excess of any star measured by IRAS corresponds to an amount of material approximately 100 times that of the Solar System. Roughly 15 to 20% of all main-sequence FGK stars have exo-zodiacal clouds at least this bright. When ISO data become available later this year, we will know more about the quantity of exo-zodiacal material as a function of various stellar properties. The sensitivity limits of ISO in its various spectral bands for this purpose are not yet known, but will probably be in the range of 10 to 100 times that of the Solar System for material outside ~50 AU (see §8.1 for further discussion of the space-based characterization of exo-zodiacal clouds), but will not be directly helpful for the critical inner zodiacal dust.

Figure 7-4 gives a possible model for the radial variation of the optical depth and dust temperature for a solar twin. The inner disk might resemble our own zodiacal cloud, as revealed by IRAS and COBE. The outer disk might show enhanced density like that of β Pictoris due to particles in the Kuiper Belt.

A critical point is that IRAS, ISO and even SIRTF measure only the outer reaches of exo-zodiacal clouds, beyond about 30 AU, because of the limited spatial resolution of these small telescopes. In all but the brightest cases, knowledge of the exo-zodiacal cloud within a few AU of the star is masked by diffracted starlight. We propose a two-phase attack on the problem of the inner zodiacal cloud using first a single large telescope (6 to 10 m) and then a ground-based interferometers consisting of two such telescopes.

7.5.1 SINGLE TELESCOPE OBSERVATIONS

Low spatial resolution searches for mid-infrared excesses will help to characterize both the quantity and distribution of cometary and zodiacal debris associated with solar-type stars. A fuller understanding of the debris disk phenomenon may help to pinpoint targets for direct imaging. For these reasons, the range of dust system properties needs to be understood as a main step on the way to finding planets. Thermal images have already been made of the β Pic disk (Legage and Pantin 1994). Improved detector arrays operating on large telescopes, such as the Keck or the IR optimized Gemini
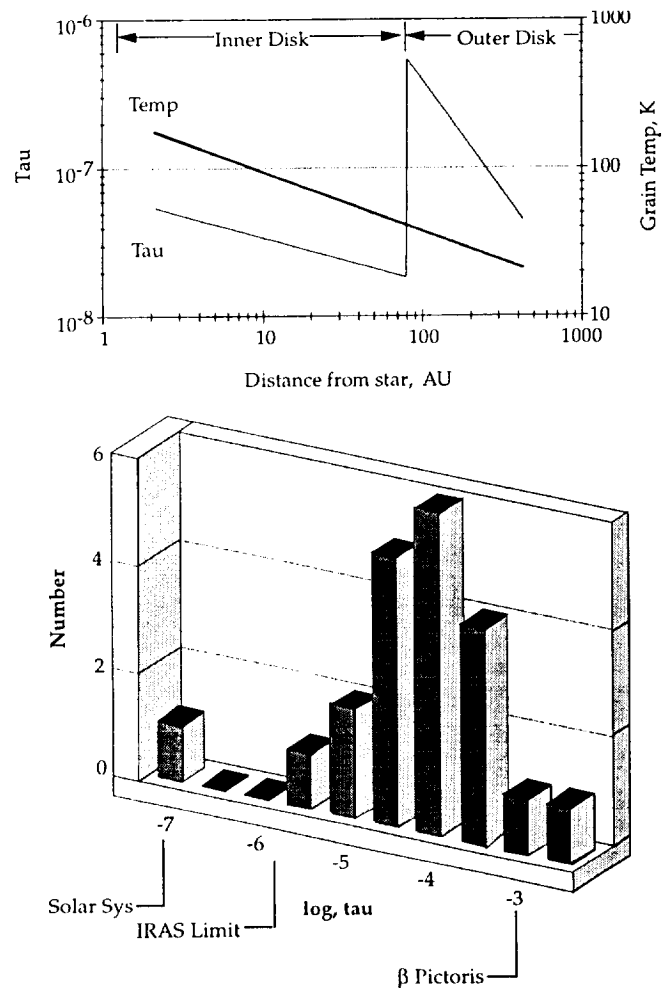
Figure 7-4. a) The radial variation of dust temperature and optical depth for an exo-zodiacal dust cloud similar to that around our Sun with an increase in surface density at 80 AU similar to that seen toward β Pic; b) A histogram showing the number of stars with various amounts of exo-zodiacal dust optical depth, as inferred from IRAS data. The IRAS sample suffers from a number of biases that ISO and SIRTF data will remedy.

8-m telescope, will make it possible to image systems with exo-zodiacal clouds with 100 to 1000 times the Solar System brightness, approaching as close as 5 AU to the central star.

7.5.2 Interferometric Observations

A pair of large, ground-based telescopes operating as a nulling interferometer could detect the 10-μm exo-zodiacal emission from stars 10 pc away down to the level of a few times the Solar System emission with resolution better than 0.5 AU (Woolf and Angel 1995). Since the detection of planets requires information on the scale of a few tenths of an AU to a few AU, there is an important role for high-spatial-resolution observations from a ground-based interferometer.

The amount of star suppression and the spatial resolution obtained with two telescopes operated as a Bracewell interferometer depends on element spacing; larger separations lead to higher resolution, but also to poorer suppression of the disks of nearby stars, compared with more closely spaced telescopes. Observations with telescope pairs such as the two Kecks (10-m telescopes on an 85-m baseline), the Large Binocular Telescope (8-m telescopes on a 14-m baseline) and the Magellan pair (6-m telescopes on a 60-m baseline) would offer complementary data which would probe the inner zodiacal disks with resolution approaching 0.1 AU and sensitivities capable of detecting as little as a few times the amount of dust as is found in our Solar System. These interferometers would detect the integrated zodiacal emission within the primary beam of one of the component telescopes, corresponding to a few tenths of an arcsec at 10 μm, or out to a radius of a few AU where most of the 10-μm emission from hot dust originates.

A disk around a solar type star 10 pc away with 100 times the surface density of the dust in our Solar System emits ~ 15 mJy at 10μm. Such a signal could be measured with a signal-to-noise ratio >100 in a few hours on a 8- to 10-m interferometer. Purely on the basis of photon statistics, disks with as little material as that present in our Solar System would be detectable with various ground-based interferometers. Typical observations in the thermal infrared can detect emission as weak as 10^{-6} to 10^{-7} of the background, implying that the sensitivity needed for this experiment will be difficult, but not impossible to achieve.

The overall sensitivity to exo-zodiacal emission also depends on factors such as the star suppression, the quality of the adaptive optics, and the telescope aperture, and the instrumental emissivity, all of which must be examined on an instrument-by-instrument basis.

7.6 CHARACTERIZATION OF YOUNG PLANETARY SYSTEMS

The observation of young, solar-type stars is a critical proving ground for theories of star and planet formation. Disks around young stars are present before, during, or after planet formation. The disks around young stars are more massive and hotter than the debris disks discussed above, but they are harder to resolve because they are farther away (~150 pc). This work will focus on the following points:

- Discover how many young stars have disks that could form planets

- Search for pre-planetary condensations and hot young planets

- Study the kinematics of hot gas in disks via near-IR spectroscopy

- Resolve disks and map radial structure, including rings and central holes

- Determine which disk properties correlate with the presence or absence of planets

Many observational techniques provide vastly more sensitive constraints on young planetary and proto-planetary systems when the "planetary" condensations are warmer and more extended than in subsequent evolutionary phases. Knowledge of which types of stars have such young planetary systems can then guide and provide a context for the more difficult searches for mature planets orbiting nearby stars of solar age. The broad understanding gained from studies of young planetary disks will also avoid dangerous preconceptions in search strategies directed towards systems with properties like the Solar System.

Four projects seem particularly relevant to these investigations. Two involve instrumentation for the Keck telescope. The other two involve radio interferometers funded by or proposed to the NSF. NASA should be cognizant of these projects and perhaps support those aspects of those telescopes that pertain directly to ExNPS needs.

7.6.1 THERMAL IMAGING FOR THE KECK TELESCOPE

A thermal infrared (5- to 35-μm) camera with a diffraction-limited pixel scale should be funded for the Keck Observatory. This high-resolution

camera would be used to characterize the luminosity, dust distribution, and composition of the inner regions (~20 AU) of proto-planetary disks and may yield detections of warm giant planets in the nearest star-forming regions. This instrumentation will provide high spatial resolution to complement the very high sensitivity expected from ISO and SIRTF. These space missions will provide a census of the thermal IR excess from large samples of stars, but without the spatial detail required for confident interpretation. This camera should use the latest generations of large format Si:xx arrays, which have been developed and optimized by NASA for SIRTF and other space programs, and should provide simultaneous imaging in the 10-, 20-, and 30-μm bands. As described in the previous section, this camera would also be useful in imaging the brightest exo-zodiacal clouds around the closest stars.

7.6.2 HIGH-RESOLUTION NEAR-IR SPECTROMETER

The Keck telescopes need a near-infrared (1- to 5-μm) spectrometer (NIRSPEC) with a resolution of about R=100,000, significantly higher than the R=25,000 (two pixel) resolution of the NIRSPEC now being built. The higher resolution is very critical for absorption-line studies of cool 100-K gas in young proto-planetary disks in the near-infrared molecular bands of H_2, CO, and H_2O. In addition, near-IR spectroscopy of molecular emission bands will provide a unique probe of hotter gas in the disks at <1 AU. These observations will elucidate both the clearing process of the inner disks and the condensation sequence, which is presumably responsible for the bifurcation between the terrestrial planets and outer giant planets. This instrument might also be used for the measurement of precision radial velocities of M stars, which are much brighter in the near-IR than in the optical.

7.6.3 SUBMILLIMETER AND MILLIMETER INTERFEROMETRY

Making the next big step in spatial resolution with millimeter (mm) and sub-millimeter arrays requires developing real-time atmospheric phase-measurement and correction techniques. With active atmospheric correction and longer telescope baselines, it will be possible to image YSOs and forming planetary systems at ~0.1-arcsec resolution (14 AU at 140 pc), clearly separating proto-planetary condensations with masses well below those of the giant planets from the surrounding nebulae. The mm and sub-mm interferometry provides the only avenue to image the gaseous (molecular) component and to measure the kinematics of the nebulae at radii > a few AU. The highest resolution and sensitivity will be obtained at

mm wavelengths by expanding the Owens Valley array baselines and at sub-mm wavelengths by expanding the existing James Clerk Maxwell Telescope -Caltech Submillimeter Observatory (JCMT-CSO) interferometer to include a Keck telescope and the Smithsonian Astrophysical Observatory (SAO) array.

7.6.4 PROPOSED NATIONAL MM-ARRAY

If located at an excellent site, the proposed millimeter array (MMA) will have both the sensitivity and wavelength coverage (particularly at sub-mm wavelengths) to enable studies of virtually all planet-forming disks in the nearest clouds at resolutions approaching ~0.02 arcsec or 3 AU. If the array were extended to 10 km baselines with operation at 350 μm, then the array might also make astrometric measurements of nearby stars.

7.7 DIRECT DETECTION AND CHARACTERIZATION OF PLANETARY SYSTEMS

7.7.1 ADAPTIVE OPTICS AND PLANET DETECTION

An evolutionary sequence of instruments on large ground-based telescopes offers the opportunity of detecting Jupiter-sized planets around bright stars (Angel 1994). The difficulty of detecting a planet against the background of scattered and diffracted star light may be surmounted in the near-infrared where atmospheric properties permit near-perfect correction of large telescopes. A planet is assumed to be detectable if its signal is 5 sigma above the stochastic fluctuations in the scattered light background from the atmosphere for less than 10 hours of integration time, and if its signal is greater than 1% of the scattered light background from the telescope optics.

- Cold, Jupiter-like planets orbiting the very closest stars may just be detectable in reflected light with the ~300 actuator AO systems now being built for the 6.5-m MMT and 10-m Keck telescopes. Since the diameter of a massive gas giant is essentially independent of mass, the reflected light contrast ratio depends only on distance from the parent star, being ~one billion for a 5-AU orbit like Jupiter. Such a contrast ratio might be achievable for a star as close as 2.5 pc and a planet at a 2-arcsec radius. These AO lower order systems will not suppress the scattered halo, but will recover a sharpened diffraction limited image for the

planet. Given halo speckles typically 3 orders of magnitude brighter than a planet, and a characteristic speckle evolution time of a few milliseconds, very long integrations (many hours) would be needed to average the halo speckle noise enough to see the planet.

- A high-order, high-speed, 10,000-segment AO system and coronagraph on a 6- to 10-m telescope could detect gas giants at 5 AU around ~50 of the brightest stars. The system would correct wavefront errors on fine spatial scales (5 cm) at high speed, (2 kHz), at 1 to 2 μm to achieve the necessary 10⁹ suppression of the scattered starlight. Figure 7-5 shows how a combination of high-speed AO plus a coronagraph can suppress the starlight and make possible the detection of a gas giant planet in one night (see Fig. 4-13).

- An interferometer consisting of two 8- to 10-m telescopes, each with 349-actuator AO system, could detect gas giants from 5 to 30 AU around 15 of the nearest stars, plus ice giants from 5 to 10 AU around 6 of the nearest bright stars. Adding high-order adaptive-optics systems to such an interferometer would enable the detection of gas giants from 5 to 30 AU, ice giants from 5 to 10 AU around several hundred nearest bright stars, plus, possibly, terrestrial planets from 1 to 2 AU around 15 of the nearest bright stars.
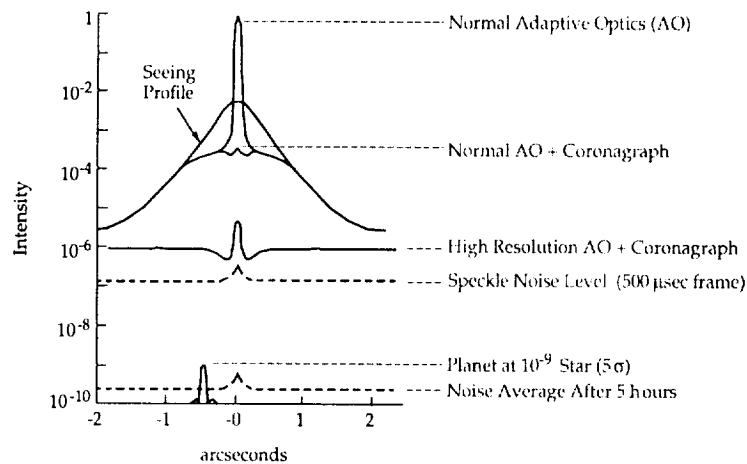
Figure 7-5. Normal Adaptive Optics (AO) systems produce a diffraction-limited core with a broad halo the size of the seeing disk. A high-speed, 10⁴ actuator AO system would suppress the halo as well.

7.7.2 OPTIMIZED CORONAGRAPHIC CAMERA FOR A BALLOON-BORNE TELESCOPE

Direct detection of planets from ground-based telescopes is made difficult by atmospheric distortions of the wavefront as well as by imperfections in telescope optics. Both of these problems might be ameliorated with a scattering-compensated 1.5-m telescope using a carefully optimized coronagraphic camera operated from a balloon at an altitude of 30 to 40 km. The primary and secondary mirror of the telescope would be carefully figured together for low scattering ($<10^{-6}$) within a central 1- to 2-arcsec field. With 16 hr of observing per star, this telescope could detect the visible or near-infrared radiation from a Jupiter within a few AU of the brightest 70 stars. The observations would take place during a balloon flight of a few weeks from a polar base. Issues of telescope-induced seeing due to radiative cooling, telescope thermal stability, and the viability of long-duration ballooning would have to be carefully investigated before undertaking this project. A significant advantage of this program would be its utility as a test-bed for high-precision wavefront control at optical wavelengths. On the basis of successful balloon flights, such a system could be used for a limited-duration space mission, e.g., as a Space Station Attached Payload.

7.8 OBSERVING THE CLOSEST STARS

While few of the nearest 1,000 stars have intrinsic astrophysical interest, their proximity makes them special for the purposes of the Road Map. We need to study these stars intensively to determine those peculiar properties that might correlate with the properties of planetary systems that might be found around them, or that might influence their suitability for planetary searches.

- The ages of stars are relevant to understanding the luminosity of cooling giant planets that might be found around these stars.

- The variability and degree of stellar activity is important because of the potential deleterious effects on radial velocity and astrometric measurements.

- The determination of binarity or higher levels of multiplicity is important since nulling interferometry works only on single stars.

- Determination of rotation periods can help determine the inclination of a putative planetary system to the line of sight. Since the physics of star and planetary formation depends on the amount of angular momentum in the collapsing disk, knowledge of the stellar component of the angular momentum budget is important.

- The amount and distribution of exo-zodiacal dust is important for reasons outlined in §7.4 and §8.1.

CHAPTER 8
SUPPORTING SPACE MISSIONS

8.1   ISO AND SIRTF

The European Space Agency recently launched the Infrared Space
Observatory (ISO) to cover the broad range of wavelengths from 2 to
200 μm. The spacecraft with its 65-cm telescope and four instruments are
working well, so that one can expect from the 24-month mission a wealth of
new information on the spatial and spectral properties of the exo-zodiacal
clouds around many stars. Of particular importance will be a better
assessment of the frequency of clouds of various brightness levels as a
function of spectral type, multiplicity, and other stellar properties; maps of
the distribution of exo-zodiacal material around the brightest systems; and
studies of the composition and size of the exo-zodiacal dust.

SIRTF will carry out many of these same studies, but with much improved
spatial resolution and sensitivity. The improvements in spatial resolution
possible with SIRTF relative to ISO will come less from increased aperture
(85 cm vs 65 cm) as from the oversampled images possible with modern
detector arrays. Increases in sensitivity relative to ISO will also come from
improved detector performance in the presence of bright stars. In the cases
of both ISO and SIRTF, the majority of the new information will concern the
outer reaches of the dust cloud, extending beyond ~30 AU (the 10-μm
diffraction limit for a star at 10 pc). For a few stars with bright exo-zodiacal
clouds, it will be possible to use image processing techniques to sample a
region slightly closer to the star.

SIRTF will be able to probe small amounts of dust in the outer zodiacal
clouds of stars that correspond to levels expected in the Kuiper Belt of our
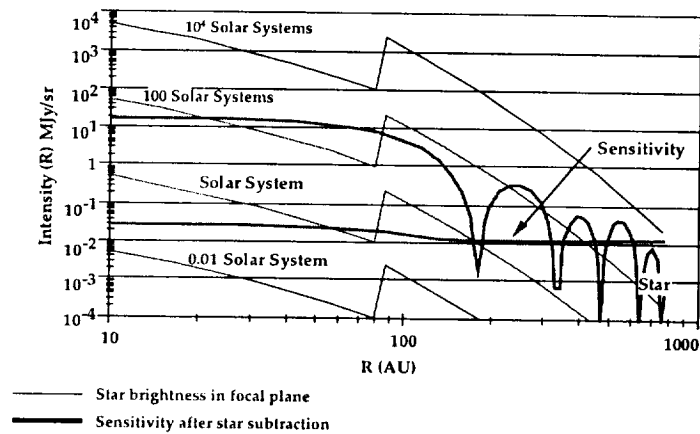
Figure 8-1. SIRTF observations at 60 μm will probe levels of the outer exo-zodiacal brightness close to that predicted to exist at the edge of our own solar system. The dust properties underlying the predicted intensities are taken from Fig. 7-4a, scaled by factors 10^4, 10^2, 1, and 10^{-2} (from top to bottom). The illuminating star is taken to be a solar analog at 10 pc.

own Solar System (Figure 8-1; Backman et al. 1996). With a dynamical theory of the evolution of material as it moves from the outer cloud into the star and with ground-based observations of the inner zodiacal clouds with a ground-based interferometer, it may be possible to develop a compete theoretical picture of the zodiacal dust environment of all nearby stars.

8.2 SPACE-BASED ASTROMETRIC DETECTION OF PLANETS

Since ground-based astrometry with long-baseline interferometers can achieve accuracy below 10 μarcsec, a nearly complete search for gas giant planets from Jupiter- to Saturn- to Uranus-mass can be conducted from the ground. The main reasons for going to space for astrometry from the standpoint of the Road Map are: 1) gaining experience with space interferometry; and 2) the possible indirect detection of Earth-like planets.

Space astrometry has the potential to search for Earths around ~100 nearby stars. Because of the short (1-yr) period of an Earth in a 1-AU orbit, discoveries would happen within 2 to 3 years. This would be in time to influence the imaging mission that would be launched in 2008 to 2010. A space interferometer might both find Earth-like planets around local stars and measure their masses

Table 8-1 gives the number of Earths detectable as a function of astrometric error. It is evident that the number of targets increases greatly as the baseline grows to 20 m. The integration time to achieve a particular sensitivity decreases markedly with baseline, as demonstrated in Table 8-1 for a 14th mag star. Interferometers of this size would be able to survey perhaps 100 stars for Earth-like planets, assuming one-half of a 2-year mission devoted to planet searches at the <1 µarcsec level with each star being visited eight times during those 2 years. Just as important as achieving the requisite instrumental sensitivity will be developing an understanding of the effects of starspots and other stellar phenomena on the ability to measure a star's position.

Table 8-1. Astrometric Detection of Earth-Like Systems

Target star 14 mag, accuracy of 0.5 µarcsec					
Baseline	2.5	5	10	15	20	meters
Integ Time	824	205	51	23	13	hours
# stars	1	5	21	47	85	targets

8.3 OPTIMIZED CORONAGRAPHIC CAMERA FOR HST

Currently, HST is not able to directly image Jupiter-like planets due to their poor intensity contrast (22.5 magnitudes fainter than the star) against scattered and diffracted starlight. An HST coronagraph could reduce scattered starlight by apodization and by precise correction of low frequency spatial errors (Malbet, Yu and Shao 1995). An optimized coronagraphic instrument would take advantage of the last unexploited optical potential of HST: high-contrast imaging based on the diffraction-limited image wings. A 40×40 element deformable mirror making very slow corrections (<0.1 Hz) could remove surface errors in the HST optics on the 5- to 10-cm scale and enable HST to detect a Jupiter in just a few hours around a nearby star.

An optional coronagraphic channel was studied by both JPL and Space Telescope Science Institute (STScI) for the 1999 Advanced Camera. The successful proposal included a coronagraphic option, but it was declined by NASA without prejudice as to the capability's merits for a future HST instrument. Such a capability would have wide application in astrophysics as well as in extra-solar planet searches.

8.4 A Dedicated Exo-Zodiacal Mapping Instrument

The most difficult aspect of measuring exo-zodiacal emission with ground-based telescopes is the high atmospheric and instrumental backgrounds. A cryogenic space system could be much smaller than the system described in §7.3, yet have the same or greater sensitivity. For example, two 40-cm telescopes on a 10-m baseline operated as a nulling interferometer could detect exo-zodiacal emission at or below the level of our own Solar System in just a few hours, with none of the systematic uncertainties associated with the bright backgrounds present on the ground. As discussed in §6.8, a dedicated exo-zodiacal mapping instrument operating for just a few months would serve as a high-fidelity test-bed for many of the cryogenic systems needed for the 75-m space IR interferometer.

8.5 An Instrument for Mapping the Local Zodiacal Cloud

A critical design parameter for the 75-m space interferometer is the intensity of the zodiacal emission around our own Sun. The falloff of this radiation as a function of wavelength and distance to the Sun can be inferred from models based on IRAS and COBE data (Figure 5-1). However, these data are insensitive to small amounts of cool dust at distances beyond 2 to 3 AU from the Sun. Doubling the amount of dust outside this distance would have little effect on the intensity measured from 1 AU, but would have a profound effect on the total emission seen by a telescope operating at 3 to 5 AU. A 10- to 20-cm telescope equipped with a simple focal plane and launched on a Med-Lite rocket could map the zodiacal emission on its way out to 5 AU. Such as mission would serve a variety of scientific and programmatic purposes: provide basic knowledge about the interplanetary dust; investigate the cosmological infrared background; help determine the optimum distance at which the interferometer would have to operate; and investigate many of the problems of operating a deep-space mission for infrared astronomy.

CHAPTER 9
ADDITIONAL ASTROPHYSICS WITH A SPACE INFRARED INTERFEROMETER

The space IR interferometer has the potential for breakthroughs in many fields of astrophysics outside of planet detection. Consider just two aspects of the interferometer, its spatial resolution and sensitivity.

9.1 SPATIAL RESOLUTION

The spatial resolution of the ExNPS interferometer will be around 0.03 arcsec at 10 μm, or roughly comparable to HST's 0.05 arcsec in the visible. The space IR interferometer is the only instrument envisioned with the resolution to make one-to-one infrared-visible comparisons of features found in HST images, or from large diffraction-limited ground-based telescopes operating in the near-infrared. As HST demonstrates daily, this level of spatial resolution is useful for studying everything from forming stars to forming galaxies.

There are two drawbacks to the routine use of the ExNPS interferometer for astrophysical imaging. First is limited uv-plane coverage, which limits the complexity and dynamic range of fields that can be imaged. The problem of uv-plane coverage can be addressed in a number of ways in the design of the interferometer: multi-wavelength baseline synthesis can be used to increase uv-plane coverage of spectrally simple sources; multiple telescopes

on intermediate baselines could be provided in addition to those needed for planet detection; retractable structures could be used to adjust the baseline lengths; separated spacecraft could be used for highly agile uv-plane coverage; or non-redundant array configurations could be used to provide multiple baselines. All of these options will be considered as part of refining the ExNPS concepts.

A second drawback of the ExNPS design is its limited field of view. Operated as a Michelson interferometer, the instrument maps out only the primary diffraction-limited beam of one of its component telescopes, e.g., ~1 to 2 arcsec diameter at 10 μm. This effect can be ameliorated by mosaicing images obtained with multiple pointings and taking advantage of the intrinsically high sensitivity of the instrument. Further, it is a straightforward extrapolation of the instrument design to provide the ability to image in a long-slit mode, wherein one simultaneously samples a strip of, say, 10 primary beams simultaneously.

9.2 SENSITIVITY

The sensitivity of just a single telescope would be spectacular compared with existing or planned facilities. Operating a 1.5-m telescope at 5 AU, where the 10-μm background is 200 times lower than that at 1 AU, would result in a system that would be $200 \times (1.5/0.85)^4$ ~2,000 times faster than SIRTF to reach a given sensitivity level. In addition to enabling deep imaging using the entire interferometer, this sensitivity could be used by a special instrument payload on one of the telescopes for either rapid, single-dish deep surveys, or for spectroscopic studies of sources initially detected by SIRTF.

9.3 INTERFEROMETER SCIENCE

Some of the general astrophysical problems that could be addressed with the space IR interferometer include:

- Map surfaces of planets and satellites to find volcanos on Io, or ice, dust, and atmospheric features on outer planets or Kuiper Belt objects.

- Map debris disks around β Pic stars. For stars with exo-zodiacal clouds too bright to find planets, it will still be interesting to map the temperature,

composition, and density distribution of exo-zodiacal dust with 0.1- to 0.5-AU resolution. The presence of gaps or composition gradients will be important clues as to the planet-formation process. The presence of clumps would indicate the effects of recent collisions or the dynamical influence of planets.

- Map proto-planetary disks in nearby star-forming regions. The ExNPS interferometer will be able to study the distribution of dust in disks around young stars with 5-AU resolution. This resolution will be adequate to study disk energetics to understand the role of stellar vs. accretion infall heating.

- With a resolution of 0.1 to 1 pc, the scale of the broad-line region, it will be possible to distinguish between starburst and AGN energy sources in infrared luminous galaxies.

- The interferometer is the only instrument that will be able to provide 10-μm counterparts to every object in Hubble Deep Field images. By pushing far below the SIRTF confusion limit, the interferometer will be able to probe the star-formation content of all the galaxies seen in deep-optical or near-infrared fields.

CHAPTER 10
THE ROAD MAP AND RECOMMENDATIONS

The ExNPS Road Map has three major parts: near-term activities to define better the problem of finding habitable planets and to develop the technologies needed for the search; a major space mission to detect and characterize habitable planets; and suggestions about how to proceed after finding the first Earth-like planets outside of our Solar System. The Road Map team agreed that its ability to forecast technological developments and scientific advances was good enough to propose the space interferometer described in Chapter 5, but insufficient to suggest how one might proceed beyond that point.

10.1 FINDING HABITABLE PLANETS IS POSSIBLE

The fundamental finding of the Road Map team is that an interferometer consisting of four 1.5-m telescopes on a 50- to 100-m baseline and operating at a distance of 3 to 5 AU from the Sun can detect and characterize habitable planets around nearby stars. This instrument could make family portraits of solar systems ranging in size from a few tenths of an AU to 10 AU around stars as far away as 13 pc. The solar systems would be imaged directly, enabling estimates to be made of the size, temperature, and albedo of individual planets. In the case of the brighter candidates, it would be possible to investigate the atmospheres of these planets using H_2O, CO_2, and O_3 as sign posts of a habitable or even of an inhabited planet.
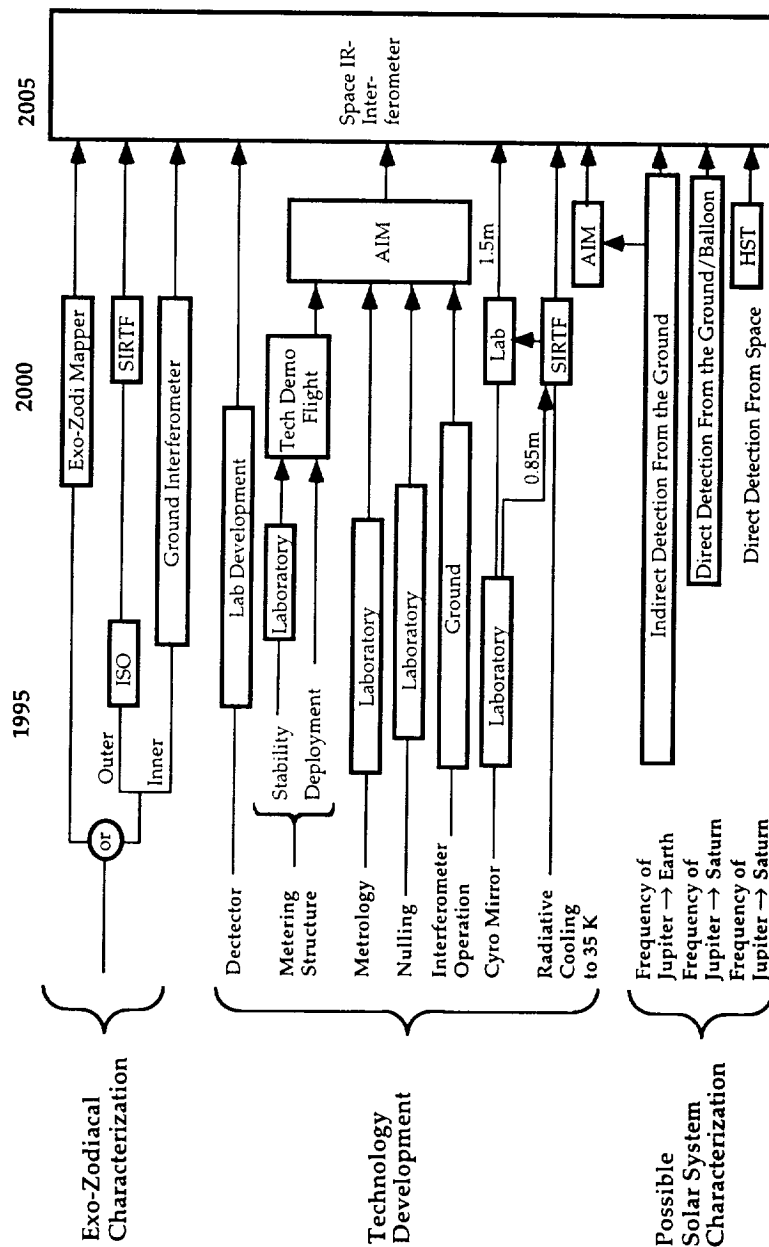
Figure 10-1. A combination of existing missions and new activities will culminate in the construction of a space interferometer for the detection and characterization of habitable planets.

As laid out schematically in Figure 10-1, a series of scientific and technological advances will be required to enable the construction of this planet-finding interferometer. These precursor activities are considered below.

10.2 PRECURSOR ACTIVITIES ARE CRITICAL

10.2.1 ADVANCES IN SCIENTIFIC UNDERSTANDING

The field of planet detection is ripe for major advances and NASA must play a major role in this area by judicious investment in individual scientists and in key facilities. The questions that need to be answered before a planet finding interferometer is constructed include: Are planets common in the galaxy? What is the relative proportion of Jupiters, Uranus's and Earths? Are planets down to the mass of Uranus common around nearby stars? What is the strength of the exo-zodiacal emission around other stars? How does our zodiacal emission fall off with distance from the Sun? What is the mass of planets around neighboring stars?

The single most important way to ensure timely answers to these questions, and to others as yet unasked, is a robust program of near-term observational and theoretical investigations. NASA must foster a community of researchers by funding scientists across a broad front of relevant disciplines. The Origins Research and Analysis (R&A) program has been a key aspect of this support. As new instruments are developed as outlined in this Road Map, it is essential that adequate peer-reviewed funding be made available to exploit these new data and to guide new developments.

Ground-based or balloon-borne instruments can answer important questions within a few years and help develop new techniques in a rapid-prototyping, low-cost environment:

- Indirect detection of planets as small as Uranus via ground-based radial velocity and astrometric measurements.

- Characterization of exo-zodiacal disks via large-telescope interferometric measurements at 10 μm.

- Direct detection of Jupiters in the visible or near-infrared using large ground-based telescopes, balloon, or HST coronagraphs.

- Statistics of the frequency of planets of various masses via an intensive microlensing survey.

Two space-based missions were deemed to be of critical importance to the Road Map:

- SIRTF will measure the emission in the outer exo-zodiacal clouds down to or below the level of our own Solar System. This information combined with various ground-based measures will provide the understanding of the exo-zodiacal brightness needed to design the infrared interferometer.

- The Astrometric Interferometric Mission (AIM), since renamed the Space Interferometer Mission (SIM), can provide astrometric detections of planets smaller than Uranus, possibly down to the mass of Earth.

Of lesser importance, but still of considerable interest, would be space missions to map both our own zodiacal cloud and the exo-zodiacal clouds of other stars.

10.2.2 Advances in Technological Readiness

Many of the experiments described above will play important technological roles in the Road Map:

- SIRTF will demonstrate passive cooling of a complete infrared telescope, deep-space operation, and the fabrication of meter-class cryogenic optics.

- SIM will demonstrate key interferometer technologies of precision metrology and deployment, as well as interferometric imaging and nulling.

- Various ground test-beds will develop lightweight optics, cryogenic mechanisms, analysis and modeling software, and system integration skills.

- A technology flight test-bed would investigate the dynamics of a large (>50-m) boom in a cold environment.

10.3 SPACE IR INTERFEROMETER WILL CHARACTERIZE HABITABLE PLANETS

The space interferometer (Chapter 5) will detect nearby planets and answer important questions about their nature using its different observational capabilities:

- Do nearby stars have planets? What is the distribution of planets in these solar systems? Are any of these planets in the habitable zone? *Broad-band interferometric imaging.*

- Does a planet contain an atmosphere? *Detection of CO_2 via spectroscopy.*

- Is the planet capable of supporting life? *Detection of H_2O via spectroscopy.*

- Is photo dissociation of H_2O prevalent on the planet? Is photosynthesis responsible for the breakdown of H_2O? *Detection of O_3 via spectroscopy. Analysis of atmosphere conditions from all the above data.*

The interferometer design is based on fundamental physical principles. One can do no better without, for example, requiring mirrors much larger than the 1.5-m optics described in Chapter 5. While the integration times required for the spectroscopy are long by most astronomical standards, it should be noted that the deep-space environment is very stable and the interferometer will operate as a closed-loop system, rigidified by laser metrology. The fear with such long integration times is that one will do worse than expected due to various systematic effects. This is always possible, even though the signal-to-noise calculations of Chapter 5 are conservative. However, even if the goal of detecting O_3 or H_2O cannot be achieved with this mission, the goals of detecting Earth-like planets, determining their sizes and temperatures, and looking for the very strong CO_2 band seem very secure.

10.4 SUCCESS WILL POSE FURTHER QUESTIONS

Our search will not cease once we have succeeded in finding the first habitable planets. We will want to know more about them: Do these planets

have moons? Are their surfaces made mostly of land, water, or ice? Are indisputable tracers of life such as methane present? Each of these questions demands technologies far beyond what we can now imagine.

Obtaining high-resolution spectra to look for methane or other signposts of life would require scaling the proposed interferometer to 10 times its proposed collecting area, either with many more or with much larger telescopes. Making multi-pixel images of individual planets would require interferometers with square kilometers of collecting area and baselines of thousands of kilometers (Figure 10-2). Either of these goals would require breakthroughs in telescope construction, e.g., highly precise, inflatable reflecting surfaces needing little or no supporting structure (Mylar balloon telescopes!) or in our ability to launch very large payloads into deep space.

Or perhaps it would prove easier to send a micro-spacecraft to probe our closest neighbors than to image them from our local vantage point. Our distant descendants might someday receive images of planets around other stars that would have the same galvanizing effect on them as the Apollo images of our Earth have had upon ourselves.

NASA must pursue a wide variety of breakthrough technologies to achieve these long-term goals, while not ignoring today's very real opportunities. Right now we have within our grasp the answers to some of humanity's oldest questions: Is the Earth unique in the Universe? Is life to be found beyond the Earth? The charge to the Road Map teams was to lay out a plan to answer these questions, if possible. Our firm conclusion is that NASA can answer these questions within the next 10 to 20 years.

Pixel / Diameter	Pixel size @ planet (km)	Image	Interferometer Requirements		
				Collecting Area	Baseline
400	32		IR	144 km²	100,000 km
			Visible	1,296 km²	5,000 km
100	128		IR	0.64 km²	24,000 km
			Visible	5.76 km²	1,200 km
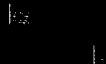
Pixel / Diameter	Pixel size @ planet (km)	Image	Interferometer Requirements		
				Collecting Area	Baseline
25	510		IR	1,024 m²	6,000 km
			Visible	9,216 m²	303 km
10	1276		IR	64 m²	2.4km
			Visible	576 m²	120 km

Figure 10-2. A progression of images with ever-increasing spatial resolution shows how the amount of information in an image increases with the number of pixels. Unfortunately, as the entries on the right of each image indicate, the difficulty of obtaining the image, either in the infrared or the optical, increases rapidly with increasing information content.

CHAPTER 11

REFERENCES

Alcock et al., 1995, *Ap. J.*, **445**, 133.

Alcock et al., 1996, *Ap. J.*, **461**, 84.

Angel, J. R. P., 1990, in *Next Generation Space Telescope*, (eds. P. Bély, C. Burrows, G. Illingworth), p. 81–94.

Angel, J. R. P., Cheng, A. W., and Woolf, N. J., 1986, *Nature*, **322**, 341.

Angel, J. R. P. and Woolf, N. J., 1996, *Ap. J.*, in press.

Angel, J. R. P., 1994, *Nature*, **368**, 203.

Backman, D. E., Gillett, F. C., and Witteborn, F. C., 1992, *Ap. J.*, **385**, 670.

Backman, D. E., Werner, M. W., and Rieke, G. H. 1996, *Ap. J.*, in press.

Bennett et al., 1995, preprint.

Bennett, D. P. and Rhie, S. H., 1996, preprint.

Boss, A. P., 1996, *Nature*, **379**, 397.

Bracewell, R. N., 1978, *Nature*, **274**, 780.

Bracewell, R. N. and McPhie, R. H., 1979, *Icarus*, **38**, 136.

Burrows et al., 1996, in preparation.

Gatewood, G., 1987, *Astron. J.*, **94**, 213.

Gatewood, G., 1996, preprint.

Gliese, W. and Jahreiss, H., 1993, Third Catalogue of Nearby Stars

Gould, A. and Loeb, A., 1992, *Ap. J.*, **396**, 104

Good, J., 1988, in *The Explanatory Supplement to IRAS All Sky Image Atlas*.

Kasting, J. F., Holland, H. D., and Pinto, J. P, 1985, *Journal Geophys. Research*, **90**, 10497.

Kasting, J. F., Whitmire, D. P., Reybolds, R. T., 1993, *Icarus*, **101**,108.

Lagage, P. O. and Pantin, E., 1994, in *Nature*, **369**, 628.

Léger, A., Pirre, M., Marceau, F. J., 1993, *Astr. Astrop.*, **277**, 309.

Léger, A., Mariotti, J-M., Mennesson, B., Olivier, M., Puget, J. L., Rouan, D., Schneider, J., 1996, *Icarus*, in press.

Mao, S. and Paczyński, B., 1991, *Ap. J.*, **371**, L63

Malbet, F., Yu, J. W., and Shao, M., 1995, *Pub. Astr. Soc. Pac.*, **107**, 386.

Marcy, G. and Butler, R. P., 1996, BAAS.

Mayor, M. and Queloz, D. 1995, *Nature*, **378**, 355.

Nakajima, T. et al., *Nature*, **378**, 463.

Oppenheimer, B. R., Kulkarni, S. R., Matthews, K., and Nakajima, T., 1995, *Science*, **270**, 1478.

Owens, T., 1980, in *Strategies for the Search of Life in the Universe*, (ed. M. D. Papagiannis), Reidel: Dordrecht, p. 177.

Pravdo, S. H. and Shaklan, S., 1995, preprint

Reach, W. T. et al., 1995, *Nature*, **374**, 521.

Shao, M., 1990, in *Next Generation Space Telescope*, (eds. P. Bély, C. Burrows, G. Illingworth), p. 160.

Shao, M. and Colavita, M. M., 1992, *Astr. Astrop.*, **262**, 353.

Stahl, S. M. and Sandler, D. G., 1995, *Ap. J. Letters*, **454**, L153.

Udalski, A. et al., 1994, *Acta Astron*, **44**, 165.

Woolf, N. J. and Angel, J. R. P., 1995, *Adaptive Optics 23, OSA Tech Digest Series* (OSA Washington, DC), p. 46.

CHAPTER 12
APPENDIX A. PARTICIPANTS IN THE ExNPS ROAD MAP

Table 12-1. Road Map Integration Team

Charles Elachi (chair)	JPL
Roger Angel	University of Arizona
Charles Beichman	Infrared Processing and Analysis Center
Alan Boss	Carnegie Institution
Robert Brown	Space Telescope Science Institute
Alan Dressler	Carnegie Institution
Freeman Dyson	Institute for Advanced Study
James Fanson	JPL
Chris Ftaclas	Hughes Danbury Optical Systems
Lawrence Goad	Itek Optical Systems
Mike Klein	JPL
Alain Léger	University of Paris
Charles Lillie	TRW
Stanton Peale	University of California, Santa Barbara
Deane Petersen	State University of New York, Stony Brook
Bob Reasenberg	Center for Astrophysics
David Sandler	Thermo Trex
Mike Shao	JPL
Richard Simon	NRAO
Domenick Tenerelli	Lockheed Martin
David Tytler	University of California, San Diego

Table 12-2. Road Map Team Led by JPL/STScI

Charles Beichman (chair)	Infrared Processing and Analysis Center
Ron Allen	Space Telescope Science Institute
Pierre Bély	Space Telescope Science Institute
Richard Capps	JPL
John Carlstrom	California Institute of Technology
Mark Colavita	JPL
Roger Doxsey	Space Telescope Science Institute
Freeman Dyson	Institute for Advanced Study
James Fanson	JPL
Chris Ftaclas	Hughes Danbury Optical Systems
Don Gavel	Lawrence Livermore Laboratory
Robert Laskin	JPL
Jim Lesh	JPL
Doug Lin	UCSC
Claire Max	Lawrence Livermore Laboratory
Tadashi Nakajima	California Institute of Technology
Scott Oliver	Lawrence Livermore Laboratory
Steve Pravdo	JPL
Bonny Schumaker	JPL
Karl Stapelfeldt	JPL
Steve Strom	University of Massachusetts
Sue Terebey	Infrared Processing and Analysis Center
Mike Shao	JPL
David Tytler	University of California, San Diego
Larry Wade	JPL
Mike Werner	JPL

Table 12-3. Road Map Team Led by University of Arizona

Roger Angel (chair)	Steward Observatory, University of Arizona
Steven Beckwith	Max-Planck-Institut für Astronomie
Alan Binder	Lockheed Martin
Ronald Bracewell	Stanford University
Adam Burrows	Steward Observatory, University of Arizona
Robert Fugate	Phillips Lab, USAF
George Gatewood	Allegheny Observatory, Univ of Pittsburgh
Shrinivas Kulkarni	California Institute of Technology
Alain Léger	University of Paris
Eugene Levy	Lunar and Planetary Laboratory University of Arizona
Kenneth Lorell	Lockheed Martin
Frank Low	Steward Observatory, University of Arizona
Jonathan Lunine	Lunar and Planetary Laboratory, University of Arizona
Don McCarthy	Steward Observatory, University of Arizona
Robert McMillan	Steward Observatory, University of Arizona
Jean-Marie Mariotti	Paris Observatory
Bernard Oliver	Hewlett Packard Corporation
Bohdan Paczyński	Princeton University
George Rieke	Steward Observatory, University of Arizona
Marcia Rieke	Steward Observatory, University of Arizona
David Sandler	Thermo Trex
Stuart Shaklan	JPL
David Stevenson	California Institute of Technology
Mark Sykes	Steward Observatory, University of Arizona
Domenick Tenerelli	Lockheed Martin
Neville Wolff	Steward Observatory, University of Arizona
Simon Worden	Falcon AFB, USAF

Table 12-4. Road Map Team Led by Smithsonian Astrophysical Observatory

Robert Reasenberg, PI	Smithsonian Astroophysical Observatory
Lawrence Goad	Itek Optical Systems
Charles Lillie	TRW
Stanton Peale	University of California, Santa Barbara
Richard Simon	NRAO
Robert Babcock	Smithsonian Astrophysical Observatory
Sallie Baliunas	Smithsonian Astrophysical Observatory
Peter Bender	National Institute of Standards & Technology
William Borucki	NASA Ames Research Center
Andrew Buffington	University of California, San Diego
Alastair Cameron	Smithsonian Astrophysical Observatory
Daniel Fabricant	Smithsonian Astrophysical Observatory
Lawrence Goad	Litton/Itek Optical Systems
Andrew Gould	Ohio State University
John Huchra	Smithsonian Astrophysical Observatory
Kenneth Johnston	U.S. Naval Observatory
David Latham	Smithsonian Astrophysical Observatory
Charles Lillie	TRW
Enrico Lorenzini	Smithsonian Astrophysical Observatory
Geoffrey Marcy	San Francisco State University
Harold McAlister	George State University
William McKinley	Litton/Itek Optical Systems
James Moran	Smithsonian Astrophysical Observatory
Stewart Moses	TRW
Michael Mumma	NASA Goddard Space Flight Center
Marc Murison	Smithsonian Astrophysical Observatory
M. Charles Noecker	Smithsonian Astrophysical Observatory
Bohdan Paczyński	Princeton University
Stanton Peale	University of California, Santa Barbara
James Phillips	Smithsonian Astrophysical Observatory
Carle Pieters	Brown University
Stephen Ridgway	Kitt Peak National Observatory
Philip Sadler	Smithsonian Astrophysical Observatory
Peter Schloerb	University of Massachusetts
Sheryl Silas	Smithsonian Astrophysical Observatory
Richard Simon	National Radio Astronomy Observatory
David Skillman	NASA Goddard Space Flight Center
Leonard Solomon	SolVisions

**Table 12-4. Road Map Team Led by Smithsonian
Astrophysical Observatory (cont.)**

Keto Soosaar	Photon Research Associates
Richard Taylor	Smithsonian Astrophysical Observatory
Wesley Traub	Smithsonian Astrophysical Observatory
Joseph Veverka	Cornell University
Robert Wilson	Smithsonian Astrophysical Observatory

Table 12-5. Blue Ribbon Panel

Charles Townes	University of California, Berkeley
Lew Allen	USAF, ret
Laurence Adams	Martin Marietta (Retired)
David Black	Lunar and Planetary Institute
Bernard Burke	MIT
Joseph Burns	Cornell University
Claude Canizares	MIT
Edward Crawley	MIT
Noel Hinners	Lockheed Martin Astronautics
Louis Lanzerotti	Bell Labs
Richard Malow	AURA
Jonathan Lunine	Lunar and Planetary Laboratory, University of Arizona
Sally Ride	University of California, San Diego
Stephan Ridgway	NOAO
Carl Sagan	Cornell University
Anneila Sargent	California Institute of Technology
Linda Schele	University of Texas, Austin
Frank Shu	University of California, Berkeley
Robert Williams	Space Telescope Science Institute
Robert Wilson	Center for Astrophysics

CHAPTER 13

APPENDIX B. REPORT OF THE TOWNES BLUE RIBBON PANEL

13.1 BLUE RIBBON PANEL REPORT

The Program "Exploration of Neighboring Planetary Systems (ExNPS)" addresses central scientific questions about the origin and evolution of planetary systems around nearby stars. The results of this proposed program of research will yield information of great importance to the scientific community, but the search for "Earth-like planets" has implications far more profound to the public at large. Human beings have been constructing overarching "world views" to explain how the cosmos got to be the way it is, and how it works, for at least as long as people have been making artifacts and art to materialize their understanding of the world. These "world views" have differed throughout history and from group to group, but central to them all is the contemplation of life, its origin, and the place of humanity in the larger framework of the cosmos. For people in the modern world, both scientists and non-scientists alike, the question centers on whether the emergence of life is a rare or unique phenomenon or is a natural and frequent product of star and planet formation. ExNPS will address this question by ascertaining the frequency of "potential life-bearing planets" in our nearby star neighborhood. The answer to this question bears on one of the most ancient of all human questions: is the life-bearing Earth unique in the cosmos or is life also to be found elsewhere?

The question in its present form has been with us ever since Christian Huygens surmised over four hundred years ago that Sirius could be a sun at an enormous distance from the solar system. In recent decades speculations

have gained momentum as astronomers have established that many newly-formed stars are accompanied by the type of circumstellar disk that theorists have long postulated as the precursor of our own planetary system. But these preliminary insights merely whet our appetite for more substantive knowledge. There exists perhaps no foreseeable discovery that would more electrify the public imagination and spark a renaissance in science education and science literacy than the direct detection and characterization of Earth-like planets around the closest 1,000 stars. The potentially unifying impact on astronomy, planetary science, and geophysics would be equally profound, since scientists interested in a wide variety of problems ranging from star and planetary-system formation to the geochemistry and evolution of terrestrial atmospheres would finally possess more than the solar-system example to study and to compare for similarities and differences. In the next few decades of transition between the twentieth century and the twenty-first, the opportunity exists for a great civilization to attack and to solve, on a scientifically sound and technologically feasible basis, one of humanity's oldest and deepest questions concerning physical origins. Any discovery of other Earth-like planets could be followed by intensive searches for evidence of extraterrestrial biological activity. We urge NASA and the nation not to let this opportunity pass.

The ExNPS program is quite ambitious, technically as well as scientifically. It is important in any such project that it not be dependent on too many technically-challenging elements which may or may not develop as hoped. It can easily be envisioned that the evolution of technologies that could be relevantly utilized in the program will advance in other contexts as well as within the program itself. Likewise, the scientific understandings of stellar and planetary system formation will evolve with time as new knowledge continues to be gained, both from continuing observations and from theoretical considerations. These advances in scientific understandings will likely cause some ExNPS objectives to be altered with time, sometimes perhaps rather abruptly. These will in turn require rethinking of some approaches and of the employed technologies.

Within this same framework, it is important to carefully evaluate the presently planned and on-going programs that might rightfully be included within the envelope of the ExNPS program. As a general rule, choices should be based on open competition and peer review.

There is a natural tendency to include projects that might have, or appear to have, some semblance of relevance to ExNPS. Very careful cost and

performance analysis needs to be carried out to justify inclusion of each project. For the ExNPS as presented to the Panel, such analyses had not as yet been done on some included projects and program elements. This may harm the program as it is initiated and evolves.

Although significant contributions towards the detection and characterization of planets neighboring stellar systems can and should be made from the ground, the goal of understanding other planetary systems can be pursued more advantageously, and in some aspects uniquely, from space with devices that provide high spatial resolution. More analysis and many careful preparatory tests are clearly needed, but the Committee is impressed with the strong case that can be made for the utility of a cooled interferometer that is sensitive in the infrared and orbiting at around 4–5 AU from the sun. The greatest advances in our knowledge of other planetary systems generally, and of earth-like planets specifically may well come from such an instrument.

The capabilities of ground-based optical to mid-IR interferometry have been increasing rapidly in the last half decade. Still better instruments are under development. NASA has been very farsighted in supporting this emerging technology and a big payoff may come in the ExNPS program. We urge continued support for development of instrumental and observational techniques for making differential astrometric measurements in the microarcsecond accuracy range from the ground. This should include support for observing programs to explore candidate stars. Real experience with demanding observations will be a great help towards attaining the hoped-for long-term results.

Recognizing that a large infrared interferometer currently appears to be the natural and best choice for achieving the ultimate ExNPS objectives, there are nevertheless a number of scientific and technical hurdles to pass before making a large commitment to this ambitious mission. The scientific prerequisites include substantially augmented efforts towards the detection and characterization (e.g., orbits, masses) of planets revolving about other stars, improved measurements of the galactic dust distribution, and improved understanding of the exo-zodiacal light. Technical developments include space qualification of interferometry technology which is already in operation on the ground (stable structures, metrology, optical path compensation), and development of new technologies specifically required for the large infrared interferometer (assembly or deployment of large structures, achromatic nulling, low noise detectors, passive cooling).

The ExNPS Integration Team report presents a rich menu of experiments and programs to address these plus other science and technology issues. While some are unique, there is considerable overlap among others. Some are already underway and merit continuation or enhancement. Some can be initiated rapidly. Others require a substantial ramp-up of activity or a series of facility or technical developments. We recommend introducing an additional level of organization into the report, with a time-line for initiating programs, for peer review of competing strategies, and with major decision points as the science and technical parameters are better understood.

It became clear during the Integration Team presentations that a significant issue in the ability of an infrared system to detect and characterize planets around neighboring stars is the intensity and spatial distribution of dust-related emission from the circumstellar regions of those stars, the so-called "extra-solar zodiacal emission." Our knowledge of this type of emission is presently very limited, coming mainly from the IRAS mission. The significance of this knowledge is that certain interferometer design concepts would appear to be ruled out depending upon whether most nearby stars have zodiacal clouds with optical depths similar to those of some stars observed by IRAS. The intensity of anticipated emission from the regions of nearby stars influences both the physical configuration of an interferometer (e.g., linear vs. planar) and the needed aperture for the interferometer elements. Additionally, there is some question as to whether spatial inhomogeneities in the dust associated with other stars might confuse possible interpretations of observational results. The extent to which such inhomogeneities exist is at present not well-known, nor is it clear, absent data, whether inhomogeneities would truly pose an interpretive problem (e.g., will the motion of a density wave in a dust disk mimic that of a planet?). In light of the strong influence of knowledge concerning both the intensity and spatial distribution of "extra-solar zodi" on the most basic aspects of an infrared interferometer design, the Panel endorses the notion of a suitably focused precursor mission to obtain the necessary data. Although the AIM project can usefully demonstrate some of the technologies which will be important to the ExNPS program, it can probably not be efficiently adapted to this particular purpose. Coordination with the ISO mission might be actively explored by NASA to see whether observations to illuminate this issue can be given high priority on that ESA mission.

Gravitational microlensing is a well-established consequence of general relativity, and indeed a program designed to utilize this physical phenomenon as a means to search for Massive Compact Halo Objects (MACHOs) has been ongoing for nearly two years. The ExNPS Integration

Team described a possible microlensing program that would survey nearly three times as many stars per night (35 million), giving rise to an estimated 350 lensing events per year. Under such a program, assuming that every lensing star has a planet located randomly in the lensing zone, the assertion is that 3-4 Earth-mass objects would be detected per year. It is important to recognize that although the microlensing technique has, in principle, the mass sensitivity to detect Earth-mass companions to stars, stars providing such microlensing are not in the solar neighborhood. They are typically located at a distance of 4-7 kpc from the Sun. Therefore, the only information from microlensing relevant to ExNPS is that dealing with the frequency of occurrence of terrestrial-mass companions to stars of a particular spectral type at these distances; detailed study of other terrestrial planets must be done on stars within roughly 13 pc of the Sun. The Panel notes two points in this regard. First, it is not obvious that the statistics for companions of any kind, be they planets, brown dwarfs, or other stars, will be the same for stars in the solar neighborhood and for the population of disk stars that are giving rise to the lensing events. This should be carefully calibrated by first undertaking sufficient observations to show that microlensing yields the correct binary frequency for field stars in the solar neighborhood. It then should be calibrated against a possible sharp cutoff in companions below approximately 0.08 solar masses, i.e., reflecting the paucity of brown dwarfs. Once these two calibrations are in hand, it will be clearer whether the frequency of planetary companions deduced from this technique is meaningful for the ExNPS program. The second point is that the Panel finds the numbers used by the Integration Team to be very "success oriented"; the number of events is likely to be much less than a few per year, implying that convincing statistics of the existence of terrestrial-mass planets by this technique are not likely to be available for nearly a decade. Given that the role of microlensing was to provide some assurance that terrestrial planets exist before building an expensive space system, this time lag is significant. The Panel does encourage the microlensing community to continue with its observational program since it may be able to help define important parameters.

There are a number of alternative approaches to detection of planetary systems in the solar neighborhood which need attention, development, or exploration. One is detection of the transit of a star by a planet, which probably will require a space platform but needs further exploration and analysis. Others include ground-based spectroscopy, interferometry, and adaptive optics, fields which are already actively pursued and which can provide valuable preparatory information for space work as well as detection of some types of planets. Recent successes in ground-based detection of sub-

stellar objects around 51 Peg and GL229 are encouraging in this respect. It is expected that space-based techniques will ultimately prove to be the best way to systematically determine the distribution of planetary masses down to terrestrial planetary sizes. But since determination that this is the case and the proper design and strategy for space-based equipment will be affected by prior knowledge obtained, it is important to be sure that alternative approaches involving ground-based techniques are not ignored and are appropriately used, at least early in the program.

Although the concept that other planetary systems exist has engaged the human mind for centuries, the possibility of carrying out a methodical, scientifically-ordered search for other solar systems has only recently been given credence. This change has taken place as technological advances have begun to provide the requisite tools.

In the last few years a number of independent reports have recommended that high priority be assigned to research programs to investigate the origin and evolution of planetary systems and to detect mature planets around other stars. These include the National Research Council's (NRC) decadal Report on Astronomy and Astrophysics, and the most recent NRC report from the Space Studies Board's Committee on Planetary and Lunar Exploration (COMPLEX), as well as the TOPS (Toward Other Planetary Systems) Report from NASA's Solar System Exploration Division. In addition, the 2000+ study of the European Space Agency concluded that a search for planets beyond our solar system should be a major enterprise in their plans until the year 2017.

With such strong support from the community and government agencies alike, programs to study other solar systems are likely to proliferate in the coming years. To ensure optimum returns, the ExNPS project must be coordinated with other efforts. There are obvious fiscal advantages to be gained by NASA if it works with other agencies, such as the National Science Foundation and ESA. Intellectual gains are also to be expected since the various programs are likely to be complementary. The ExNPS program also accords well with the thematic organizational structure currently being implemented at NASA headquarters, encompassing as it does a variety of contributing programs (both ground- and space-based observational projects, theoretical studies, and technology development) under one unifying concept—can we detect and study planets beyond our solar system?

Based on current five-year budget projections for NASA, the agency's space science budget will decline. Under such conditions, care should be taken to not start a new program like ExNPS at the expense of important existing projects and plans without carefully weighing their relative merits. But ExNPS is an exciting and worthwhile goal—one with tremendous positive potential to affect how we view ourselves as a civilization and as a sentient species. The nation would be wise to find resources for making this investment in our long-term future.

January 10, 1996

Blue Ribbon Panel Members:

Lew Allen
Laurance J. Adams
David Black
Bernard Burke
Joseph Burns
C.R. Canizares
Edward Crawley
Noel Hinners
Louis Lanzerotti
Jonathan Lunine

Richard Malow
Sally Ride
Stephen Ridgway
Carl Sagan
Anneila Sargent
Linda Schele
Frank Shu
Charles H. Townes, Chairman
Robert Williams
Robert Wilson

CHAPTER 14

APPENDIX C. IMPLICATIONS OF THE EXPLORATION OF NEIGHBORING PLANETARY SYSTEMS

Dr. Alan Dressler
Carnegie Institute of Washington

There are questions that are as old as humanity. This sounds profound, but maybe it's really not. These questions—"Who are we?" "Where did we come from?"—Perhaps they actually define humanity. I remember, as far back as high school, discussions of what makes humans special in the animal kingdom. A popular answer in those days was "the ability to use tools," but today we know that to some degree other creatures use tools, to alter their environment and prosper as a species. Some people have suggested that it is the human brain's obsession for organization that defines the human animal, but, clearly, these people have never seen the condition of my office. Nowadays it is fashionable, and certainly very interesting, to say that the capacity for complex language is the defining human trait. No other Earth creature has developed language to such an extent that its cultural evolution became cumulative (that is, Lamarckian and exponential), thereby leaving its dawdling biological (Darwinian) evolution in the dust.

But could we still be missing the point? Could language development be yet another symptom and not the "disease," if you'll forgive this unkind characterization? What I'm suggesting is that asking questions like "Who are we?" is the unique human trait, because it expresses our awareness of

self. I suspect, but cannot prove, that no other species on this planet recognizes that it is a species, and that by asking "What makes us special?" we have just answered the question with the question.

Striving to discover our origins and our place in the universe is, then, a pursuit like art and architecture, music and literature they are the essential expressions of what it means to be human. It is not surprising that, throughout history, the most gifted minds have wondered about our origins and speculated about other worlds and the possibility of other creatures like us. What makes this such an obsessive search, in my opinion, is just that: here on Earth, there are no others like us.

What we are trying to do here is begin a new era in this quest. For many millennia we've been recording our speculations about the existence of other worlds, and in the last few hundred years, through science, we've actually begun to accumulate real data on the subject. In the last two decades we've made great strides in exploring our own Solar System and peering into the cloaked cradles of other planetary Systems in the making. But these are nibbles around the edges of what we really want to know. They are the appetizers; the program you've heard outlined today is the main course: direct evidence for other worlds like Earth and, possibly, the presence of life on them.

I am an astronomer, but the study of planetary systems is about as far as it can be from any area where I can claim competence. Nevertheless, I have been captivated by the possibility that an answer to one of humanity's oldest questions might be found in my lifetime. One of the things that makes this project so important, I think, is that it allows scientists with a broad range of backgrounds and interests to collaborate on an inspirational enterprise that has implications for the future role of all of science in our society. Let me explain why I think this is so. For the last two years I have been the chair of a committee named "HST & Beyond" chartered by AURA and the Space Telescope Institute Council to consider the directions of space astrophysics in the next few decades. Our committee mainly represents the astronomers who are using the Hubble Space Telescope; we have been fortunate to have a group of brilliant researchers in cosmology, the evolution of stars, galaxies, the early universe, cosmo-chemistry, etc. Only two of our committee members work in the area of planetary astronomy. Nevertheless, our committee has identified the search for other planets like Earth as one of the major goals of our science for the next decades. We came to this recommendation completely independently of the activity within NASA that has led us here today.

I would like to explain why, after extensive discussions, our committee of mostly galactic and extragalactic astronomers chose to highlight the search for Earth-like planets as one of two major goals, the other being the direct observation of galaxies in formation in the early universe. The explanation has to do with asking basic questions about why we do science and what we offer to our patrons, the public, in return for their generous support. We can all point to the benefits of biological research to better health or the food production, or to the electronic revolution brought about through solid-state physics. These are tangible results of science that make life more comfortable, or at least, more amusing. But astronomy's contribution is different, we think. It is in satisfying the hunger of the human mind. We found it useful to identify two aspects of this: the quest for the exotic, and the quest for origins.

The quest for the exotic is seen in our fascination with black holes, quasars, pulsars, we see these bizarre manifestations of the laws of physics as laboratories for understanding how the universe is put together, but people who care little or nothing about physics share the scientist's fascination with these odd creatures of the universe. We believe that this is a pure expression of human curiosity and the desire for discovery; these tales help us recapture our childhood exploration of the world; they interrupt the routine of everyday life with the promise of something new and wonderful.

Our other quest is with our origins. Humans seem discontent to merely accept our existence, but are drawn to wonder where we came from and what is our relation to the lights in the sky. From the earliest mythologies to the latest philosophical treatises, this theme runs strong. We can all be amazed with the strides made by science in this century towards understanding the evolution of our world, the Big Bang theory, nucleosynthesis, stellar evolution, general relativity, and the many discoveries of geology, paleontology, and biology. We are writing a great novel, with a wonderful story. Many of the chapters are fleshed out, or at least outlined.

However, from our astronomical perspective, we recognized two yawing gaps. One is our substantial ignorance about the birth of galaxies: despite decades of heroic efforts, not a single primeval galaxy that might be the precursor of a Milky-Way-like system has been identified. Our committee concluded that a large filled-aperture space telescope optimized for the 1–5 micron wavelength region is the most direct route to observing the actual building of common galaxies, in the expected redshift range $2 < z < 5$. The other nearly empty chapter is our subject here today. We have no direct

evidence for an Earth-like planet beyond the Solar System, and thus no opportunity to inquire about the likelihood of the conditions for our existence, and the possibility of other life forms. To watch galaxies form in the early universe, and to find other planets like Earth, are two monumental goals in the search to understand our origins. They are goals worthy of a civilization. This is why the HST & Beyond committee, composed mainly of galactic and extragalactic astronomers, embraces the search for Earth-like planets as a fundamental part of our enterprise. We believe it will have the same appeal for scientists over a broad range of fields, some far removed from astronomy. We hope that this particular project will allow scientists to rally around a common goal, helping them to articulate to the public what science is all about, what are its basic goals, and how it can help answer some of our deepest, age-old questions.

From the outside, the scientific enterprise can appear scattered and even self-serving. A project like this helps focus both the public and scientists themselves on what are the basic goals of science. It gives us an opportunity to bring our fellow citizens along on this adventure.

NASA is about exploration, maybe more than it is about science or technology. No clearer evidence of this can be found than the Apollo program to land a man on the Moon in the 1960's. The public was enthralled and swept up in the adventure, and some of the scientists in this room can trace the road that led them here back to sitting on the living room floor in front of the television as pictures came back from the Moon. In my opinion, what is marvelous about the project we are discussing today is that it offers the possibility of reviving that excitement, giving NASA a new mission of exploration that can capture public interest as it did thirty years ago. I'm sure that's what Administrator Goldin is counting on. What is doubly exciting about this project is that it combines great adventure with great science, sort of like putting the Hubble Space Telescope and the Moon landing together. That is a dynamite combination.

If we succeed in this mission, we will open a new frontier of space science. As did the Bahcall report, the HST & Beyond committee has identified interferometry from space as a crucial new technology in our study of the universe. The technology that will be developed in the Road Map program includes the ability to do microarcsecond astrometry and to build constructive interferometers that will produce images with milliarcsecond resolutions in visible light.

The astrometry program will establish fundamental distances to stars within our galaxy and even to nearby galaxies, a major step in defining the distance scale of the universe and the structure and evolution of our galaxy. How wonderful it will be to actually know the distances to Galactic Cepheid or RR Lyrae variables: the first rung of the extragalactic distance ladder will then be totally secure. Likewise, fixing the distances to globular clusters would remove this important uncertainty to the ages of the oldest stars; this matter has become central to the cosmological model as we home in on the Hubble constant and other parameters of the model.

Milliarcsecond resolution pictures would allow us to break through what are until now impenetrable barriers in our understanding, to observe the detailed structure of quasars and strange stellar systems like SS433. Detailed imaging of the surfaces of other stars will yield fundamental data on stellar structure and evolution. With pictures of nearby galaxies at such resolution we can study the stellar population and kinematics, star by star, to a level of detail that has only been possible within our own galaxy. Such observations could be decisive in the study of galaxy evolution.

These are just examples of the diverse phenomena that can be studied in no other way than by imaging interferometry from space. We can dream about a future space interferometer observatory with a half-dozen 10-meter telescopes spread over a kilometer baseline, probing the universe to a depth and resolution we can scarcely imagine. The HST & Beyond committee sees this kind of instrument, broadly applicable to the questions of astrophysics, as the scientific descendant of the Road Map program.

Finally, I want to touch on what I hope could be the long-term legacy of this program. If we can conquer the technical hurdles, I believe that we are likely to find Earth-like planets around other stars. Probably some will be found in a habitable zone, and low resolution spectra will show a tantalizing variation in the atmospheres of these planets. I don't really expect any of the first few good candidates to show ozone or other evidence for biological activity, but, of course, who knows? Either result would be fantastic: that life is abundant in the universe would drive future generations to explore further these other worlds and their biology, possibly driven by the search for sentient life. If, on the other hand, we find that Earth-like planets are rare, or, if they are common, that life may be rare, this will be perhaps an even more astounding result that will propel us to look harder, to learn just how rare we are. Once an Earth-like planet or two has been identified, once a

mother can point to the night sky and say to her son "there's a planet like Earth going around that star"; the world will become obsessively fascinated, I believe, with finding out about that world, and finding other ones. Dan Goldin wondered about taking a picture of such a world, like the picture of Earth taken from the Moon by the Apollo astronauts. Although the technology to accomplish this is far beyond our reach today, it may be within reach in the year 2025, and the world community could rally to join in such an inspiring mission.

I think it likely that the first results of the search for Earth-like planets will whet the appetite, of scientist and citizen alike, for more examples, especially for cases that show evidence of life. A larger version of the interferometer we have been discussing, with a capability for higher resolution spectroscopy to reveal the presence of weaker atmospheric features, could well be the goal embraced by a next generation of planetary explorers. And, since these are nearby stars, we will be able to contemplate, for the first time, the possibility of sending an actual probe to another world beyond the Solar System, a sort of "Voyager to planet Xanadu"; I have no way of judging whether such a spacecraft could be built in the next century, or whether the public would have the patience to invest in a project that might take 50 years to bear fruit, but what makes me take this seriously is that, from books, movies, and television, it is clear that this kind of voyage is much on our minds. There has never been a reason to raise it beyond the level of fantasy, but, for the first time, there would actually be an address to send a spacecraft. Who can say what the effect will be on the collective consciousness of humanity, and what energies it might unleash? When you allow yourself to contemplate such things, you may believe that we are on the threshold of a new age of discovery that could affect the destiny of our species.

ACRONYMS

AGN	Active Galactic Nucleus
AIM	Astrometric Interferometry Mission
AO	Adaptive Optics
ASEPS	Astronomical Studies for Extra-Solar Planetary System
CCDs	Charge Coupled Device
COBE	Cosmic Background Explorer
COMPLEX	Committee on Lunar and Planetary Exploration
CSO	Caltech Submillimeter Observatory
ESA	European Space Agency
ExNPS	Exploration of Neighboring Planetary Systems
HST	Hubble Space Telescope
IBC	Input Band Conduction
IR	Infrared
IRAS	Infrared Astronomical Satellite
ISO	Infrared Space Observatory
JCMT	James Clerk Maxwell Telescope
JPL	Jet Propulsion Laboratory
LEO	low Earth orbit
MACHO	Massive Compact Halo Objects
MIT	Massachusetts Institute of Technology
MMA	Millimeter Array
NASA	National Aeronautics and Space Administration
NIRSPEC	Near-Infrared Spectrometer
NOAO	National Optical Astronomy Observatory
NRAO	National Radio Astronomy Observatory
NRC	National Research Council
NSF	National Science Foundation
OASES	Outpost for the Analysis and Spectroscopy of Exo-Planetary Systems
QWIPS	Quantum Well Infrared Photodetectors

R&A	Research and Analysis
SAO	Smithsonian Astrophysical Observatory
SEP	solar-electric propulsion
SIM	Space Interferometry Mission
SIRTF	Space Infrared Telescope Facility
STScI	Space Telescope Science Institute
TOPS	Toward Other Planetary Systems
UCSC	University of California, Santa Cruz
YSO	Young Stellar Objects