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Introduction

GOALS AND BACKGROUND

From the times of the ancient Greek and medieval scholars, many have speculated that other worlds must exist and that some would harbor other forms of life. But up to now, no instrument, not even the Hubble Space Telescope (HST), has had the sensitivity to see even one of the large planets now known to exist around nearby stars (Chapter 3). But a new kind of telescope, an infrared interferometer, offers the sensitivity and imaging capability to detect and characterize planets as small as the Earth in orbit around nearby stars. Modern technology has brought the centuries-long interest in finding habitable planets of other stars within our grasp.

There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system. We see only the suns because they are the largest bodies and are luminous, but their planets remain invisible to us because they are smaller and non-luminous. The countless worlds in the universe are no worse and no less inhabited than our Earth.

GIORDANO BRUNO (1584) IN
DE L'INFINITO UNIVERSO E MONDI

NASA's Origins program reflects this confluence of ancient curiosity and modern skills. The Terrestrial Planet Finder (TPF), an interferometer operating in space at infrared wavelengths, will combine enormous sensitivity and high spatial resolution to advance our understanding of all aspects of planetary systems beyond our own: from their birth in nearby star-forming regions and subsequent evolution, to the potential habitability of Earth-mass planets orbiting stars up to 15 pc away. These studies will in turn shed light on the development of our own solar system and on the origin of life on Earth. TPF will seek answers to the following questions:

- Are there Earth-like planets in the "habitable zones" around their parent stars where the surface temperature is capable of supporting liquid water over a range of surface pressures?

- What are the compositions of the atmospheres of terrestrial planets orbiting nearby stars? Do their spectra show the presence of water and carbon dioxide?
- Are there atmospheric components attributable to primitive life such as ozone, seen in the Earth's atmosphere? Is there evidence for other reactive constituents that are far from equilibrium, such as oxygen and methane in the Earth's atmosphere, whose simultaneous presence is hard to explain by purely physical processes?
- What are the physical properties such as size, density, albedo, and temperature of those planets of a few Earth-masses and larger, whose existence will have been demonstrated by indirect techniques when TPF flies?
- How do planets form out of the disks of solid and gaseous material around young stars?

In addition, TPF will explore a wide range of physical processes in the universe with unprecedented detail, including the icy cores of comets, protostars condensing out of interstellar matter, the winds of dying stars, and the cores of distant ultra-luminous galaxies.

I should not hesitate to stake my all on the truth of the proposition—if there were any possibility of bringing it to the test of experience—that at least some one of the planets which we see is inhabited. Hence I say that I have not merely the opinion, but the strong belief that there are inhabitants in other worlds.

IMMANUEL KANT (1781)
THE CRITIQUE OF PURE REASON

The search for planets beyond the solar system has been proposed by a variety of NASA advisory committees, extending back almost a decade to the National Research Council (NRC)-COMPLEX (1990), NRC-*Search for Life's Origins* (1990) and TOPS (1992) reports. The basic concept adopted for TPF was described in *A Road Map for the Exploration of Neighboring Planetary Systems* (ExNPS Report 1996), which represented the consensus view of more than 100 scientists, engineers, and technologists. Three teams of researchers, two selected competitively from university and industrial communities, worked on the ExNPS study, which was forwarded to the NASA Administrator after review by a "blue ribbon" panel chaired by Professor Charles Townes. Independently of the ExNPS activity and at approximately the same time, the *HST and Beyond* report (Dressler 1996) recommended the development of an infrared interferometer to search for terrestrial planets.

The basic concept underlying TPF as described in the ExNPS report involves direct detection and spectroscopy in the 7-20 µm region of the spectrum, where the Earth itself emits most of its energy and is most readily detected against the glare of the sun. In this part of the spectrum atmospheric constituents produce very strong, deep features that would be detectable even though the planetary signal is very weak (Angel, Cheng, and Woolf 1986). The method of nulling interferometry was first suggested by Bracewell (1978) and was adapted for deep stellar cancellation by the use of multiple interfering elements and achromatic beam combination (Shao 1990; Angel 1990). Modulation of the planet's signal is effected by rotating the interferometer around the line of sight to the star, as proposed by Bracewell, and allows reconstruction of images showing multiple planets orbiting a star (Angel and Woolf 1997). A key feature of the ExNPS interferometer was an orbit located far from the sun to avoid thermal background from the zodiacal dust in our own solar system. Leger *et al.* (1993) developed this concept to allow the use of small telescope apertures as part of a proposal to the European Space Agency for the Darwin mission (Penny *et al.* 1998). The ExNPS facility was envisioned as a nulling interferometer consisting of four 1.5-2 m mirrors on a fixed 75 m baseline operating in low background conditions at 5 AU to study terrestrial planets 15 pc away.

Continued study reconfirms the basic approach of a nulling interferometer operating in the 7-20 µm part of the spectrum to detect and characterize terrestrial planets. For example, since the ExNPS report was published, the method of Bracewell nulling has been demonstrated both in the laboratory with rejection factors in excess of 25,000 at visible wavelengths, and astronomically toward the star Betelgeuse with a rejection factor of ~25 in the infrared (Hinz *et al.* 1998), giving an image of the dust cloud around this star (Chapter 10).

The implementation of TPF has evolved in three ways since the ExNPS study. First, since large, light-weight optics are being developed for the Next Generation Space Telescope (NGST), it is reasonable to consider using large apertures for an interferometer operating in the higher background conditions at 1 AU. Operation closer to the sun simplifies many of the systems-engineering and mission-design aspects of the project relative to a mission at 5 AU. Second, we now envisage using free-flying interferometer elements rather than a connected system of telescopes. The flexibility of separated spacecraft enables the interferometer to be tuned for each planetary system under study and allows observations on many baselines for detailed imaging of astrophysical objects. Finally, more complex interferometer configurations using path length modulation and rapid chopping are being considered to minimize the effects of long-term detector drifts and to reduce the need for rapid rotation of a free-flying constellation. An illustrative mission concept uses four 3.5 m telescopes operating at 1 AU on separated spacecraft with maximum baselines of about 1 km (Table 1.1 and Chapter 11).

RELATIONSHIP OF TPF TO OTHER PROGRAMS

Carrying out TPF as part of an affordable, low-risk program requires a sequence of projects that build on one another, with each mission feeding new scientific understanding and technological capabilities forward into the next. TPF will build on the scientific and technical foundations that will be laid down over the next 10 years (Table 2.1). The ground-based interferometers and the Space Interferometry Mission (SIM) will provide an essential census of planetary companions with a mass limit approaching that of the Earth for the closest stars. TPF will draw up its target lists based in large part on the results of these and other indirect searches for planets (Chapter 3). SIRTF and the ground-based interferometers will provide information on the zodiacal dust clouds that represent a source of noise and possible confusion in the search for planets around other stars (Chapter 5).

While the technology of TPF presents numerous challenges, by the time that TPF enters its development phase, NASA and its academic and industrial partners will already have built and operated ground- and space-based interferometers, flown multiple separated spacecraft in highly precise formations, and developed large lightweight apertures for space (Chapter 12). These technologies will all contribute to the implementation of TPF as outlined in Table 2.1.

Table 2.1. Scientific and Technological Precursors to TPF

Project	Science	Technology
Ground-based Interferometers: Keck Interferometer Large Binocular Telescope (LBT) Very Large Telescope Interferometer (VLTI)	Exo-zodiacal emission Planet census	Interferometry hardware and software Nulling Community training
Space Infrared Telescope Facility (SIRTF)	Exo-zodiacal emission Planetary companions	Passive cooling Drift away orbit IR detectors
Space Technology 3 (ST-3)	–	Formation flying Interferometer operations
Space Interferometry Mission	Planet census Exo-zodiacal emission	Interferometry hardware, software, operations Nulling
Next Generation Space Telescope (NGST)	Exo-zodiacal emission Planetary companions	Lightweight optics Cryogenic actuators Active coolers

OVERVIEW OF THIS REPORT

The remaining chapters in this report describe the search for habitable planets around nearby stars and the development of TPF as follows:

- Chapter 3: The status of planet searches currently underway and in the era when TPF will start operations.
- Chapter 4: Indicators of life that might be expected in the atmospheres of planets, ranging from pre-biotic, pre-photosynthetic, and photosynthetic.
- Chapter 5: The problem of the zodiacal dust clouds surrounding other stars.
- Chapter 6: Operation of TPF as interferometer for nulling and regular imaging.
- Chapter 7: The TPF target list. What stars will TPF examine in its search for planets?
- Chapter 8: Illustrative problems spanning a variety of astrophysical investigations with TPF in its imaging and nulling modes.
- Chapter 9: A sample mission that combines planet searches, planet characterization, and additional astrophysics.
- Chapter 10: Progress in the demonstration of nulling techniques and a roadmap for further work.
- Chapters 11 and 12: The mission concept used to address TPF's feasibility, and to assess the readiness of key technologies.
- Chapter 13: Programmatic issues such as schedule and cost for TPF.
- Chapter 14: A discussion of how TPF fits into a decades-long program of detecting and characterizing our nearest planetary neighbors and of searching for life beyond the solar system.

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