Terrestrial Planet Finder: the search for life-bearing planets around other stars

Charles A. Beichman

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The Terrestrial Planet Finder: The Search for Life-Bearing Planets Around Other Stars

C.A. Beichman
IPAC, Jet Propulsion Laboratory,
California Institute of Technology, Pasadena CA

Abstract

The Terrestrial Planet Finder (TPF) will detect and characterize Earth-like planets around nearby stars. NASA is currently funding a number of small studies to look at trade-offs in the design of TPF. The possible trade-offs include orbit location (1 to 5 AU), aperture size (4 to 2 m), and physically connected baselines vs. separated spacecraft flying in close formation. The performance of TPF depends critically on the brightness of the local zodiacal dust cloud at the observing site, and on the brightness and degree of structure in the zodiacal dust cloud around other stars. Sensitivity calculations indicate that TPF could accomplish its goals using 4-5 m telescopes operating at 1 AU. Such a mission would have many advantages relative to a mission operating smaller telescopes in lower background conditions at 5 AU.

Introduction

Drawing on reports such as *Toward Other Planetary Systems (TOPS)* and *Exploration of Neighboring Planetary Systems* (ExNPS; 1996), scientists have identified a strategy to search for and to characterize life beyond the solar system. The foundation of this strategy lies in ongoing results in astronomy, biology, and technology:

- Biologists have extended the range of extreme habitats where life on Earth can be found, suggesting that the development of life is a robust process that may have been repeated elsewhere in the cosmos.

- Astronomers have detected planets of Jupiter-mass around nearly a dozen nearby stars, bolstering the paradigm that planets are a natural accompaniment to the formation of stars.

- Technologists and engineers have identified techniques to make large, low-cost telescopes in space, enabling the construction of the Terrestrial Planet Finder (TPF) interferometer envisioned in the ExNPS report.

Together, these advances strengthen the case for a search using astronomical techniques for life outside our solar system.

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The Biological Fingerprints of Life

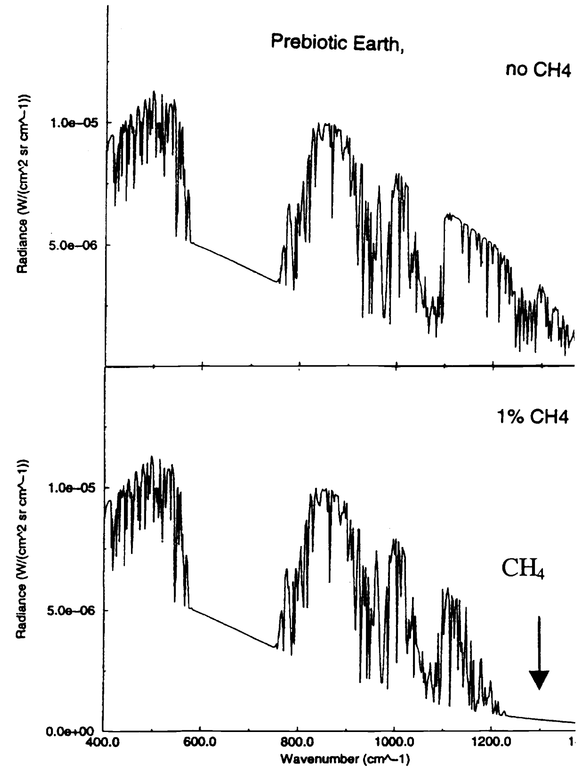

Figure 1. Calculations by Kasting (priv. comm.) show detectable amounts of CH_4 in a pre-photosynthetic Earth

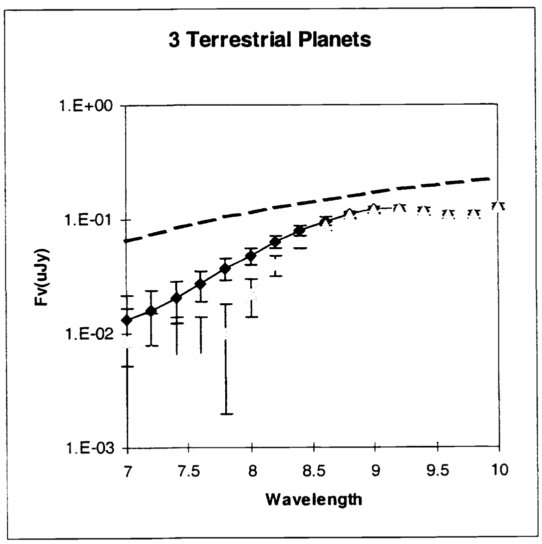

Figure 2. Simulated TPF spectrum showing a 265 K blackbody (top), a planet with O_3 and H_20 (middle), and a planet with O_3, H_2O and CH_4 (bottom).

The ExNPS report (1996) identified tracers in the 7-17 μm portion of the spectrum, in particular ozone (O_3) that would characterize a life-bearing, oxygen-rich planetary atmosphere (Leger *et al.* 1994). Another interesting trace gas would be methane (CH_4), the presence of which in an oxygen-rich atmosphere would be most simply attributable to the presence of life. However, in an atmosphere like that of the present-day earth, methane is quite rare, 1.7 ppmv (Kasting 1993) and its line at 7.6 μm would be quite difficult to detect without an order of magnitude greater sensitivity and spectral resolving power than is possible with current technology. The search for methane in a direct Earth analog would require a follow-on mission to TPF.

The Earth was not, however, always oxygen-rich. Appreciable amounts of O_2 and its proxy O_3 have been present in detectable amounts only for the past 1-2 billion years. What tracers might there be of early life, before photosynthetic reactions gave rise to the large amounts of oxygen present in our own atmosphere? New calculations (Kasting, private communication) suggest that methane-producing life on a pre-photosynthetic world would produce enough atmospheric CH_4 to be detected by TPF (Figure 1). Unfortunately, since there are abiotic sources of CH_4 such as volcanic vents, the detection of CH_4 would not be conclusive of the presence of life.

By observing in the 7-17 μm band with a spectral resolution of ~20, TPF has a good chance of identifying habitable environments and perhaps life itself on other planets across almost the entire range of evolutionary stages as existed over 3.5 billion years on Earth. Some cases, such as a CH_4 -rich atmosphere might be ambiguous, but the detection of a warm, dense, wet atmosphere, with a variety of trace gasses would be extremely interesting in the context of the development of primitive life. Figure 2 shows a simulated low resolution spectrum of three planets (1 $R_\oplus$) located 10 pc away. One planet shows only emission from a 265 K blackbody; the second shows absorption due to O_3 (9.8 μm) and H_2O (<8 μm); the third adds CH_4 (7.6 μm) to the O_3 and H_2O.

The Exo-Zodiacal Emission

Although the exo-zodiacal emission associated with dust around the target star remains an important limitation to the detectability of planets, detailed sensitivity calculations indicate that planets can be detected toward stars systems with <10 times the level of Solar System dust emission. A workshop on exo-zodiacal emission (Backman *et al.* 1998) concluded that:

- It is impossible to predict the level of warm (300 K) dust that might be found in the habitable zone around a star on the basis of its age, spectral type, or the amount of material in a Kuiper Belt (as measured in the far-IR. Too many variables such as the existence and configuration of giant planets or the presence or absence of an asteroid belt affect the amount of dust in the inner reaches of a solar system. It is necessary to measure the amount of dust in the habitable zone of each star directly.

- The fact that our own solar system would have a zodiacal cloud a factor of 5-10 less bright in the absence of our asteroid belt led the workshop participants to conclude that solar systems with as little zodiacal dust as our own, or less, might be common.

- The zodiacal emission is quite smooth with the exception of wakes or other dynamic features directly associated with the presence of planets. These wakes could be considered either as signposts for the presence of planets or as a confusing source of false planets.

- Over the next few years, astronomers will measure the amount of material in the dust clouds around neighboring stars to optimize planet detection strategies for specific stars. Important facilities for the measurement of zodiacal clouds include the Keck Interferometer and Large Binocular Telescope (LBT) which will measure the thermal emission from dust around to the habitable zone; the Space Interferometer mission (SIM) which will measure scattered visible light from dust around stars like β Pictoris; and SIRTF which will measure the amount of dust in the Kuiper Belts of neighboring stars.

The TPF Observatory

Over the past year, three contractors (Lockheed-Martin, TRW, and Ball Aerospace) and one university group (Miller at MIT) have investigated possible TPF configurations and mission concepts. They studied two orbital locations (1 and 5 AU) and two configurations (monolithic vs. separated spacecraft). As a result of these studies, the present TPF concept utilizes 2-m and 4-m telescopes built using NGST technology and operating as a nulling interferometer with a 75-100 m baseline at 1 AU.

The version of TPF described in the ExNPS report (cf. Angel and Woolf, 1997) operated at 5 AU to take advantage of the 100-300 times lower level of zodiacal emission within our solar system. However, Woolf and Angel (1998) and Beichman and Velusamy (1998) pointed out that the presence of zodiacal emission around the target star obviates to a considerable degree the advantage of operating in a low background location. Since the target star carries its own noise source with it, the lower background of the 5 AU site does not make as much of a difference as it would for fainter targets. Table 1 gives the signal and noise sources for observatories located at 1 and 5.2 AU (circularized using a Jupiter flyby). The table lists the number of detected photoelectrons in a 10^4 sec integration time for an observation at 10 μm with a spectral resolution of 20. It is clear that the sensitivity of the two sites is quite similar with both reaching SNR~3-5.

Table 1. Sensitivity of TPF at 1 and 5 AU		
Signal/Noise Source *(e^- in 10^4 s)*	*Value at 5 AU (1:2:2:1 m Telescopes on 75 m baseline)*	*Value at 1 AU (2:4:4:2 Telescopes on 75 m baseline)*
Earth at 10 pc *(~ 0.25 μJy at 10 μm)*	1.6×10^3	6.6×10^3
Local Zodiacal Emission @ β=30° *(incl. ISM cirrus)*	7.0×10^3	9.7×10^5
Exo-Zodiacal Emission (nulled)	1.7×10^5	6.7×10^5
Nulled Starlight *(max. null depth 10^{-6})*	1.6×10^4	6.5×10^4
Detector Dark Current	5.0×10^4	5.0×10^4
Total Counts	2.4×10^5	1.7×10^6
Noise (√counts)	490	1300
Signal to Noise Ratio (SNR)	3.3	4.9

Operation at 1 AU offers many advantages over a 5 AU mission, despite the disadvantage of higher local zodiacal background. Advantages of a 1 AU mission include rapid all-sky coverage, semi-annual observations of promising stars, larger observatory mass, abundant solar power and communication bandwidth, and shorter overall mission duration.

The second critical mission design trade-off concerns the interferometer configuration: monolithic structure or separated spacecraft. Preliminary industrial studies favor a separated spacecraft design for scientific flexibility (tuning the interferometer on a star-by-star basis to ensure the appropriate null, general purpose astronomical imaging), ease in integration and test, and overall system mass. Table 2 summarizes the wet masses required for four possible configurations based on the industrial studies and on the study by Miller and his collaborators at MIT (this conference). These masses are consistent with launch by a Titan 4 or Arianne 5E.

Table 2. Illustrative TPF System Masses (kg)		
	Orbital Location	
Mission Concept	*1 AU Heliocentric Orbit*	*5.2 AU (Jupiter circularized)*
Monolithic	4340	3280
Separated Spacecraft	2700	1400

Technologies

Technology advancements are critical to the successful, affordable development of TPF. These advances will come from on-going Origins missions and well as from dedicated technology programs. Critical technologies and associated missions are listed in Table 3. With these technologies in place by 2007, the mission will be in a robust shape for a new start.

In addition to specific missions, laboratory work and tests using ground-based telescopes will be an important part of the program. Figure 3 shows a demonstration of 10 μm nulling from a ground-based telescope. As described elsewhere in this conference, Hinz *et al.* (1998) have used a simple nulling

Table 3. Key TPF Technologies	
Mission or Project	*Technology*
SIRTF	Cryogenic Optics, Passive Cooling, IR Detectors, 1 AU Orbit
Keck Interferometer, Large Binocular Telescope, VLTI	Interferometer technology, nulling, imaging (IR)
SIM	Interferometer technology, nulling, imaging (visible)
DS-3	Separated spacecraft interferometry, formation flying
NGST	Large Cryogenic optics, precision deployments

interferometer to reject the starlight from α Ori to reveal its ring of extended dust emission. The best null demonstrated in these experiments was about 20:1.

Conclusions

Over the next 10 years, a vigorous program for the detection of planets with masses from Jovian to sub-Uranian using measurements of radial velocity, astrometry, precision photometry, and direct imaging will advance our understanding of the formation of planetary systems, refine the target list for planet searches, further our understanding of the exo-zodiacal dust clouds, provide a training ground for students, lead to the development of relevant techniques such as interferometry, and serve as a catalyst for scientific and popular interest in the program. In parallel with these scientific advances, technological developments for various Origins and other projects will lead to a state of technological readiness for TPF sometime around 2007. By the start of the second decade of the next millennium, NASA, perhaps in collaboration with other nations, will undertake a dramatic mission to search for terrestrial planets and for signs of life outside the confines of our solar system.

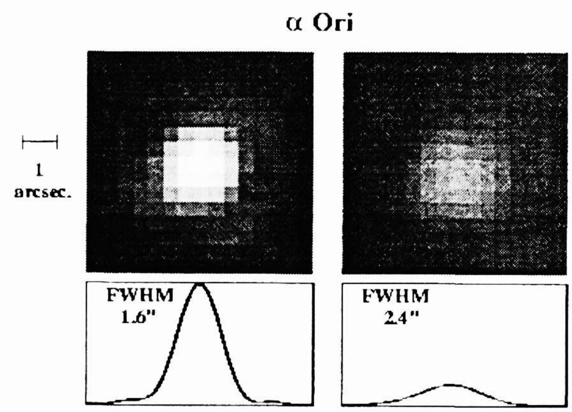

Figure 3. Images of α Ori from the MMT with and without an interferometric null. (Hinz *et al.* 1988, this conference).

Acknowledgments

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