NASA'S TERRESTRIAL PLANET FINDER MISSION: THE SEARCH FOR HABITABLE PLANETS

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ABSTRACT

The Terrestrial Planet Finder (TPF) is one of the major missions in the NASA Office of Space Science Origins Theme. The primary science objective of the TPF mission is to search for, detect, and characterize planetary systems beyond our own Solar System, including specifically Earth-like planets. This paper describes the current status of TPF as well as outlines the plans for near term science investigations, mission studies and technology development leading to a mission architecture selection in the 2006 time frame in support of a launch by the middle of the next decade.

1. INTRODUCTION

From a humanistic perspective, one of the most profound questions of our time is whether or not Earth-like planets—habitable or already life-bearing—exist elsewhere in the universe. NASA's Origins Theme in the Office of Space Science seeks to address this subject from a scientific perspective. The defining questions which NASA's Origins Theme [1] seeks to answer are: (1) Where did we come from? and (2) Are we alone? The top level scientific motivation for this endeavor has been discussed in a series of reports over the past decade including: The Search for Life's Origins [2]; TOPS: Toward Other Planetary Systems [3]; A Roadmap for Exploration of Neighboring Planetary Systems (ExNPS) [4]; HST and Beyond [5]; and, Terrestrial Planet Finder- Origins of Stars Planets and Life [6]. The interested reader is referred to these documents for more detailed information and numerous references to the scientific and technical literature.

The specific science objectives of the Origins Theme are: (1) To understand how today's universe of galaxies, stars and planets came to be; (2) To learn how stars and planetary systems form and evolve; and, (3) To explore the diversity of other worlds and search for those that might harbor life. The Terrestrial Planet Finder (TPF) Mission as one of the major missions in the Origins Theme will address these questions and objectives. The specific goal of the TPF mission is to search for and characterize Earth-like planets as well as explore and understand the formation and evolution of planets and ultimately, of life beyond our Solar System.

The search for Earth-like planets will not be easy. The targets are faint and located close to parent stars that are > 1 million times (in the infrared) to > 1 billion times (in the visible) brighter than the planets. However, the detection problem is well defined and can be solved using technologies that can be developed within the next decade. To meet the TPF mission goal requires a census of planets orbiting a statistically significant number of nearby stars down to the mass of the Earth; an understanding of the physical and biological processes that make a planet habitable and that might lead to the evolution of a "living" planet; and the direct examination of nearby planets for signs of life. With these goals in mind, the specific objectives of the TPF mission, as articulated by the TPF Science Working Group (TPF-SWG) are summarized below.

The primary objective of TPF is to detect radiation from any Earth-like planets located in the habitable zones surrounding a statistically significant number of solar type stars. Following detection, TPF will characterize the orbital and physical properties of the detected planets to assess their habitability and characterize their atmospheres to search for potential biomarkers among the brightest Earth-like candidates.

A secondary, but very important objective of TPF is to detect radiation from and characterize a variety of solar system constituents in addition to Earth-like planets. Our understanding of the properties of terrestrial planets will be scientifically most valuable within a broader framework that includes the properties of all planetary system constituents, e.g., both gas giant and terrestrial planets, and debris disks. Some of this information, such as the properties of debris disks and the masses and orbital properties of gas-giant planets, will become available with currently planned space or ground-based facilities. However, the spectral characterization of most giant planets will require observations with TPF. TPF's ability to carry out a program of comparative planetology across a range of planetary masses and orbital locations in a large number of new solar systems is by itself an important scientific motivation for the mission.

Finally, TPF will be able to collect data on a variety of targets of general astrophysics interest. An observatory with the power to detect an Earth-like planet orbiting a nearby star will provide an unprecedented capability for such ancillary science observations.

2. BIO-SIGNATURES AND PLANET CHARACTERIZATION

Early discussions by the TPF-SWG led to the conclusion that observations in either the visible/near infrared or mid-infrared portions of the spectrum were scientifically important and technically feasible. A sub-committee of the TPF-SWG was established under the leadership of Dr. David Des Marais, an astrobiologist from the NASA Ames Research Center, to assess the two wavelength regimes with respect to their suitability for addressing TPF science requirements. Their report [7] can be summarized briefly as follows:

- Photometry and spectroscopy in either the visible/near infrared or mid-infrared region of the spectrum would give compelling information on the physical properties of planets as well as on the presence and composition of an atmosphere.

- The presence of molecular oxygen (O_2) or its photolytic by-product ozone (O_3) are the most robust indicators of photosynthetic life on a planet.

- Even though H_2O is not a bio-indicator, its presence in liquid form on a planet's surface is considered essential to life and is thus a good signpost of habitability.

- Species such as H_2O, CO, CH_4, and O_2 may be present in visible/near infrared spectra of Earth-like planets (0.7-1.0 micron minimum and 0.5-1.1 microns preferred).

- Species such as H_2O, CO_2, CH_4, and O_3 may be present in mid-infrared spectra of Earth-like planets (8.5-20 microns minimum and 7-25 microns preferred).

- The influence of clouds, surface properties, rotation, etc. can have profound effects on the photometric and spectroscopic appearance of planets and must be carefully addressed with theoretical studies in the coming years.

3. SCIENCE REQUIREMENTS

Based on the goals and objectives of the TPF mission, the work of Des Marais' group, the contributions of the TPF-SWG and its precursor groups, and many other contributors, the TPF-SWG has developed a set of preliminary Science Requirements for the mission. At the highest level, these is a strong scientific rationale for an observatory with a reasonably large field of view, 0.5-1 arcseconds, both to search the nearest stars for terrestrial planets and characterize them and to characterize the giant planets and disks around a subset of stars (for example a Jupiter at 5 AU around a star at 10 parsecs). The preliminary Science Requirements as developed by the TPF-SWG are summarized below.

TPF should be designed to detect and characterize terrestrial-type planets within the habitable zone around nearby stars where terrestrial-type planets are defined to be "Earth-sized" objects, between 0.5 and 2 times the radius of the Earth with masses, for rock-metal planets, from 0.1-10 times the mass of the Earth.

TPF should fully satisfy these science requirements for 30 late-F, G and K-dwarf "core" stars. TPF should be able to partially satisfy these science requirements for an additional "extended" sample of 120 late-F, G and K-dwarf stars as well as M-dwarf, early-F and A star targets of opportunity. A TPF "stretch" mission goal should be to meet these science requirements for the full set of 150 stars.

Completeness in terms of the orbital space searched around each star must allow for a "highly confident" search for planets within the habitable zones of nearby stars. Within the *continuously* habitable zone defined as 0.9-1.1 AU for a G-type star ($\propto L^{1/2}$ in units of the solar luminosity), TPF should be able to detect with 95% completeness terrestrial planets with at least half the surface area of the Earth and with Earth albedo. With a more generous habitable zone defined as 0.7-1.5 AU for a G-dwarf, TPF should be able to detect with 95% completeness an Earth sized planet with Earth albedo.

TPF should be able to obtain spectra in an effort to determine the existence of an atmosphere, detect water, detect carbon dioxide (in the infrared), and detect oxygen/ozone or methane if these are present in astrobiologically interesting quantities. The wavelength range should be 0.5-0.8 microns (extension to 1.05 microns desirable) in the optical and 6.5-13 microns (extension to 17 microns desirable) in the infrared, with spectral resolutions of 75 and 25 respectively. The spectrometer should be capable of $R>100$ for the brightest sources. Detections of Rayleigh scattering and the absorption edges of photosynthetic pigments are desirable as well.

TPF should also detect and take spectra of many giant planets around stars out to at least the orbital location of our own Jupiter. These observations will greatly increase our knowledge of the physical properties of giant planets, their evolution, and their influence on the dynamical environments in which habitable planets may or may not flourish.

The survey of core and extended stars to detect planets, including at least 3 visits, should be completed in ≈2 years. Additional visits for detected planets to determine the orbits and to characterize them are required beyond the 2 year detection phase.

4. ARCHITECTURE STUDIES

Over the last quarter century, there have been a number of studies of the feasibility of space observatories for the detection of planets beyond our solar system [3.4.5]. In 1999, JPL published a description of a formation-flying, nulling infrared interferometer (the 'TPF Book design") consisting of four spacecraft each supporting a 3.5-m telescope, and a separate spacecraft for the beam combiner [6]. The optics on each spacecraft have a multi-layer thermal shield to provide passive cooling to 35 K. The spacecraft are positioned along a line oriented normal to the direction of observation and collector telescopes relay the starlight to a beam combiner so as to maintain the optical paths through the system equal to within a few cm. The array is rotated around the line-of-sight over a 6-hour period while observing the source. The starlight is rejected in a nulling beam-combiner with the use of delay lines and the planet light is sent through a spectrometer. Two or more beam combining modules allow the flexibility of changing the observing mode (θ^6 null or θ^4 null with chopping). An artist's conception of this concept is shown in Fig. 1.

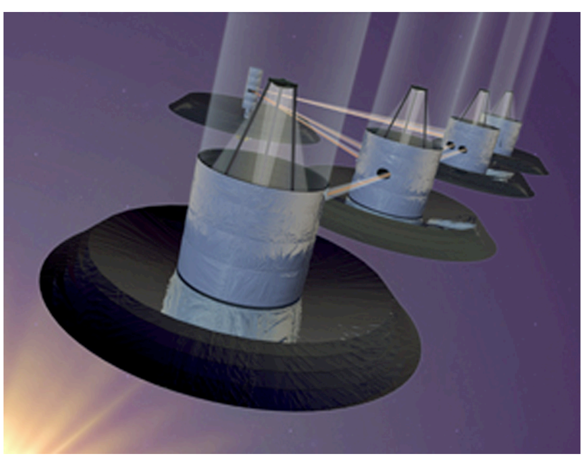

Fig. 1. An artist's conception of the TPF Book Design, a formation flying nulling infrared interferometer [6].

The TPF Book design is in many respects similar to early versions of ESA's Darwin mission concepts [8] which also used free-flying telescopes, but in a two-dimensional array that potentially has some advantages for the rejection of exo-zodiacal light.

In March, 2000, the TPF project at JPL solicited Pre-Phase A Architecture Studies from the community and selected four university/industry teams to examine a broad range of instrument architectures capable of directly detecting radiation from terrestrial planets orbiting nearby stars, characterizing their surfaces and atmospheres, and searching for signs of life. Over the course of two years, the four teams incorporating more than 115 scientists from 50 institutions worked with more than 20 aerospace and engineering firms in support of the study.

In the first year, the study teams and the TPF-SWG examined approximately 60 wide-ranging ideas for planet detection. In January, 2001, four major architectural concepts with a number of variants were selected for more detailed study. These included the previously studied formation-flying infrared interferometer. Following a second year of study, in January, 2002, two broad architectural classes, infrared interferometers (both the formation flying type and the structurally connected type) and visible/near infrared coronagraphs, were found to appear sufficiently realistic to the study teams, the TPF-SWG, an independent Technology Review Board, and to the TPF Project that further study and technological development was recommended to NASA.

The primary conclusion from the TPF Pre-Phase A Architecture Study [9] was that with suitable technology investment starting now, a mission to detect terrestrial planets around nearby stars could be launched by the middle of the next decade (2010–2020). The two classes of architectures deemed suitable for further investigation are summarized below.

4.1 <u>Coronagraph Architectures</u>

The TPF science could be accomplished at visible/near infrared wavelengths with a large telescope (5-10 meter diameter aperture) equipped with a selection of advanced optics to reject scattered and diffracted starlight (apodizing pupil masks, coronagraphic stops, and deformable mirrors, etc.). Such an instrument can make direct images of reflected light from Earth-like planets. While conceptually simple to operate at the system level, such an instrument offers significant technical challenges at the component/assembly/sub-system level, including construction of a very high surface quality primary mirror (approximately $\lambda/100$), a very large (probably deployable) telescope and precise (approximately $\lambda/3{,}000$), stable (approximately $\lambda/10{,}000$) wavefront control. To achieve the required level of wavefront correction required, a deformable mirror of up to 10,000 actuators may be required. The time to survey 150 stars three times each to ensure high reliability detections of planets is estimated to range from 45 days for one coronagraph design to 2 years for one of the shaped pupil designs using a lower-precision primary mirror.

The coronagraph teams investigated the prospects of their designs for general astrophysical observations, assuming it were possible with a low additional cost to the overall mission. A large, conventional telescope equipped with a visible coronagraph readily lends itself to a traditional suite of astronomical instrumentation.

An artist's conception of one version of a large visible coronagraph developed by the Ball Aerospace team as part of the TPF Pre-Phase A Architecture Study [9] is shown in Fig. 2.

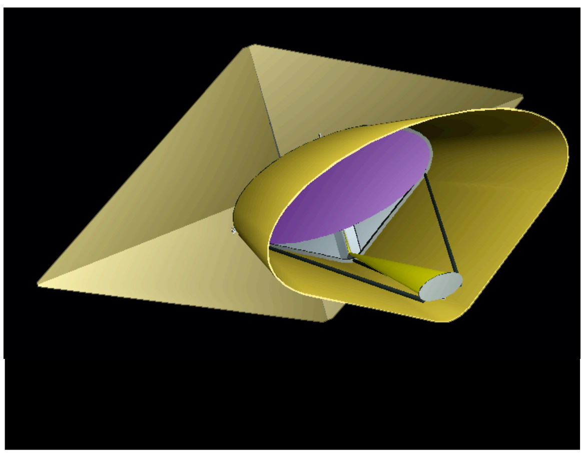

Fig. 2. Artists conception of a large visible coronagraph system utilizing an off-axis, elliptical 4x10 meter primary mirror.

4.2 Interferometer Architectures

Alternatively, the TPF science could be accomplished at mid-infrared wavelengths with nulling interferometer designs using from three to five 3–4 meter diameter telescopes—located either on individual spacecraft flying in formation separated by up to 20-200 meters or on a large 20-40 meter long structure. Such instruments could directly detect the thermal radiation emitted by Earth-like planets. While no single component/assembly/sub-system appears to be unusually challenging, this architectural class presents significant technical challenges at the system level, including passive cooling, nulling, beam transport, and formation flying or large precision deployable structures. The time to survey 150 stars three times each is estimated to be approximately 120 days for both of the interferometer concepts.

The interferometer teams also investigated the prospects of their designs for general astrophysical observations, assuming it were possible with a low additional cost to the overall mission. An infrared interferometer offers the possibility of dramatic gains in sensitivity and angular resolution particularly in the case of the formation flying version. Such an instrument could be utilized in specialized applications such as investigating star-forming disks or the cores of active galaxies.

An artist's conception of one version of a formation flying interferometer (the TPF Book Design) was shown in Fig. 1. An example of one version of a structurally connected infrared interferometer (without its sunshade) developed by Lockheed-Martin as part of the TPF Pre-Phase A Architecture Study [9] is shown in Fig. 3.

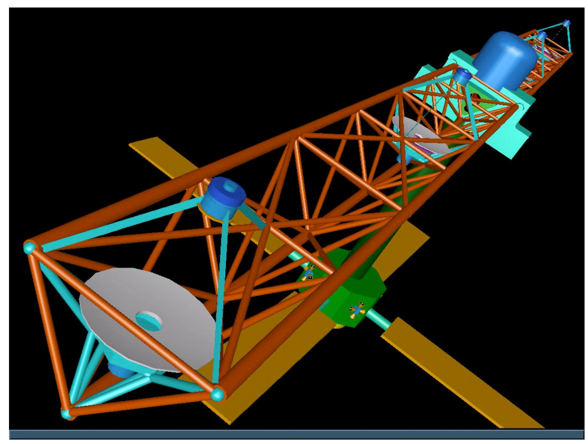

Fig. 3. Artist's conception of a structurally connected infrared interferometer system (without sunshade) utilizing four collector telescopes.

4.3 Smaller Scale Mission Architectures

In addition to their recommendations with regard to the feasibility of various architectures to meet the TPF science requirements, the study teams and the TPF-SWG strongly suggested that there were important scientific questions that could be addressed by missions of smaller scale than the fully capable TPF. For example, a mission of lesser capability would be able to detect Earth-like planets around a few tens of stars within 10-20 parsecs if any exist, and study the composition and physical properties of gas-giant planets around stars as far away as 50 parsecs. Such a mission—perhaps consistent with the scale of NASA's Discovery or New Frontiers programs—might be carried out either in the visible (an active coronagraph on an apodized 2–3-meter aperture telescope) or in the infrared (a nulling interferometer with 1-2 meter telescopes on a 10–20 meter structure).

5. NEAR TERM PRE-PHASE A PLANS

5.1 Overview

The TPF studies to date have established that observations in either the visible/near-infrared or mid-infrared wavelength region would provide important information on the physical characteristics of any detected planets, including credible signposts of life. In fact, the two wavelengths provide complementary information so that in the long run, both would be desirable. The choice of wavelength regime for TPF will—in the estimation of the TPF-SWG and the independent Technology Review Board—be driven by the technological readiness of a particular technique.

The challenge of developing the technologies required to enable any of the candidate architectures will require substantial funding over the next several years to bring them to the appropriate level of readiness. The major goal of the TPF pre-phase A activity is to identify and select an architecture for the TPF mission. The architecture selection will be based heavily on the technological feasibility demonstrated for candidate architectures. Over the period FY2003 to FY2006, the TPF project will perform activities focused on achieving this goal no later than FY2006 to support a Phase A start in FY2007 and a launch by 2015. The TPF Project has planned periodic opportunities to narrow the scope of the investigations or make an early downselect, based on results from the technology development and design studies or on programmatic factors.

The TPF Technology Plan [10] summarizes the top-level scope, approach, and metrics for development and acquisition of technology during the Advanced Study Phase (Pre-Phase A) to establish feasibility of a candidate TPF architecture(s) and support entry into Phase A. During this period, the project will focus on science, technology, and system design studies associated with the interferometer and coronagraph architectures. TPF will be a technologically rich mission requiring demonstration or inheritance of numerous technologies. NASA is committed to a well-funded technology development program, which will be carried out in the following context.

The bulk of TPF funding will be targeted to demonstrate the key technologies needed for both architecture classes. The goal will be to develop the critical technologies necessary for discriminating between architectures to a NASA Technology Readiness Level (TRL) of ~5 by mid FY2006. Technology demonstration will be performed through a combination of efforts at JPL and significant competed/directed efforts in industry and at universities. Several major technology solicitations have already been executed or are in preparation.

JPL, with support from industry and university experts and the TPF-SWG, will perform detailed mission studies of point designs for the coronagraphic and interferometric versions of TPF.

Approximately 10% of the total TPF budget will be allocated on an annual basis to support TPF preparatory science investigations and fellowships with the goal of better understanding the nature and, if possible, the frequency of occurrence of Earth-like planets around other stars. The highest priority science questions to which these investigations should respond will be determined by the TPF-SWG and described in a TPF Precursor Science Roadmap. These funds will be awarded through a combination of directed studies and competitive processes such as NASA Research Announcements (NRAs).

Annual reviews will be held to assess the state of knowledge and development and assist in determining if termination, acceleration, or reduction of any technology efforts is warranted, or if an architecture selection is possible prior to 2006.

Through a Letter of Agreement (LOA), now signed, TPF will coordinate with the European Space Agency's Darwin Study with the goal of achieving consensus on a common architecture for a potential joint planet-finding mission. Specifically, the LOA calls on NASA and ESA to do the following:

- Designate DARWIN & TPF study phase managers to work together;
- Designate scientists to serve as members of the other agency's Science Team and participate in joint planet finding science related studies and activities;
- Conduct jointly, architectural concept studies for a planet finding mission, including proposing a baseline mission architecture for selection by NASA and ESA management;
- Conduct technology development planning and provide technology development results to the extent necessary to support planning for a joint ESA/NASA planet finding mission and technology demonstration missions.

The scientific exchanges suggested considerable interest in an international collaboration on a mission to address one of humanity's oldest questions, "*Does life exist beyond our Earth?*"

5.2 Architecture Maturation Process

The architecture studies described earlier in this document have provided a set of baseline technology needs and requirements that have been utilized to plan and initiate the technology development process for TPF. During pre-phase A, the TPF-SWG will continue to define and refine the mission science requirements including both the science floor and the goals. These in turn will be passed on to the Interferometer and Coronagraph Design Teams, which will generate point designs and associated error budgets/specifications and identify technology needs and concerns, including performance requirements and priority.

The technology needs will then be assessed, and approaches to meet them will be identified. Mitigation approaches will include system engineering analysis, inheritance, and technology demonstration/ development. Where technology development is required, the technology teams will be advised, and they will work to address the need. As the technology development proceeds and matures, results, including quantitative performance data will be passed back to the Design Teams. Thus, in an iterative process, the feasibility of the point designs will be determined, and the technology performance requirements will be updated.

Ultimately, the estimated cost of the candidate point designs will be determined by the engineering and design teams working with experienced cost analysts. This information along with the technology development results and the design studies will be used in the architecture selection process.

5.3 Technology Development

Based on the architecture studies by the industry/academia teams, the TPF Project has identified preliminary TPF requirements, key technologies to be developed, and associated performance goals to demonstrate feasibility of the various architectures. The identified key technologies and performance goals are consistent with current understanding of the TPF technology and mission needs, as identified through several years of study of candidate architectures (mid-infrared interferometers and visible/near infrared coronagraphs). Development tasks have also been identified to address the key technologies within the TPF Project Work Breakdown Structure. The lists of currently planned technology development/demonstration are included below.

Technology efforts in support of the visible/near infrared coronagraph architectures include:

- Technology Demonstration Mirror
- High Contrast Imaging Testbed
- Advanced Coronagraph Technologies
- Mask & Stops Technology
- Wavefront Sensing & Control Technology
- High Actuator density Deformable Mirror
- Sub-Å Wavefront Sensing
- Integrated Modeling of Optical Systems

Technology efforts in support of the infrared interferometer architectures include:

Core Technology
- Achromatic Nulling Testbeds (Room Temperature and Cryogenic)
- Advanced Nulling Technology
- Phasing Testbed
- Spatial Filters
- Cryogenic Delay Lines
- Cryocoolers

Structurally Connected Architecture
- Structurally Connected Interferometer Testbed
- Cryogenic Structures Modeling & Technology

Formation Flying Architecture
- Formation Interferometer Testbed
- Formation Algorithms & Simulation Testbed
- Formation Sensor Testbed
- Formation Control Testbed

The interested reader can refer to the TPF Technology Plan [10] for more detailed descriptions of these efforts.

5.4 Science Studies

Our understanding of planetary systems has undergone a profound shift in the past several years. Beginning with the remarkable discoveries of planets orbiting other stars like the sun by Mayor and Queloz [11] and Marcy and Butler [12], the field has been transformed from a situation in which speculation, educated guesses, and extrapolation from a single studied example (our own system) have been abruptly replaced by the empirical wealth of nearly 100 different planetary systems, with several new planets being discovered every month. Yet these discoveries just reveal the tip of the iceberg. If our solar system is a typical abode for planets, these giant planets would probably be accompanied by at least that many sibling terrestrial planets.

The sheer variety of planetary systems -- including hot Jupiters, eccentric giants, and resonance locked pairs – has come as a surprise. The current situation is perhaps analogous to the time during which Tycho Brahe was accumulating planetary observations of unprecedented accuracy, but before Kepler's synthesis of the laws of planetary motion and Newton's discovery of universal gravitation.

There is a need for TPF precursor science including both observational and theoretical programs focused on the issues of planetary formation and evolution, which can explain the observed variety of planets and provide a road map to the likely distribution of terrestrial worlds like our own. This information is critical to our growing understanding of how solar systems, terrestrial planets, and ultimately abodes of life like our own form and evolve. In addition, some of this information is directly relevant to the design of TPF.

A TPF Precursor Science Roadmap [13] is currently in preparation as a companion document to the TPF Technology Plan [10]. This document will describe key scientific information needed to assess the architecture and scope of TPF as well as to lay the foundation for the next decade of research relevant to the search for life on other worlds. This document will represent a broad consensus of the science community on the areas of scientific importance, which support the goals of TPF.

This science community is worldwide. Of particular note is the collaboration between NASA and ESA on the joint scientific objectives of the TPF and Darwin missions. This Roadmap is intended to be inclusive, both of the Darwin science goals, but also of the precursor science efforts in Europe and worldwide. The four most important challenges for precursor science activities for TPF are:

- To assess or better constrain the fraction of stars with terrestrial-sized, potentially habitable planets. TPF is perhaps the most technically challenging mission of any planned in space science. The mission is defined in scope, complexity, cost, and scientific return by the answer to the question: "How common are Earth-like planets around nearby stars?";

- To learn how dust disks around other stars can help us to understand better the formation and evolution of planets, can act as a signpost for the presence of planets, and might potentially disrupt TPF's ability to detect planets;

- To carry out a thorough, systematic, comprehensive, and in-depth study of potential TPF targets, including critical observations with HST, SIRTF, Keck-I, LBT-I, VLT-I, Herschel, MOST, COROT, Eddington, and Kepler observatories; and

- To build a community infrastructure centered on the forthcoming TPF science projects.

Precursor science research including both observational and theoretical investigations will be actively supported by NASA and in particular the TPF Project.

This TPF Precursor Science Roadmap will present a multidisciplinary approach to preparing the way for TPF. It will reflect the breadth and diversity of the growing field of the study of extrasolar planetary systems. For TPF, we must be sure that we are posing the scientific questions correctly; and that we will be able to interpret the results that TPF will deliver. No single observing method or numerical model provides the whole story, so the approach laid out in the Roadmap proposes many interlocking, interdisciplinary studies. Taken together, they will lay the foundation for an entirely new field of scientific endeavor for the twenty-first century: the exploration of planetary systems in our solar neighborhood – their physical, chemical, and biological properties; and their formation and evolution.

6. CONCLUSION

One of mankind's longest standing questions is: "*Are we alone in the universe?*" The successful detection of an Earth-like planet with an environment suitable for life as we know it would have dramatic implications for humanity's view of our place in the universe. The scientific answer to this question builds not only on astronomy and space sciences, but draws on geophysics, atmospheric physics, biophysics and organic chemistry. Observations conducted from space over the next two decades will provide the key to understanding the origin of life and its evolution in the universe by allowing us to detect and study Earth-like planets and to characterize them as possible abodes of life. Although for centuries this question has been the topic of vigorous philosophical and religious debate, we have finally arrived at a time when our technology has advanced to a state that allows us to address this question with the tools of science.

Current and future ground and space-based observatories have taken and will continue to take the first small steps with the discoveries of additional planets via radial velocity studies, transits, and the imaging of hot young planets (or brown dwarfs). Within the next decade, approved NASA mission such as SIM, Kepler, and JWST will take the next important steps by carrying out a planetary census and imaging Jupiter-mass planets around the nearest stars. But it will only be with the launch of TPF that we will be able to address the central questions of Earth-like planets, habitability and life beyond our solar system.

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