Terrestrial Planet Finder
Science Overview

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What will TPF do?

• Survey the local stellar neighborhood for terrestrial planets
  – Sample size: ~150-250 stars
  – Direct detection in optical or mid-IR

• Characterize the planets it detects
  – Orbital solutions
  – Low-resolution (R~50) spectroscopy
  – Search for possible biomarkers

• Learn about the formation and evolution of planetary systems
  – TFP study multiple-planet systems with giant and terrestrial planets, dust clouds

• General astrophysics
  – Use TPF’s unique capabilities for astrophysical imaging
  – Design is driven by planet-searching requirements
  – Little incremental cost to the mission
Fundamental Facts To Remember About the Search for Planets and Life

- The necessary ingredients of life are widespread
  - Observation reveals uniformity of physical and chemical laws
  - Origin of the elements and their dispersal is well understood
  - Carbon bonds is unique and ubiquitous: Forget Silicon life.
- Life on Earth can inhabit harsh environments
  - Micro- and environmental biology reveals organisms in extremes of temperature, chemistry, humidity.
- Life affects planetary environment in a detectable way
  - Our own atmosphere reflects the presence of primitive through advanced life
- Planets are a common outcome of star formation
  - Modern theory of star formation makes planet formation likely

Organic Chemistry Ubiquitous: in Comets...

<table>
<thead>
<tr>
<th>Species</th>
<th>Abundance</th>
<th>Detection Method(s)</th>
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<tbody>
<tr>
<td>H2O</td>
<td>100</td>
<td>IR, radio, IR, UV</td>
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<tr>
<td>CO</td>
<td>23</td>
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<tr>
<td>CO2</td>
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<td>0.005</td>
<td>UV</td>
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</table>
**Star & Planet Forming Regions**

IR, submm, mm spectra reveal gas phase, ices, mineralogical signatures of many species, incl: $\text{H}_2\text{O}$, $\text{CO}_2$, $\text{CH}_3\text{OH}$, $\text{CO}$, $\text{CH}_4$, formic acid ($\text{HCOOH}$) and formaldehyde ($\text{H}_2\text{CO}$), etc.

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**Signatures of Life**

- **Oxygen** or its proxy **ozone** is most reliable biomarker
  - *Ozone* easier to detect at low *Oxygen* concentrations but is a poor indicator of quantity of *Oxygen*
- **Water** is considered essential to life.
- **Carbon dioxide** indicates an atmosphere and oxidation state typical of terrestrial planet.
  - Long wavelength lines in both near (1 $\mu$m) and mid-IR (16 $\mu$m) drives angular resolution and system temperature (mid-IR)
- **Abundant Methane** can have a biological source
  - Non-biological sources might be confusing
  - High spectral resolution and short wavelength rejection
- Find an atmosphere out of equilibrium
- Expect the unexpected

Visible and mid-IR provide significant atmospheric signatures and potential biomarkers
Gas Giant Planets

- Over 100 planets found using radial velocity wobble
  - ~10% of stars have planets
  - Most orbits < 2-3 AU
  - Half may be multiple systems

- Planets on longer periods starting to be identified
  - 55 Cancri is solar system analog

- Astrometry (SIM) and radial velocity will determine solar system architecture to few $M_\oplus$

Marcy et al.

Space Interferometer Mission (SIM) Will Make Definitive Planet Census

What We Don’t Know
- Are planetary systems like our own common?
- What is the distribution of planetary masses?
  - Only astrometry measures planet masses unambiguously
- Are there low-mass planets in “habitable zone”?

A Deep Search for Earths
- Are there Earth-like (rocky) planets orbiting the nearest stars?
- Focus on ~250 stars like the Sun (F, G, K) within 10 pc
- Sensitivity limit of ~3 $M_\oplus$ at 10 pc requires 1 μas accuracy

A Broad Survey for Planets
- Is our solar system unusual?
- What is the range of planetary system architectures?
- Sample 2000 stars within ~25 pc at 4 μas accuracy

Evolution of Planets
- How do systems evolve?
- Is the evolution conducive to the formation of Earth-like planets in stable orbits?
- Do multiple Jupiters form and only a few (or none) survive?
TPF Science Requirements-I

- Detect and characterize terrestrial-sized planets around nearby stars.
- Satisfy requirements for "core sample" of 30 (late-F, G and K dwarf) stars.
- Partially satisfy requirements for "extended" sample of 120 additional stars (late-F, G, and K dwarf) as well as M-dwarf, early-F, and A-star targets of opportunity.
  - Survey of core and extended stars, including at least 3 visits, should be completed in ~2 years.
  - Additional visits of detected planets to determine orbits beyond the 2 year detection phase.
- A "TPF stretch mission" should meet the above requirements for the full sample of ~150 stars.
- Within the CHZ (0.9-1.1 AU for a G-type star \( \propto L^{1/2} \)), TPF shall be able to detect with 95% completeness, terrestrial planets at least half the surface area of the Earth with Earth's albedo.
  - Within a more generously defined HZ (0.7-1.5 AU for a G-dwarf), TPF shall be able to detect an Earth-sized planet with Earth albedo with 95% completeness.

TPF Science Requirements-II

- TPF must be able to obtain spectra in an effort 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 0.5-0.8 \( \mu m \) (1.05 \( \mu m \) desirable) in the optical and 6.5-13 \( \mu m \) (17 \( \mu m \) desirable) in the infrared, with spectral resolutions of 75 and 25, respectively.
  - Spectrometer capable of R>100 for the brightest sources.
  - Detection of Rayleigh scattering and the absorption edges desirable.
- Strong desire for large field of view, 0.5-1.0 arcsec, to search the nearest stars for terrestrial planets and to characterize giant planets in Jupiter-like orbits.
TPF Candidate Architectures

- **Visible Coronagraph**
  - System concept is relatively simple: 4-10 m mirror on a single spacecraft
  - Components are complex
    - Build adequately large mirror of appropriate quality ($\lambda/100$)
    - Hold ($\lambda/3,000$) with ($\lambda/10,000$) stability during observation with deformable mirror

- **IR Interferometer**
  - Components are simple: 3-4 m mirrors of average quality
  - System is complex: 30 m boom or separated spacecraft with $\sim$ nm stability

Spectral Range and Resolution

![Graph showing spectral range and resolution with various water vapor concentrations.]
Atmospheric Spectrum Reveals Physical Characteristics and Signs of Life

- Good physical indicators and atmospheric tracers in both visible and mid-IR
- TPF spectroscopy at resolution $R \sim 50$

![Graph](image1.png)

*Christensen and Pearl 1997*

![Graph](image2.png)

*Wölf, Traub and Jucks 2001*

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Four Hard Things About TPF

- **Sensitivity (relatively easy)**
  - Detection in hours $\rightarrow$ spectroscopy in days in Visible or mid-IR
  - Need 12 m$^2$ of collecting area ($\geq 4$ m) for star at $\sim 10$ pc
  - Integration time $\propto$ (distance/diameter)$^4$

- **Angular resolution (hard)**
  - 100 milliarcsec is enough to see $\sim 25$ stars
    - But this requires $\geq 4$-m coronagraph or $\geq 20$-m interferometer
  - Baseline/aperture $\propto$ distance

- **Starlight suppression (hard to very hard)**
  - $10^{-4}$ to $10^{-6}$ in the mid-IR
  - $10^{-8}$ to $10^{-10}$ in the visible/near-IR

- **Solar neighborhood is sparsely populated**
  - Fraction of stars with Earths (in habitable zone) unknown
  - Unknown how far we need to look to ensure success
  - Surveying substantial number of stars means looking to $\sim 15$ pc
The Observational Challenge!

- But not near a 5\textsuperscript{th} mag star

- HST/HDF reaches V=30 mag

- SIRTF/GOODS will reach 0.2 $\mu$Jy at 8 $\mu$m in 25 hours

Current SWG sub-groups

- Science Program (Lunine)
  - How Many Stars? Signatures

- Education & Public Outreach (Backman)
  - Convince Colleagues
  - Convince Public

- Design Ref. Mission (Brown)
  - Targets, Zodi, Observing Scenarios

- Precursor Science (Lint)
  - Freq of Earth Target Selection

- Interferometer (Johnson)
  - PFI or SCI

- Coronograph (Traub)
  - $\sim$1m or $\sim$8-10m

- Ancillary Science (Kuchner)
  - Comparative Planetology
  - General Astrophysics

- Technology (Miller)
  - What is possible?
TPF Precursor Science Roadmap

- What observational and theoretical / modeling programs should be done to help the choice of TPF architecture?
- What observational and theoretical / modeling programs should be done to help define the scientific “scope” of TPF?
- What should be done to ensure that the scientific infrastructure is built to support TPF?
- What areas of extrasolar planet research should be supported to develop the field and make a firm foundation for correctly interpreting TPF science results?

Questions for TPF Precursor Science

- What is $\eta_\odot$?
  - Transits (MOST, COROT, Kepler/Eddington)
  - Theory extrapolating from gas giant statistics $\rightarrow$ terrestrial planets
- What is level of exo-zodiacal emission?
  - SIRTF (Kuiper belts @ 3-300 of AU)
  - Keck-I/LBT-I/VLT-I (Zodiacal clouds at $\sim$0.3-3 AU)
  - Theory extrapolating from dust distribution $\rightarrow$ terrestrial planets
- What wavelength region should we observe?
  - Atmospheric and bio-markers from visible to mid-IR
- What are physical properties of giant planets?
  - Advance understanding and demonstrate techniques
- What controls orbital stability in region of habitable zone?
  - Are solar systems “dynamically full” with planets in all stable orbits?
- What are properties of target stars?
  - Activity, presence of giant planets, zodi disks, gal/x-gal backgrounds

5-10% of TPF budget will support scientific activities
How Many Planets Are Enough?

- How many stars to avoid mission failure ($N_p = 0$)
- How many stars to ensure enough planets ($N_p = 5, 10$?)

$\eta_\oplus \rightarrow \# \text{ Stars} \rightarrow \text{Dist} \rightarrow \text{(Aperture, Baseline)} \rightarrow \text{Cost} \rightarrow \text{Schedule}$

Angular Resolution $\rightarrow$ Sample Size

Potential TPF Targets (FGKM)

- Coronagraphs at $>3\lambda/D$
- Interferometers at $>1\lambda/B$

Radius of Habitable Zone (mas)

Cumulative Number

Cost (SS, Launch Date)
Precursor Science Timeline

- Precursor science goals are linked to major project milestones

<table>
<thead>
<tr>
<th>Phases</th>
<th>Advanced Studies</th>
<th>Formulation</th>
<th>Implementation</th>
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<tr>
<td></td>
<td>Pre-Phase A</td>
<td>Phase A</td>
<td>Phase D</td>
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<tr>
<td>Advanced Studies</td>
<td>Mission &amp; System</td>
<td>Mission &amp; System</td>
<td>Assembly Test &amp; Launch</td>
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<tr>
<td></td>
<td>Definition</td>
<td>Review</td>
<td>Ops (ATLO)</td>
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<tr>
<td></td>
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<td>Launch</td>
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<td>Build</td>
<td></td>
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</table>

- Key Gates
  - Concept Approved
  - Preliminary Mission & System Review
  - Preliminary Design Review
  - Approval for Build
  - ATLO Start
  - Launch

- Gate Criteria
  - Mission Feasibility
  - Project Feasibility
  - Project Viability
  - Technical Viability
  - Launch Readiness

- Precursor Science
  - Exozodi levels Known
  - Freq of Earths Known
  - Biomarkers Identified
  - Resolution Known
  - # of Targets for Survey Known
  - Preliminary Target List
  - Target List Finalized

- Programmatic Decisions
  - Architecture
  - Mission Scope
  - Chosen
- Decided

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How Will We Learn About $\eta_\oplus$?

- Radial velocity, transit data from ground-based, early space-based missions (MOST and COROT)
  - Search for Jupiters $\rightarrow$ Saturns on day/month/year orbits
- Theoretical interpretation of available data
  - Extrapolation from properties of giant planets
  - Interpretation of properties of exo-zodiacal disks from SIRTF, Keck-I/LBTI
Target list selection

- Selection based on:
  - Stars closer than 25 pc
  - Spectral type F, G, K dwarfs
  - Eliminate close binaries etc.
  - Extended sample: include M dwarfs, early F, A

How Will We learn About Exozodiacal Dust?

- Exozodiacal dust may degrade the ability of TPF to detect planets
  - Hence an understanding of the likely levels of dust around TPF targets is important to the TPF design
  - At high levels, could be design discriminator between interferometers and coronagraphs
- Learning how dust disks form around other stars can help us to understand better the formation and evolution of planets
- Dust disks can act as signposts for the presence of planets
- Robust determination of the amount of exozodiacal emission around potential TPF targets using a combination of space-based and ground based telescopes.
Star Formation & Protoplanetary Disks

- The formation of planets is an integral part of our theory of how stars form
  - Hundreds of planetary masses of gaseous and solid material in the protostellar disk
- Solar System-scale dust disks found around nearby stars

SIRTF Observations of Disks

- Low/high metals
- 1 Myr to 5 Gyr
- Grain composition
- Reach 1-10x Kuiper belt at 70 μm

- SIRTF launches April 28 (oops), August TBD after 25 years!
**Table 1. Key Missions and Scientific Contributions to TPF Precursor Science**

<table>
<thead>
<tr>
<th>Instrument / Mission</th>
<th>Science Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>*</td>
<td>Architecture Decision (Entry into Phase A)</td>
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<tr>
<td>SIRTF</td>
<td>IRS-MIPS survey of ∼250 stars for exozodiacal dust at ∼5 AU</td>
</tr>
<tr>
<td>Radial velocity monitoring</td>
<td>Detect planets of Saturn mass or less at 2–3 AU to help refine the incidence of low mass planets</td>
</tr>
<tr>
<td>COROT-MOST</td>
<td>Transits of planets of 8–10 Earth mass at &lt;0.5 AU to help refine incidence of low mass planets</td>
</tr>
<tr>
<td>Keck-I, LBT, VLTI</td>
<td>Warm dust (10 μm) for ∼150 stars for exozodiacal dust at 0.5–2 AU</td>
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<tr>
<td>Theory/modeling</td>
<td>Estimate of frequency of Earth-like planets based on giant planets detected by radial velocity or other techniques</td>
</tr>
<tr>
<td>Theory/modeling</td>
<td>Refine spectral signatures to be searched</td>
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<tr>
<td>*</td>
<td>Scientific scope (Entry into Phases B, C, D)</td>
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<tr>
<td>Kepler</td>
<td>Statistics of Earth-like planets (transiting) to determine incidence of low-mass planets</td>
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<tr>
<td>Eddington</td>
<td>Statistics of Earth-like planets (transiting) to determine incidence of low-mass planets</td>
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<tr>
<td>*</td>
<td>Target List Refinement (now until launch, Phase E)</td>
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<tr>
<td>SIM</td>
<td>Detect potential TPF target systems by finding planets. Few Earth-mass planets around nearby stars</td>
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<tr>
<td>JWST/HST</td>
<td>Images of TPF target fields R&gt;10 mag; F,(8 μm) &lt; 1 μJy</td>
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<tr>
<td>SIRTF/Interferometers/Herschel/SOFIA</td>
<td>Characterize exozodiacal emission of potential targets</td>
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**Collaboration on TPF/Darwin**

- Strong ESA/NASA interest in joint planet-finding mission
  - Collaborative architecture studies
  - Discussions on technology planning and development
- Joint project leading to launch ~2015
  - Scientific and/or technological precursors as required and feasible
Second TPF/Darwin Conference

- Dust Disks and the Formation, Evolution and Detection of Planetary Systems
  - Featuring new SIRTF images/spectra of zodi disks, etc.
- San Diego, July 26-29, 2004 (confirmed dates)

2nd Darwin/TPF Conference

Overall goal to develop the field of extra-solar planet research
- Involve the community in establishing high level goals for TPF/Darwin
- Address research relevant to design and architecture of TPF/Darwin.

1. Assess results on exo-zodiacal disks from SIRTF, Keck-I etc.
   - What is frequency of EZ clouds of different levels?
   - How to combine outer zodiacal cloud (SIRTF) to the inner zodiacal cloud (Keck-I, LBT-I, VLT-I) that will be measured by TPF?
   - What does EZ tell us about the presence or absence of planets?

2. Investigate link between physical conditions in early solar nebula and astrobiology.
   - How might astronomical conditions in the Hadean/Archaen period affect the formation and evolution of life?
   - What does EZ imply in terms of bombardment and infall?
   - What other astronomical properties of a star and planetary system might be relevant to the formation of stable, habitable planets, e.g. dynamics of giant planets, UV/X-ray output of stars, chemistry of nebular material

3. Discussion of TPF/Darwin designs, science requirements and technology advances