Searching for Earth-Like Planets:

NASA’s Terrestrial Planet Finder Space Telescope

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The Big Question: Are We Alone?

- Are there Earth-like planets?
- Are they common?
- Is there life on some of them?
Extrasolar Planets—Where We Are Now

There are more than 120 Extrasolar planets known today.

Most of them have been discovered by detecting a sinusoidal doppler shift in the parent star’s spectrum due to gravitationally induced wobble.

This method works best for large Jupiter-sized planets with close-in orbits.

One of these planets, HD209458b, also transits its parent star once every 3.52 days. These transits have been detected photometrically as the star’s light flux decreases by about 1.5% during a transit.

Recent transit spectroscopy of HD209458b shows it is a gas giant.
Some of the Extrasolar Planets

INNER SOLAR SYSTEM

MERCURY  VENUS  EARTH  MARS

Tau Bootis

3.8 M_J

51 Peg

0.47 M_J

Upsilon Andromedae

0.68 M_J

55 Cancri

0.84 M_J

Gliese 876

2.1 M_J

Rho Cr B

1.1 M_J

HD 114762

0.6 M_J

70 Vir

6.6 M_J

16 Cyg B

1.7 M_J

47 UMa

2.4 M_J

Gliese 614

4.0 M_J

ORBITAL SEMIMAJOR AXIS (AU)
Future Extrasolar Planet Missions

- 2006, Kepler a space-based telescope to monitor 100,000 stars simultaneously looking for “transits”.

- 2007, Eclipse a space-based telescope to directly image Jupiter-like planets.

- 2009, Space Interferometry Mission (SIM) will look for astrometric wobble.

- 2014, Terrestrial Planet Finder Coronagraph (TPF-C) space-based telescope to directly image Earth-like planets.

- 2020, Terrestrial Planet Finder Interferometer (TPF-I) space-based telescope to directly image Earth-like planets.
• **DETECT:** Search 150-500 nearby (5-15 pc distant) Sun-like stars for Earth-like planets.

• **CHARACTERIZE:** Determine basic physical properties and measure “biomarkers”, indicators of life or conditions suitable to support it.
5. Why Is It Hard?

- If the star is Sun-like and the planet is Earth-like, then the reflected visible light from the planet is $10^{-10}$ times as bright as the star. This is a difference of 25 magnitudes!

- If the star is 10 pc (33 ly) away and the planet is 1 AU from the star, the angular separation is 0.1 arcseconds!

Originally, it was thought that this would require a space-based infrared nulling interferometer (TPF-I).

However, the current plan is first to build a single large visible-light telescope with an elliptical mirror (4 m x 10 m) and a *shaped pupil* for diffraction control (TPF-C).
Visible vs. Infrared

SAO Solar System Model at 10 PC

$I_\lambda$ (erg/cm$^2$ s $\mu$m)

$\lambda$ ($\mu$m)

Star

J, V, E, M, Z
The Shaped Pupil Concept

Consider a telescope. Light enters the front of the telescope—the pupil plane.

The telescope focuses the light passing through the pupil plane from a given direction at a certain point on the focal plane, say \((0, 0)\).

However, a point source produces not a point image but an Airy pattern consisting of an Airy disk surrounded by a system of diffraction rings.

These diffraction rings are too bright. An Earth-like planet is only about \(10^{-10}\) times as bright as its Sun-like star. The rings would completely hide the planet.

By placing a mask over the pupil, one can control the shape and strength of the diffraction rings. The problem is to find a shape that puts almost no light in a dark zone that is very close to the Airy disk.
The Shaped Pupil Concept

Consider a telescope. Light enters the front of the telescope—the *pupil plane*.

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However, a point source produces not a point image but an *Airy pattern* consisting of an *Airy disk* surrounded by a system of *diffraction rings*.

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Circular Aperture—Airy Pattern
Central Obstructions are an Example of a Shaped Pupil

Logarithmically scaled plots of 2-D point spread functions for apertures with and without a 30.3% central obstruction. White is 1 and black is $10^{-4}$.

Without (Tak Refractor):

With (Questar):
Spiders are another Example of a Shaped Pupil

Pleiades image taken with Tak FSQ-106N equipped with *dental floss* spiders.
Spiders are another Example of a Shaped Pupil

Pleiades image taken with Tak FSQ-106N equipped with dental floss spiders.
Performance Metrics

Inner and Outer Working Angles: $\rho_{\text{iwa}}$ and $\rho_{\text{owa}}$

Contrast: Ratio of intensity of light in dark zone to the intensity at the center of the PSF.

Airy Throughput ($T_{\text{Airy}}$): Amount of light falling within the inner working angle measured as a percent of the total amount of light entering a clear aperture.

Comment on Units Angular quantities, like $\rho_{\text{iwa}}$, are given in units of wavelength over aperture ($\lambda/D$). Hence, the statement $\rho_{\text{iwa}} = 6$ means an angle of $6\lambda/D$ radians. For $\lambda = 500\text{nm}$ and $D = 10\text{m}$, this translates to $6 \times 500 \times 10^{-9}/10 = 3 \times 10^{-7}$ radians, which is the same as 0.062 arcseconds.

A planet 1au from its star when viewed from 10 parsecs (33ly) has an angular separation of 0.1 arcseconds.
Circular Aperture—Airy Pattern

\[ \text{FWHM} = 1.02 \quad \rho_{\text{iwa}} = 1.24 \quad T_{\text{Airy}} = 84.2\% \]

No dark zone.
Apodization

A mask is all-or-nothing. What about using tinted glass, where the degree of tint varies over the aperture? This is called *apodization*.

\[
\text{FWHM} = 2 \quad \rho_{\text{iwa}} = 4 \quad T_{\text{Airy}} = 9\%
\]

Excellent dark zone. **Unmanufacturable.**
David Spergel’s One Pupil Mask

\[ \text{FWHM} = 1.9 \quad \rho_{iwa} = 4 \quad T_{\text{Airy}} = 43\% \]

Small dark zone...Many rotations required
My Multiple Pupil Mask

FWHM = 2.0  \( \rho_{iwa} = 4 \)

\( T_{\text{Airy}} = 30\% \)

Throughput relative to ellipse
11\% central obstr.
Easy to make
Very few rotations
12. Masks from NIST

[Images of masks from NIST]
13. Our Optical Bench Layout
Jeremy Kasdin tinkers with the laser.
Our TPF Optics Lab

Jeremy adjusts the intensity.
Our TPF Optics Lab

Yours truly pointing at his Starlight Express camera. Can’t see it?
Our TPF Optics Lab

How about now?
Lab Results: Theory vs. Practice

Brightest pixel $\approx 1,642,000,000$. Sum of 21 one-hour exposures.
16. Butterfly Mask

We need better mirrors. We need deformable mirrors.
Red and Green
18. An Alternative Approach
19. Apodization
Pupil Mapping

Advantages:

• 100% throughput

• Implicit magnification... effectively $\text{iwa} \approx \frac{1\lambda}{D}$.

Disadvantages:

• Diffraction effects limit achievable contrast to $10^{-5}$ for a pure pupil-mapping system.
Pupil Mapping for High Contrast (PIAA)

Designed for $10^{-10}$. Delivers $10^{-5}$. 
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