Direct Imaging Earth-Like Planets In Habitable Zones

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Wunch Talk
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http://www.princeton.edu/~rvdb
Direct Detection
Why Earthlike in Habitable Zone is Hard

- **Bright Star/Faint Planet:** In visible light, our Sun is $10^{10}$ times brighter than Earth. That’s 25 mags.

- **Close to Each Other:** A planet at 1 AU from a star at 10 parsecs can appear at most 0.1 arcseconds in separation.

- **Far from Us:** There are less than 100 Sun-like stars within 10 parsecs.
Can Ground-Based Telescopes Do It?

- Atmospheric distortion limits resolution to about 1 arcsec. Note: Resolution refers to equally bright objects. We also need high contrast. That’s much more difficult.

- Segmented optics limits contrast

- Current adaptive optics not good enough

No they can’t (at least not yet)!
Can Hubble Do It?

No it can’t!

The problem is diffraction

Would have to be $1000 \times$ bigger (in each dimension!)
Telescope w/ Unobstructed Aperture

Doesn't Work! Requires an aperture measured in kilometers to mitigate diffraction effects.
Two Classes of Solutions

- External Occulters
- Internal Coronagraphs
Two Classes of Solutions

- *External Occulters*
- *Internal Coronagraphs*
The fundamental size and separation for a starshade are LARGE.
Poisson didn’t believe the wave theory of light. He pointed out that light falling on a circular object would have a bright spot at the center of its shadow.

Arago did the experiment.

Poisson was wrong.
A Fun Experiment
Plain External Occulter (Doesn’t Work!)

Circular Occulter

Shadow isn’t dark enough

Poisson’s Spot!

Simulated star/planet image
Shaped Occulter
Space-based Occulter (TPF-O)

Telescope Aperture: 4m, Occulter Diameter: 50m, Occulter Distance: 72,000km
Starshade Stowage and Deployment
A Real Petal...
Two Classes of Solutions

• External Occulters

• *Internal Coronagraphs*
Types of Coronagraphs (TPF-C)

- Hybrid Lyot
- Apodized Pupils
- Shaped Pupils
- Pupil Mapping (PIAA)
- Vector Vortex
- Phase Masks
- Visible Nuller
- Hybrids
The abrupt edge of the telescope’s “mirror” causes the bright diffraction rings.

Solution: Use tinted glass to ease the transition from transparent to opaque.
Some of the Math

The image-plane electric field $E()$ produced by an on-axis plane wave (i.e., starlight) and an apodized (i.e., tinted) aperture defined by an apodization function $A()$ is given by the Fourier transform:

$$E(\xi, \zeta) = \int \int e^{2\pi i (x\xi + y\zeta)} A(x, y) dy dx$$

$$E(\rho) = 2\pi \int_0^{1/2} J_0(2\pi r \rho) A(r) r dr,$$

where $J_0$ denotes the 0-th order Bessel function of the first kind.

**NOTE:** The electric field depends linearly on the apodization function.

The intensity is the square of the electric field.

The unitless pupil-plane “length” $r$ is given as a multiple of the aperture $D$.

The unitless image-plane “length” $\rho$ is given as a multiple of focal-length times wavelength over aperture ($f\lambda/D$) or, equivalently, as an angular measure on the sky, in which case it is a multiple of just $\lambda/D$. (Example: $\lambda = 0.5\mu$m and $D = 10$m implies $\lambda/D = 10$mas.)
Find *apodization* function $A()$ that solves:

\[
\begin{align*}
\text{maximize} & \quad \int_0^{1/2} A(r)2\pi rdr \\
\text{subject to} & \quad -10^{-5} E(0) \leq E(\rho) \leq 10^{-5} E(0), \quad \rho_{iwa} \leq \rho \leq \rho_{owa}, \\
& \quad 0 \leq A(r) \leq 1, \quad 0 \leq r \leq 1/2, \\
& \quad -50 \leq A''(r) \leq 50, \quad 0 \leq r \leq 1/2
\end{align*}
\]

An infinite dimensional *linear programming* problem.
Pupil with “Optimal” Tinting

Mirror with Softened Edge

Image of Star

Mathematically Perfect... But Unmanufacturable!
Shaped Pupil Coronagraph

20 Petal mask

Image plane (20 petals)

Image plane (150 petals)

Still excellent, but still unmanufacturable.
Which Space-Based Observatory Seems Easiest To Build...

**Coronagraph.** A four to eight meter off-axis telescope with built-in diffraction control scheme and active adaptive optics to maintain unprecedented wavefront quality (1/10,000-th wave) over the course of very long exposures (light throughput of the diffraction control system is only about 10%).

**Occulter.** A four meter diffraction limited telescope and a specially configured 50 meter tip-to-tip occulter “flying” 72,000 km in front of the telescope with station-keeping to within a ±1 meter tolerance over the course of a multihour exposure.

REMINDER: We landed humans on the moon and brought them safely home again.
WFIRST Space Telescope
Repurposed NRO Spy Satellite

Similar to Hubble.
Aperture: 2.4 meters.
Central Obstruction and Spiders.