Starlight Suppression
Technologies for Direct Imaging of Exoplanets

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So Many Ways to Find a Planet
The Case for Direct Imaging

1858 confirmed exoplanets with mass and semi-major axis estimates. Retrieved from [http://exoplanetarchive.ipac.caltech.edu](http://exoplanetarchive.ipac.caltech.edu) on 07.28.2015
The Case for Direct Imaging

319 confirmed exoplanets with mass, semi-major axis, radius and stellar age estimates.
**Photons Are Precious**

High resolution ($\lambda/\Delta\lambda \approx 4000$) spectrum of giant planet HR 8799c with best-fit model spectrum. [Konopacky et al., 2013]

Transit spectrum spectrum of neptune-sized planet GJ 436b with various model spectra overlaid. [Knutson et al., 2014]
Conventional Telescopes Are Not Conducive to Imaging Planets

Telescope schematic: a finite-sized aperture captures light that is focused onto a detector.

The system impulse response (Point Spread Function) in log scale.
Planets are Very Faint and Very Close to Stars

The first minimum of the Airy disk occurs around $1.22\lambda/D$ (this also sets the resolution limit of the system). For a 4 m aperture in visible light this is around $1 \times 10^{-5}$ degrees.

The light reflected from the Earth is 10 billion times dimmer than the light emitted by the sun. The brightest (self-luminous) planets are still one million times fainter than their host stars.

Commercial CCDs can achieve contrasts of 2048:1
The human eye can achieve 16384:1

So we have to block out the star.
In 1931 Astronomers Got Tired of Chasing Eclipses

Photo by Miloslav Druckmüller
In 1931 Astronomers Got Tired of Chasing Eclipses

The first Lyot Coronagraph [Lyot, 1939].

Photo by Miloslav Druckmüller
Coronagraphy 101

Schematic of Lyot coronagraph. Based on [Sivaramakrishnan et al., 2001].
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Apodized Pupil Lyot Coronagraphy

Apodizer
Focal Plane
Mask
Lyot
Stop
Detector

Apodized pupil Lyot coronagraph.

Pupil  FPM  FPM+Lyot  Apodizer+FPM+Lyot
Issues and Limitations

- Still limited by the diffraction limit of the telescope
- Coronagraph design is highly dependent on telescope aperture (and becomes much more complicated for complex apertures)
- Many coronagraph designs are highly sensitive to misalignment and vibration
- Any surface errors on any of the optics degrade performance
- Modern designs rely on deformable mirrors to create regions of high contrast. These introduce further limits on the search space and are not yet flight-qualified
What If You Block the Light Outside the Telescope?

Images courtesy of N. J. Kasdin
With the Right Shape, you get a Deep Shadow
Why Would This Work?

Babinet’s Principle

The light passing around the occulter plus the light passing through an occulter-shaped hole is a free-space plane wave.

You can design your occulter to produce the shadow you want at the telescope aperture (with no Poisson spot).

Simulated shadow cast at the telescope pupil for separations of 18 to 100 thousand km. [Vanderbei et al., 2007]

Minimum angular separation is now a function only of geometry, not wavelength!
You Have To Get the Shape Just Right

Starshade contrast for various shape errors. [Shaklan et al., 2010]

Manufacturing tolerances in $\mu$m, alignment tolerances in m.
Issues and Limitations

- Sunlight can reflect from the occulter back into the telescope, further limiting allowable viewing geometries.
- Starshade must be repositioned between observations with average transit times of weeks.
- Starshade stationkeeping may interfere with observations (depending on propulsion system).
- Not really practical in any geocentric orbits (need to go to L2).
- Impossible to fully validate flight systems on the ground (have to use scale models and carefully constructed proxy experiments).
How We Take Data is as Important as the Instrument

Animations by P. Ingraham
Next-Gen Ground-Based Planet Imagers
The Gemini Planet Imager
[Macintosh et al., 2012, Macintosh et al., 2014]. Slide by M. Perrin.

- **Adaptive optics system** (LLNL) corrects for atmospheric turbulence and optical imperfections.
- **Coronagraph masks** (AMNH) block diffracted light from the star.
- **Super-smooth optics** reduce scattered starlight.
- **Infrared calibration sensor** (JPL) keeps coronagraph aligned.
- **Mechanical structure and top-level software** (NRC Canada) holds and connects subsystems.
- **Infrared integral field spectrograph** (UCLA & U. Montreal) makes images and spectra of planets.
- **Adaptive optics system** (LLNL) corrects for atmospheric turbulence and optical imperfections.
51 Eri b - GPI’s First Planet Discovery
[Macintosh et al., 2015]

Animation by Robert De Rosa (UC Berkeley), Christian Marois (NRC Herzberg, University of Victoria)
WFIRST-AFTA

- 2.4 m aperture primary mirror
- Wide Field Imager/Spectrometer & Integral Field Unit
- Internal Coronagraph with Integral Field Spectrometer
- Overall Dry Mass: 4059 kg (CBE)
- Structure: high stiffness composites; modular packaging for avionics
- GN&C/Propulsion: inertial pointing, 3-axis stabilized, mono-prop system for stationkeeping & momentum unloading
- Continuous 600 Mbps Ka-band to dedicated ground station
- GEO orbit
- Delta IV Heavy launch
WFIRST-AFTA Coronagraphs

Downselect shaped pupil (top) and hybrid lyot (bottom) coronagraph schematics
WFIRST-AFTA Search Space
NASA’s UV, Visual, & IR Astrophysics Facilities

Adapted from Testimony to Congress Given by J. Grunsfeld (May 5, 2013)
Other Direct Imaging Mission Concepts
Open Questions and Challenges

1. Are there starlight suppression system designs that can further decouple performance from spacecraft stability and loosen manufacturing and alignment tolerances?
2. How can we jointly optimize the design of active and passive wavefront control systems?
3. Are there further gains possible with improved post-processing algorithms?
4. How do we design an exoplanet imaging mission that optimally takes into account what we know about the distributions of planetary parameters?
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*Science*. 


