The Terrestrial Planet Finder Mission: Detecting and Characterizing Earth-like Planets Orbiting Nearby Stars

Robert J. Vanderbei

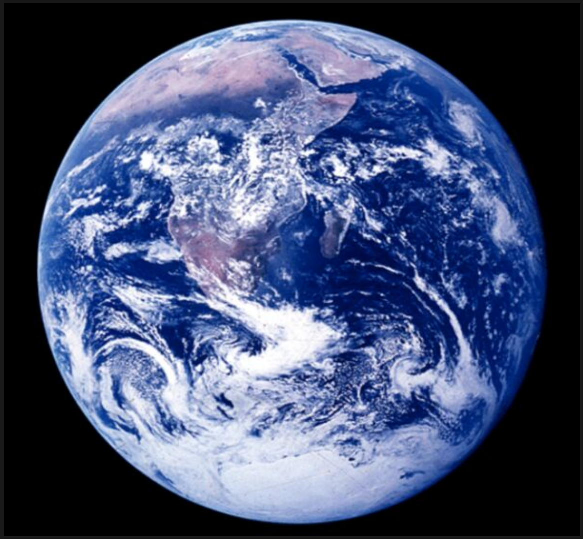
June 11, 2003
North Jersey Astronomy Group
Montclair State University

Member: Princeton University/Ball Aerospace TPF Team

http://www.princeton.edu/∼rvdb

The Big Question: Are We Alone?

- Are there Earth-like planets?
- Are they common?
- Is there life on some of them?



Exosolar Planets—Where We Are Now

There are more than 100 Exosolar planets known today.

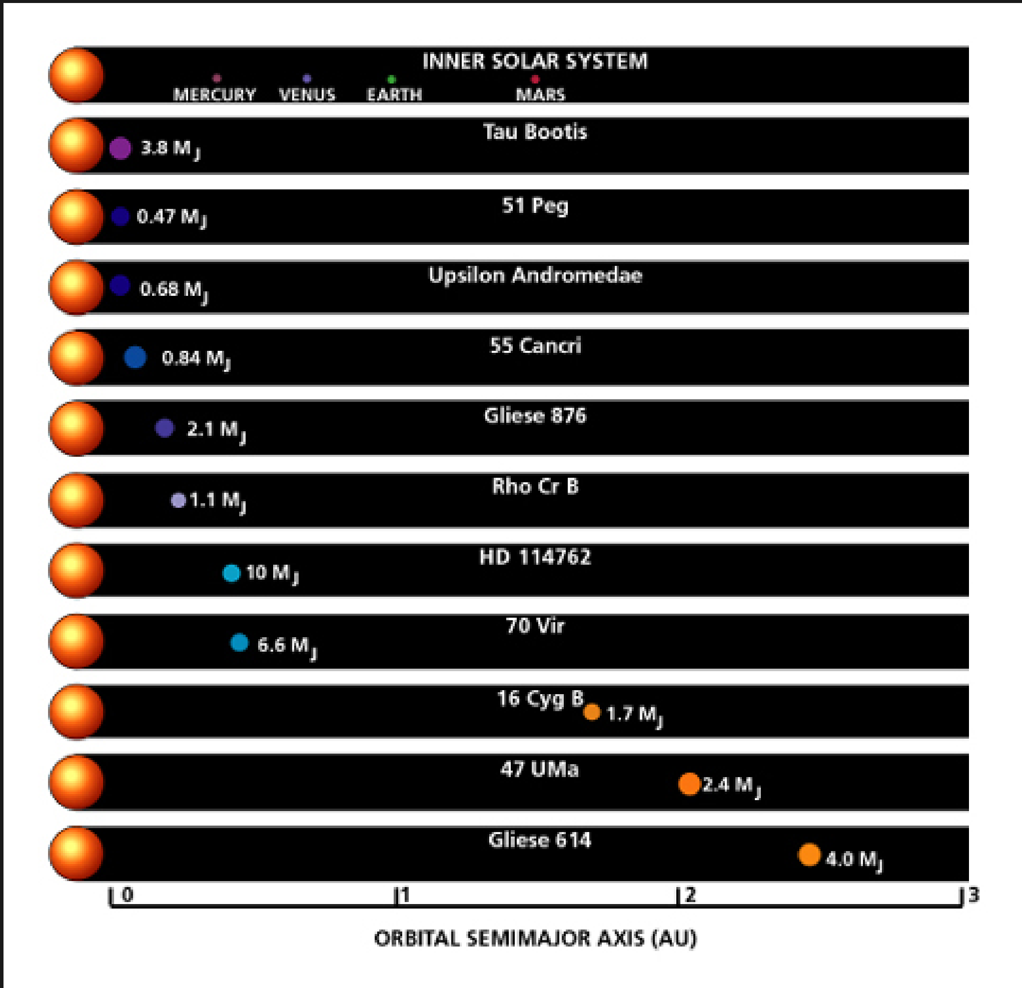
Most of them have been discovered by detecting a sinusoidal doppler shift in the parent star's spectrum due to gravitationally induced wobble.

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 and that its atmosphere contains sodium, as expected.

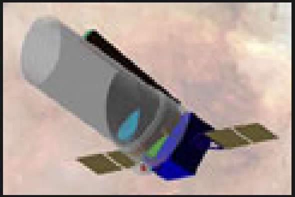
Some of the ExoPlanets



Future Exosolar 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, Darwin is a space-based cluster of 6 telescopes used as an interferometer.
- 2014, Terrestrial Planet Finder (TPF) space-based telescope to directly image Earth-like planets.

Terrestrial Planet Finder Telescope

- 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.

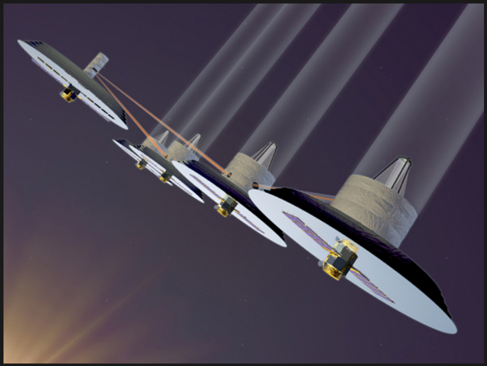
Why Is It Hard?

- 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 multiple mirror nulling interferometer.

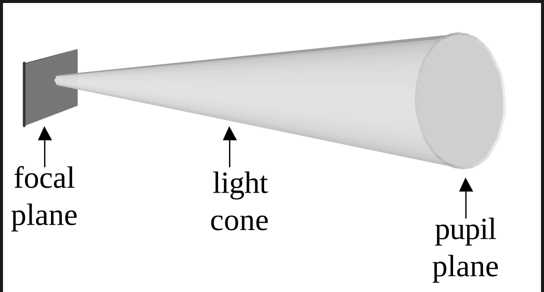
However, a more recent idea is to use a single large telescope with an elliptical mirror (4 m x 10 m) and a *shaped pupil* for diffraction control.



HD209458 is the bright (mag. 7.6) star in the center of this image.
The dimmest stars visible in this image are magnitude 16.
An Earth-like planet 1 AU from HD209458 would be magnitude 33, and would be located 0.2 pixels from the center of HD209458.

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 $(0, 0)$.

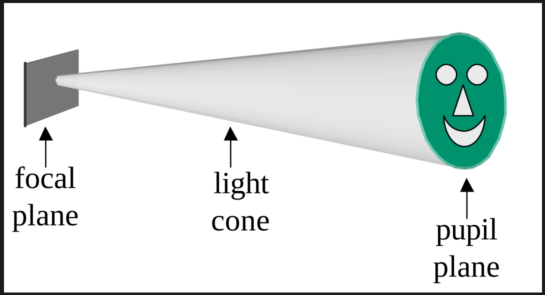
However, the wave nature of light makes it impossible to concentrate all of the light at a point. Instead, a small disk, called the *Airy disk*, with diffraction rings around it appears.

These diffraction rings are bright relative to any planet that might be orbiting a nearby star and so would completely hide the planet. The Sun, for example, would appear 10^{10} times brighter than the Earth to a distant observer.

By placing a mask over the pupil, one can control the shape and strength of the diffraction rings. The problem is to find an optimal shape so as to put a very deep *null* very close to the Airy disk.

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 $(0, 0)$.

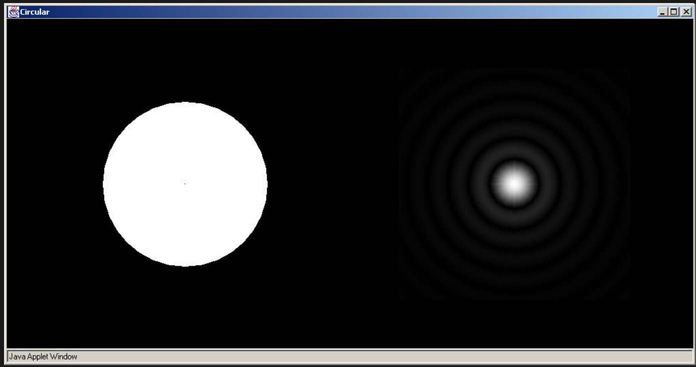
However, the wave nature of light makes it impossible to concentrate all of the light at a point. Instead, a small disk, called the *Airy disk*, with diffraction rings around it appears.

These diffraction rings are bright relative to any planet that might be orbiting a nearby star and so would completely hide the planet. The Sun, for example, would appear 10^{10} times brighter than the Earth to a distant observer.

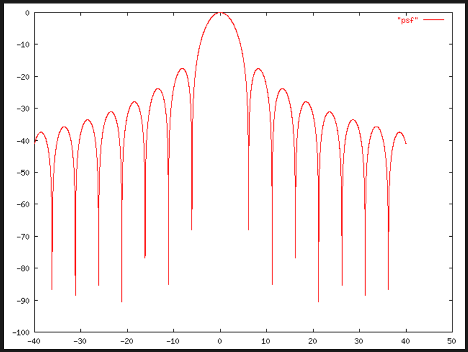
By placing a mask over the pupil, one can control the shape and strength of the diffraction rings. The problem is to find an optimal shape so as to put a very deep *null* very close to the Airy disk.

Airy Disk and Diffraction Rings

A conventional telescope has a circular openning as depicted by the left side of the figure. Visually, a star then looks like a small disk with rings around it, as depicted on the right.



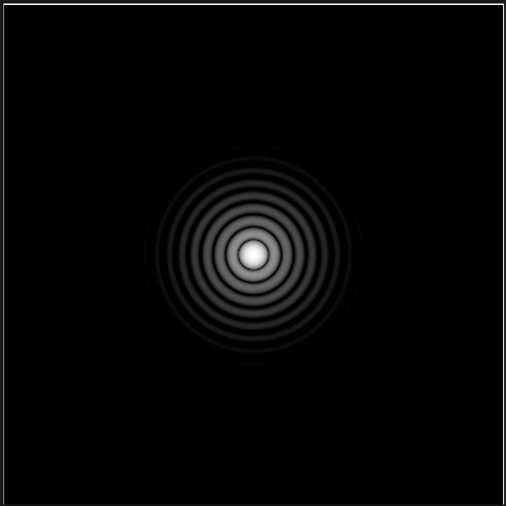
The rings grow progressively dimmer as this log-plot shows:



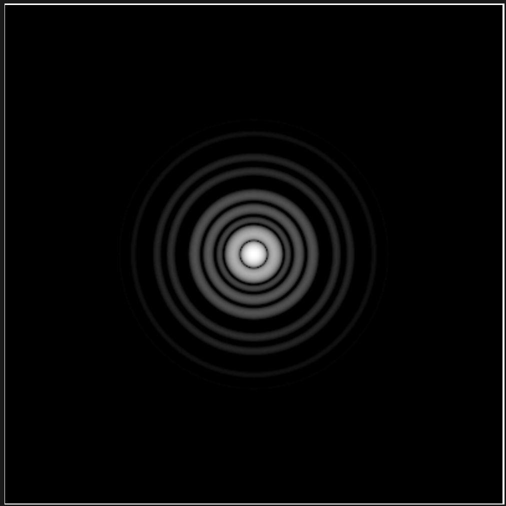
Central Obstructions are an Example of a Shaped Pupil

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 (refractor):

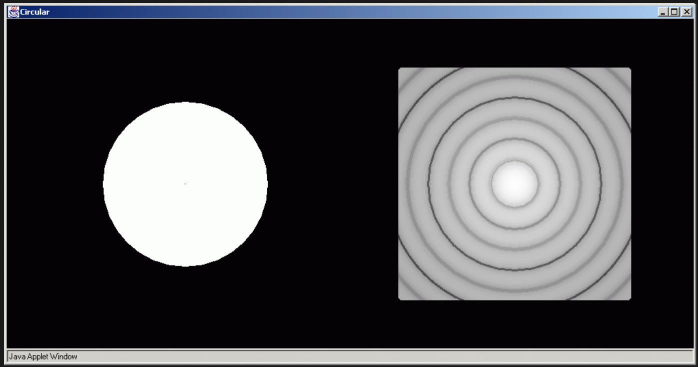


With (Questar):



Airy Disk and Diffraction Rings—Log Scaling

Here's the unobstructed Airy disk from the previous slide plotted using a logarithmic brightness scale with 10^{-11} set to black:

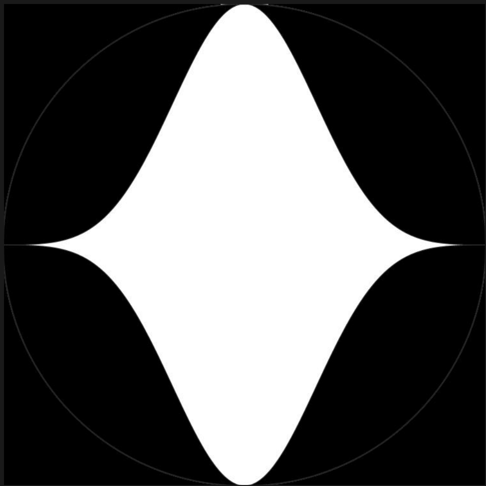


The problem is to find an aperture mask, i.e. a pupil plane mask, that yields a 10^{-10} dark zone somewhere near the first diffraction ring. *A hard problem!* Such a dark zone would appear almost black in this log-scaled image.

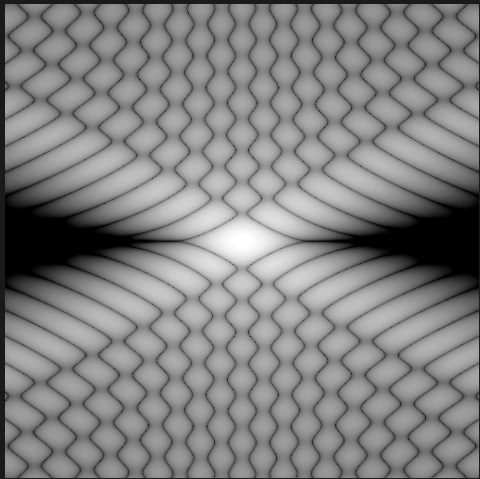
Optimal Shaped Pupil Masks

The problem is to maximize light throughput, i.e. the open area of the mask, subject to the constraint that the intensity of the light in a specified dark zone $\mathcal{O}$ is at most 10^{-10} as bright as at the center of the star's Airy disk.

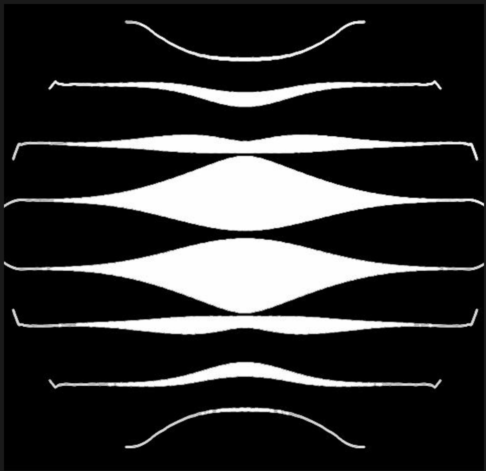
Kasdin-Spergel Prolate Spheroidal Mask

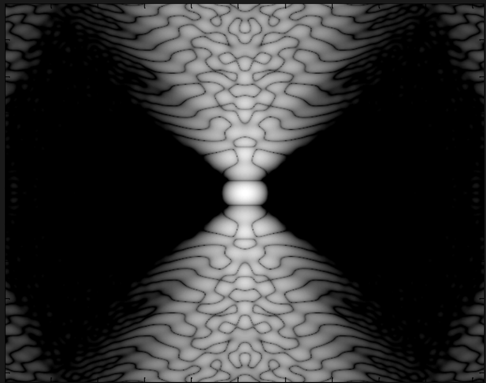


PSF for Single Prolate Spheroidal Pupil

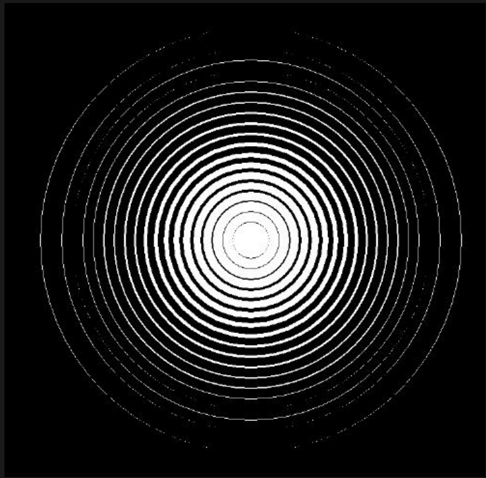


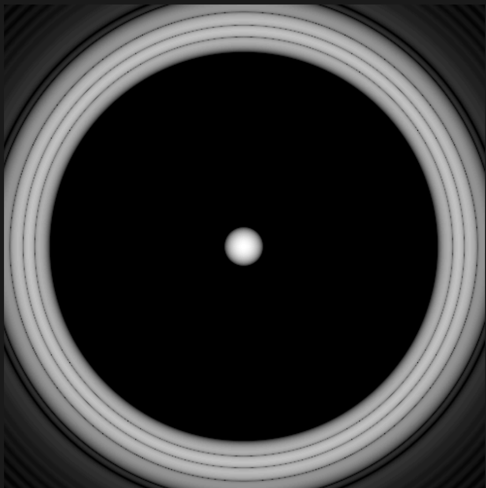
Best Mask: 8-Pupil Mask

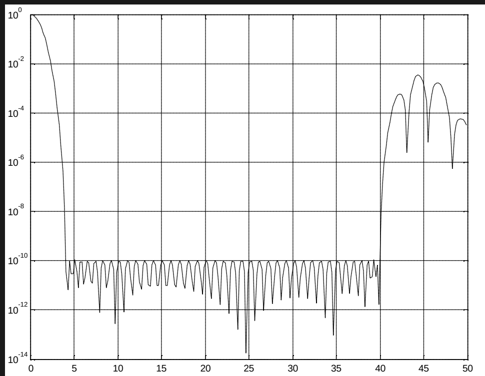




Circularly Symmetric Masks—Spider Masks

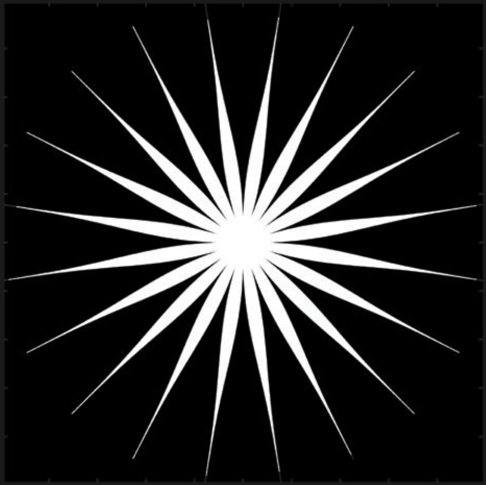


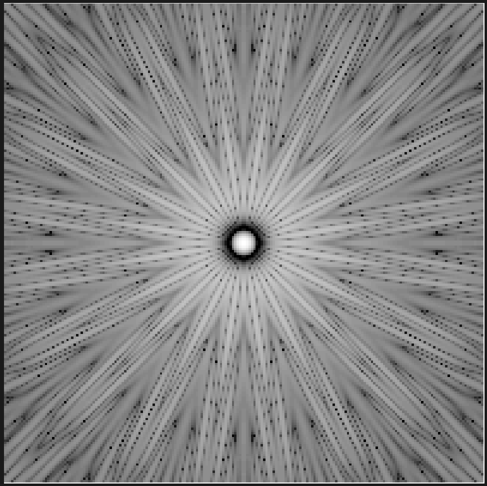


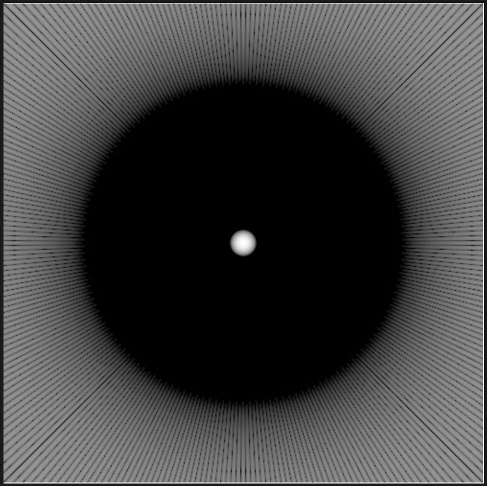


Home Page
Title Page
Contents
Page 17 of 28
Go Back
Full Screen
Close
Quit

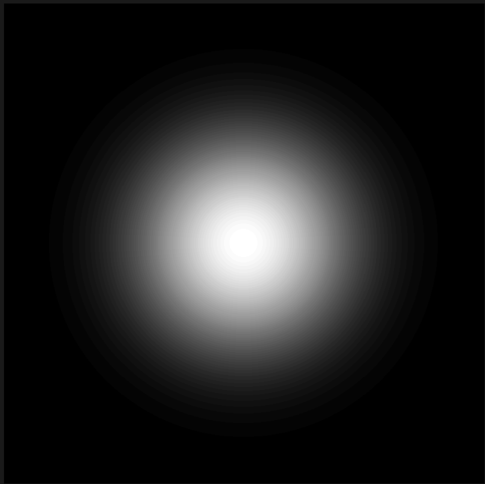
Circularly Symmetric Masks—Starshaped Masks

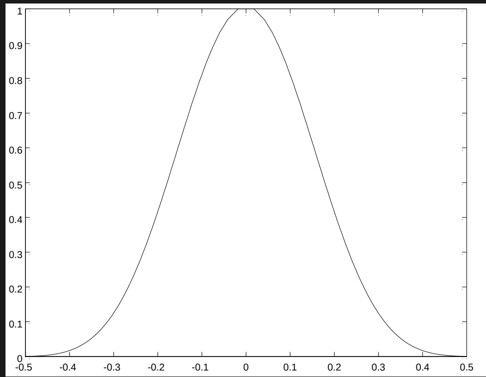


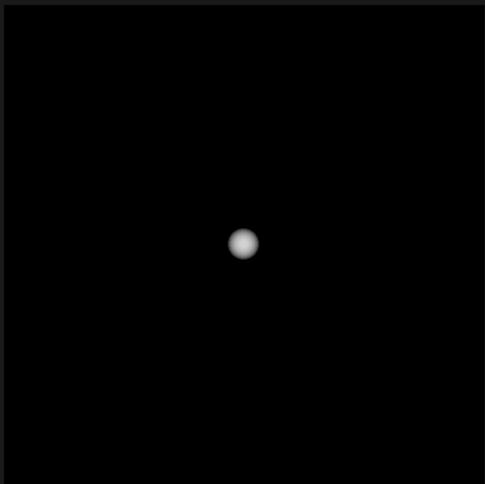


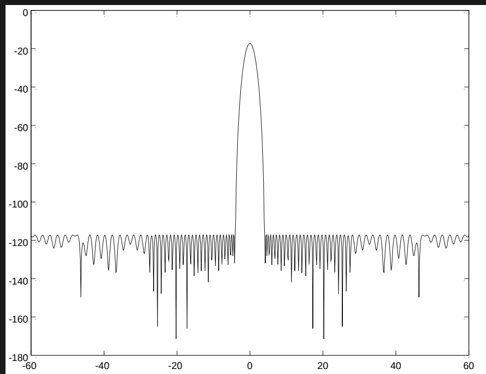


Apodization—Tinting Glass







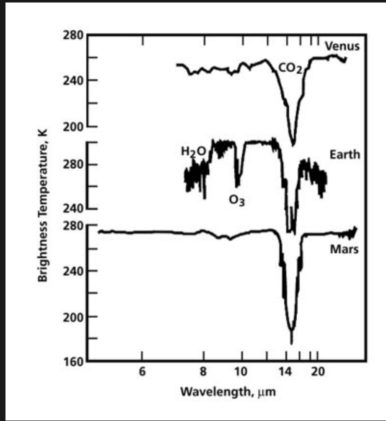


Characterization

Spectroscopy

Spectra provide information on:

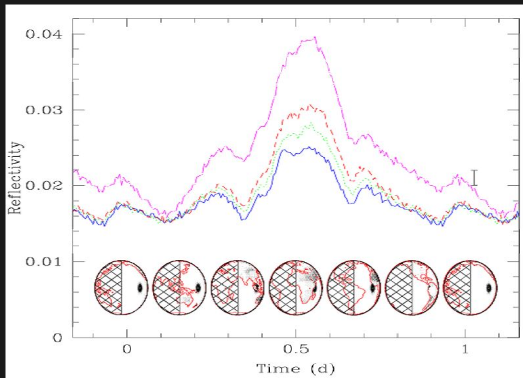
- CO_2
- H_2O
- O_3
- Chlorophyl



Photometry

Daily variation provides information on:

- weather/clouds
- existence of oceans
- rotational period
- land fraction
- ice cover

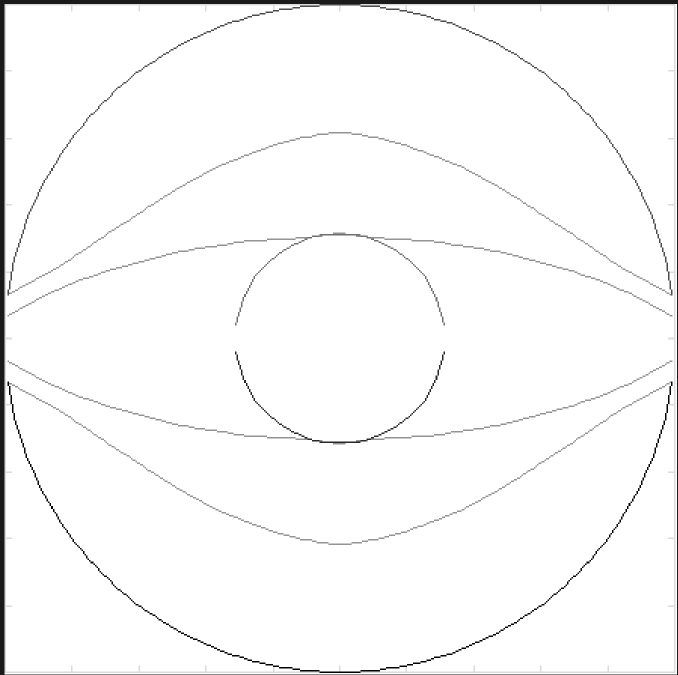


Home Page
Title Page
Contents
Page 21 of 28
Go Back
Full Screen
Close
Quit

Field Test

Dim Double Splitter Mask

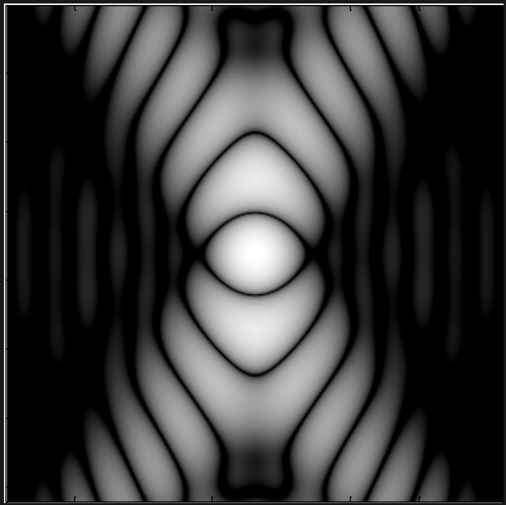
A mask was made for a 3.5" Questar. The mask was cut from paper with scissors (a crude tool at best) according to the template shown, backed with cardboard, and framed with 4" PVC endcap.

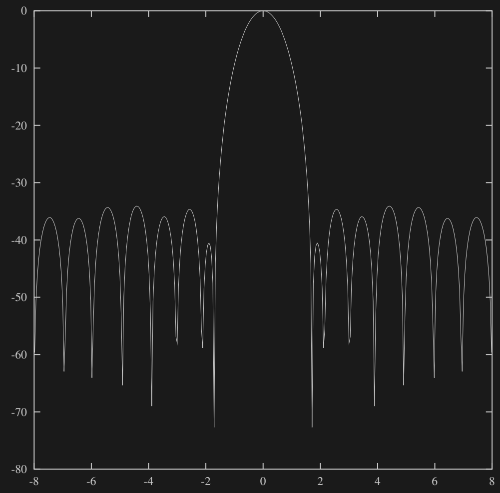


The outer circle represents the full aperture, the inner circle the central obstruction, and the remaining arcs the mask openning.

Computed PSF

Logarithmically scaled plot of the 2-D point spread function and a graph of its x-axis slice. White is 0 dB and black is -40 dB. Throughput is 18.2%.



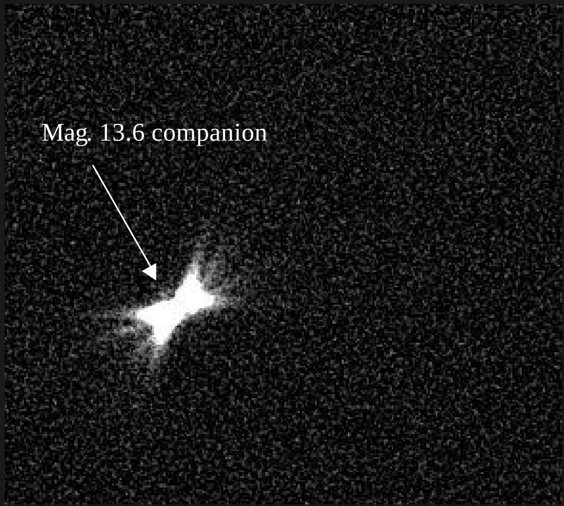


31 Leonis

31 Leonis is a dim double.
Primary/secondary visual magnitude: $4.37/13.6$
Luminance difference $= 9.2 = -36.8$ dB
Separation: $7.9" = 6.9\lambda/D$ (at 500nm). Position Angle: $44°$

Without mask:

With mask:

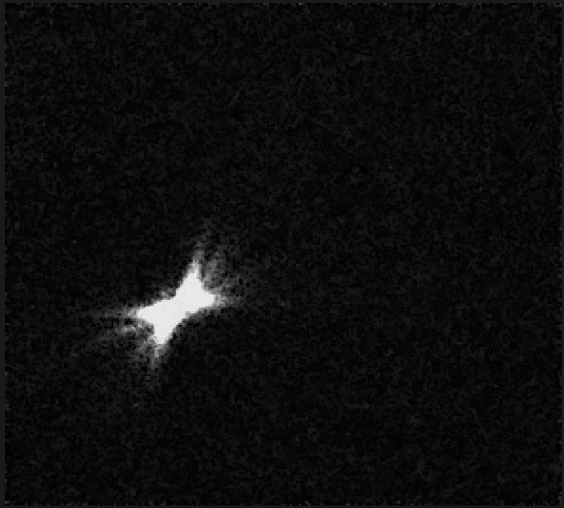


The secondary is to the upper left of the primary in the mask image.

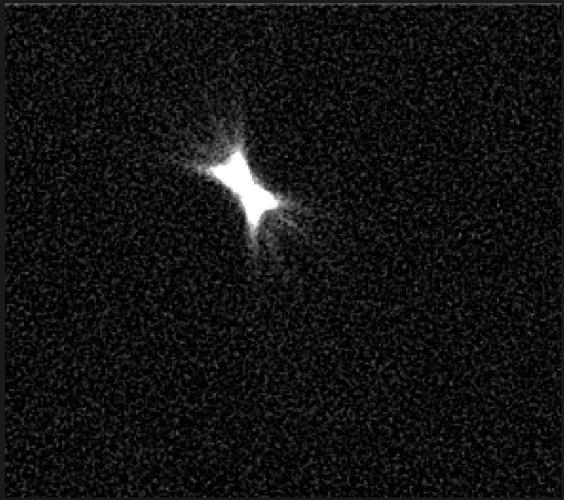
Is it real?

We took another image with the mask rotated about 90°. The rotated mask shows no hint of a secondary:

Original orientation:



Rotated:



Conclusions

- Detection of extrasolar terrestrial planets orbiting nearby stars is technically very difficult but may well be practical within the foreseeable future.

- A space-based telescope with an elliptical mirror and a shaped aperture provides the contrast needed to detect and perhaps characterize such planets.

- The spectra and light curves of such planets can provide clues about their properties.

- The first detected extraterrestrial life might well be extrasolar plants rather than ETs!

Where are the diffraction rings?

The images were taken with a Starlight Express MX-916 CCD camera. No filters were used. The camera is sensitive to all visible light and well into the infrared. Hence the rings, whose radii are proportional to wavelength, get blurred by the averaging over the broad spectrum of wavelengths.

In addition, the companion is located at $6.9\lambda/D$ at 500nm. At 750nm, it is $4.6\lambda/D$. At this Airy distance it is impossible to detect a contrast ratio of -36.8 dB.