The Search for Earth-like Planets: Yes We Can

Robert J. Vanderbei

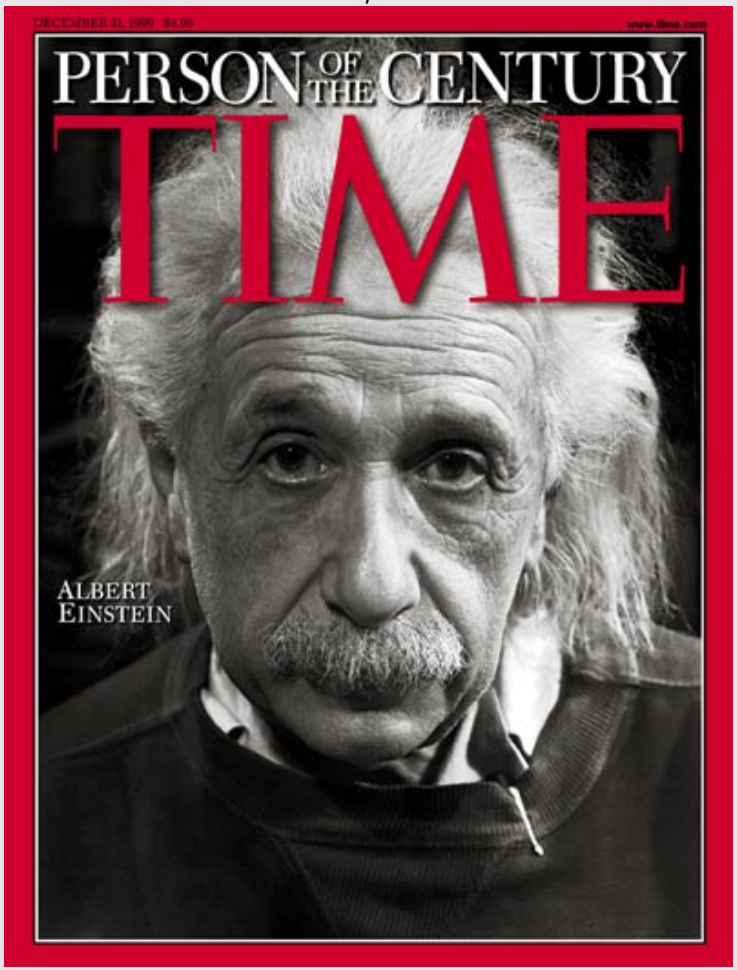
2008 November 11

Princeton Alumni Association of Canada
Toronto Chapter

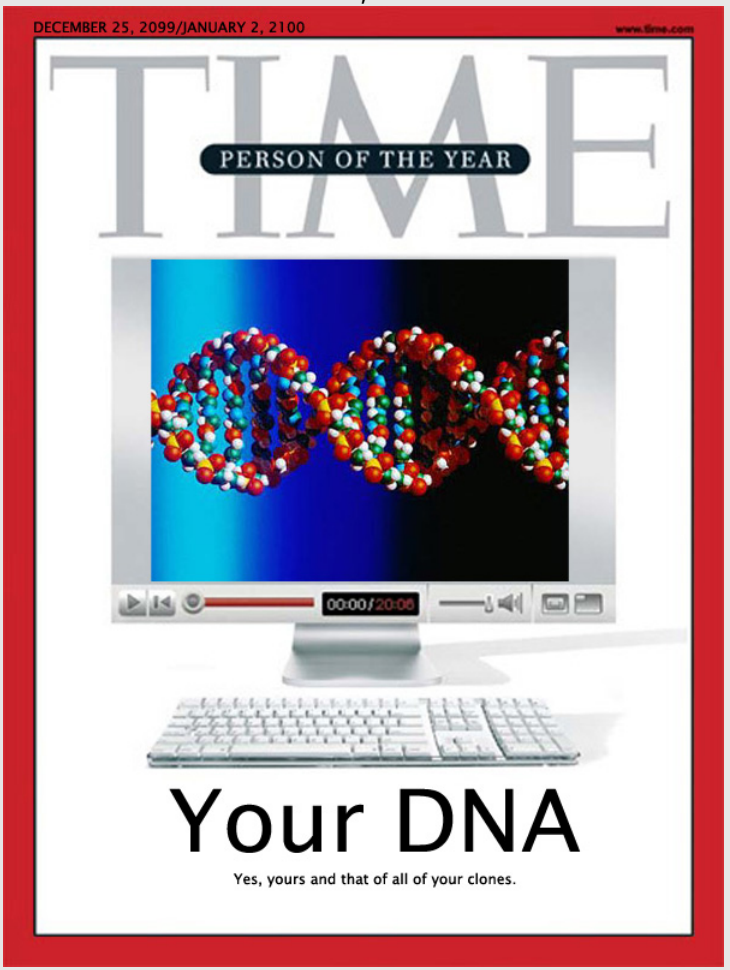
http://www.princeton.edu/∼rvdb

The Big Questions: Then and Now

Jan 1, 2000



Jan 1, 20??



Are We Alone?

Indirect Detection Methods

More than 300 planets found so far

Wobble Methods

Radial Velocity.

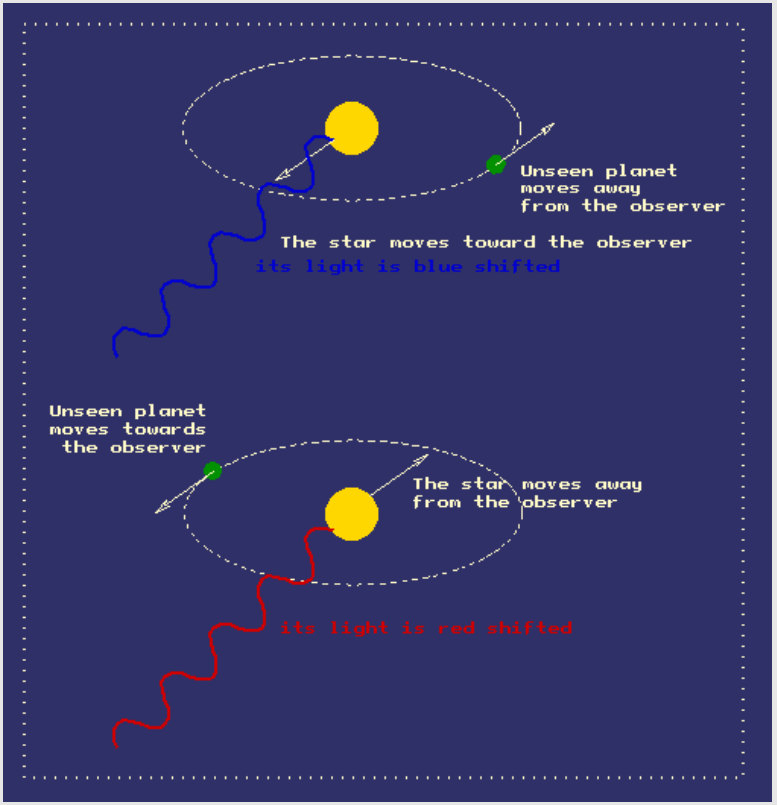
For edge-on systems.

Measure periodic doppler shift.

Astrometry.

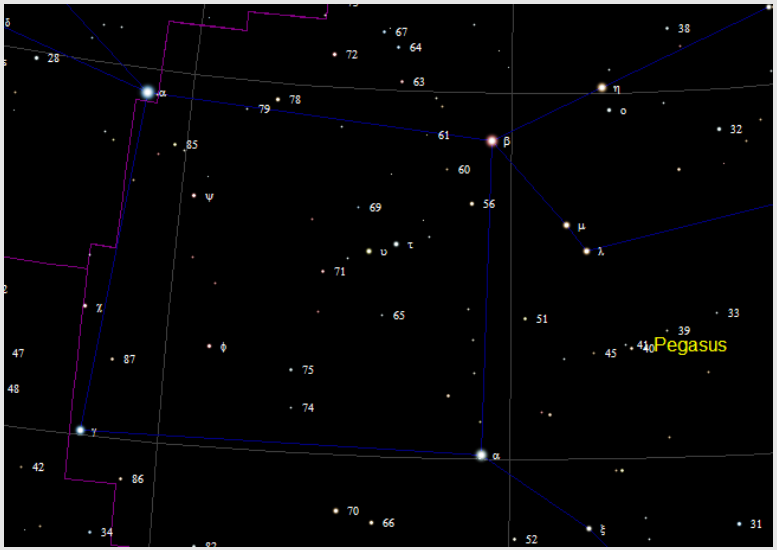
Best for face-on systems.

Measure circular wobble against background stars.



First Discovery: 51 Pegasi b

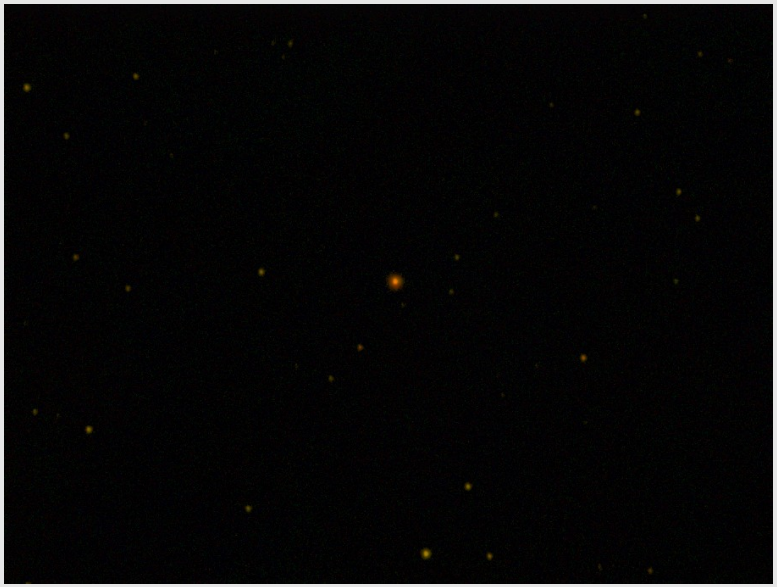
- Mayor and Queloz (1995)
- Mag. 5.5 main sequence star
- Detected by *radial velocity* method
- Velocity difference: 70 m/s $= 160$ mph
- Period: 4.2 days
- Separation: 0.05 AU
- Angular separation: 0.0035 arcseconds
- Mass: $> 0.47 M_{\mathrm{J}}$
- Hot Jupiter



Notable Recent Discovery: Gliese 581c

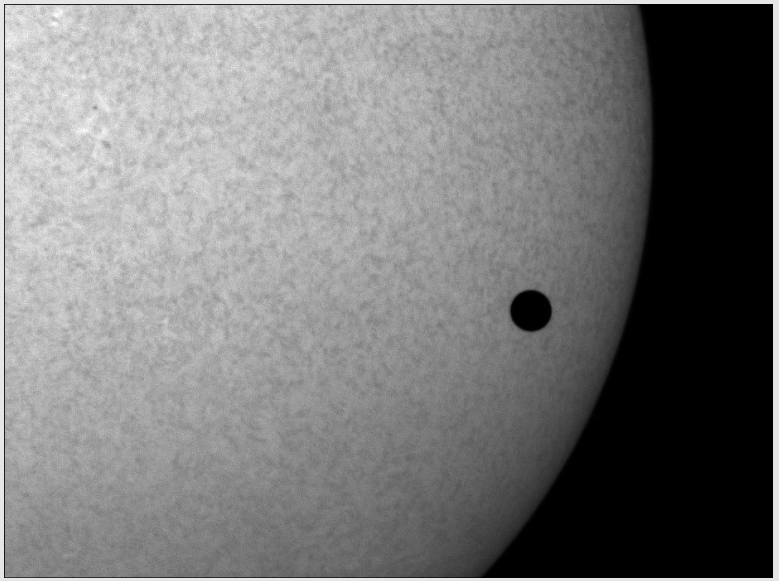
Possibly Terrestrial

- Mag. 10.5 red dwarf
- Detected by radial velocity method
- Period: 13 days
- Separation: 0.07 AU
- Angular Separation: 0.012 arcseconds
- Mass: $> 5M_{\mathsf{E}}$

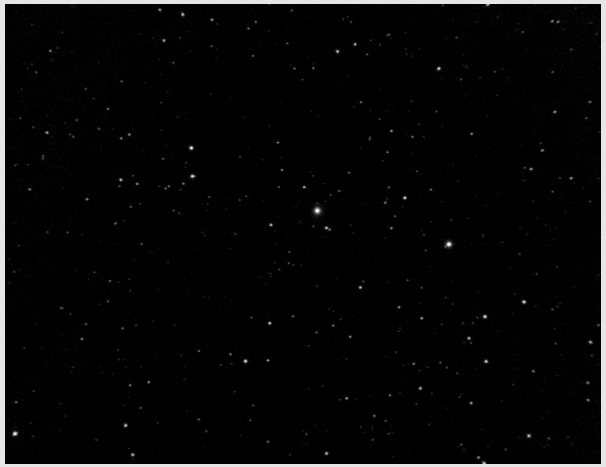


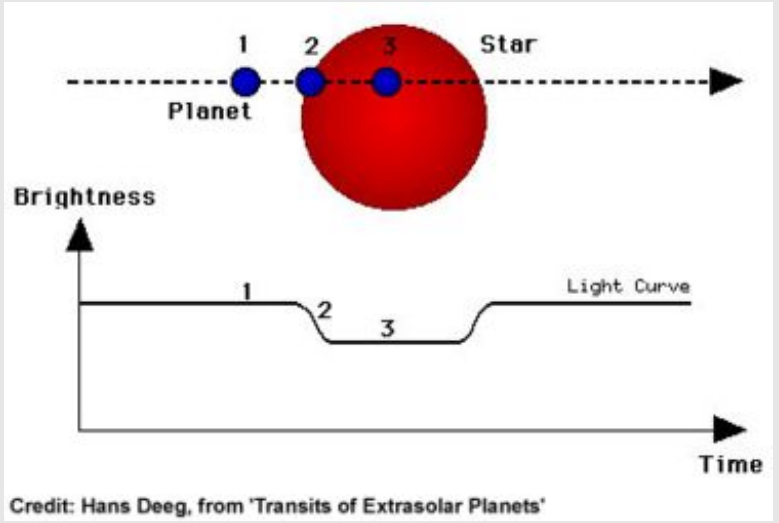
Transit Method

- HD209458b confirmed both via RV and transit.
- Period: 3.5 days
- Separation: 0.045 AU (0.001 arcsecs)
- Radius: $1.3R_{\mathrm{J}}$
- Intensity Dip: $\sim 1.7\%$
- Venus Dip $= 0.01\%$, Jupiter Dip: 1%
- Kepler and Corot



Venus Transit (R.J. Vanderbei)





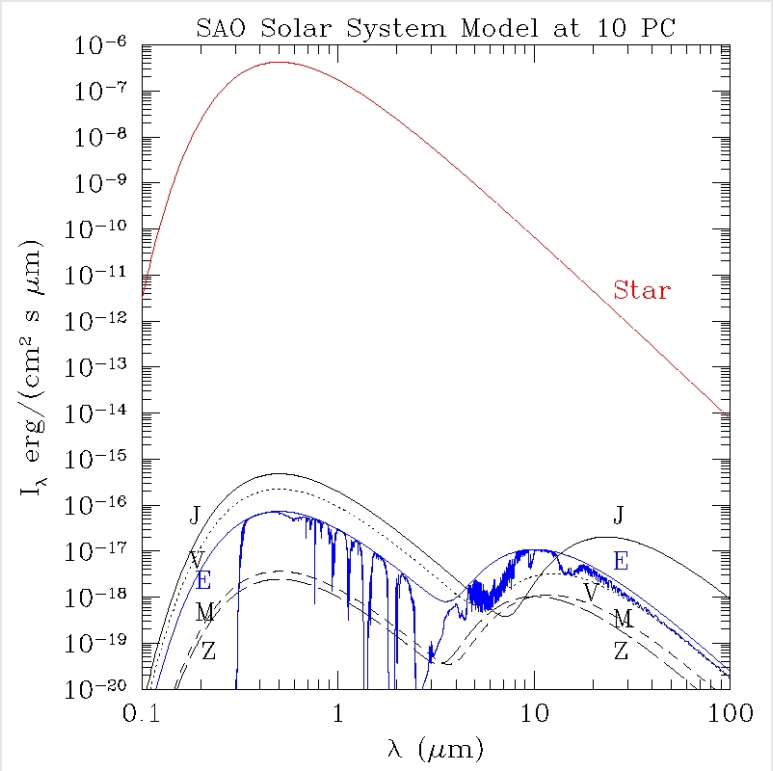
Credit: Hans Deeg, from 'Transits of Extrasolar Planets'

Direct Detection

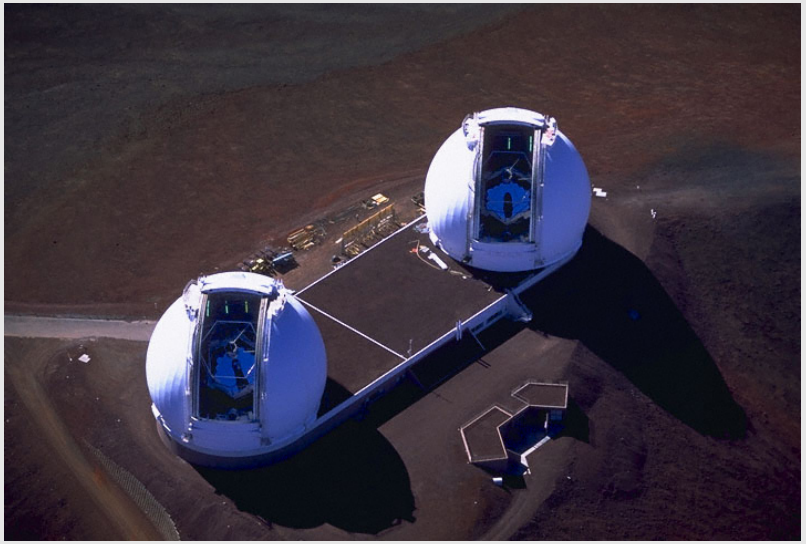
Why It's Hard

Premise: If there is intelligent life "out there", it probably is similar to life as we know it on Earth.

- *Bright Star/Faint Planet:* In visible light, our Sun is ten billion times brighter than Earth.
- *Close to Each Other:* A planet at 1 AU from a star at 33 light-years can appear at most 0.1 arcseconds in separation. (The full moon is 1800 arcseconds in diameter.)
- *Far from Us:* There are less than 100 Sun-like stars within 10 parsecs.



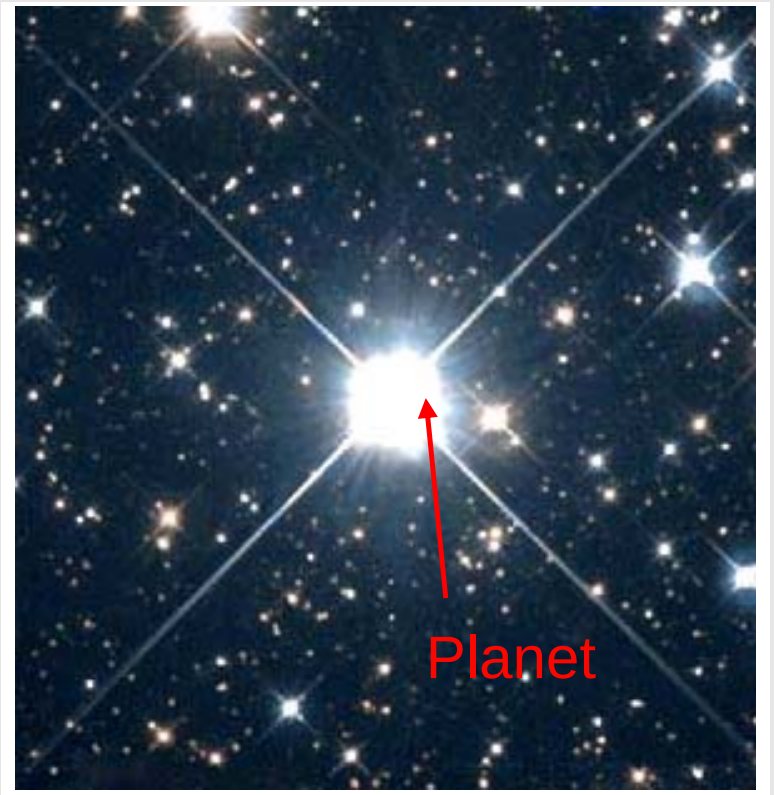
Can Ground-Based Telescopes Do It?



- Atmospheric distortion limits *resolution* to about 1 arcsec.
  Note: Resolution refers to equally bright objects.
  If one is much brighter than the other, then it is more difficult.
- Large aperture with adaptive optics.
- Interferometry.

No they can't!

Can Hubble Do It?

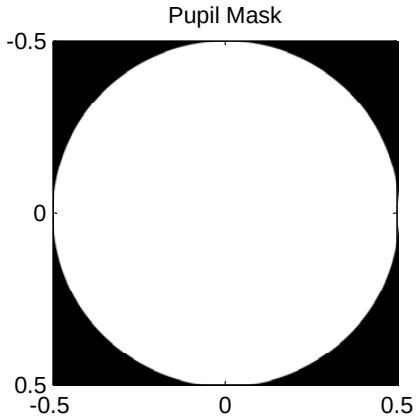


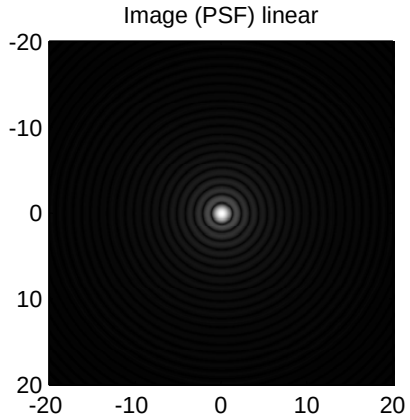
No it can't!

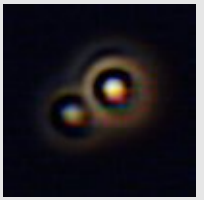
The problem is diffraction

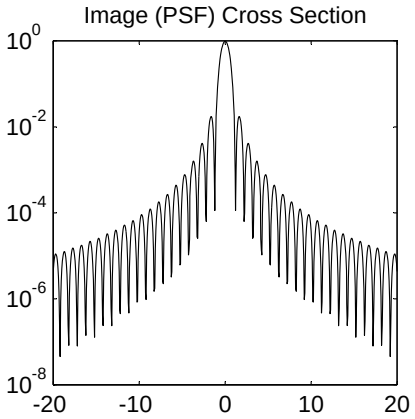
The Problem is Diffraction

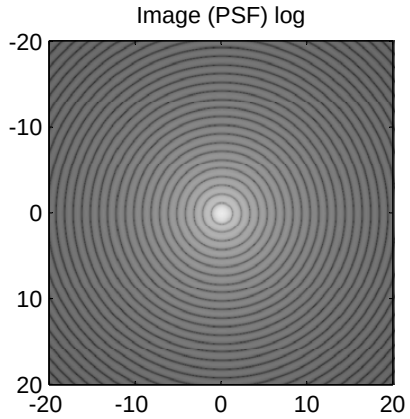
Requires an telescope with a mirror measured in *kilometers* to mitigate diffraction effects.







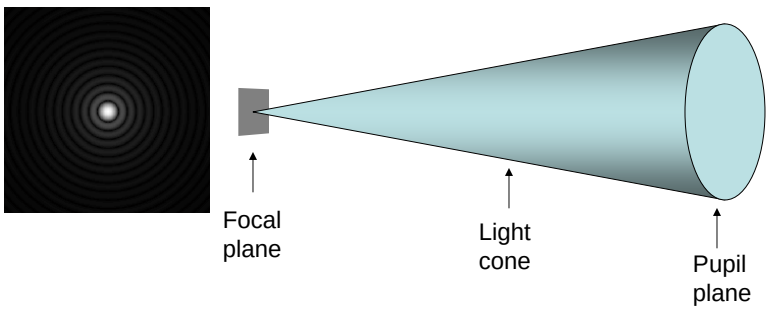




Diffraction Control via Shaped Pupils

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*.

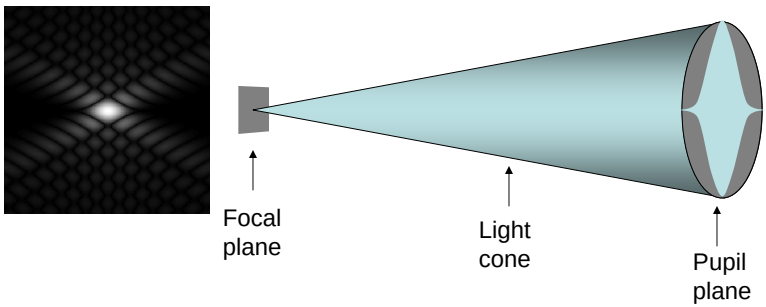
These diffraction rings are too bright. The rings would completely hide the planet.

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

Diffraction Control via Shaped Pupils

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 $(0, 0)$.

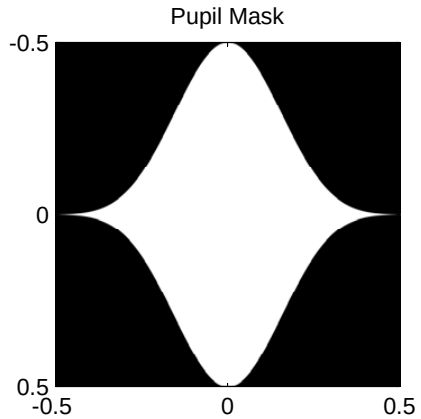


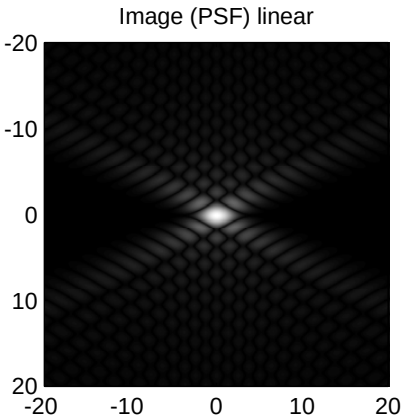
However, a point source produces not a point image but an *Airy pattern* consisting of an *Airy disk* surrounded by a system of *diffraction rings*.

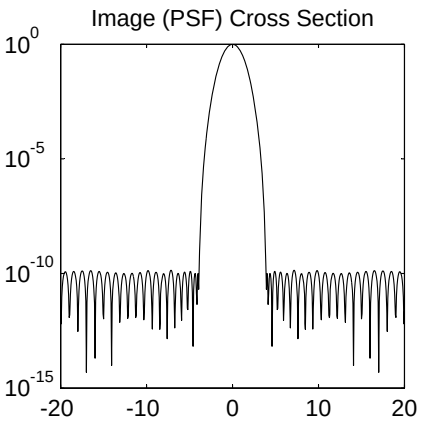
These diffraction rings are too bright. The rings would completely hide the planet.

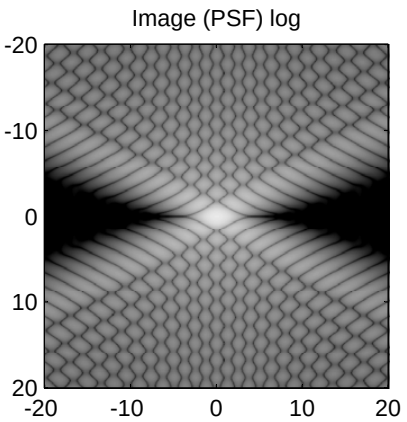
By placing a mask over the pupil, one can control the shape and strength of the diffraction rings. The problem is to find an optimal shape so as to put a very deep *null* very close to the Airy disk.

The Spergel-Kasdin-Vanderbei Pupil

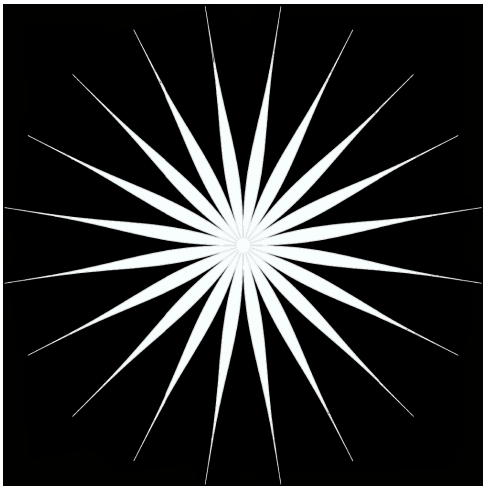




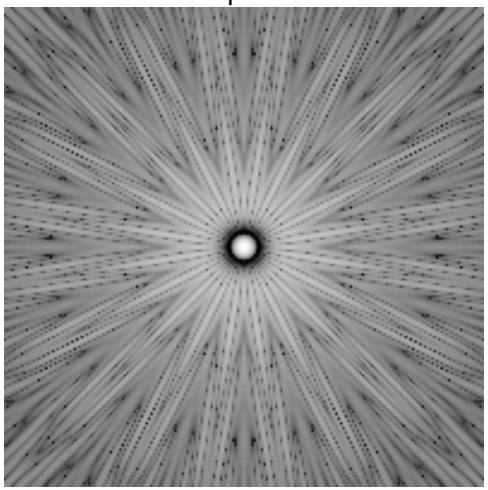




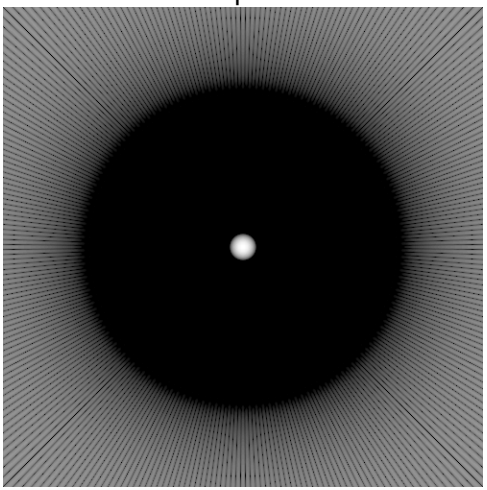
Shaped Pupil Coronagraph (TPF-C)



20 petals



150 petals



Maybe We Can!

Apodized Pupil Coronagraph (Unmanufacturable)

Apodized pupil

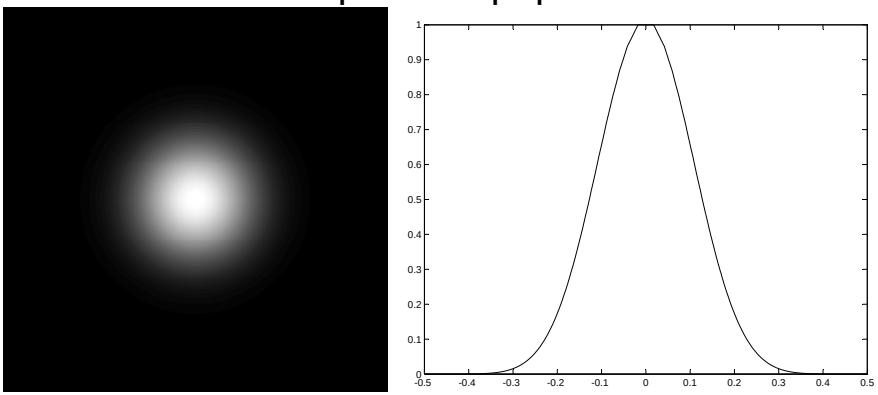
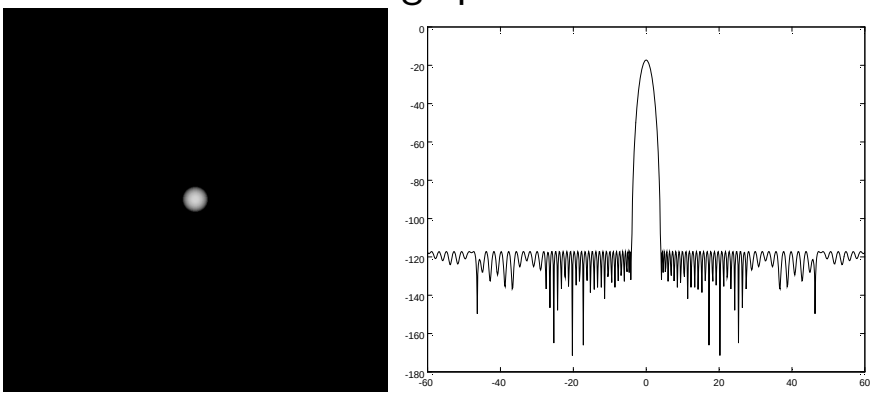
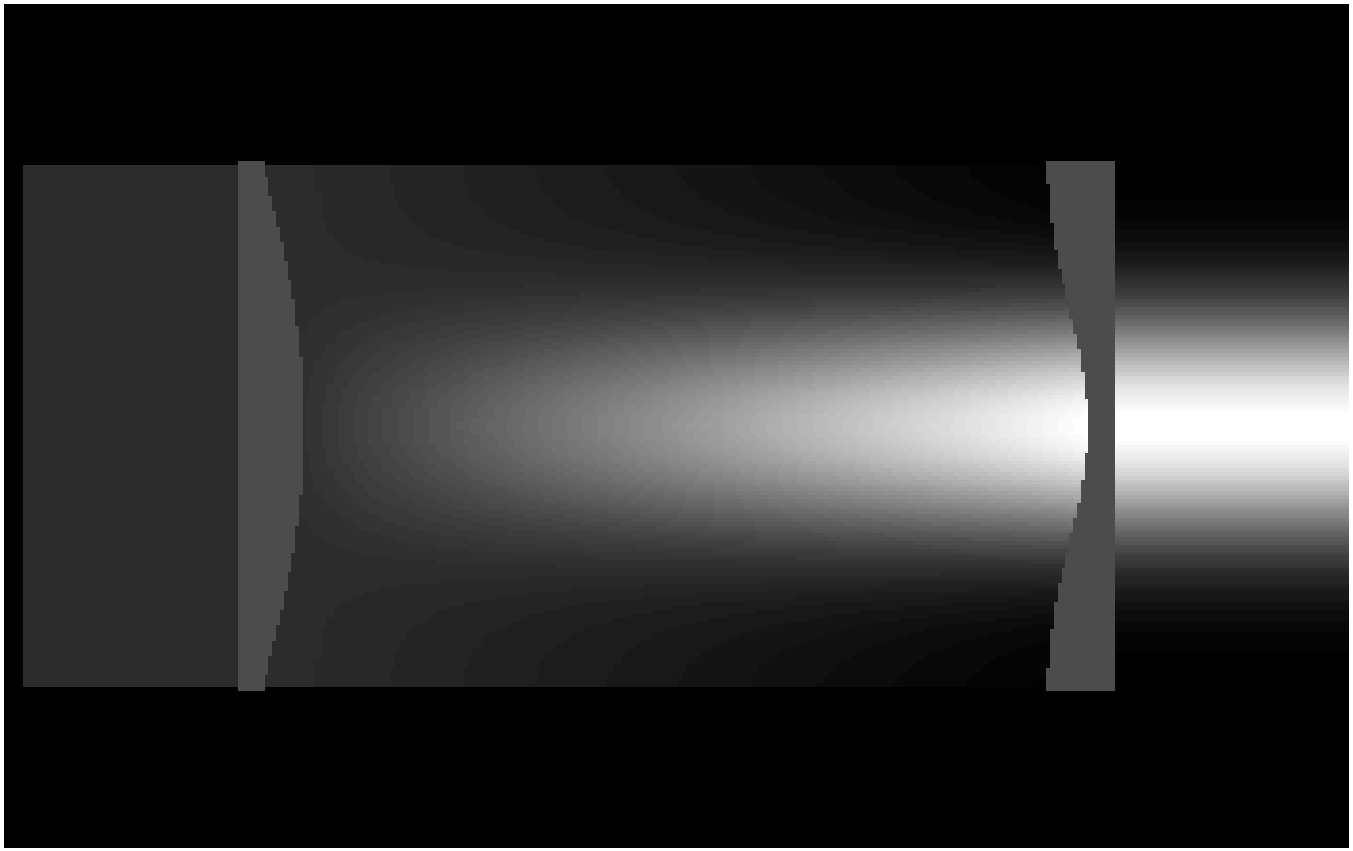


Image plane



Pupil Mapping (TPF-C)

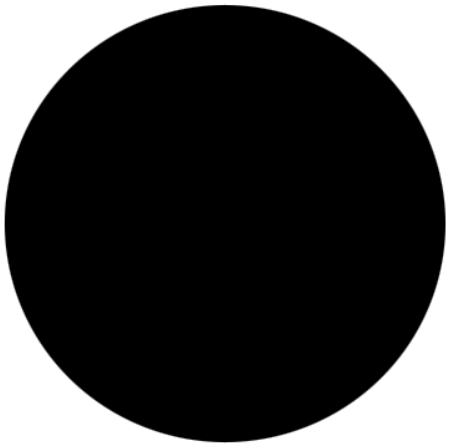


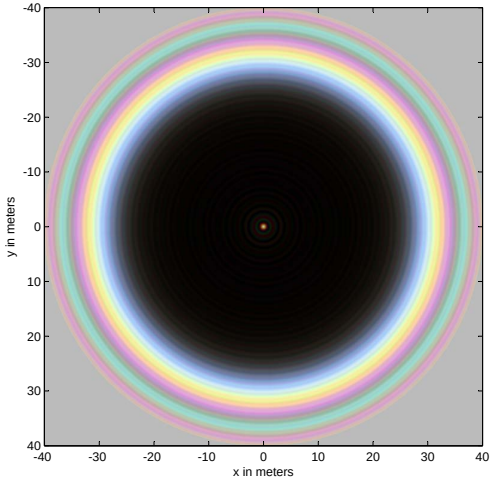
All above methods require optics of extraordinary quality: $1/10,000$ wave precision.

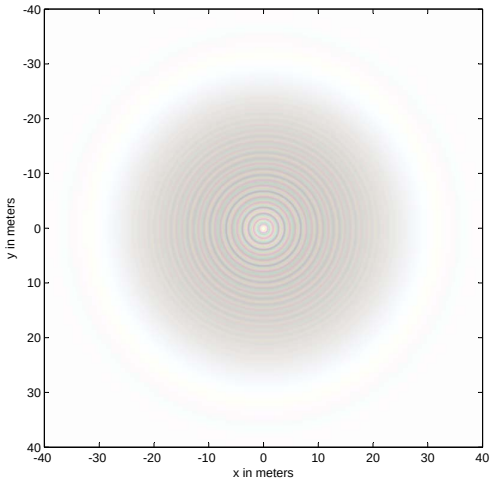
Space-based Occulter (TPF-O)

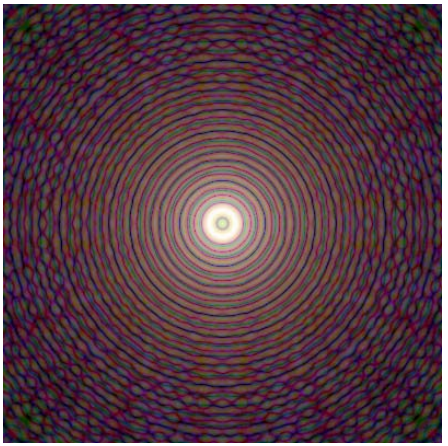
Telescope Aperture: 4m, Occulter Diameter: 50m, Occulter Distance: $72,000$km

Plain External Occulter (Doesn't Work!)









Shaped Occulter