Notice PLEASE

- **Wednesday (today):**
  - **TIMESTEP (N305 at 5 pm):**
  - **Tech Internships and Careers in Industry for Astronomy & Physics Majors**

- **Thursday:**
  - **normal study session**
  - **Science Colloquium**

“Precision Radial Velocity & Photometry from the Ground: Advances, Prospects & Challenges”

Dr. Suvrath Mahadevan (Penn State)

I shall discuss the challenges involved in making these difficult measurements with the Doppler radial velocity technique, and the evolution of the design of these instruments as they seek ever-tighter control of environmental parameters, higher resolution and efficiency, and to observe large spectral regions in the optical and infra-red.

NEID spectrometer
3.5 m WIYN 3.5 m

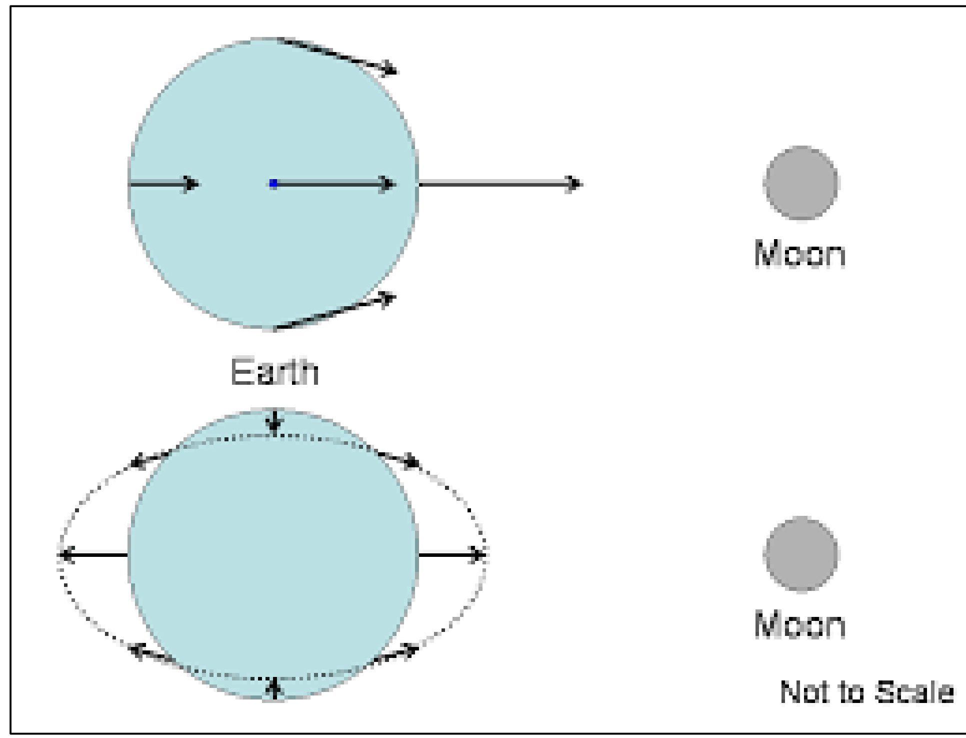
Habitable Zone Planet Finder
10 m Hobby-Eberly

Steward Obs.
weekly colloquium - Thursdays
(3:30 pm in room N210)
4:30 pm refreshments in the lobby

The r^{-2} Effects of Gravity:
tides, Roche Limit, Hill Sphere

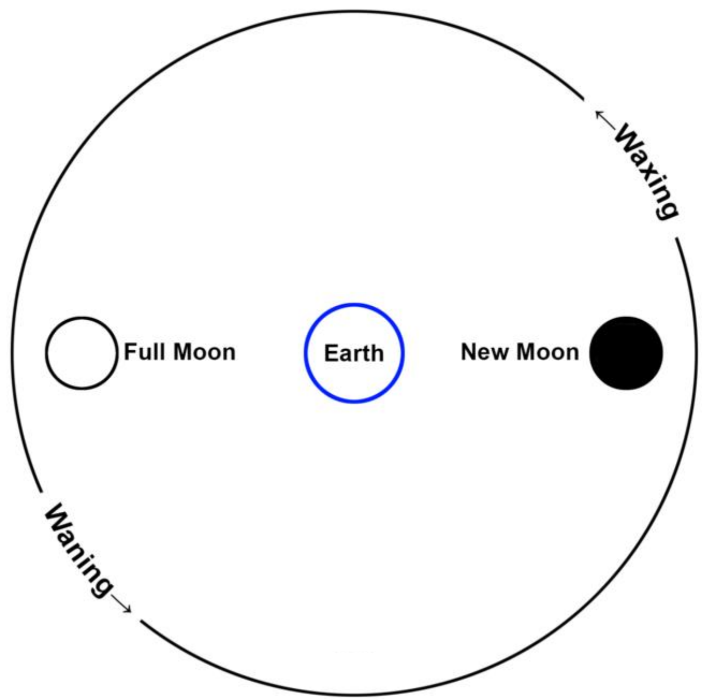
Tidal Forces

$$\frac{dF_{moon}}{dr} = \frac{2GMm}{r^3}$$

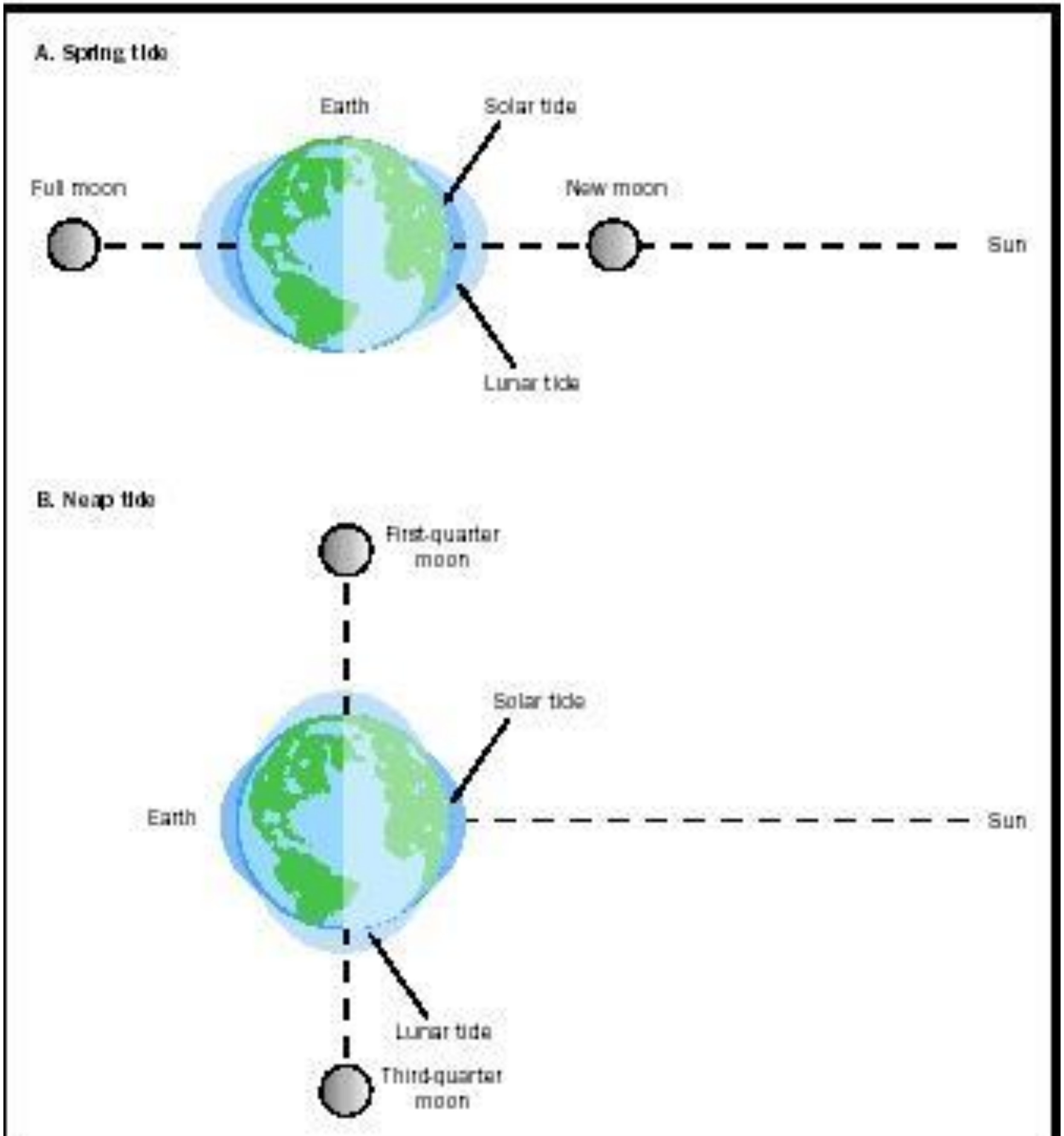


Which lunar phase produces the highest tides on Earth?

By what percentage?



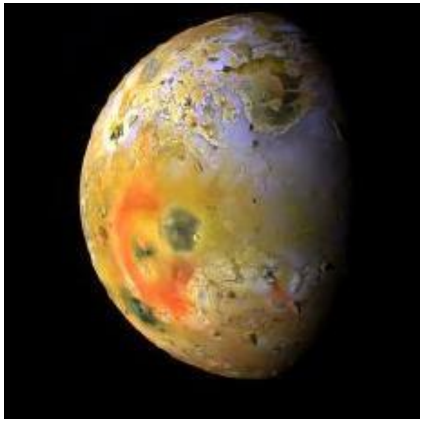
Friday's class: The moon causes a 6.8% variation in force across Earth's diameter.


A. Spring tide
Earth
Solar tide
Full moon
New moon
Sun
Lunar tide
B. Neap tide
First-quarter moon
Solar tide
Earth
Sun
Lunar tide
Third-quarter moon

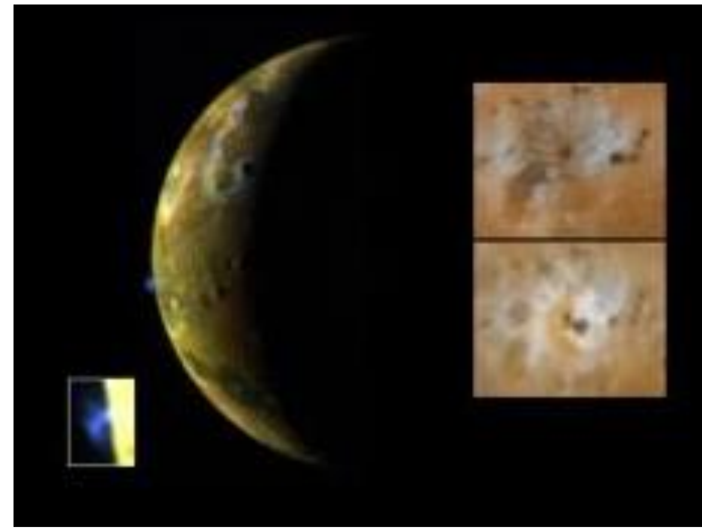
100 Volcanoes in Action!

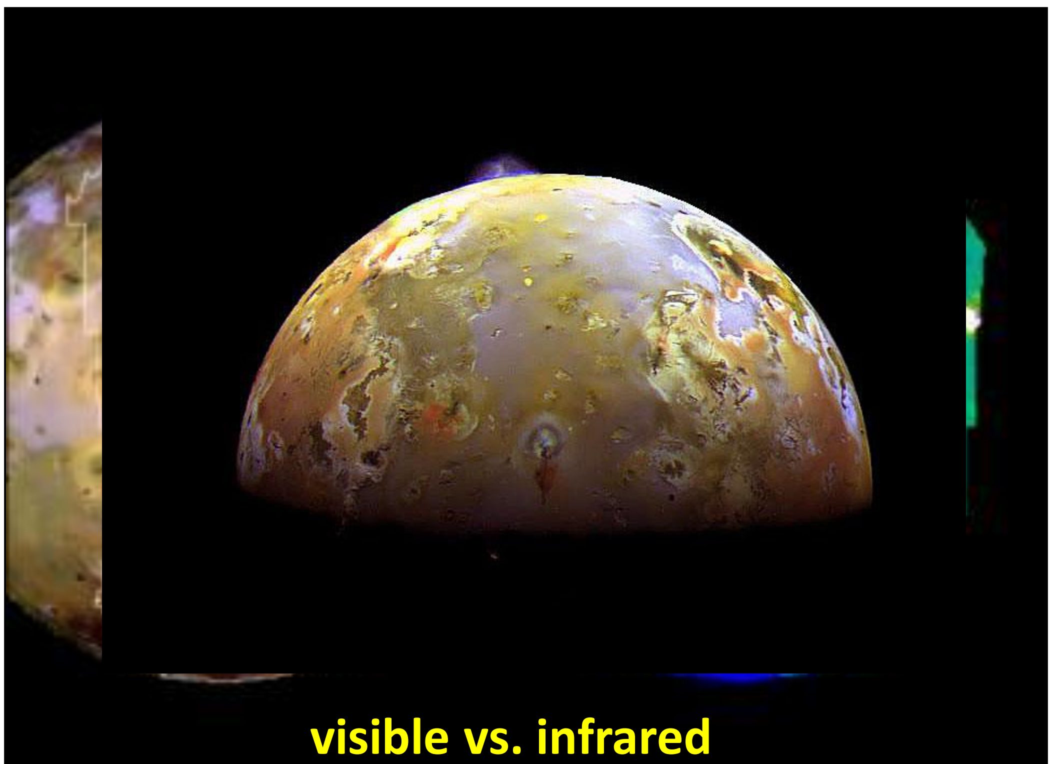
Io has no impact craters

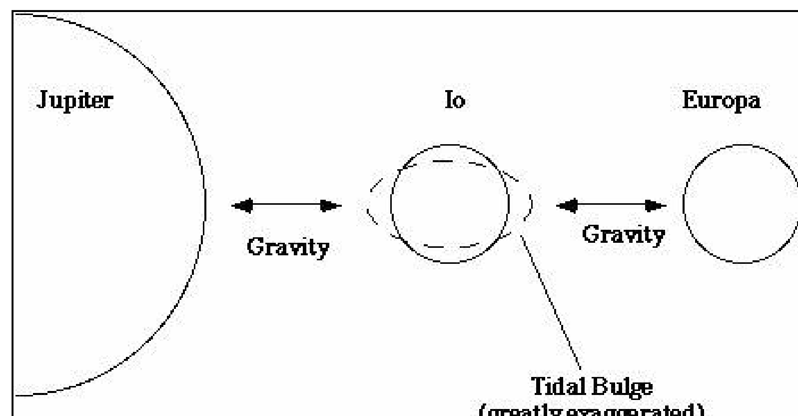
they've been covered up!



Sulfur-based volcanism

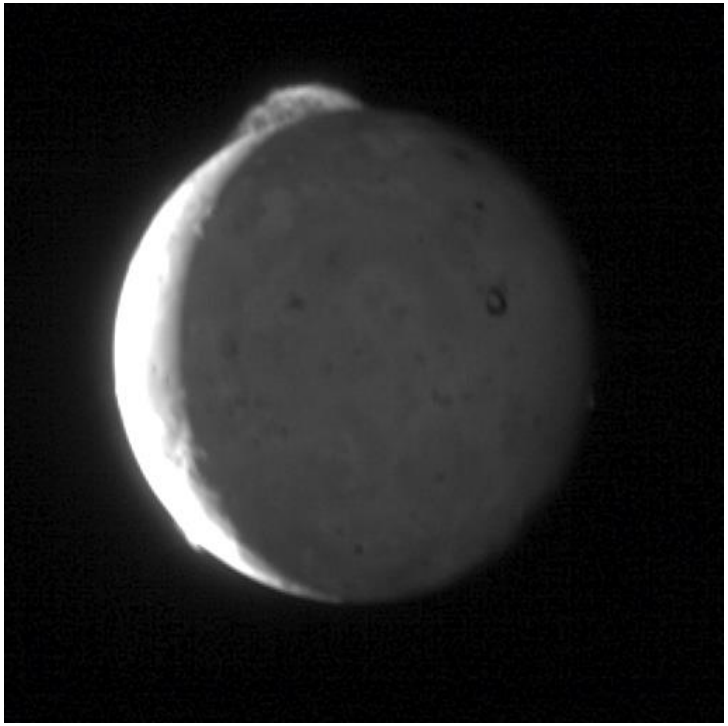


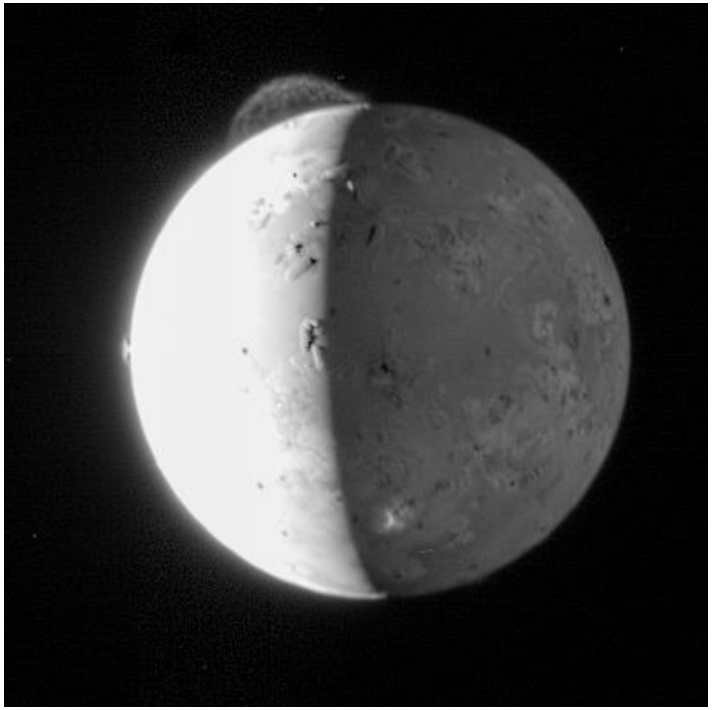




Starry Night: "Io_Europa"

Tvastar Plume Movie
(8 min)
1 ton of gas (sulfur, oxygen) escapes Io each second from its volcanoes



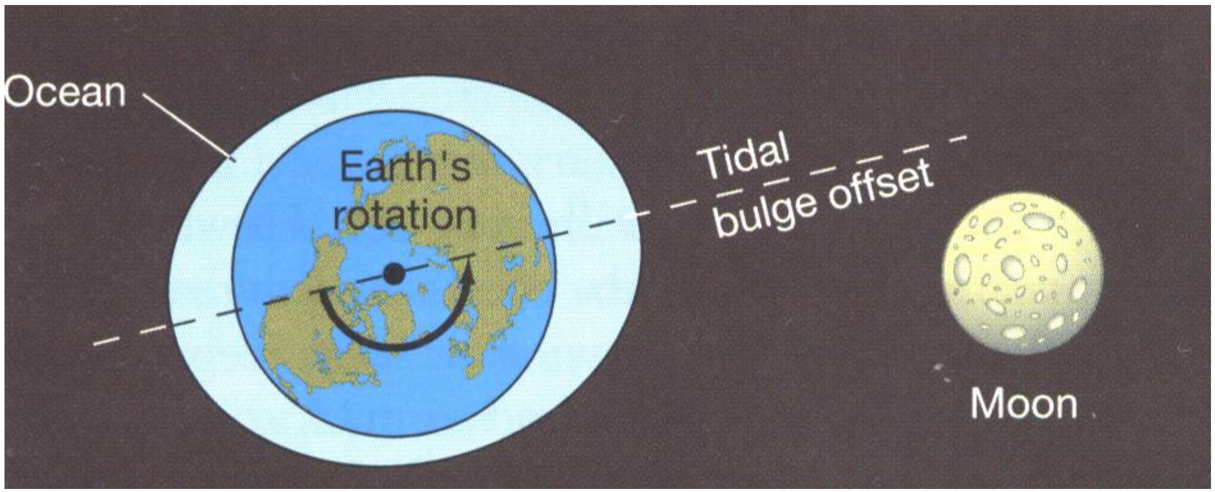


Plume reaches 200 miles high but source is below horizon by 80 miles

Saturn’s Moon Enceladus

Tidal Evolution

Earth rotates faster than the Moon revolves.
Earth-Moon and Pluto-Charon



The Moon slows the Earth 0.002 seconds each century.

The Moon recedes from Earth at 3.8 cm per year:

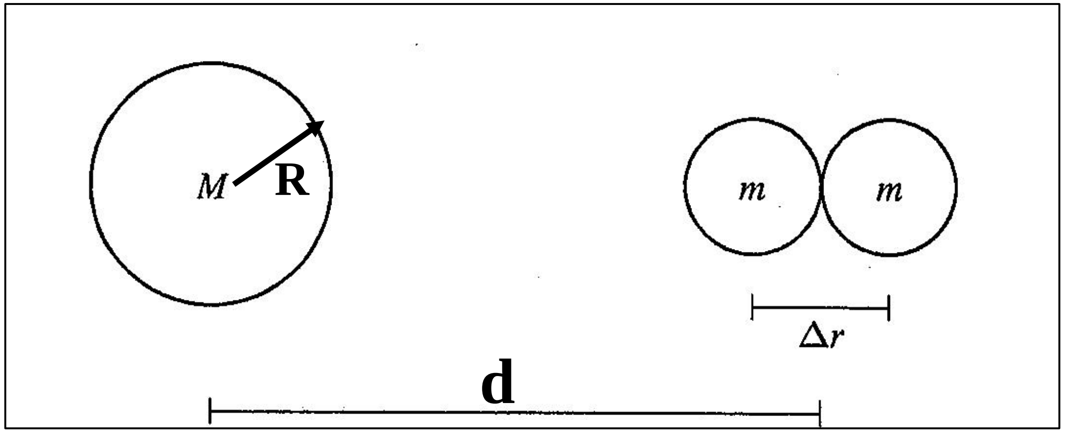
About the rate your fingernails grow!

Someday the Earth AND the Moon will keep same sides toward each other. A day will equal a month (47 of our present days).

Roche Limit (d_R)

depends on satellite's density and rigidity

Did you do the derivation?



$$d_R \approx 2.4\,(\rho_M / \rho_m)^{1/3}\ R$$

$$\frac{d_R}{R} \approx 2.4\,(\rho_M / \rho_m)^{1/3}$$

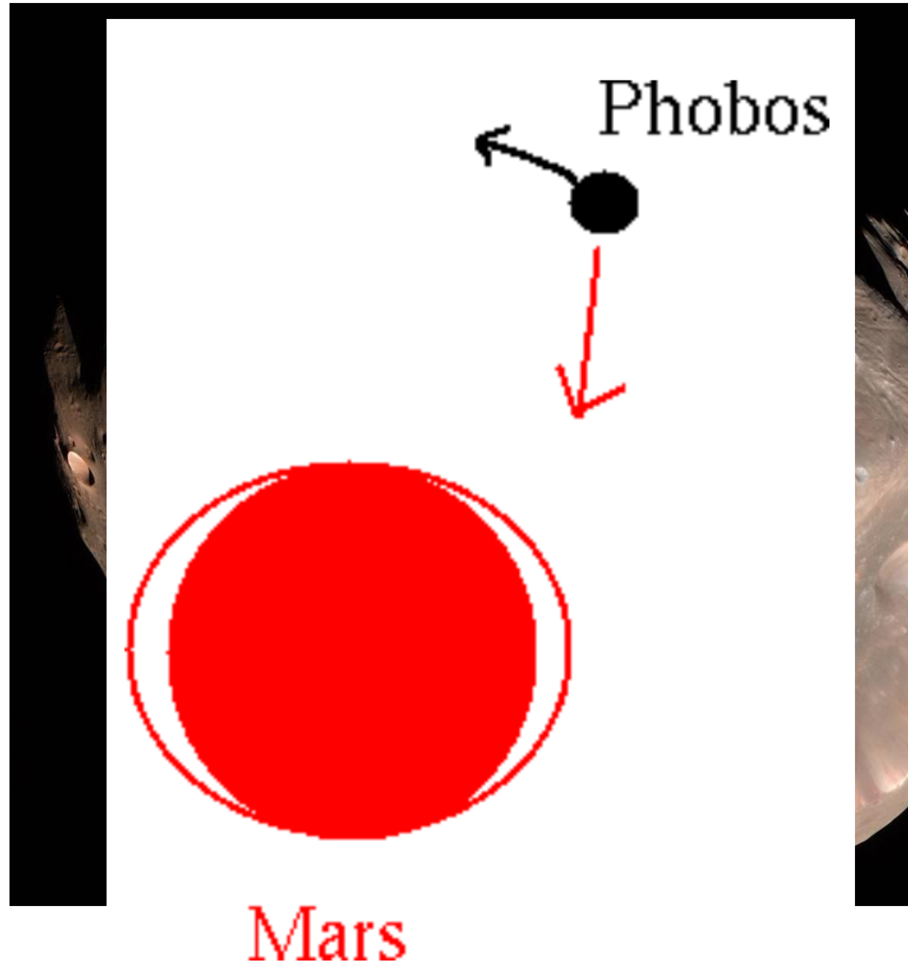
What assumptions?

What if?

- $\rho_M = \rho_m$
- $\rho_m < 0.5\ \rho_M$

The r^{-2} Effects of Gravity:
tides, Roche Limit, Hill Sphere

- **Phobos is closer to its planet than any other moon in the solar system: 3700 miles.**
- **Phobos' orbits decreases by about 6.6 feet (2 meters) every hundred years.**
- **Scientists expect the moon to be pulled apart in 30 to 50 million years. Why?**
- **The long, shallow grooves lining the surface of Phobos are likely early signs of the structural failure that will ultimately destroy this moon of Mars.**



stretch marks ?

Hill Radius ("Sphere")

"instability limit"

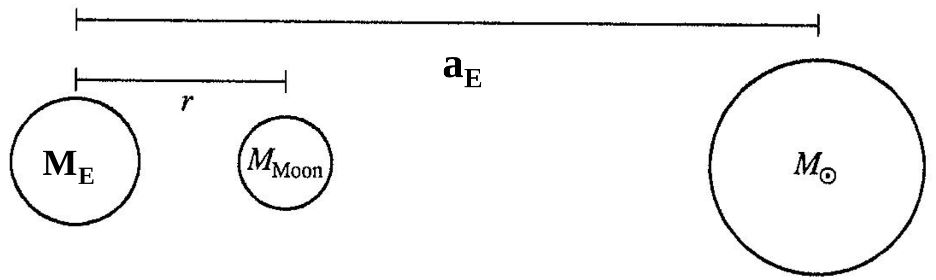


FIGURE 4.9 The Moon and the Earth, with masses M_{Moon} and $M_\oplus$, respectively, form a gravitationally bound system with separation r. The Sun, with mass $M_\odot$ at a distance $a_\oplus$ from the Earth, perturbs the Earth–Moon system. (Not to scale.)

What approach to this equation?

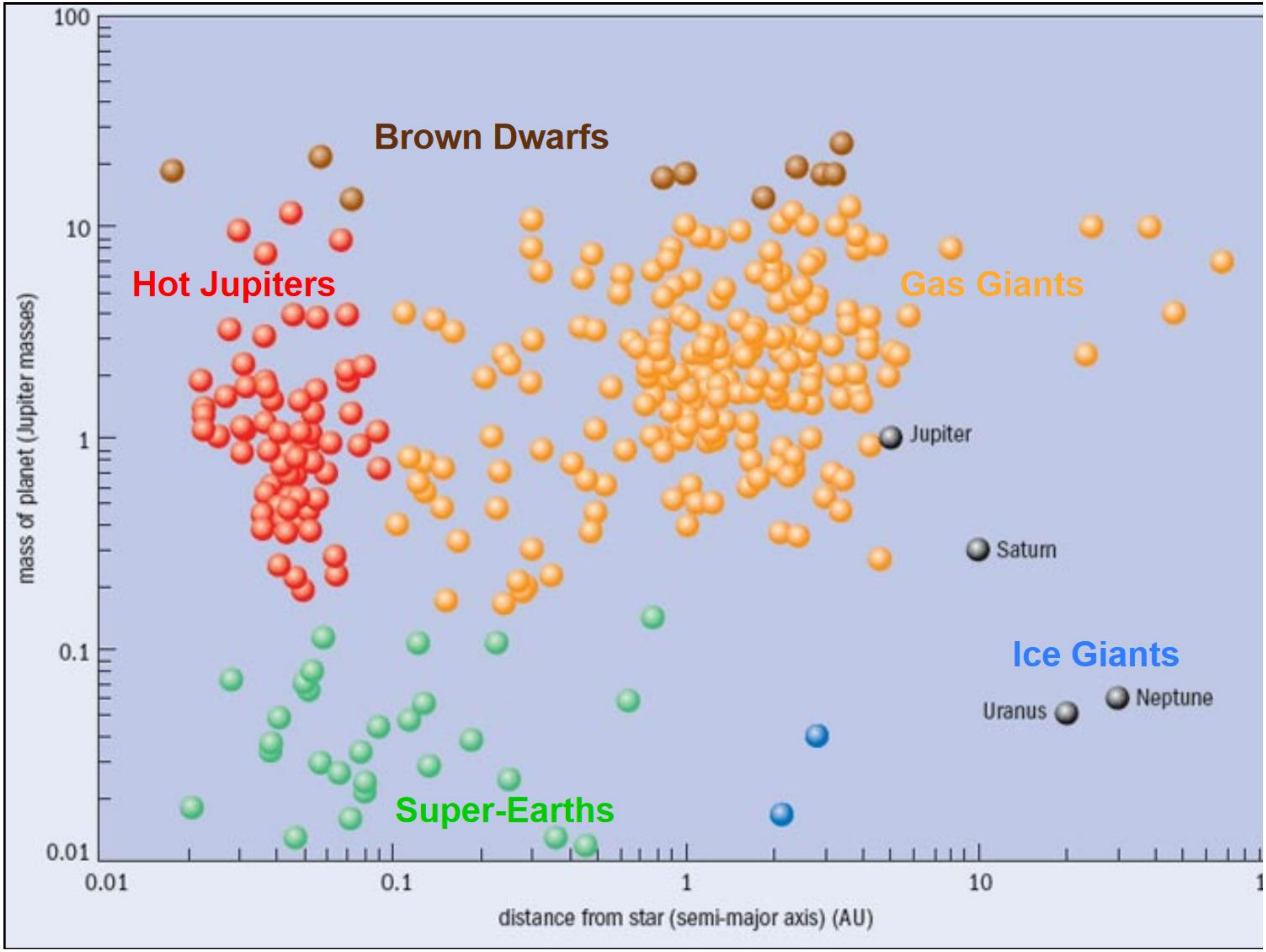
$$d_H \approx (M_E / 2M_\odot)^{1/3}\ a_E$$

Problem

If Jupiter migrated 100x closer to the Sun (i.e., the distance of a typical Hot-Jupiter exoplanet), would the Galilean moons survive?

Calculate the change in Hill radius (r_H).

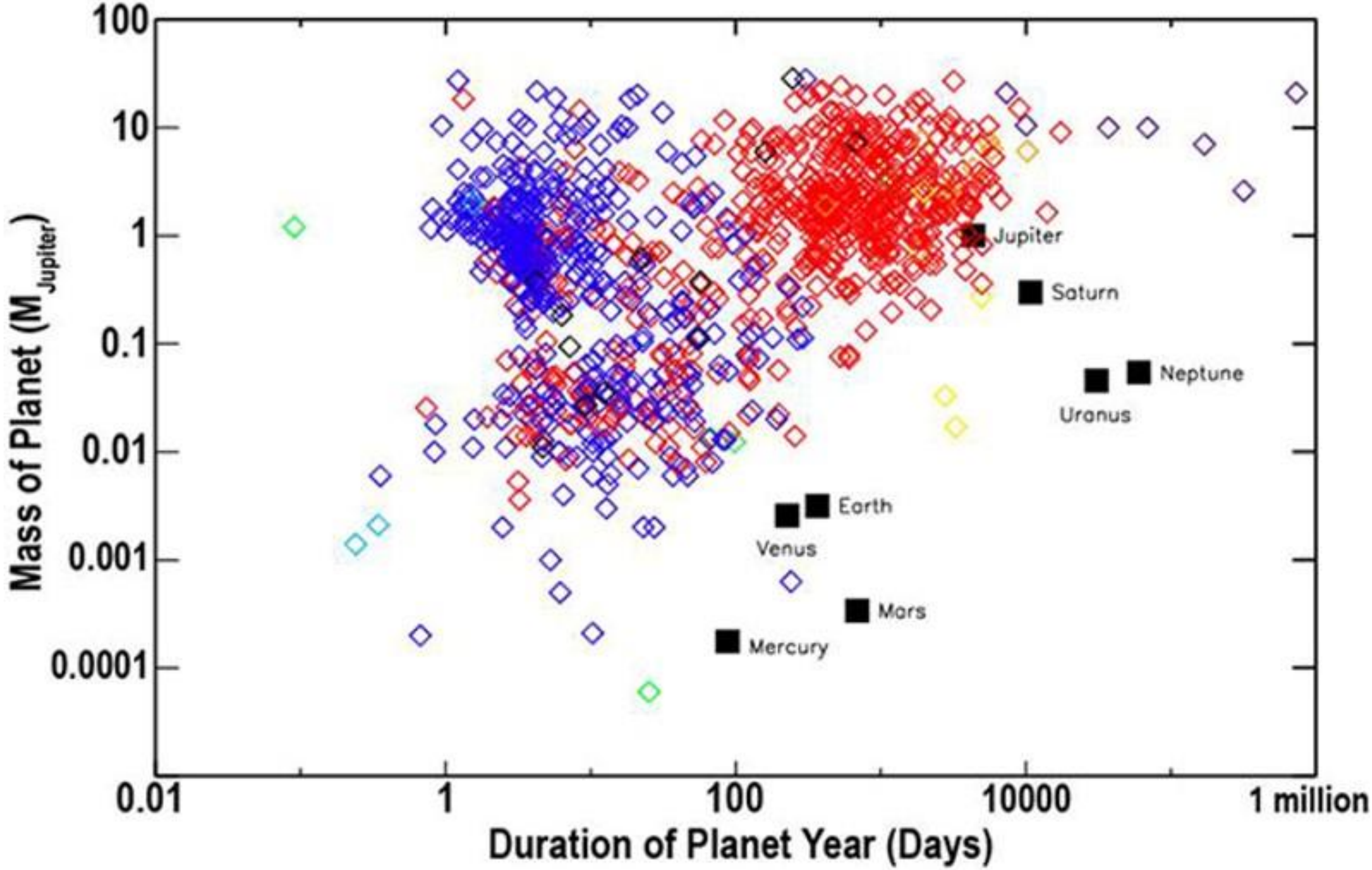
$M_{Jup} \approx 0.001\ M_{sun}$
Galilean moon distances: $(0.41 – 1.9) \times 10^6$ km



Brown Dwarfs
Hot Jupiters
Gas Giants
Ice Giants
Super-Earths
Jupiter
Saturn
Uranus
Neptune
mass of planet (Jupiter masses)
distance from star (semi-major axis) (AU)
100
10
1
0.1
0.01
0.01
0.1
1
10

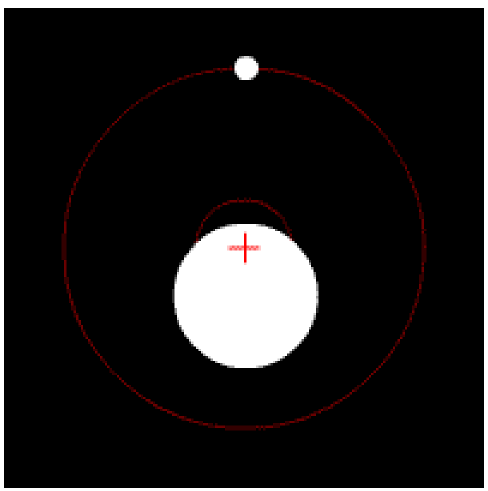
Exoplanets !

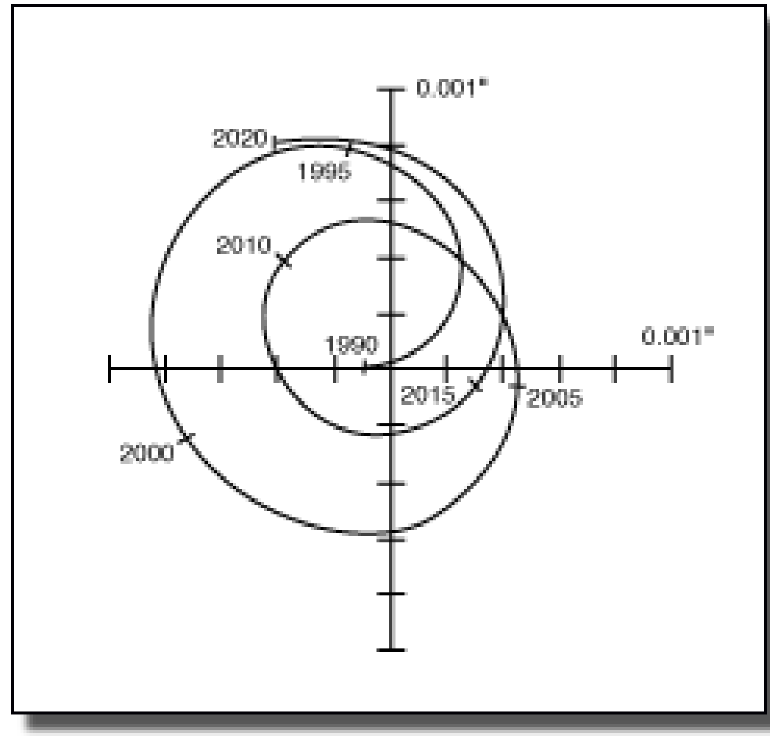
Which are detected directly and which indirectly?



Indirect Method #1

astrometry



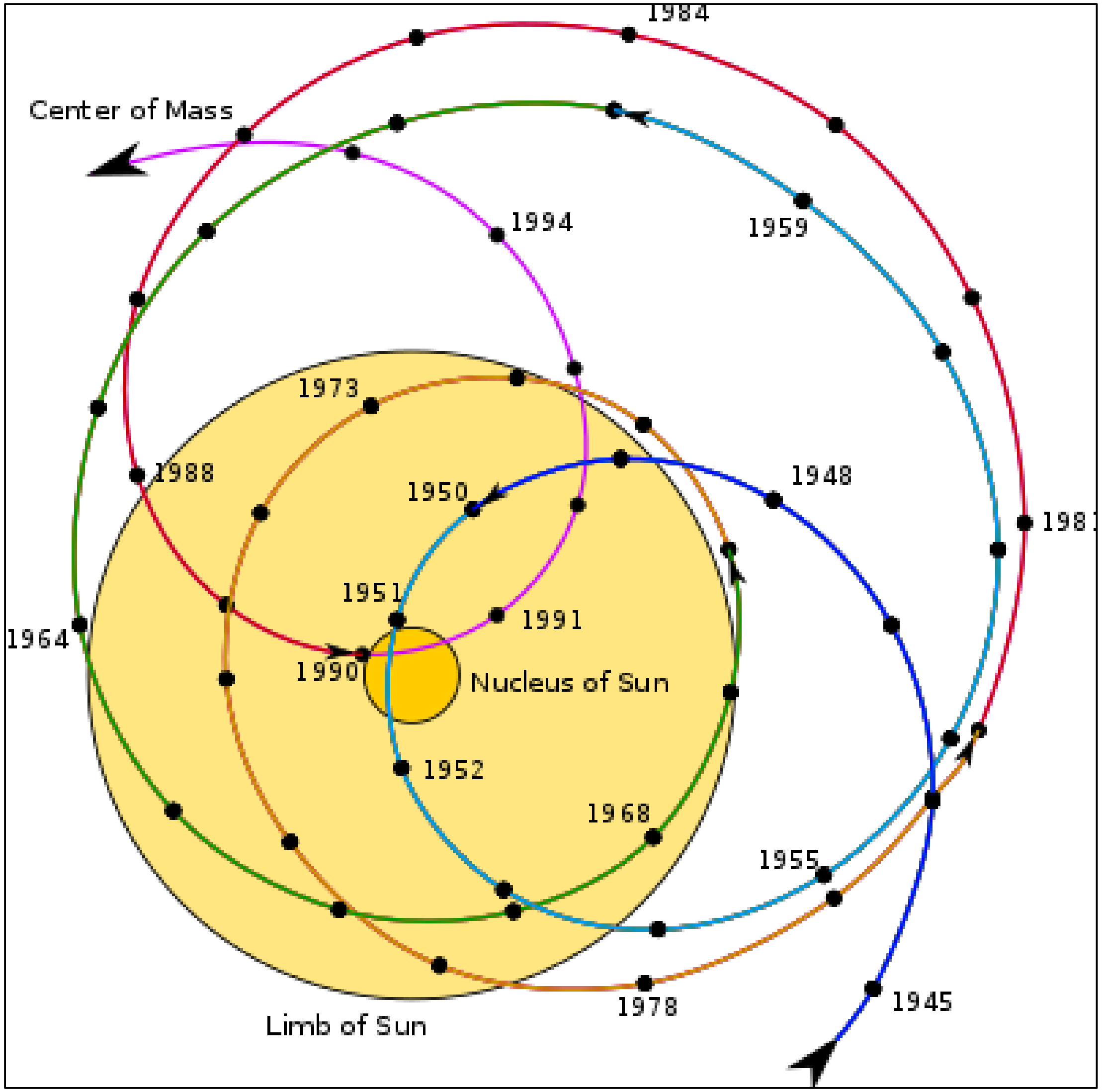


Astrometric displacement of the Sun due to Jupiter as seen from 10 parsecs.

Watch how stars move relative to a background of other stars.

Why is this method challenging?

Motion of Solar System's "Barycenter"



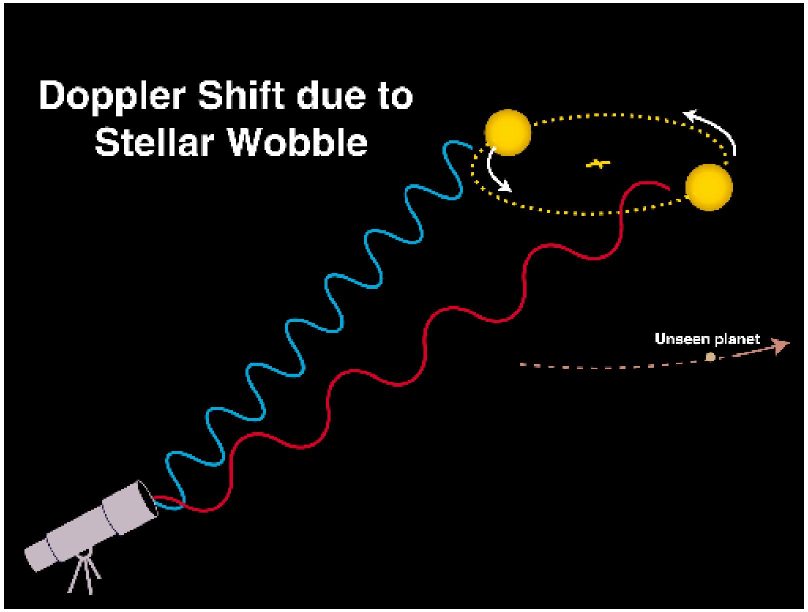
Indirect Method #2
Doppler shift and spectroscopy

<u>Center-of-Mass:</u>

planet and star

both objects move around it

The Sun moves 10 meters/sec and takes 11 years to make one full circle.



$$\Delta\lambda / \lambda = v_r / c$$

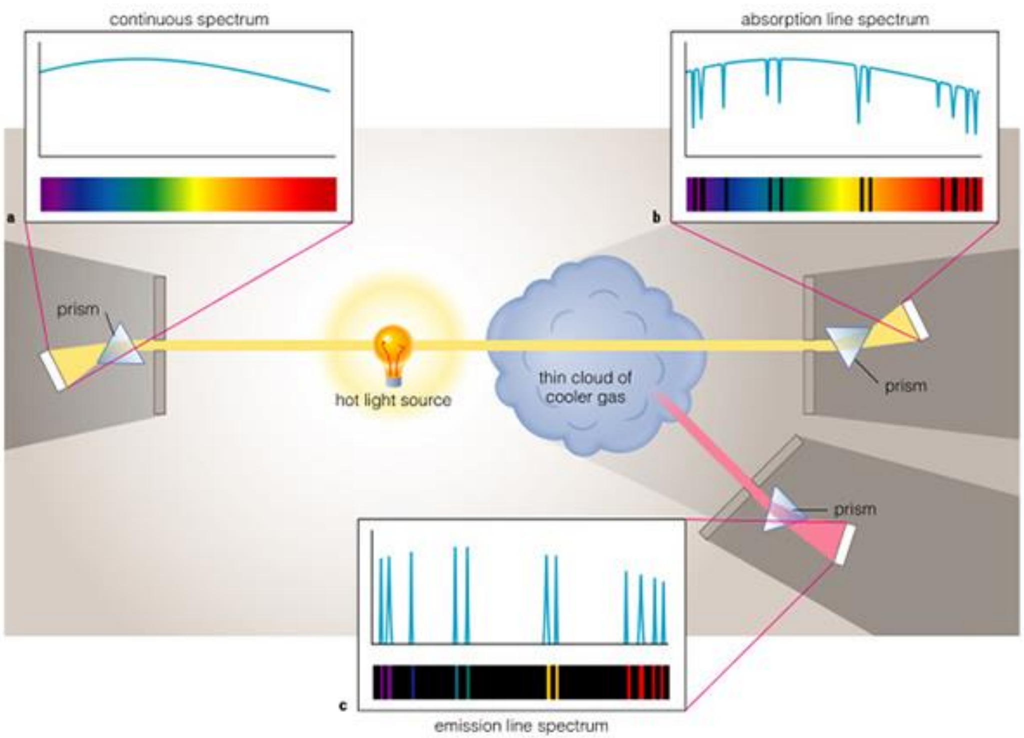
Problem

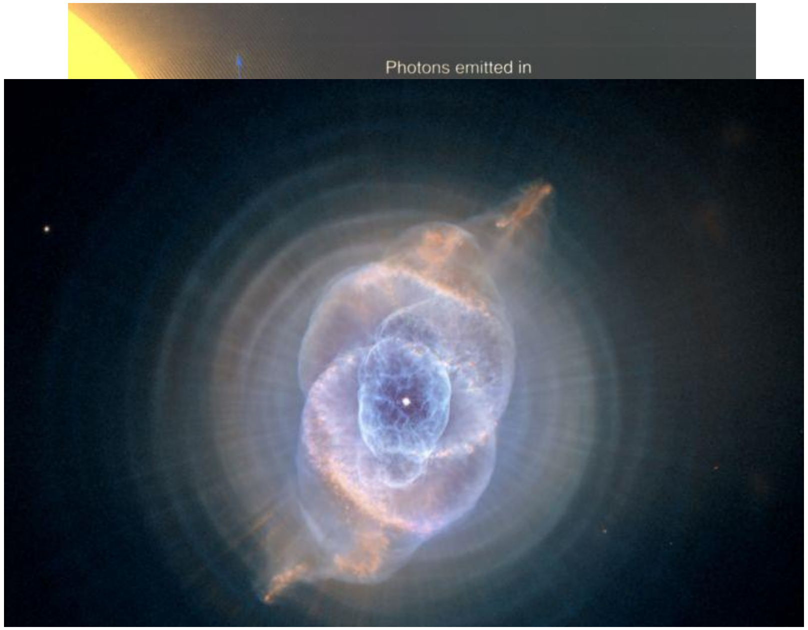
Some of today's exoplanets were discovered by precise monitoring of the Doppler Effect in visible light from the parent stars. The Doppler Effect causes a change in wavelength ($\Delta\lambda$) proportional to v/c, where v is the star's velocity back-and-forth caused by the planet's gravity.

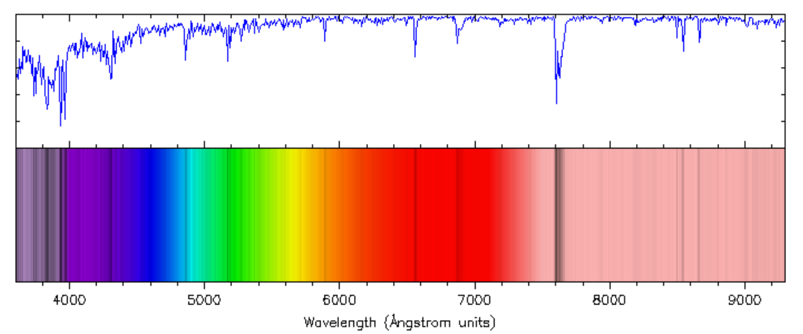
$$\Delta\lambda/\lambda = v/c$$

Today's technology can measure velocities of <1 msec^{-1}. What is the resulting wavelength shift ($\Delta\lambda$)? Are you surprised by this answer; why or why not?

Spectroscopy

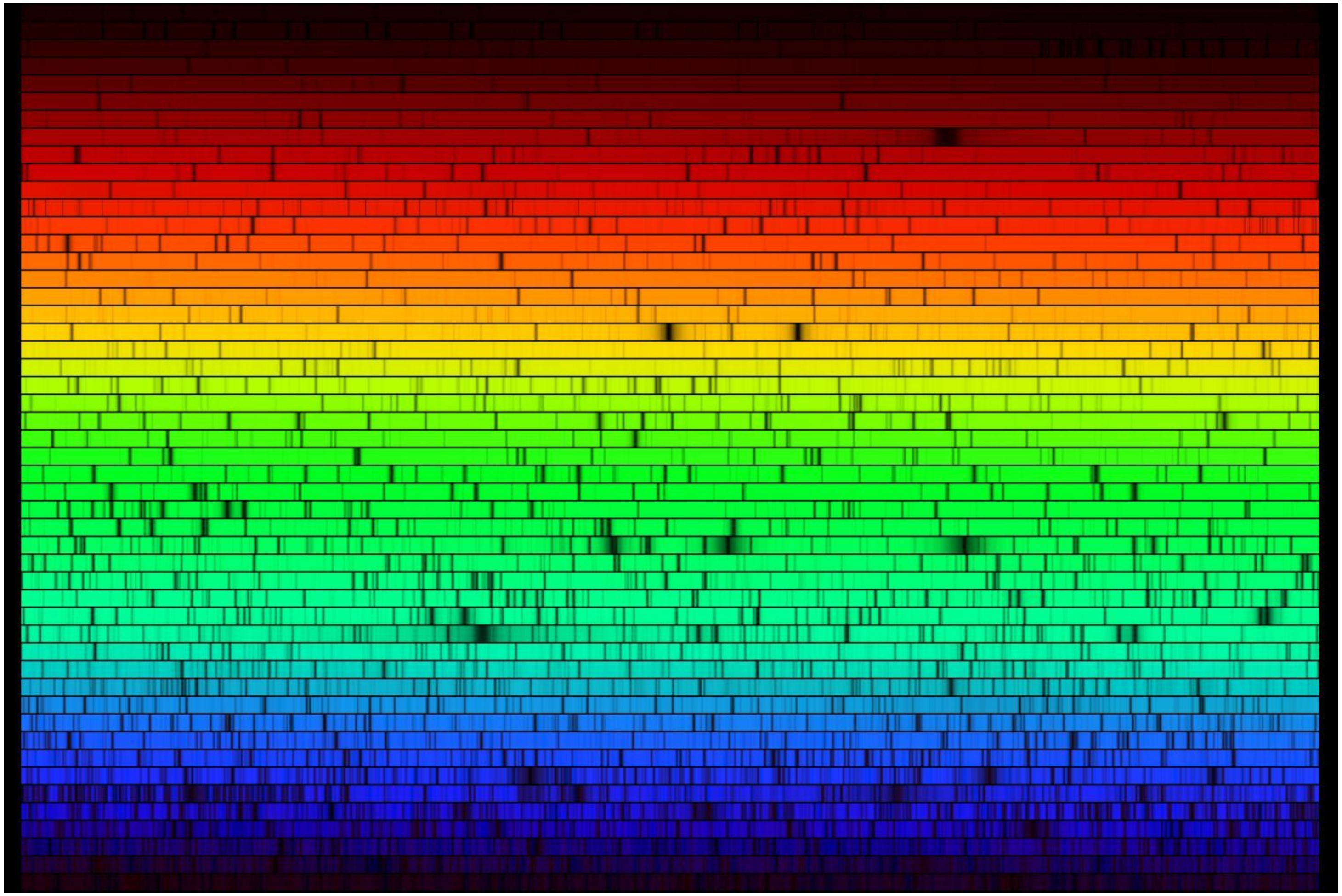






Data from "Photometric Atlas of the Solar Spectrum from 3000 to 10,000 A" by L. Delbouille, L. Neven, and C. Roland
Institut d'Astrophysique de l'Universite de Liege, Observatoire Royal de Belgique, Liege, Belgique, 1973

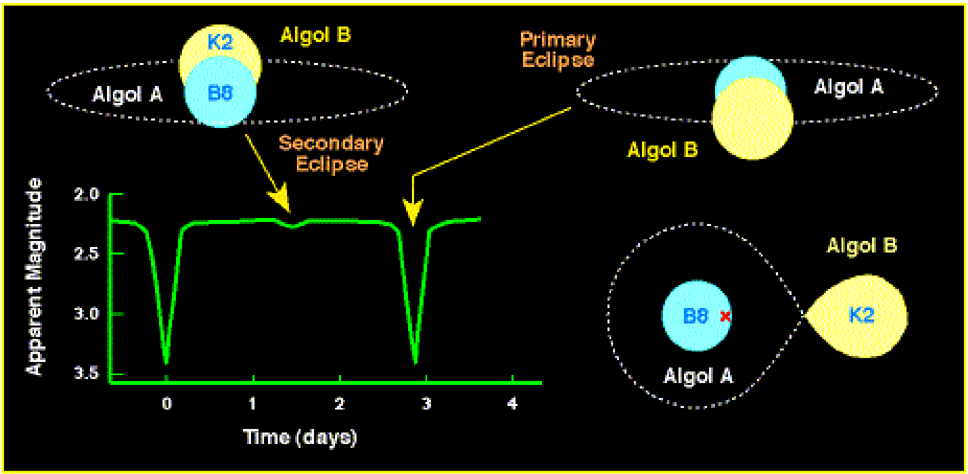
Solar Spectrum

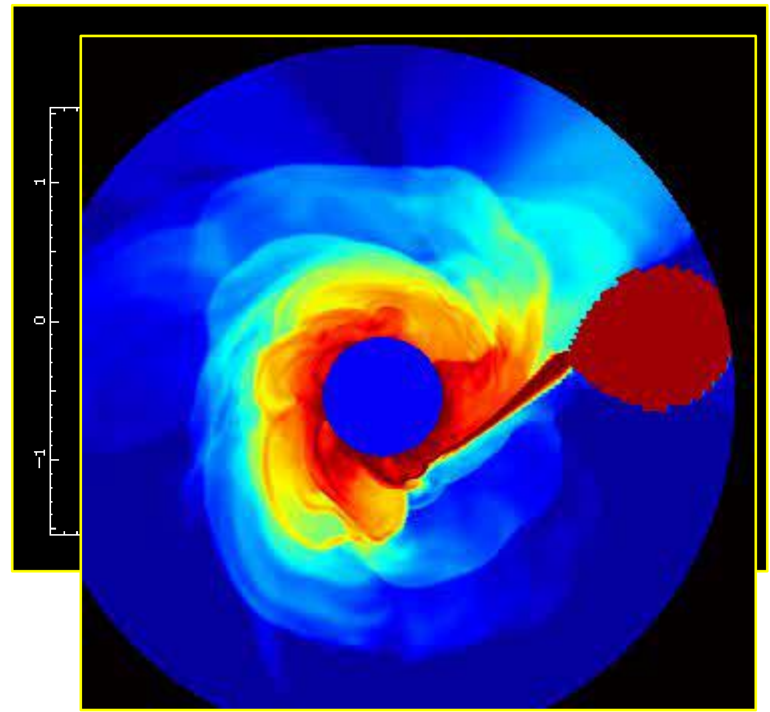


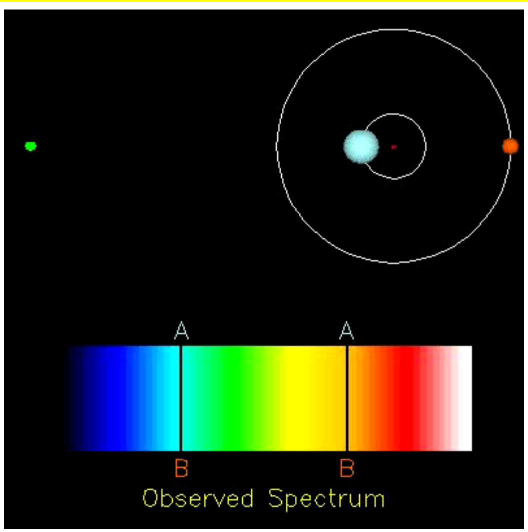
Algol (β Perseus)

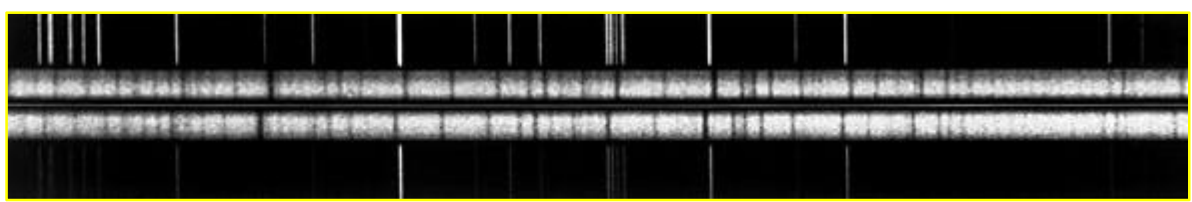
eclipsing binary (2.86739 days)

distance: 92 light-years = 28 parsecs







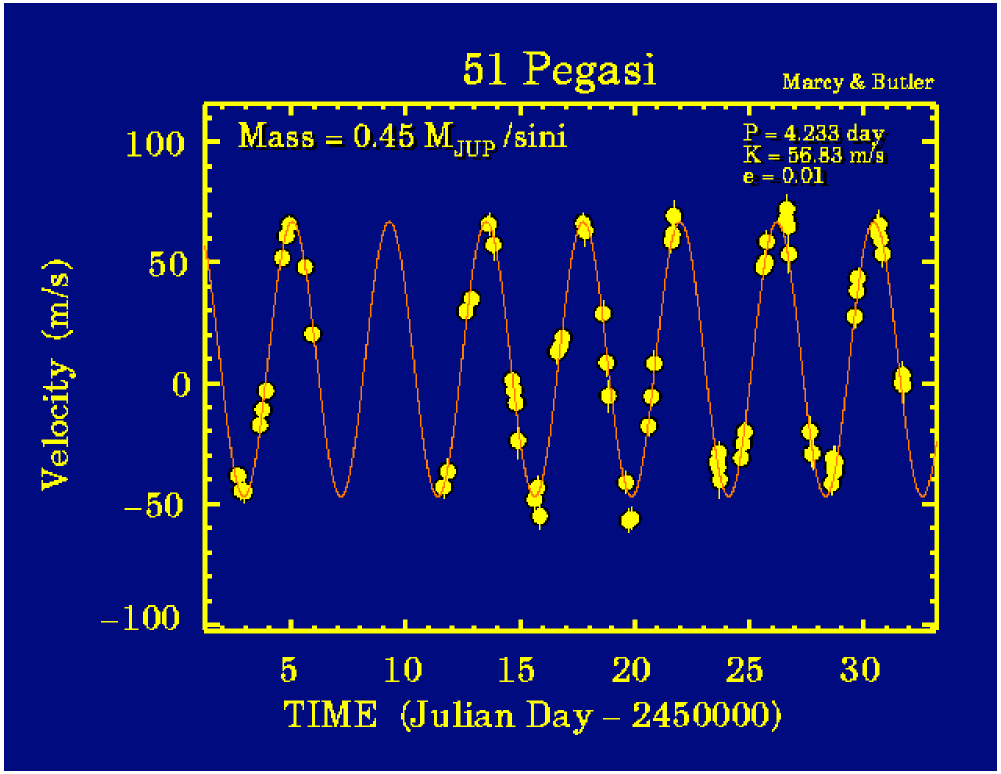


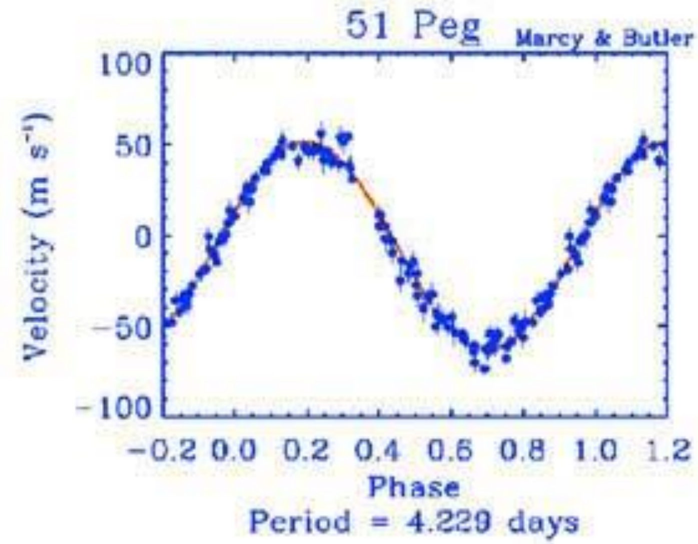
movie

The First Extra-Solar Planet

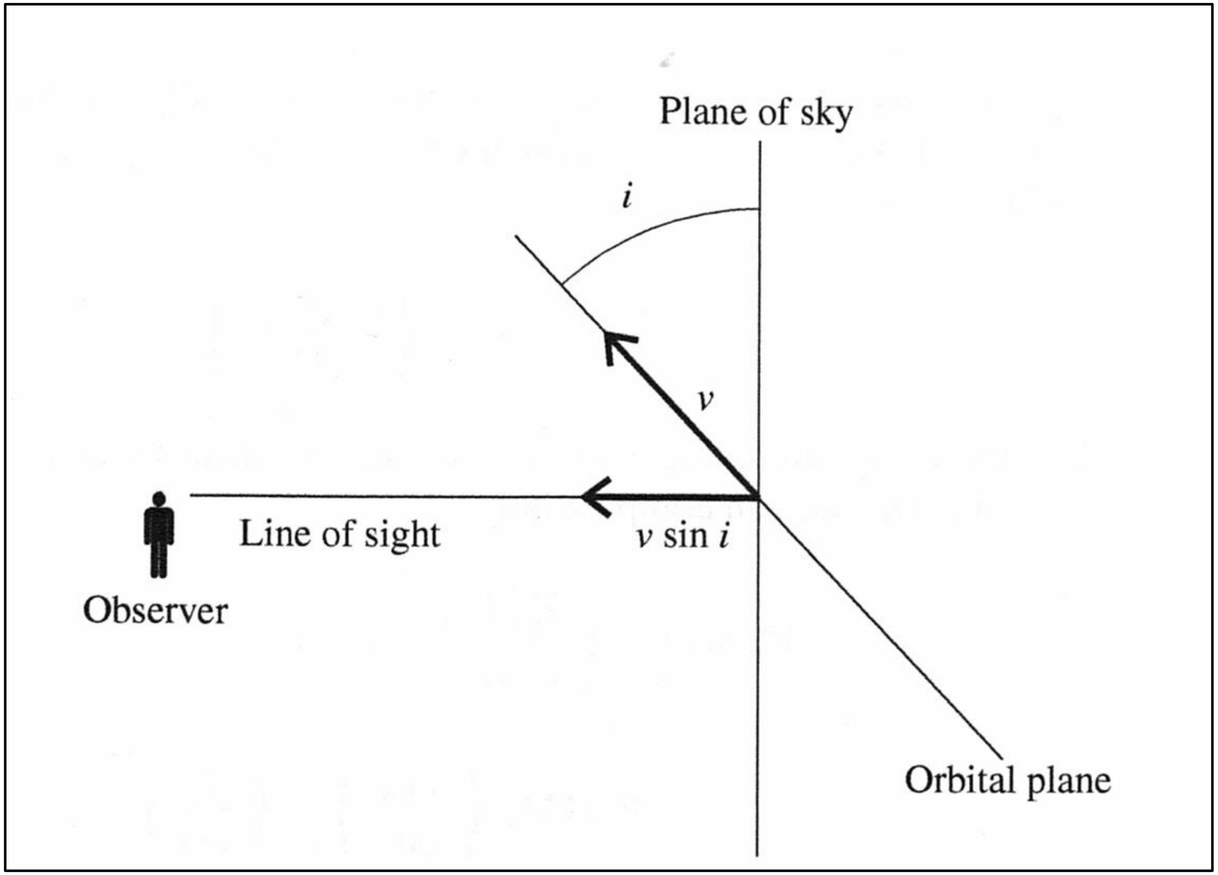
1995: 51 Pegasus b

Do you notice anything unusual about this graph?





Projected Radial Velocity

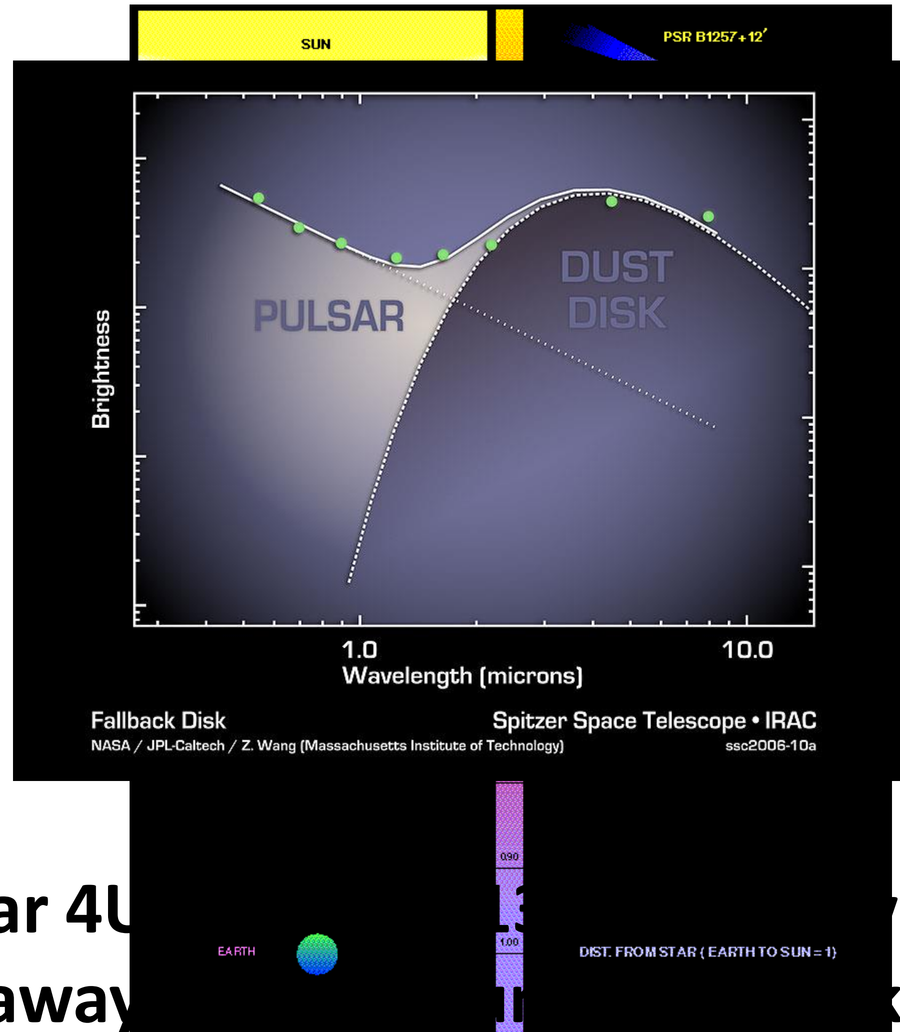


Pulsar Planets (PSR B1257+12)

the first extra-solar planets were discovered around a dead star

Second Generation Planets?

0.02, 3.9, 4.3 M_{Earth}



Pulsar 4U … years
away …

Kepler's 3rd Law
equation (12.21)

$$M_p \sin i \approx 11\ M_e\ (M_s)^{2/3}\ P^{1/3}\ (v_s \sin i)$$

P (years), M_s (M_{sun}), v (m/sec)

$$v_s\ \alpha\ M_p M_s^{-2/3}\ P^{-1.3}$$

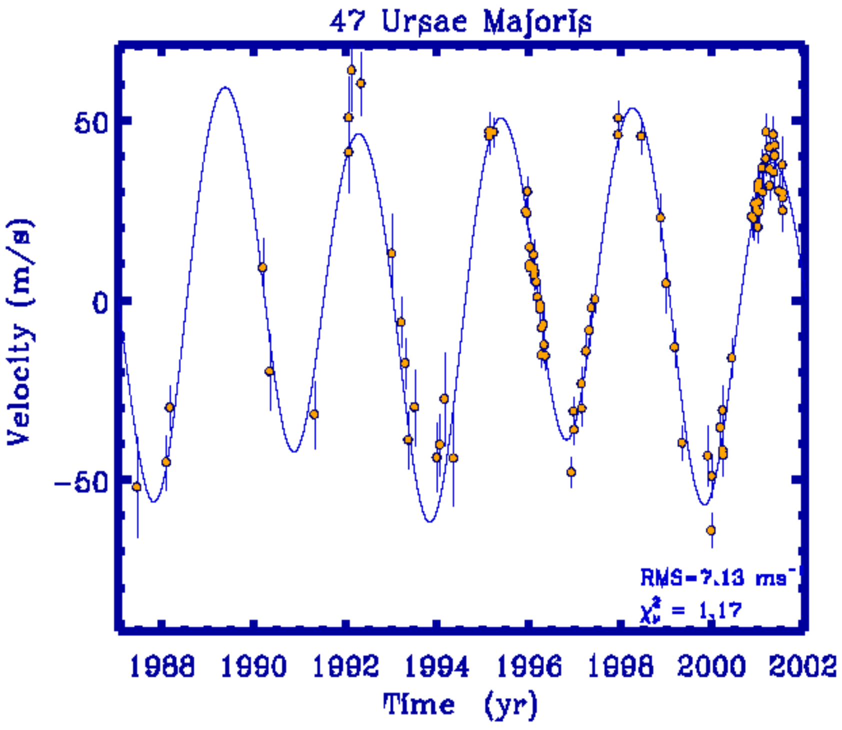
What characteristics of exoplanets would promote detection by the Doppler Effect?

Problems
exoplanet: 47 UMa b

- **47 UMa A**
  - **1.48 L_{sun} and 1.08 M_{sun}**

- **Assuming the period of the orbit from the velocity curve is 2.95 years, calculate the planet's semi-major axis (in AU).**

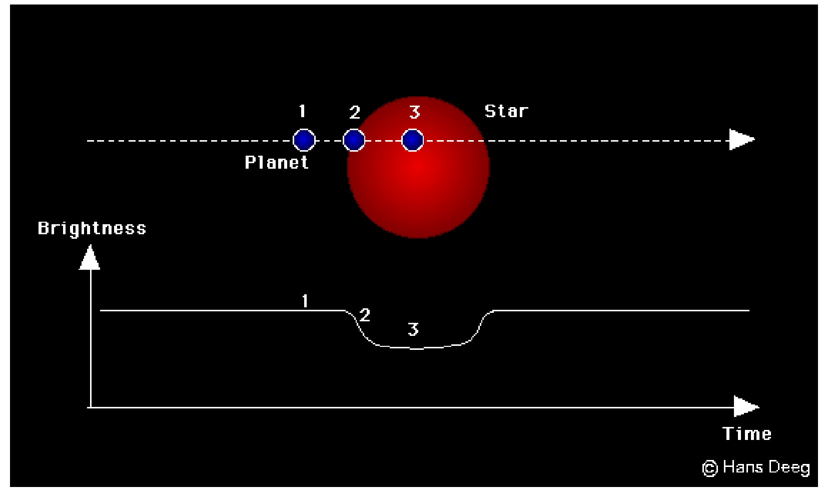
- **Estimate the minimum mass of the planet (quote as a ratio to the mass of Earth).**



Indirect Method #3

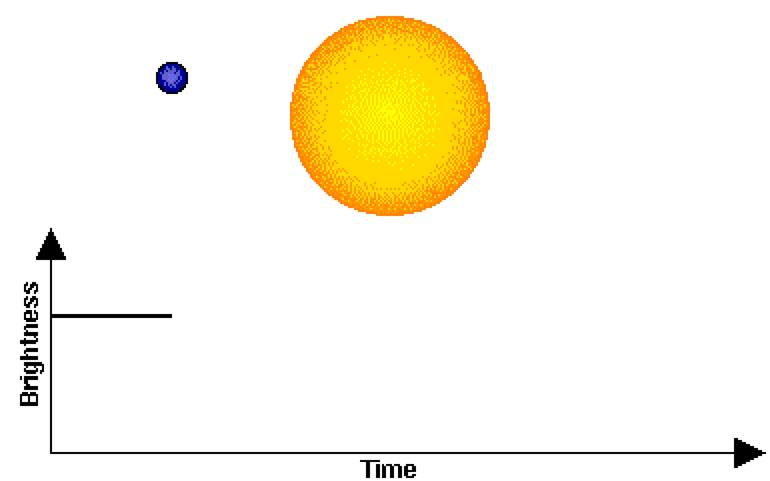
eclipses (“transits”)

probabilities: 0.5% (Earth-like); 10% (Jupiter-like)



A planet can cross in front of a star diminish some of the star’s light.

How does the drop in flux scale with diameter of the planet?



What signal strength do you expect?

Sun-Jupiter= ?

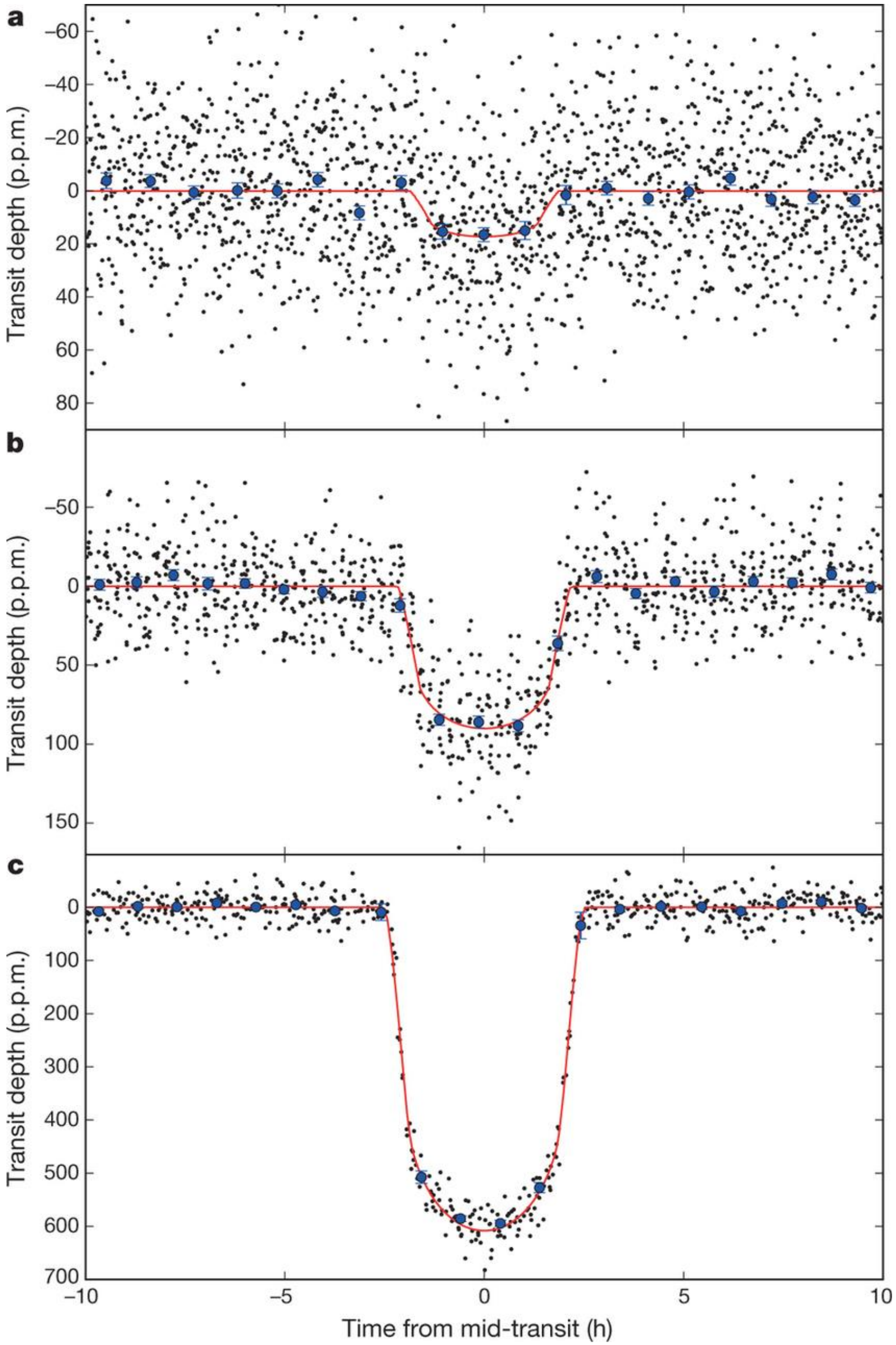
Sun-Earth = ?

Solution

- **Fractional change in area**
  - **(AREA – area) / AREA**
  - **$(\pi R^2 - \pi r^2) / \pi R^2$**
  - **$1 - (r/R)^2$**

- **$R_{Jup} \sim 0.1\ R_{Sun}$**
  - **So, Jupiter would reduce the Sun's light by 1%.**

- **$R_{Earth} \sim 0.01\ R_{Sun}$**
  - **So, Earth would diminish Sun's light by ~0.01 %.**
  - **1 part in 10^4 = 100 ppm**
  - **duration of expected eclipse ~2-16 hours.**



Kepler 37 b,c,d planets

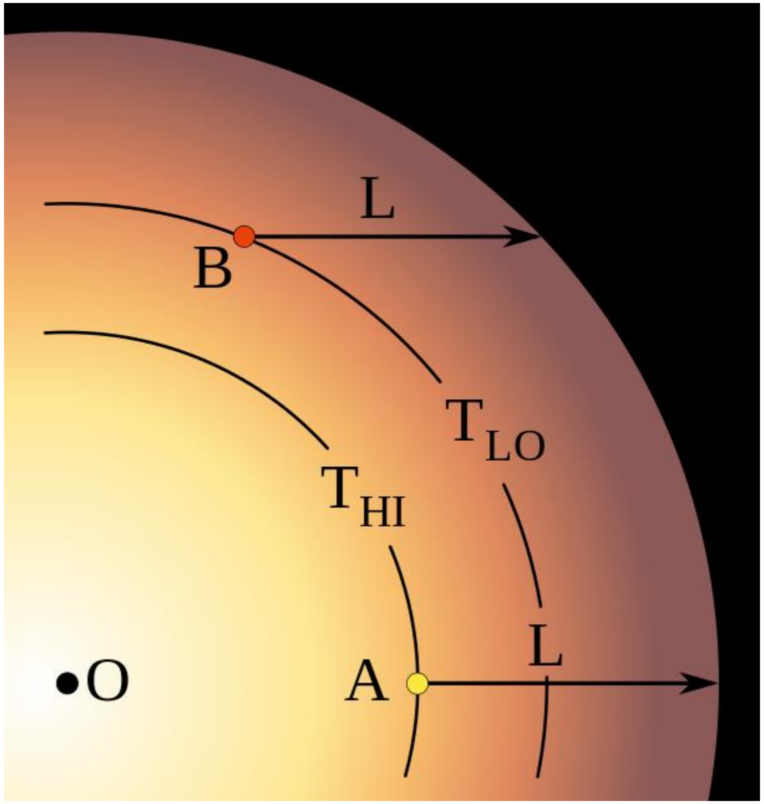
R_{Earth} =

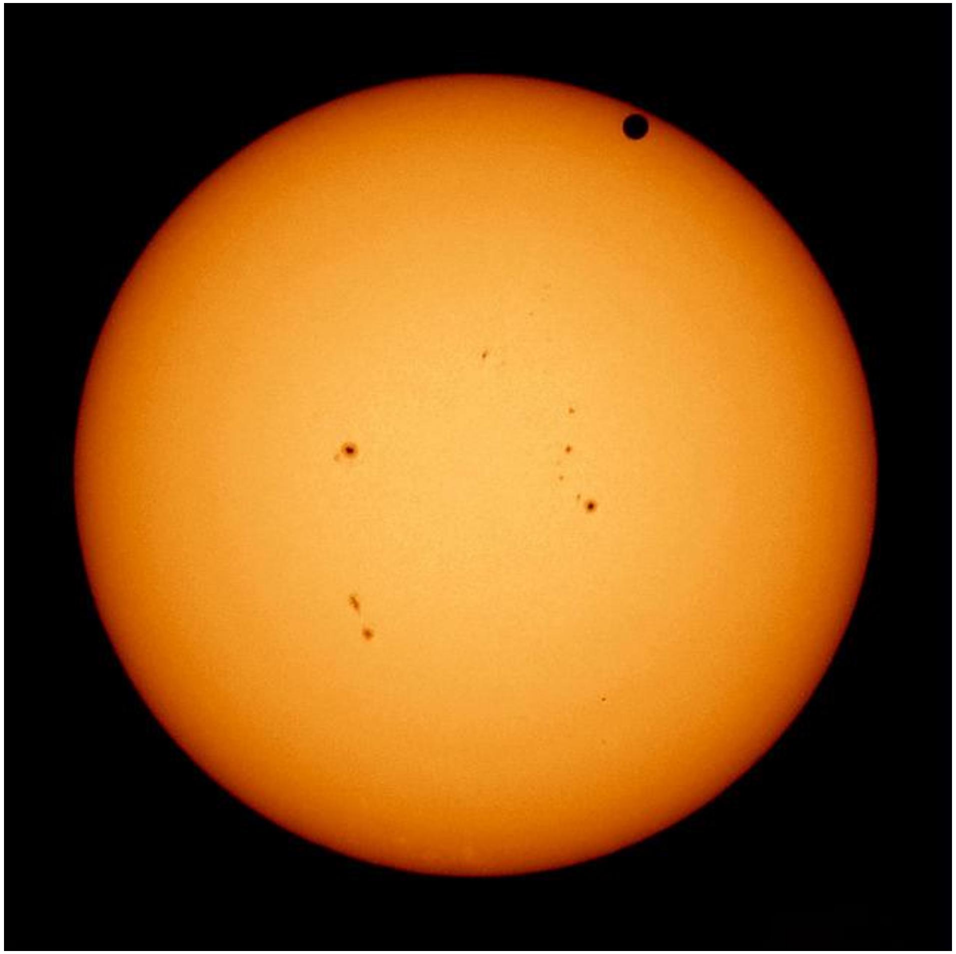
0.35

0.74

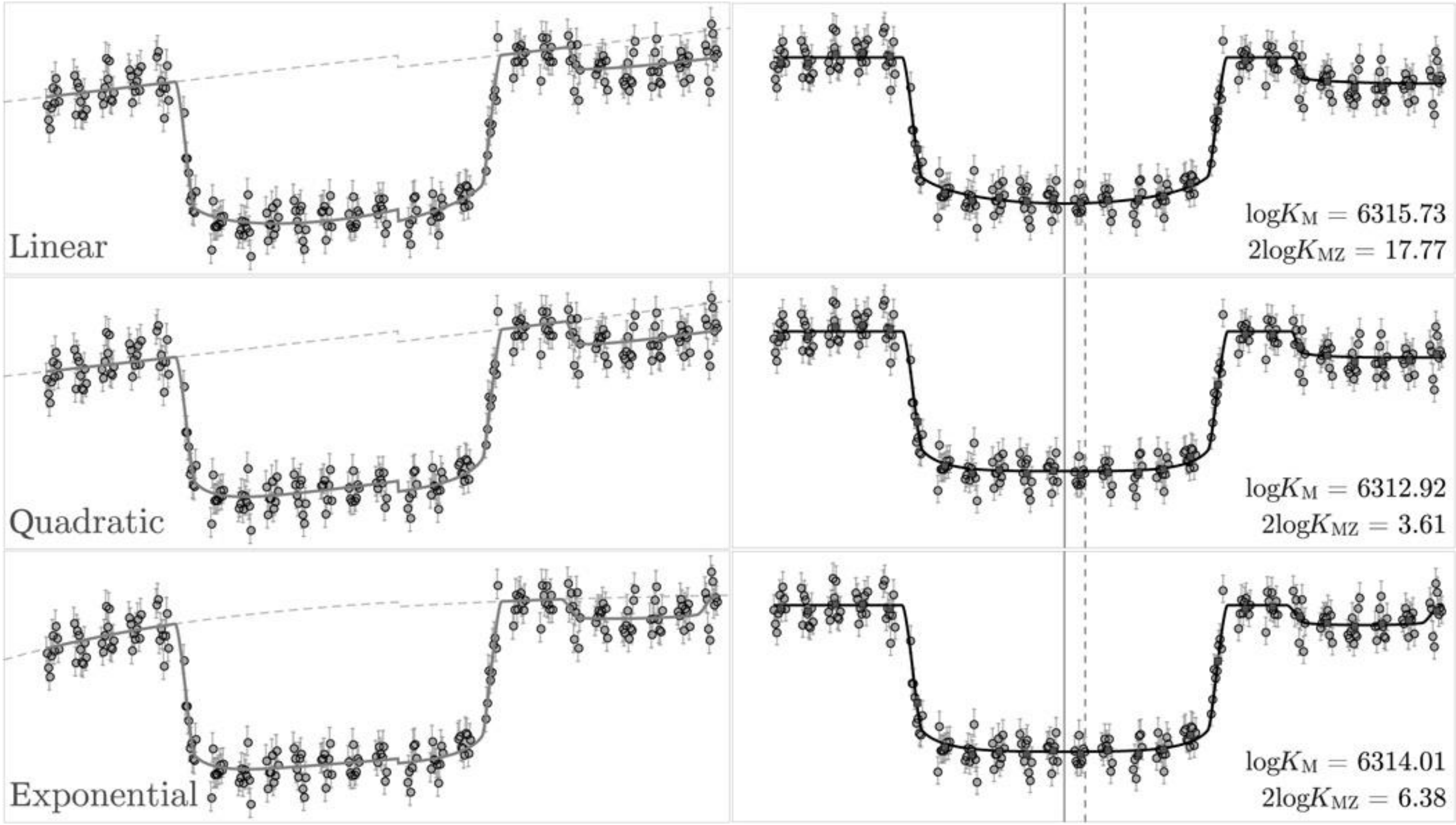
2

Limb Darkening of Stars





Kepler-1625b



Kepler-1625b
transit detection of exomoon ?
observers followed up with HST instead of Kepler

- **Location:**
  - Cygnus
  - RA ~19:41 and DEC ~40^{o}
- **Star**
  - m_v = 13.9
  - distance 7181 pc
  - mass ~0.96 M_{Sun}
- **Exoplanet**
  - mass 3180 M_{Earth}
  - radius = 6-11 R_{Earth}
  - a = 0.8 AU
  - HST transit time occurred earlier by 77.8 min

Kepler Mission

- **The objective was a combined differential photometric precision (CDPP) of 20 parts per million (PPM) on a magnitude 12 star for a 6.5-hour integration.**

TESS Mission
Transiting Exoplanet Survey Satellite

- **TESS's two-year all-sky survey will focus on nearby G, K, and M-type stars with apparent magnitude brighter than magnitude 12.**

- **Approximately 500,000 stars will be studied, including the 1,000 closest red dwarfs across the whole sky, an area 400 times larger than that covered by the *Kepler* mission.**

- **The photometric precision for a 10th magnitude star is estimated to be about 200 ppm, so TESS will be sensitive to super-Earths around bright stars.**
-

Direct Imaging

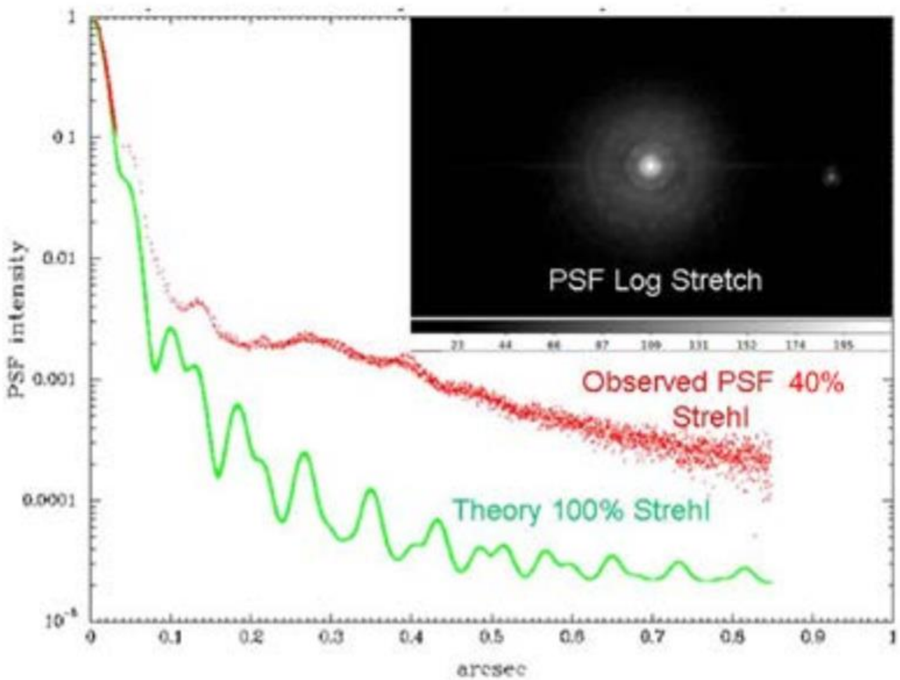


Fig 3: Deep PSF (40% Strehl) at 0.98 µm PSF (140 nm rms WFE with just 200 modes). Modified from Close et al. 2013. Note how the 35 mas resolution of the PSF allows for a raw contrast of 500 at just 0.1” separation. In this manner good inner working angles and contrasts can be achieved with visible AO even if the Strehls are lower than in the NIR.