Extra-Solar Planets

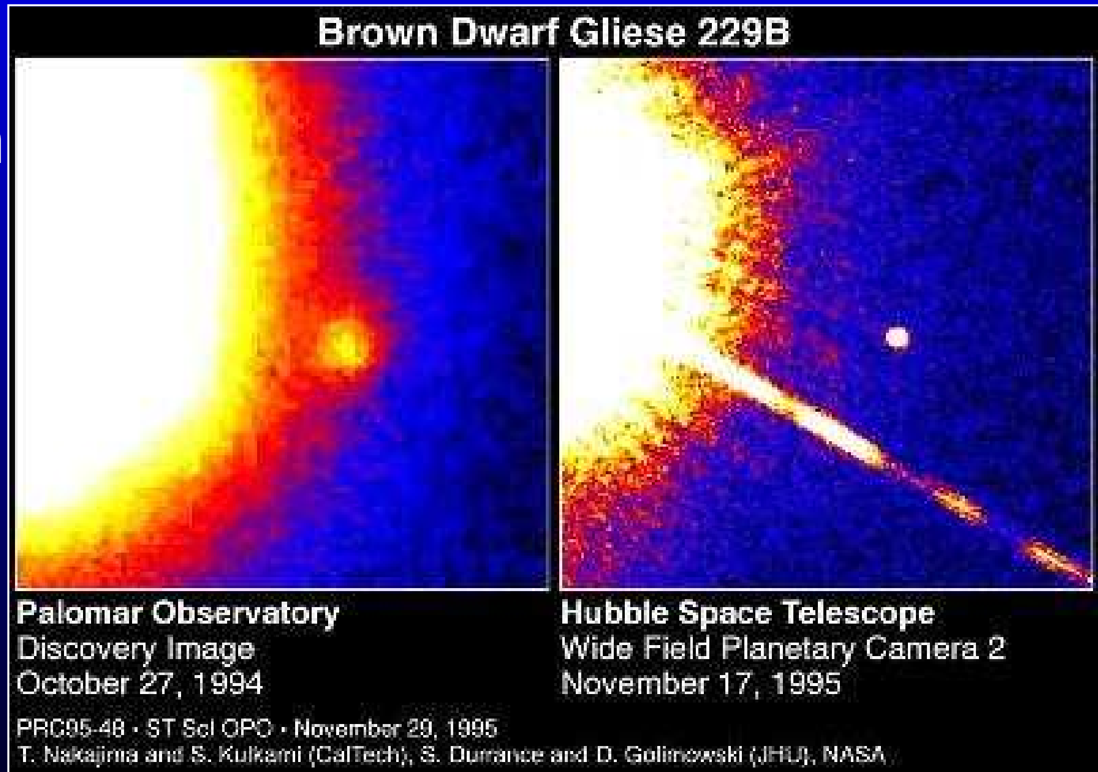
Planets are plentiful

The first planet orbiting another Sun-like star was discovered in 1995. We now know of 209 (Feb 07).

Including several stars with more than one planet - true planetary systems

How do we find these planets?

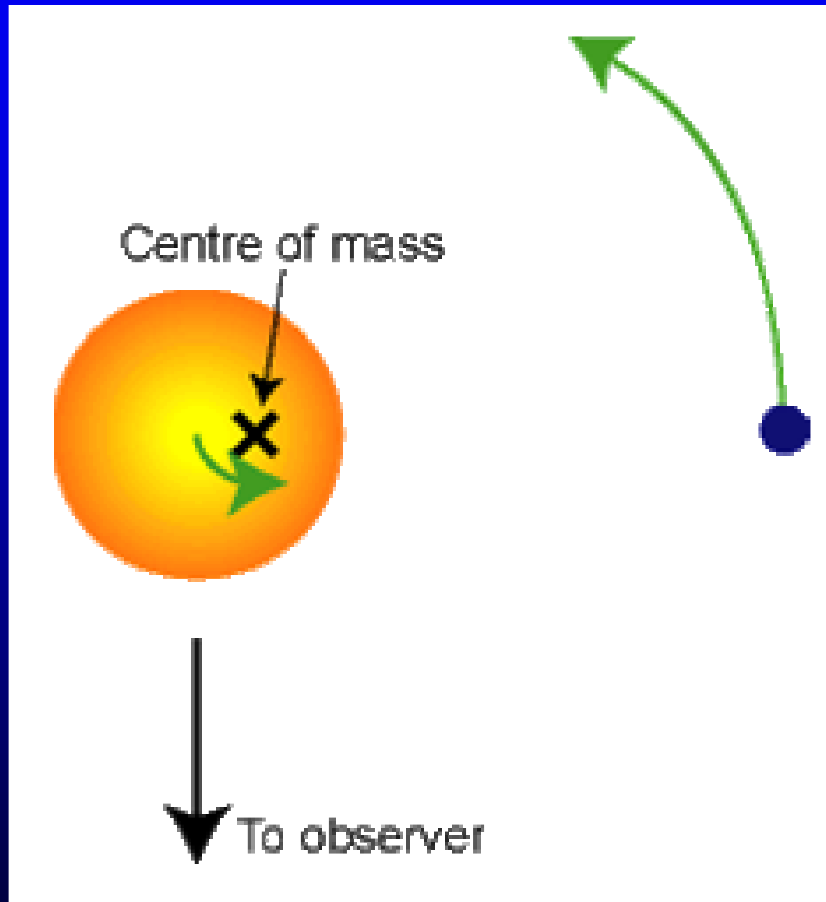
We can't easily take photographs of them - they're too faint in comparison to their parent star



Observed with the VLT

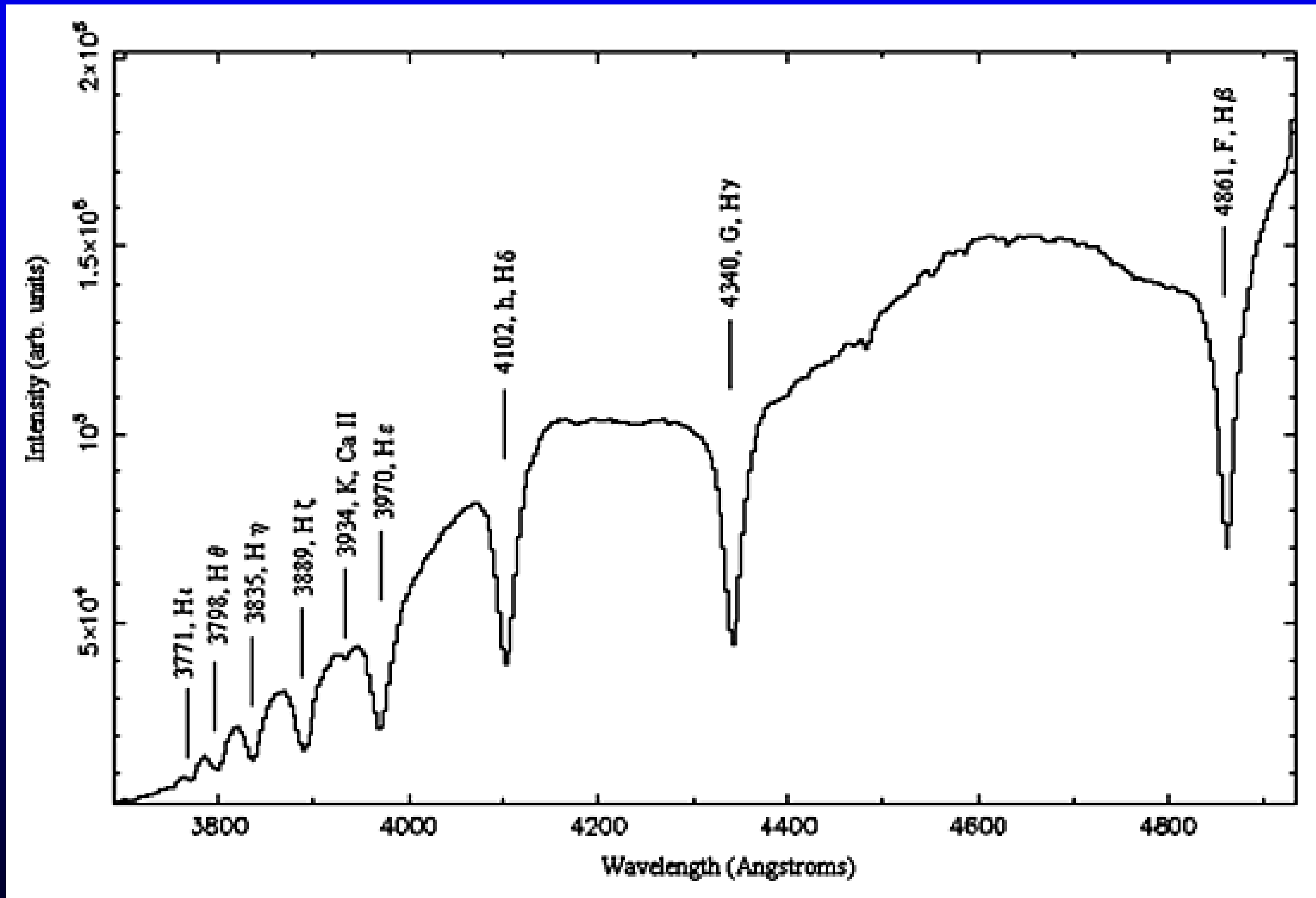
The “Doppler wobble” method

The star wobbles back and forth under the gravitational influence of its orbiting planet



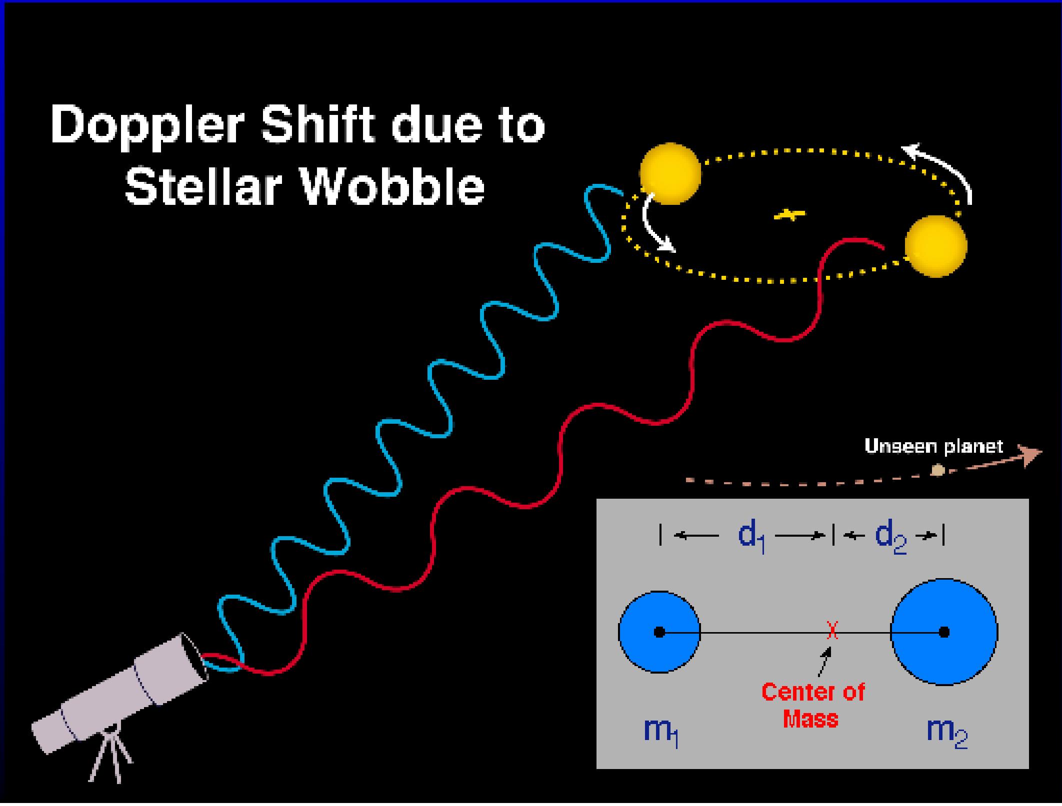
The “Doppler wobble” method

The spectra of stars show absorption lines at specific wavelengths

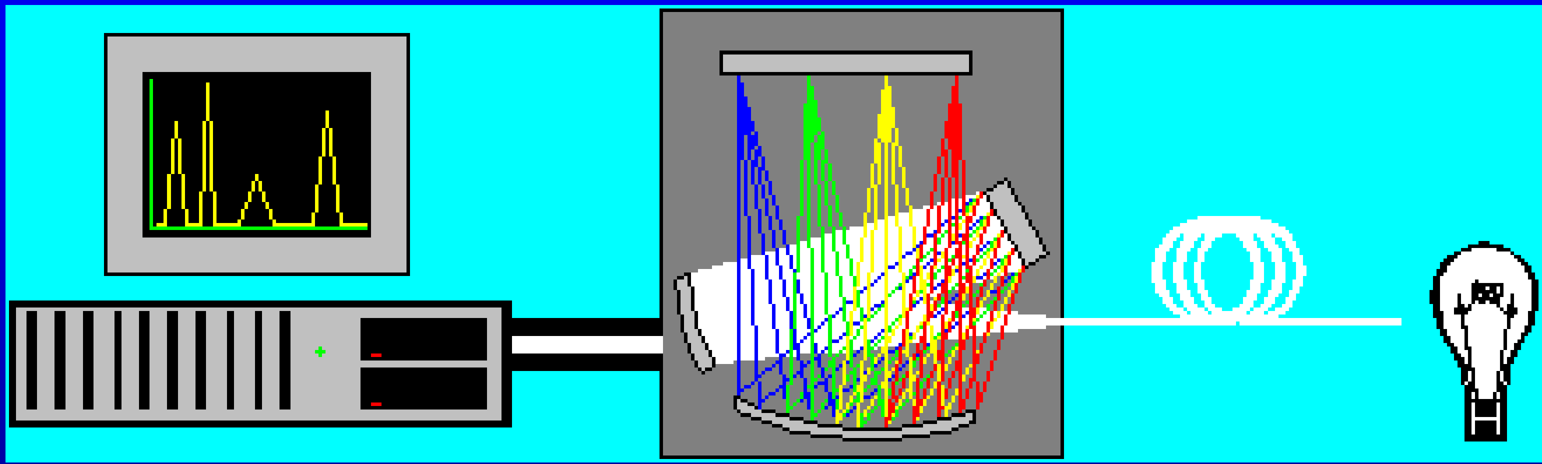


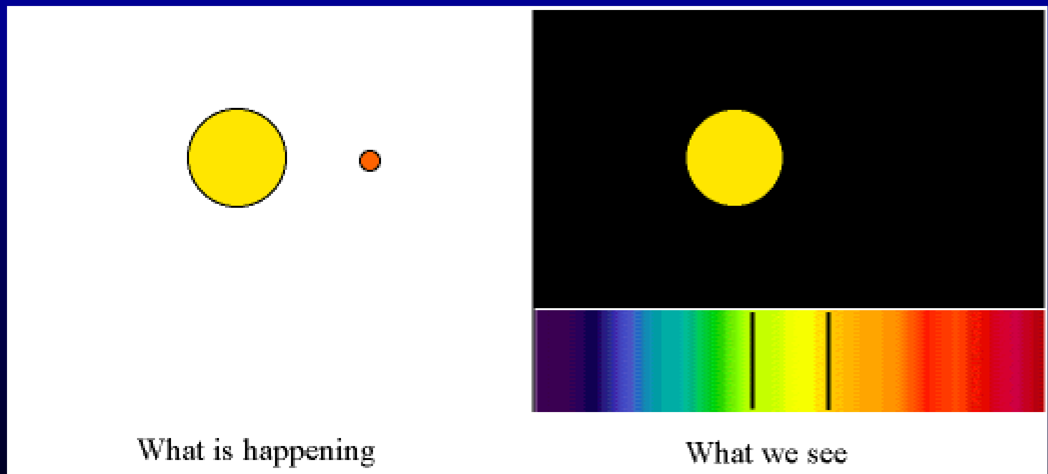
Discovering Extra-Solar Planets

- Method 1 – Use the fact that the Sun and Planet co-rotate around their common centre of gravity.
  - So the star will be moving around a small ellipse whose size depends on the mass and distance of the planet.
  - Precise measurements of the doppler shift in the spectral lines of the star can show up this motion and hence detect the planet.

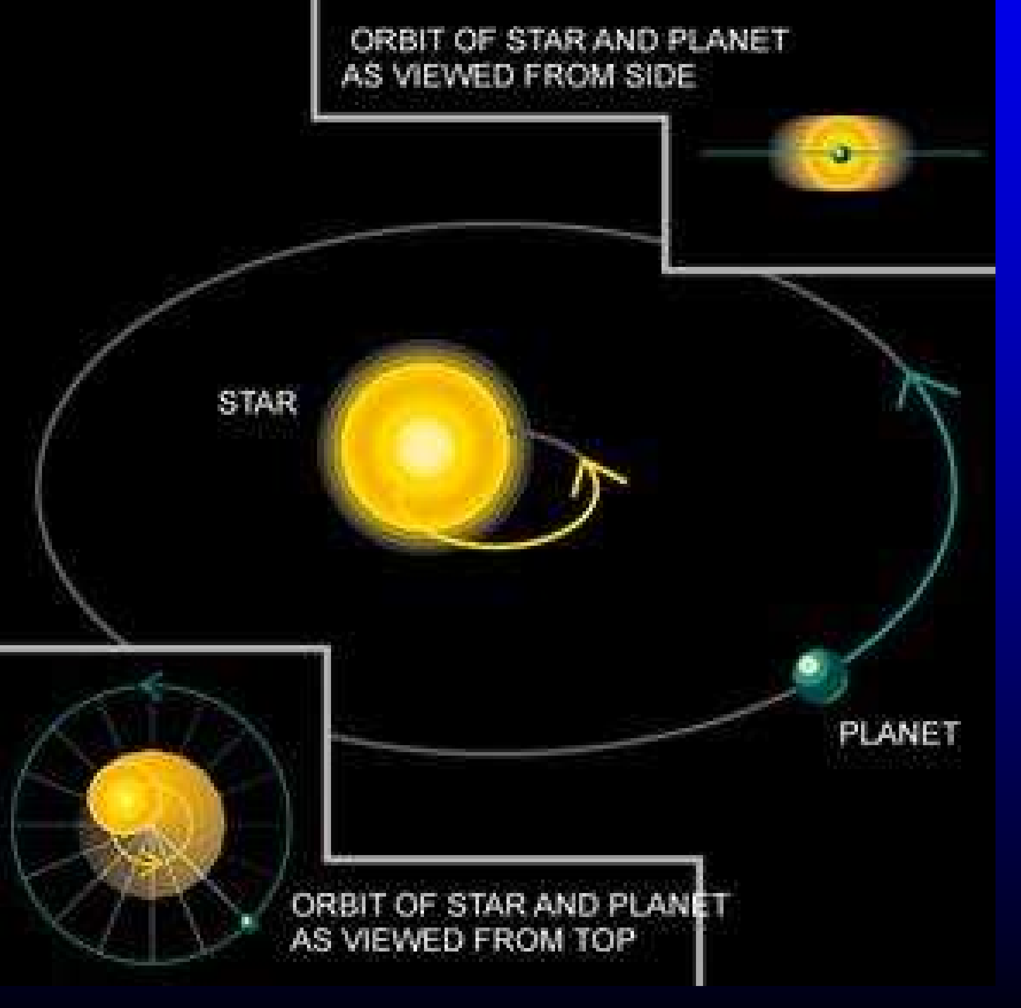


Using a very sensitive spectrometer!

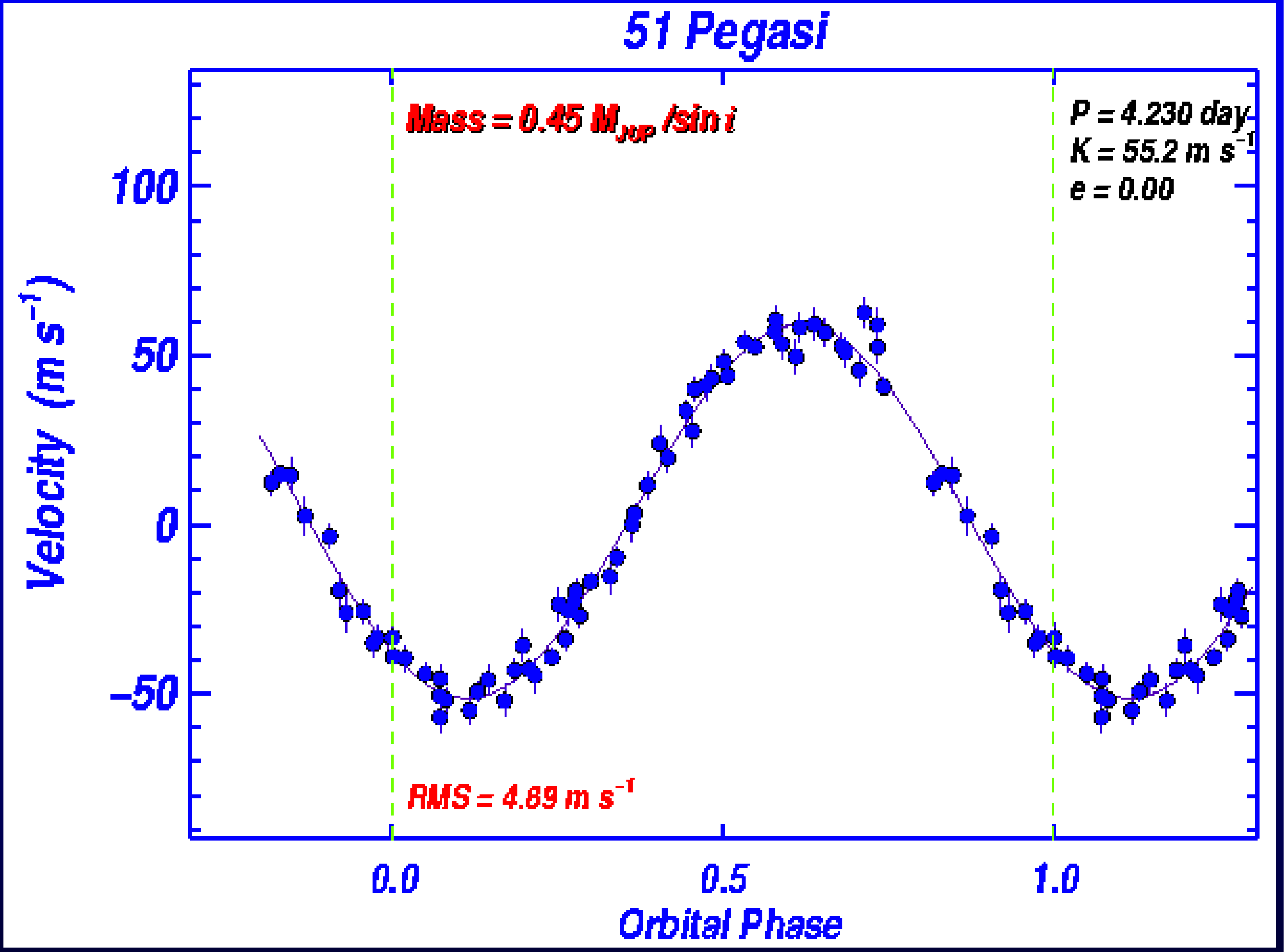




Doppler method will not work if orbital plane is at right angles to us



The “Doppler wobble” method

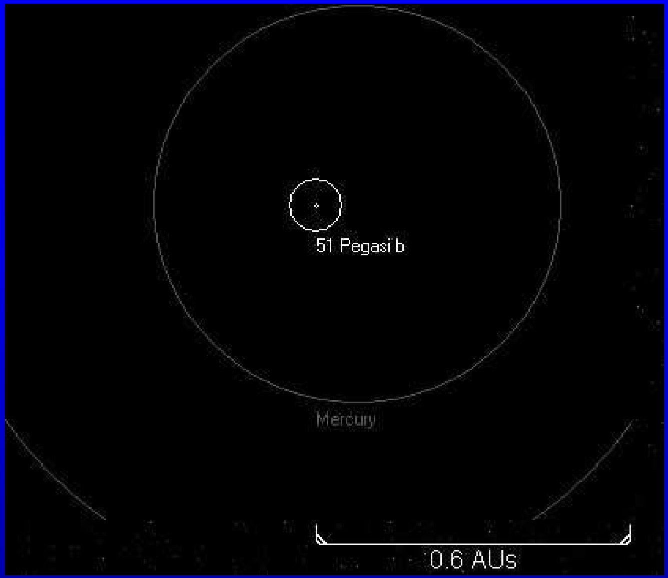


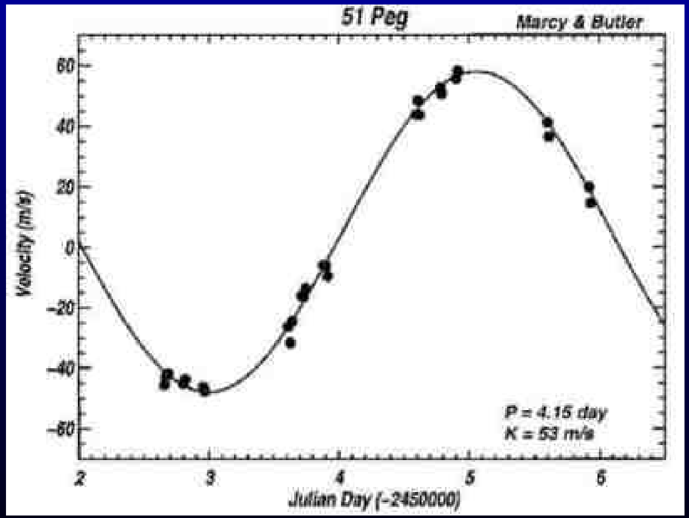
The light from the star is Doppler shifted back and forth

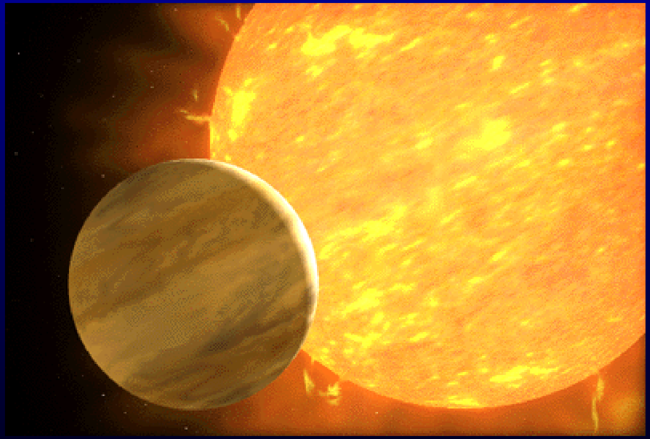
Biased to high-mass planets close to parent stars

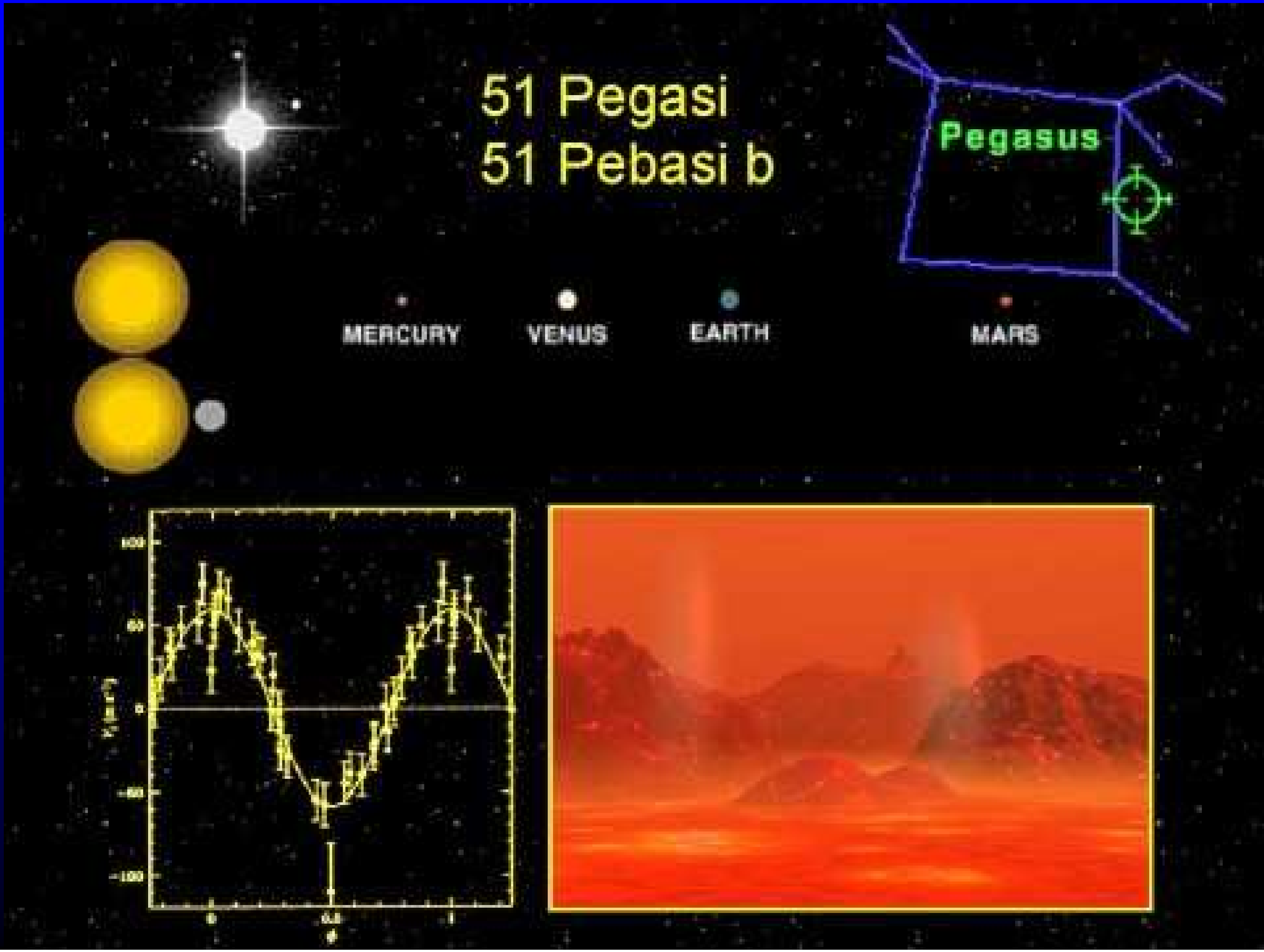
51 Pegasai

- The first planet detected around a normal star.
- Period just 4 days!
- A gas giant very close to its star.

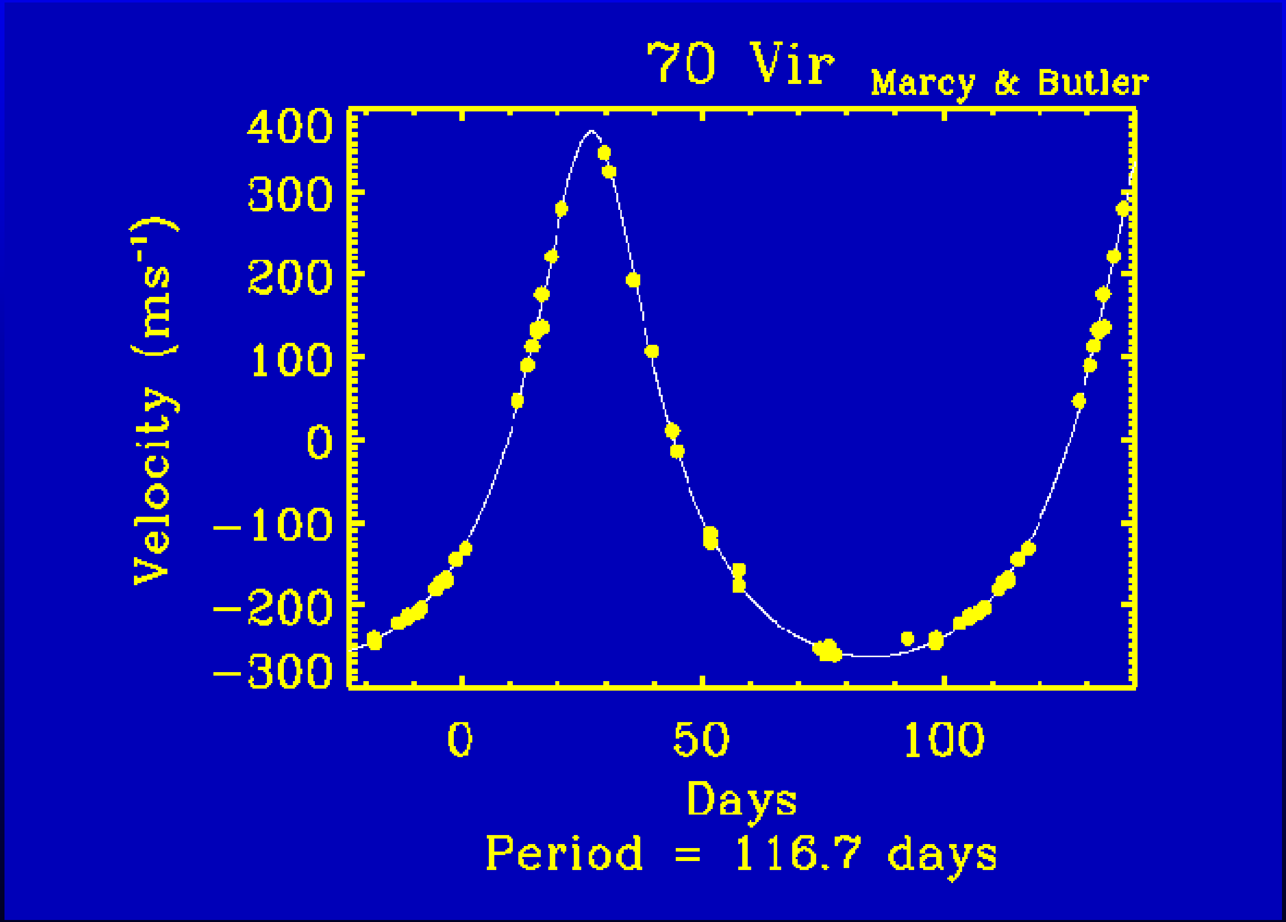




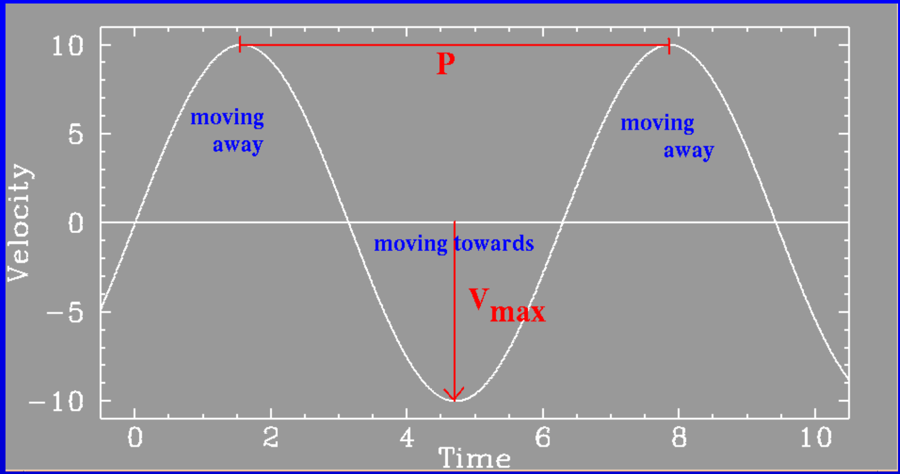



51 Pegasi
51 Pebasi b
Pegasus
MERCURY
VENUS
EARTH
MARS

An elliptical orbit

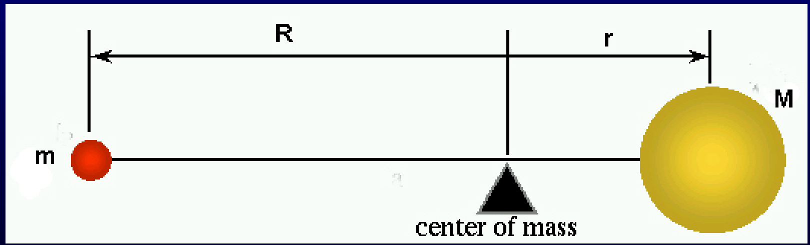


How do you find the Mass and Distance of the Planet?



- 1) From the peak velocity of the star – when it is coming towards us or going away from us - and the period of the oscillation we can calculate the circumference of the orbit of the star and hence its distance from the centre of mass of the system.

$$r_{star} = V_{max} \times P \ / \ 2 \times \pi$$



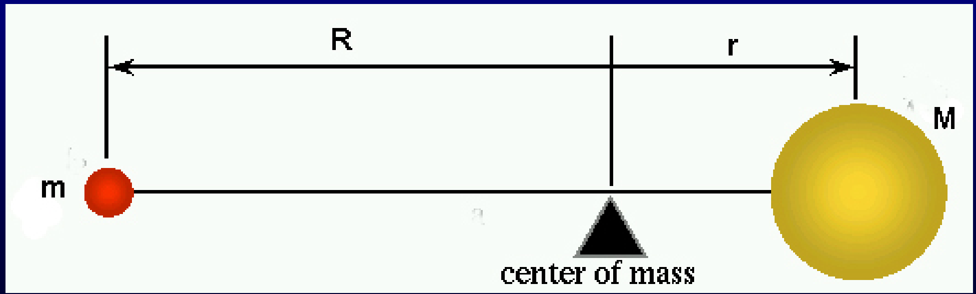
- To simplify the the following calculation assume that the planet is very much less massive that the star.
- From Kepler's Third Law we can calculate the Radius of the orbit of the Planet.
  - If R is in AU, and the period is in years, then for a 1 solar mass star.

    $p^2 = R^3$

    So this gives us the distance in AU

    Knowing 1 AU in metres one can then calculate R in metres

- "balancing" about the centre of Mass
  - $M r = m R$
  - So $m = (M_{sun} \times r) / R$



Example: 1 Solar Mass Star, Period 4 years, V_{max} = 20m/sec

$R_{star} = 20 \times 4 \times 365 \times 24 \times 3600 / 2 \times \pi$

$= 4 \times 10^{8}$ m

From Kepler's third law : $p^2 = R^3$

$R_{planet} = ((4)^2)^{1/3}$

$= 2.5$ AU

$m_{planet} = 1x\ r/R = 1 \times 4 \times 10^{8} / 2.5 \times 1.49x10^{11}$

$= .001$ Solar masses

NB Jupiter has a mass of .001 Solar masses so this is a gas giant planet of 1 Jovian Mass.

What objects might there be orbiting a star?

Other Stars in Binary or Multiple Star systems.

masses > 0.08 M_{sun}

2) Brown Dwarfs

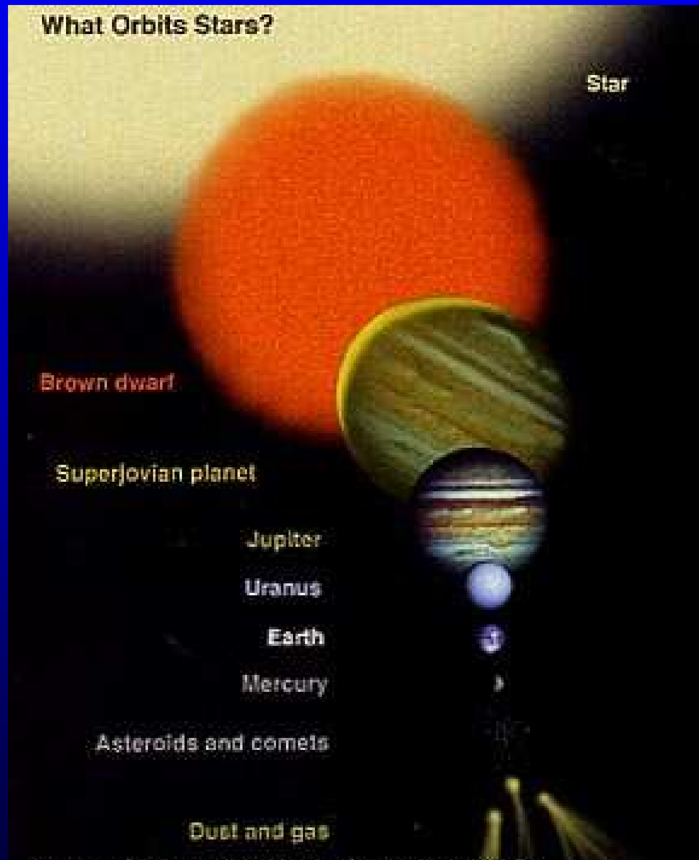
Not quite stars

0.08 M_{sun} > m > 0.03 M_{sun}

3) Planets

masses < 0.01 M_{sun}

So planets so far found only up to 17 x Jovian Mass

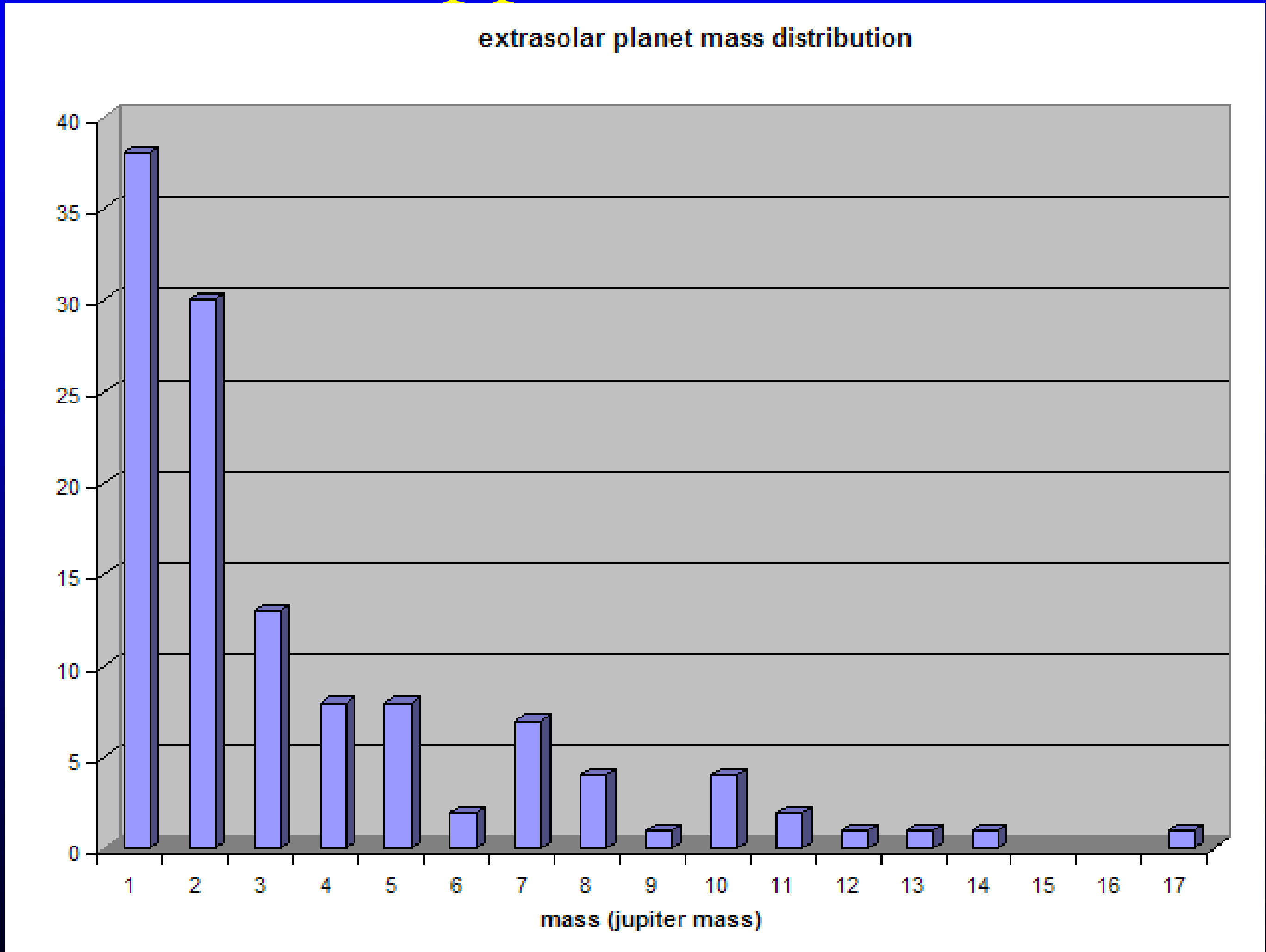


From Color Plate 14, Copyright USB

Doppler Shift Limitations

- Present doppler precision is ~ 3m/sec.
  - Effect of Jupiter on the Sun gives a V_{max} of ~20m/sec
  - BUT that of Earth is a 1/10 m – 30 times less than can be detected at present
- We must observe for at least one orbit of the planet. Saturn orbits the Sun every 29.4 years. Only ~ 12 years of observations so far so, as yet, difficult to detect planets distant from their Sun.

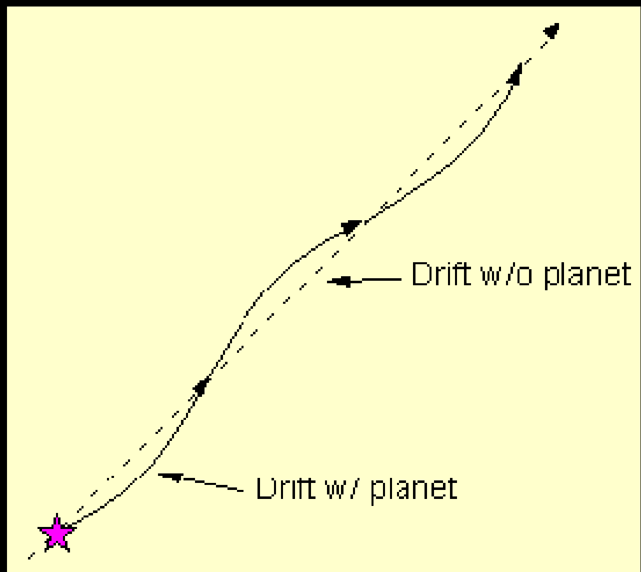
Extra-solar planet masses from Doppler Method



Method 2

Astrometric Method

- Star normally drifts in a straight line in the sky
- Unseen planetary companion causes it to "wobble"
- Wobble is due to stellar reflex motion
- Astrometry is art of measuring very accurate positions



- Wiggles in the motion of a star across the sky
  - Called Proper Motion, usually a straight line, but not in the case of Sirius! Its companion is a dead star called a White Dwarf.
  - No planets discovered this way – yet.

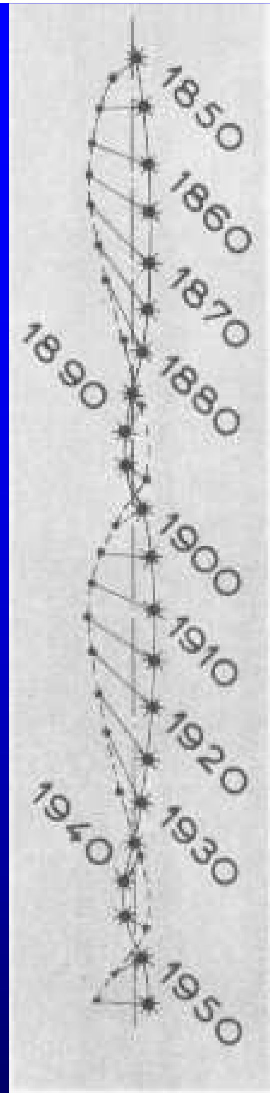


Fig. 574 — The sinuous proper motion of Sirius revealed the existence of its companion long before it had ever been seen.

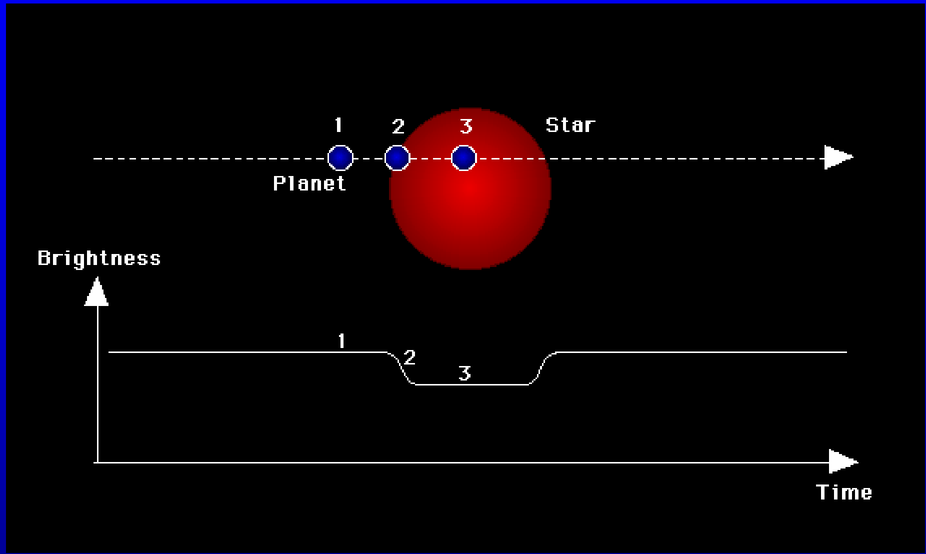
NB

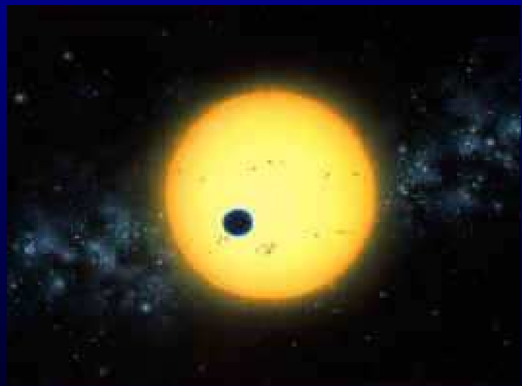
- Method 1 cannot work if the orbital plane of the extra solar planet is at right angles to us.
- Method 2 will work when Method 1 cannot.
- Method 2 cannot work if the if the orbital plane of the extra solar planet includes the Earth.
- BOTH will work when the orbit of the planet is inclined at intermediate angles

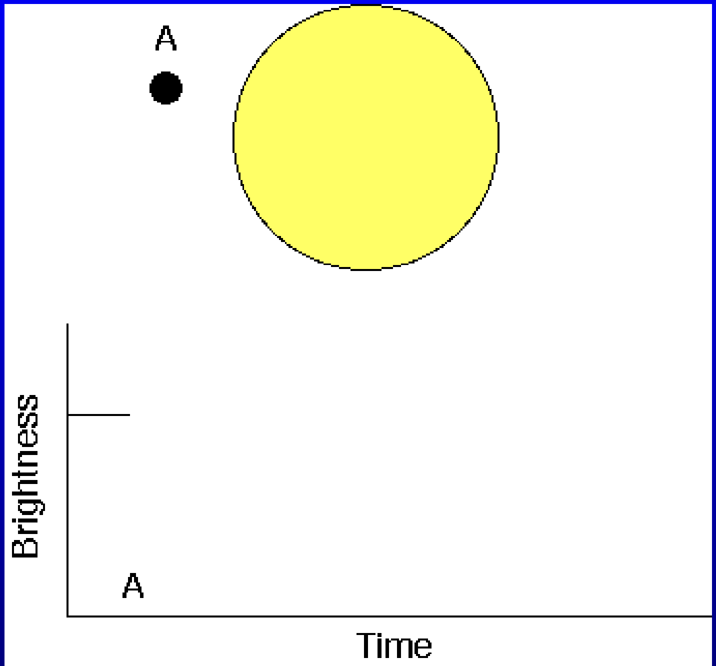
Method 3: Planetary transits

- Detect the transit of a planet as it crosses the face of the star. This results in a slight drop in luminosity

– Method 3 can only work if the orbital plane of the planet includes the Earth.

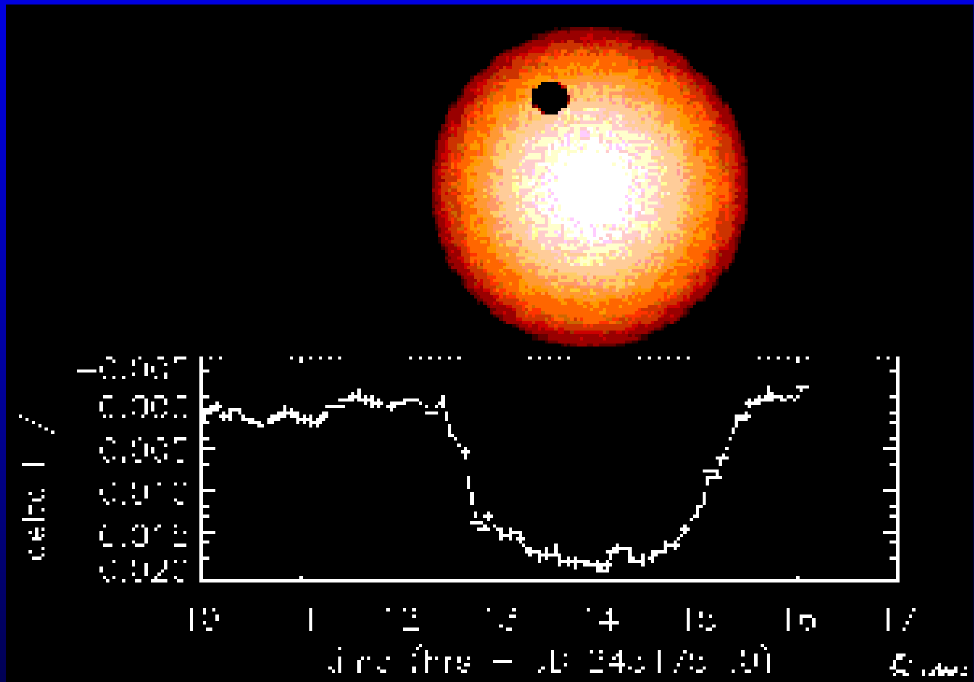


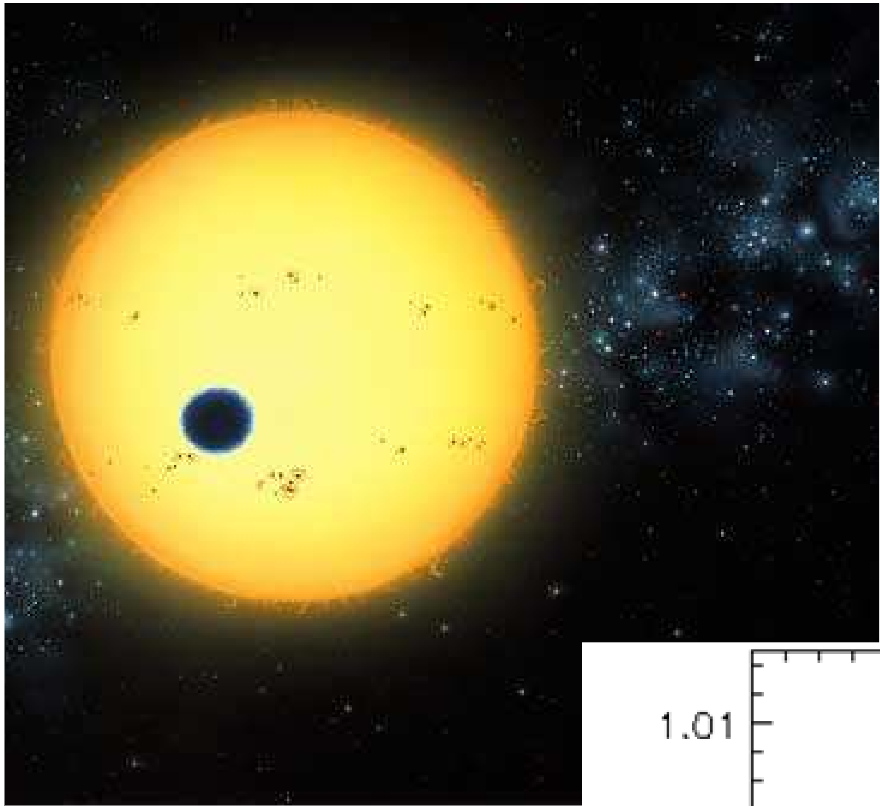




Large planet transits its sun.

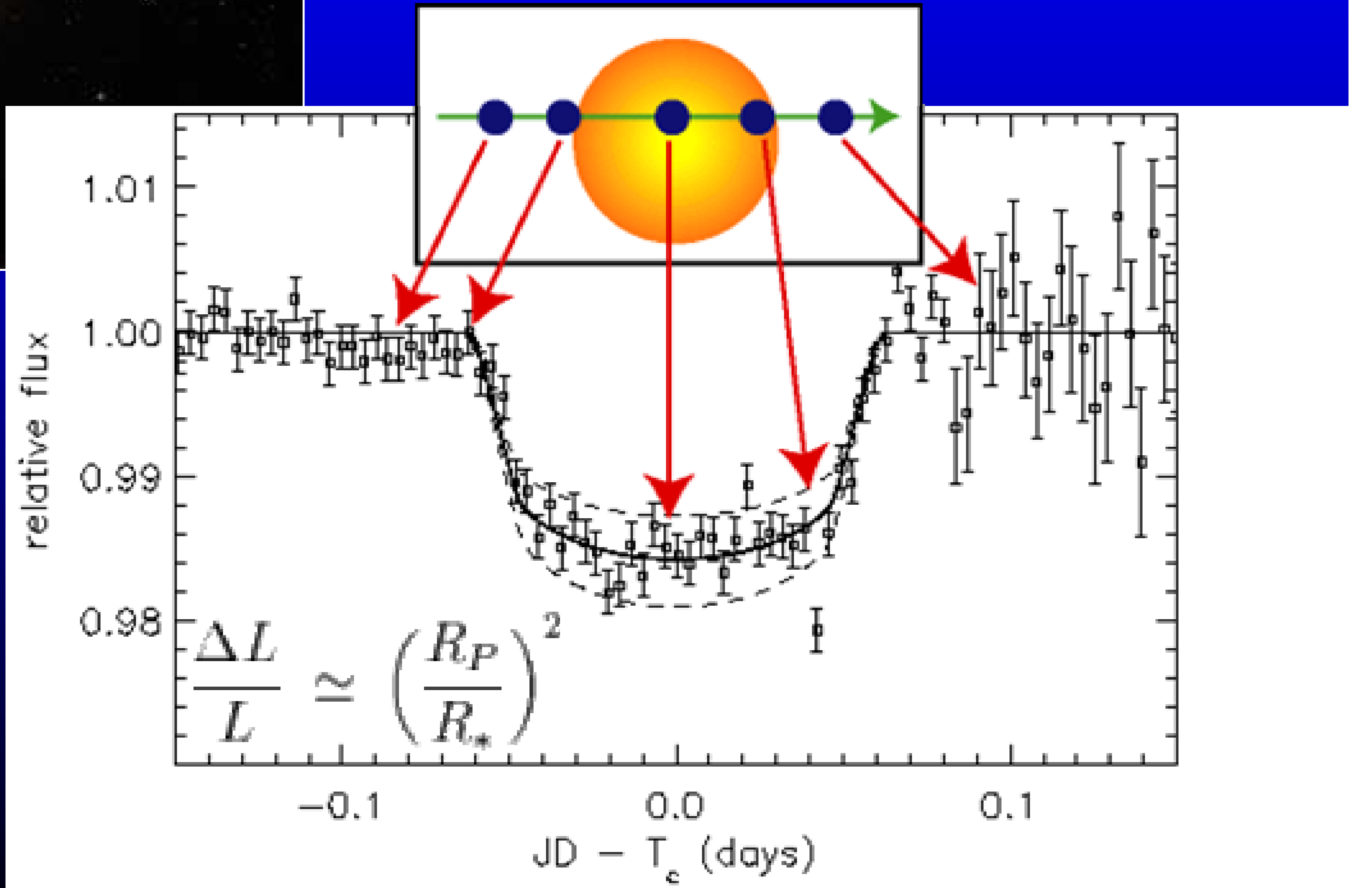
An example





The Transit Method

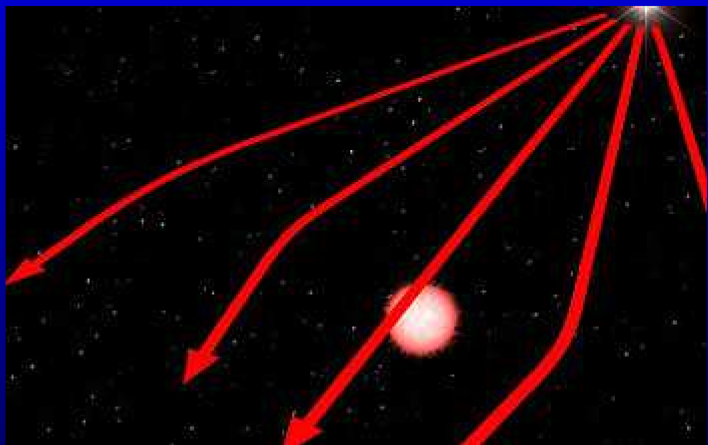
Look for the dip in light from a star as a planet passes in front

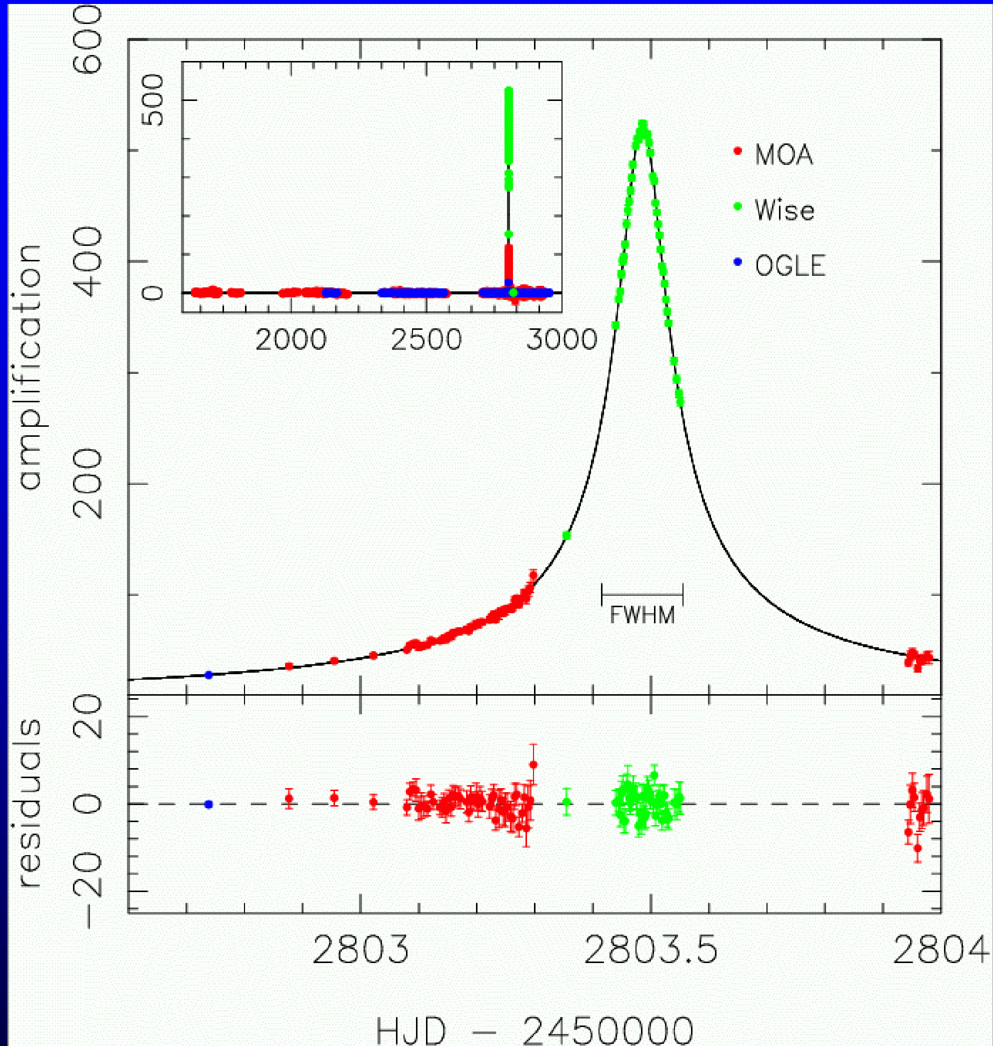


Best done from space – NASA Kepler mission in planning phase

Has the potential to detect Earth-like planets

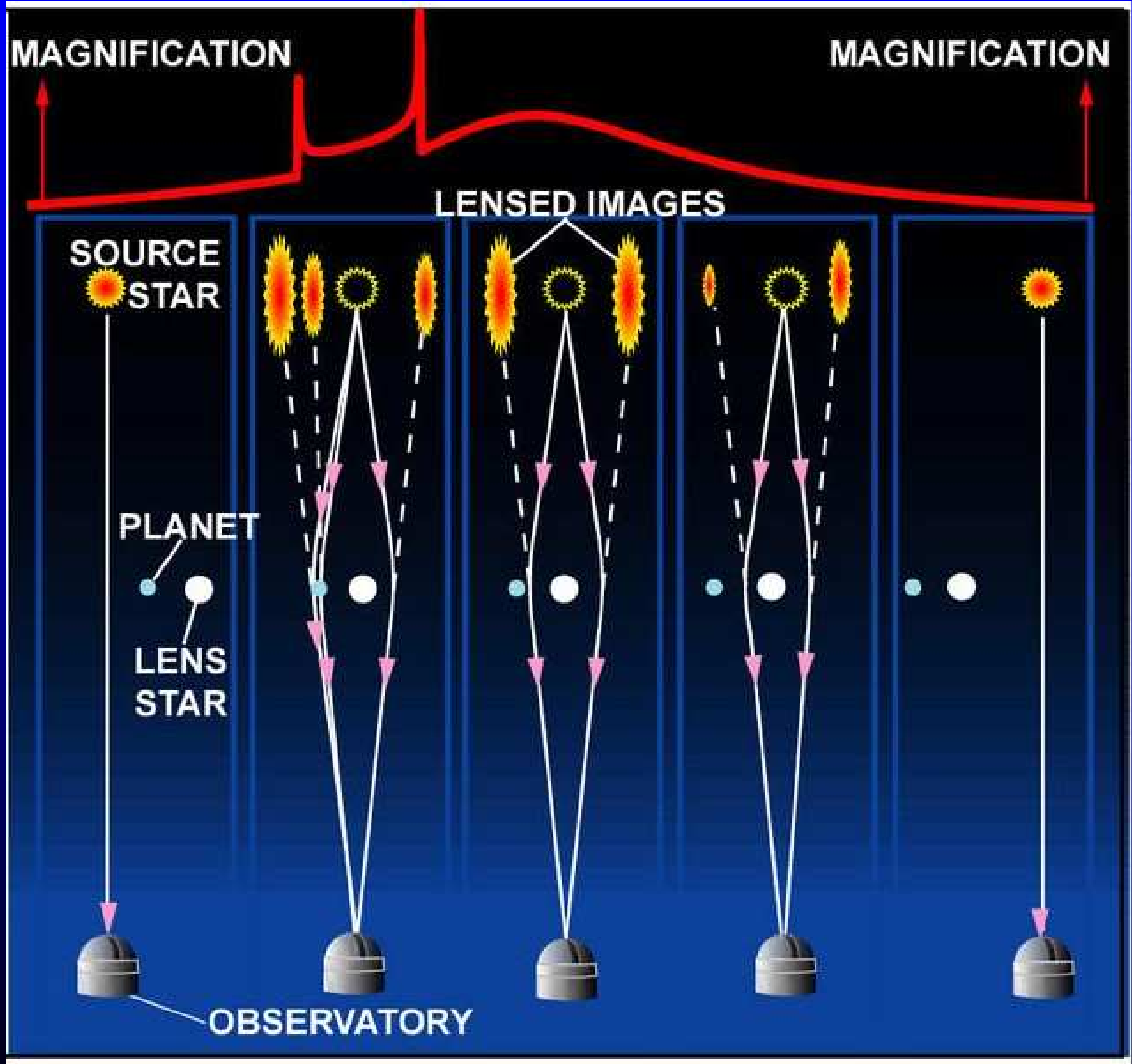
Method 4 Gravitational Micro-lensing



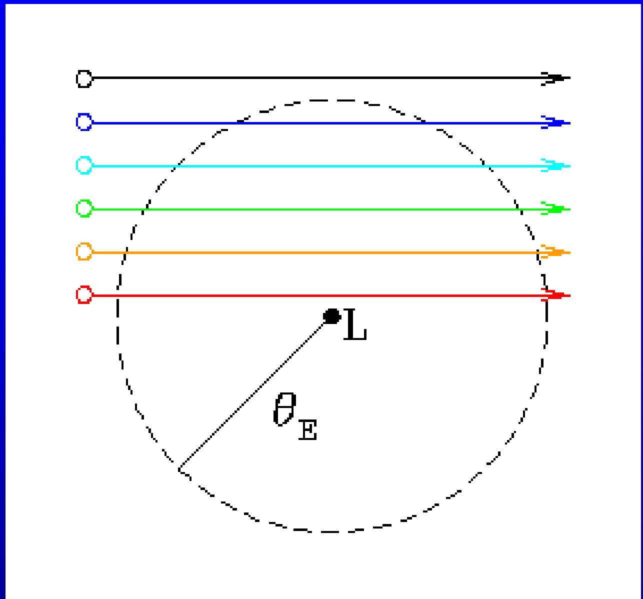


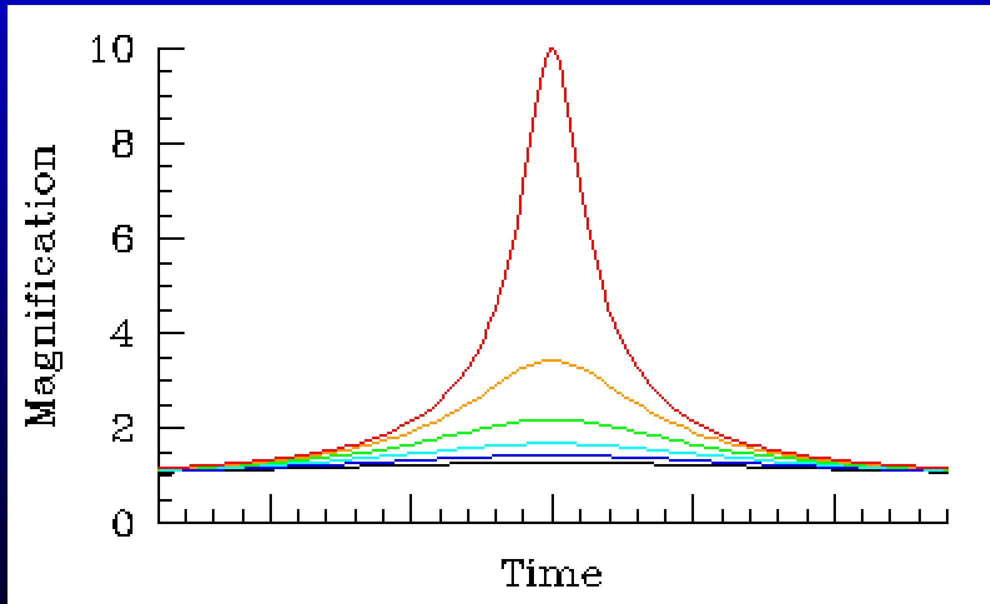
The microlensing method

Look for the increase in brightness of a distant star as another star with planet passes in front.

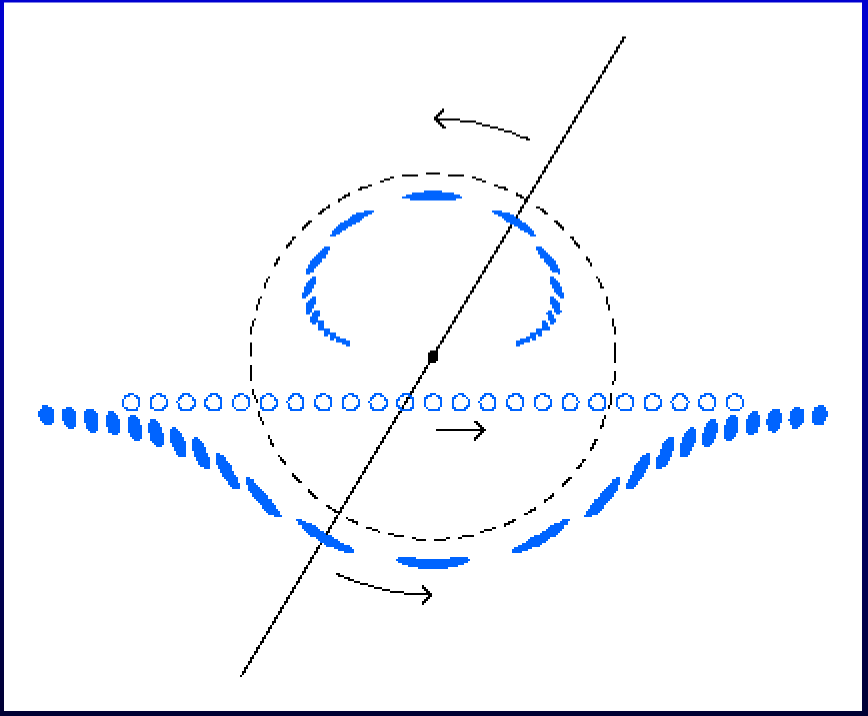


“Magnification”

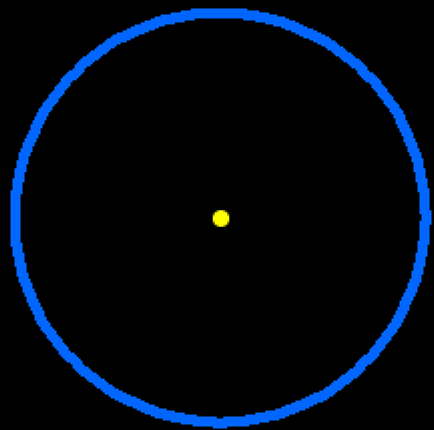




Size of the patch indicates relative brightness

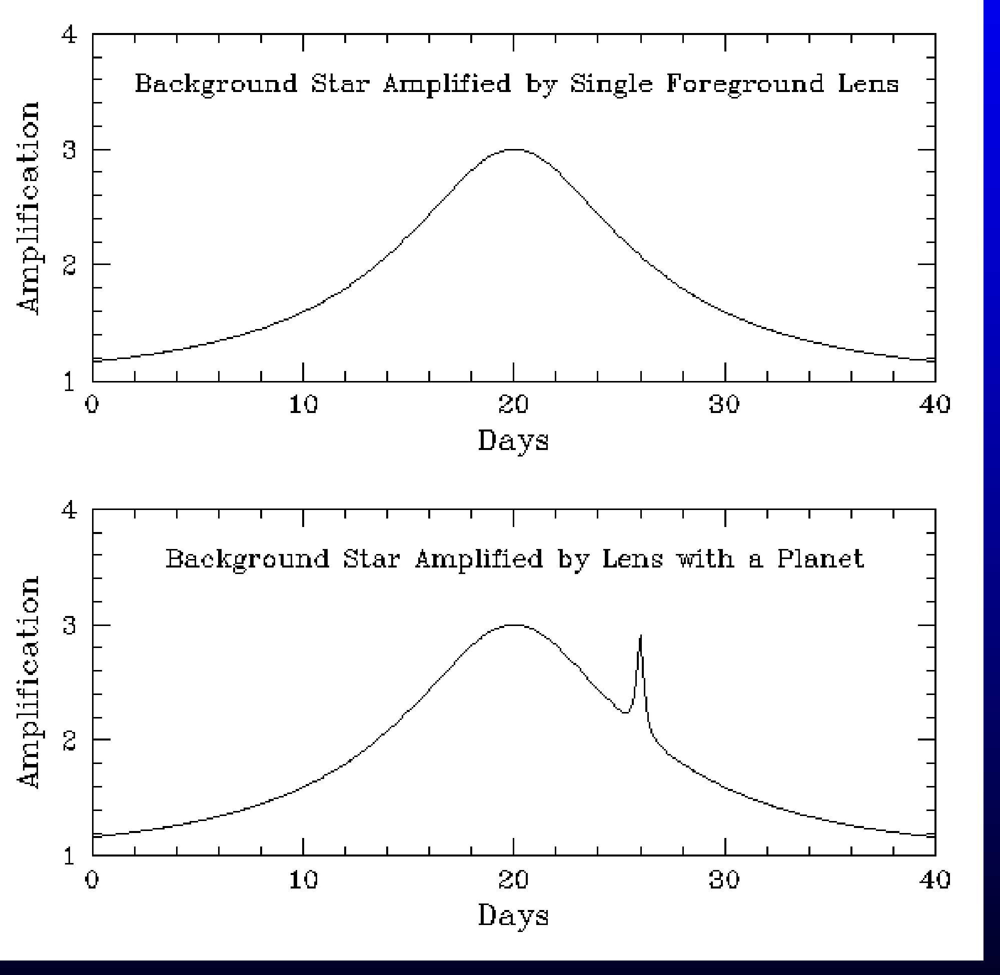


What we see

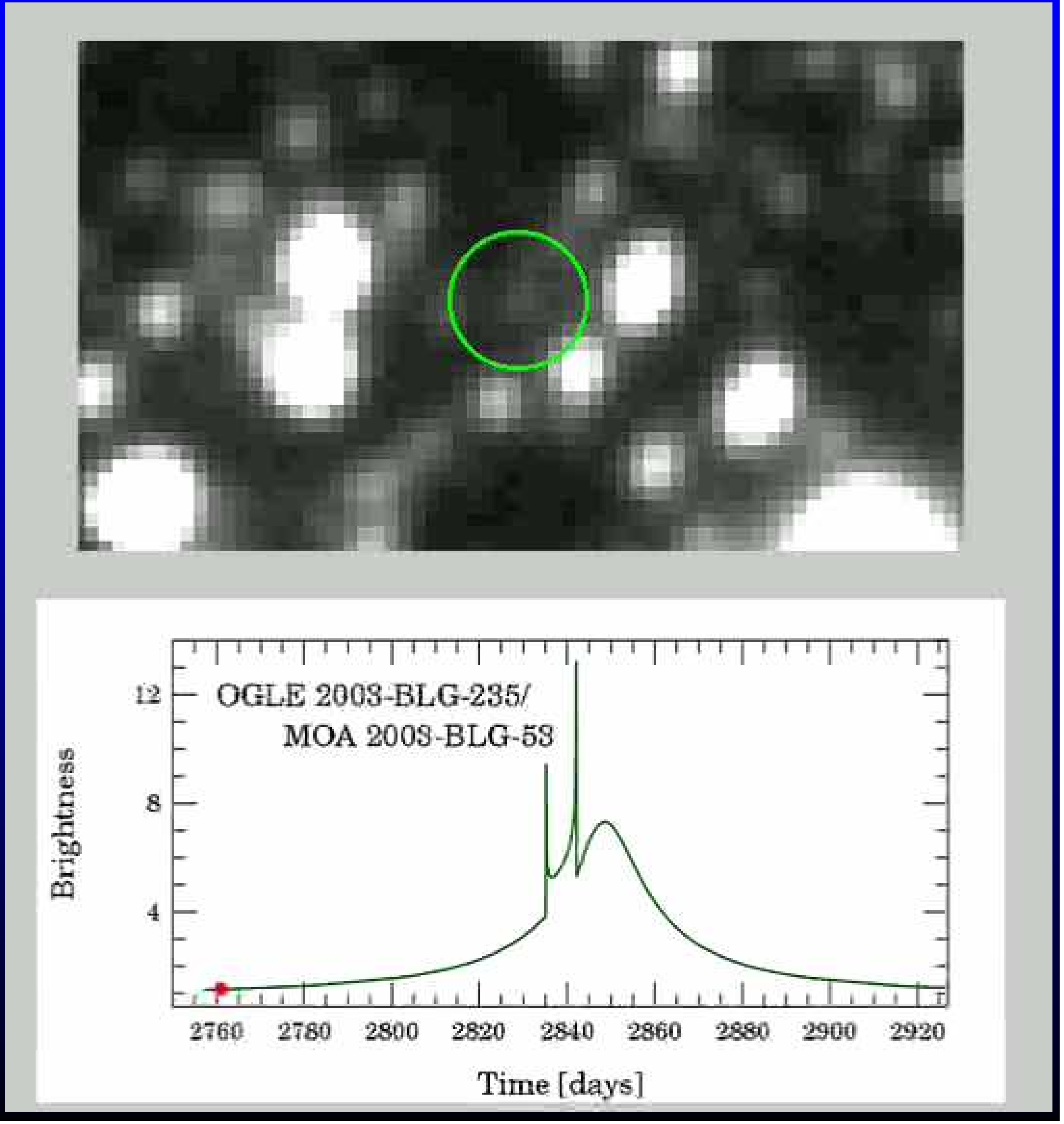


If a distant star passes directly behind a nearer star, the distant star will be imaged as a ring around the nearer star. Usually the alignment is not exact.

Effect of a planet

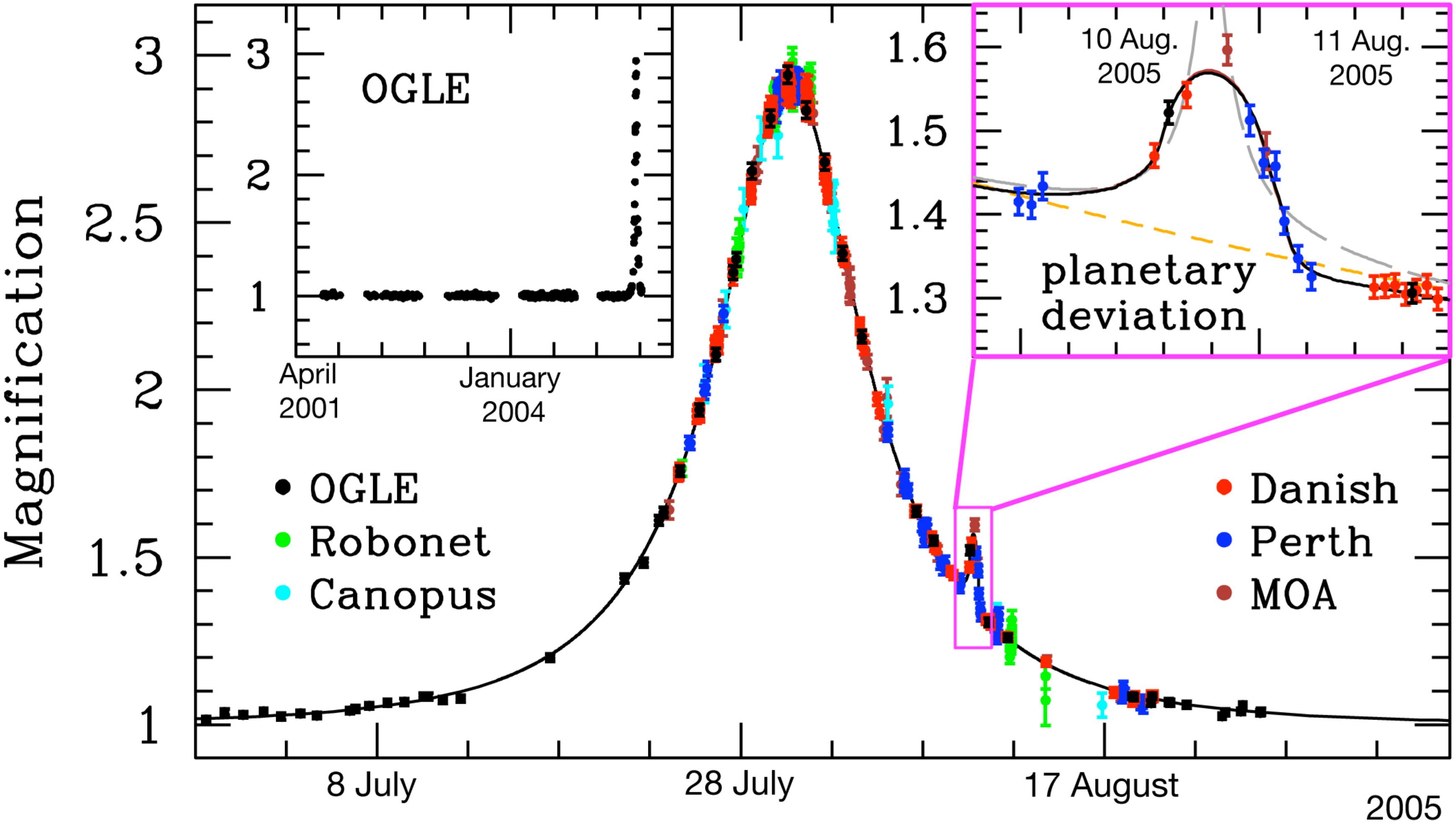


The microlensing method



First discovery announced 2004 May 10.

Has the potential to detect Earth-like planets.

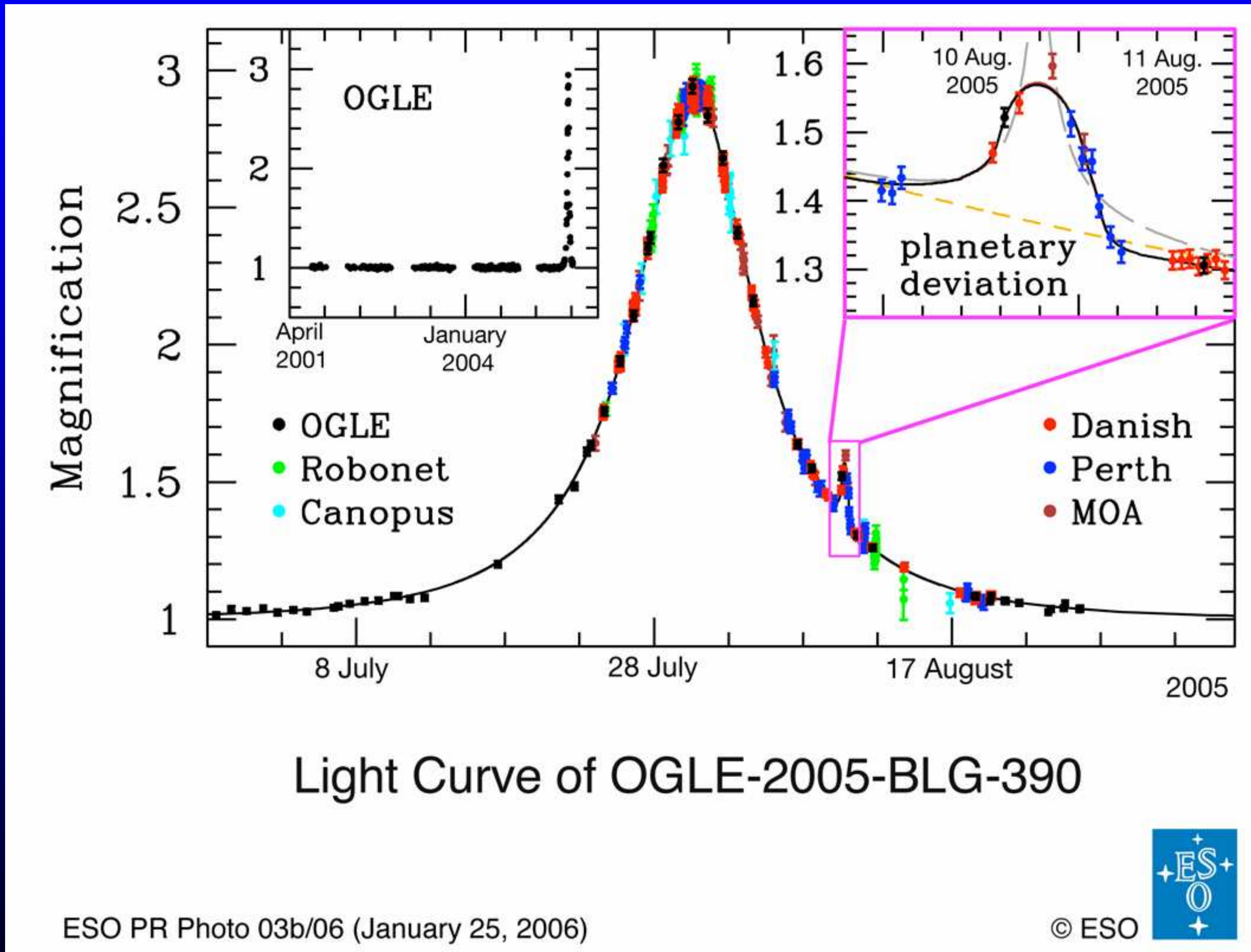


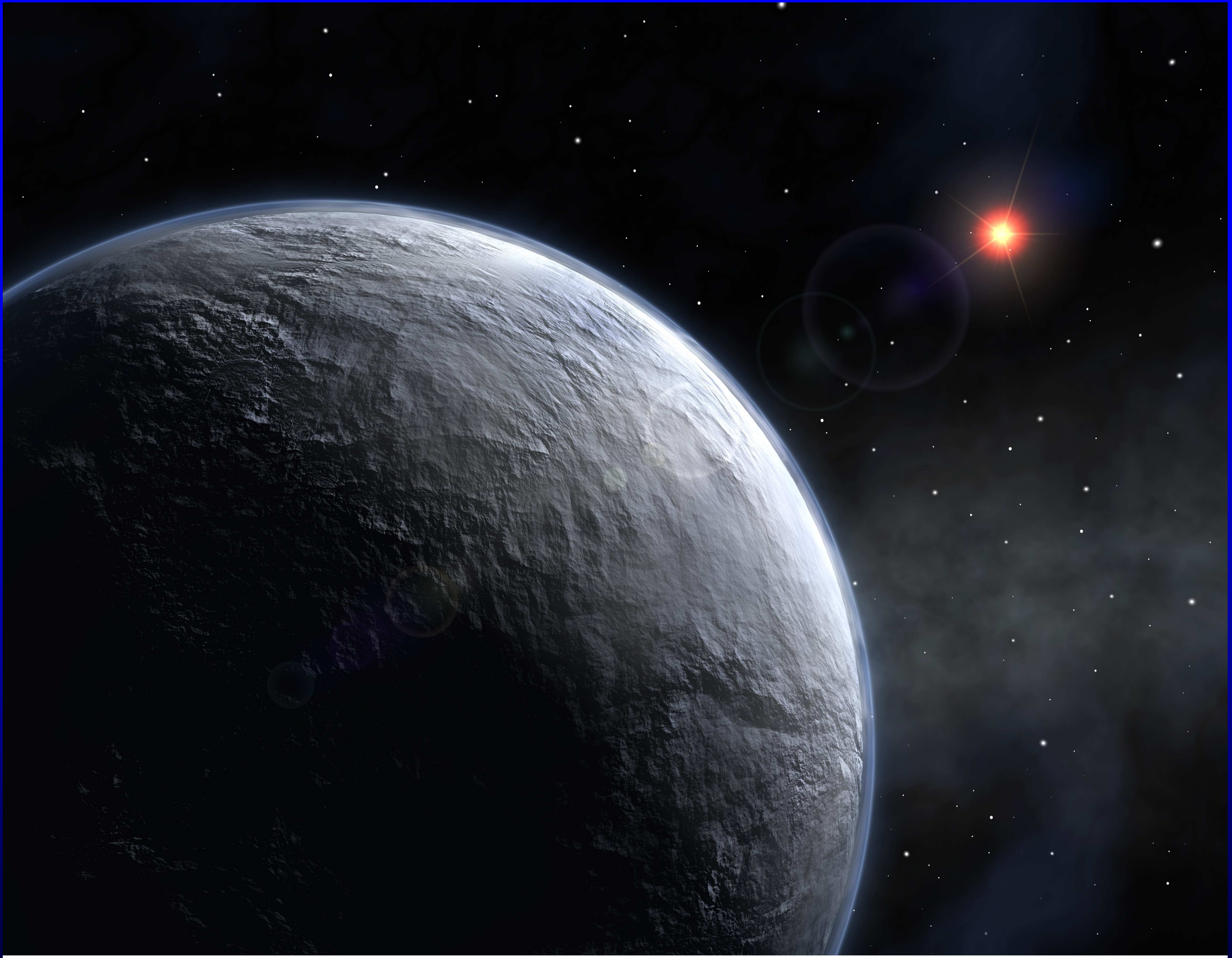
Light Curve of OGLE-2005-BLG-390

ESO PR Photo 03b/06 (January 25, 2006)

Smallest Planet So Far

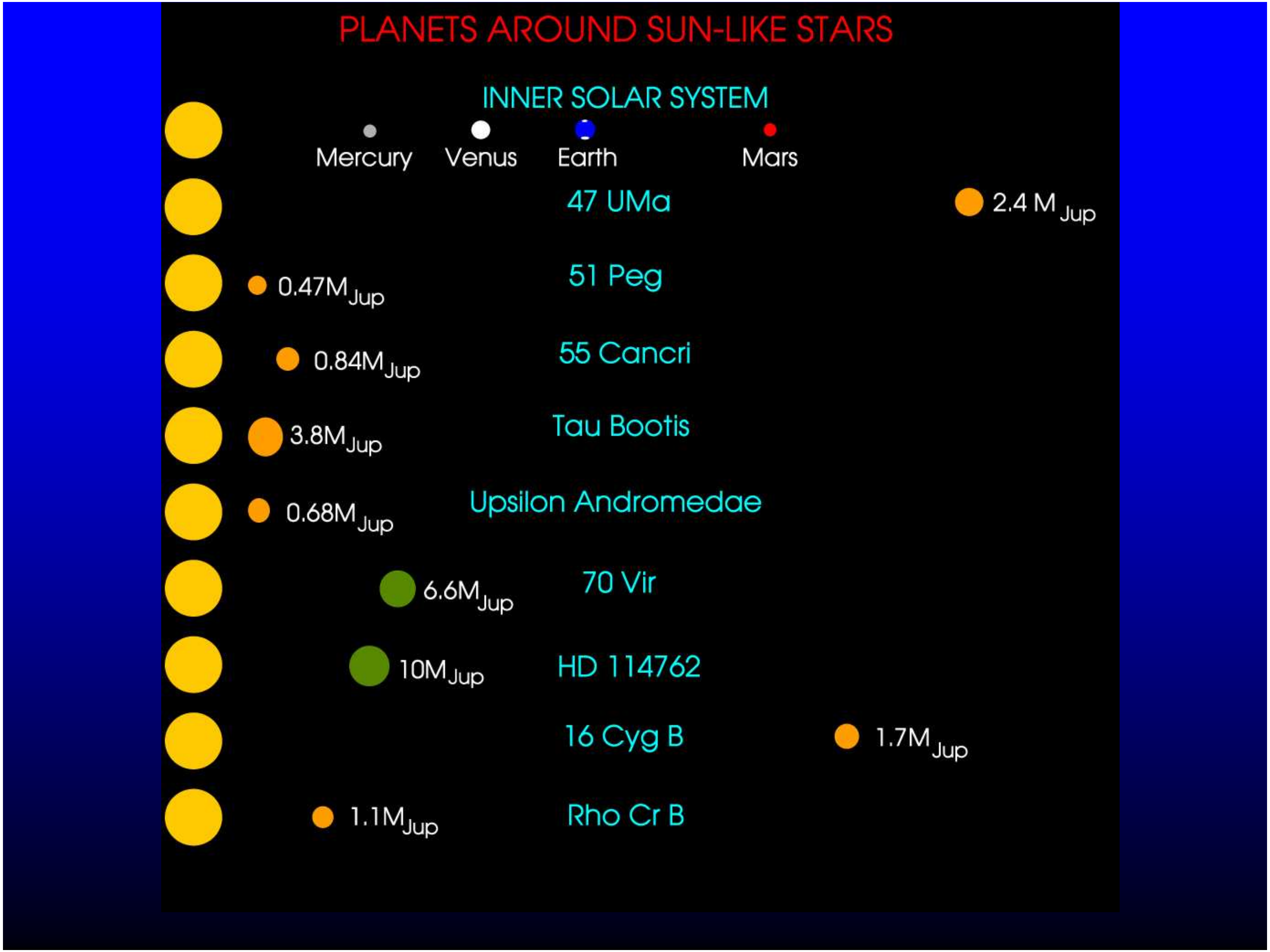
- 5 x Earth mass
- Discovered by a collaboration including Jodrell astronomers
- 100 million stars routinely monitored
- 120 lensing events in progress at any one time

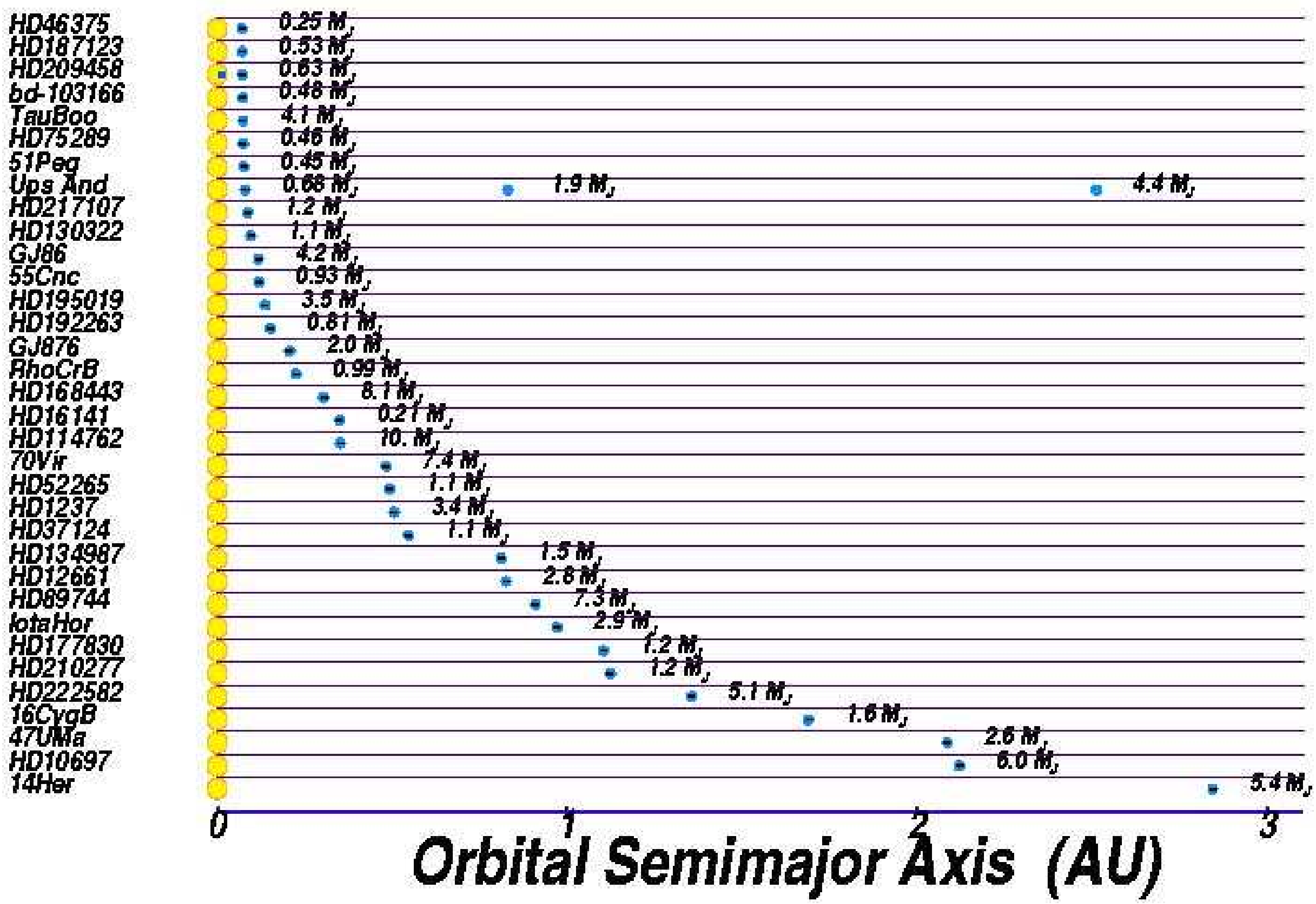




Five Earth Masses Icy Extrasolar Planet
(Artist's Impression)

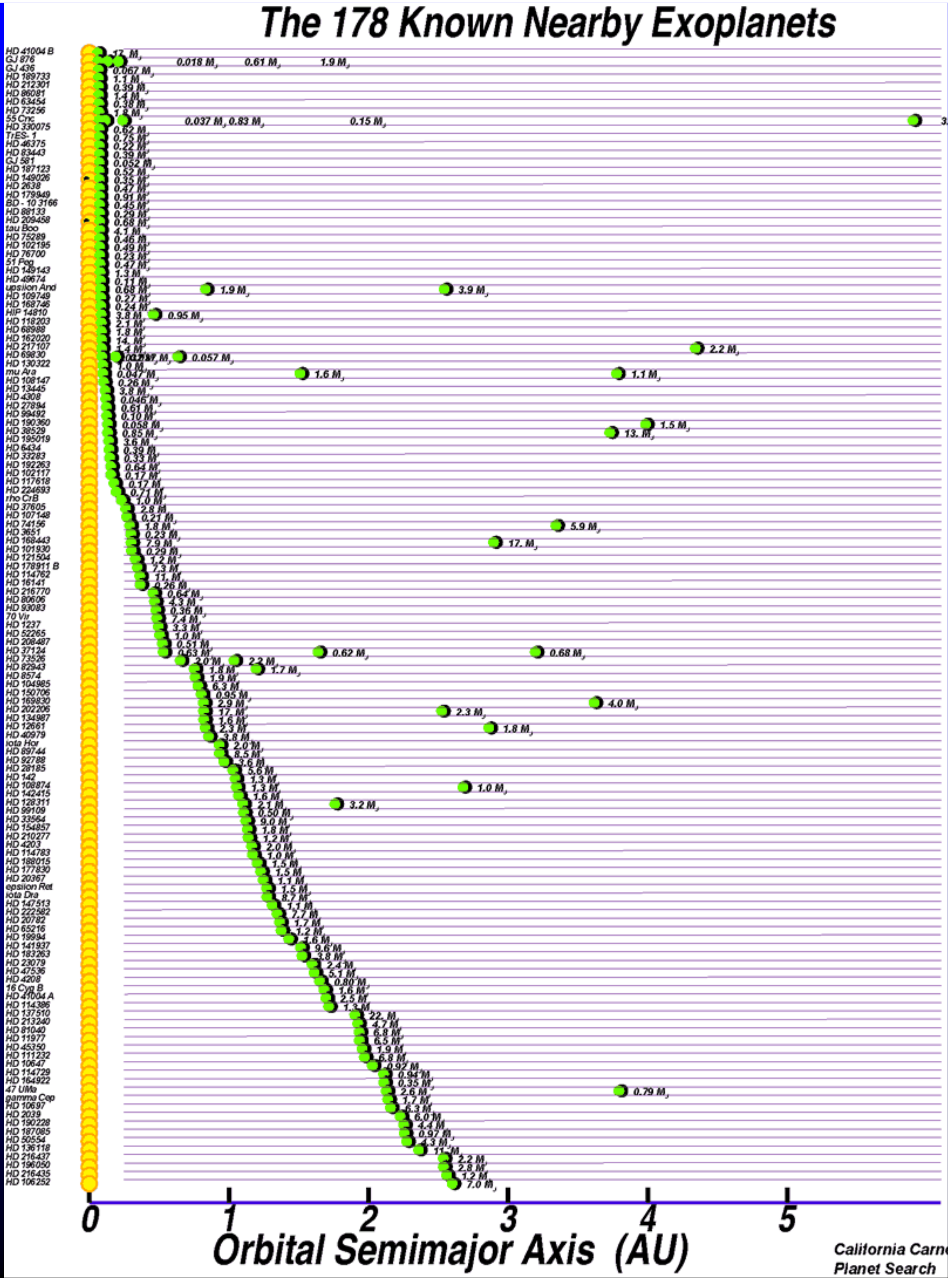
ESO PR Photo 03a/06 (January 25, 2006)


PLANETS AROUND SUN-LIKE STARS
INNER SOLAR SYSTEM
Mercury
Venus
Earth
Mars
47 UMa
2.4 M Jup
51 Peg
0.47M Jup
55 Cancri
0.84M Jup
Tau Bootis
3.8M Jup
Upsilon Andromedae
0.68M Jup
70 Vir
6.6M Jup
HD 114762
10M Jup
16 Cyg B
1.7M Jup
Rho Cr B
1.1M Jup

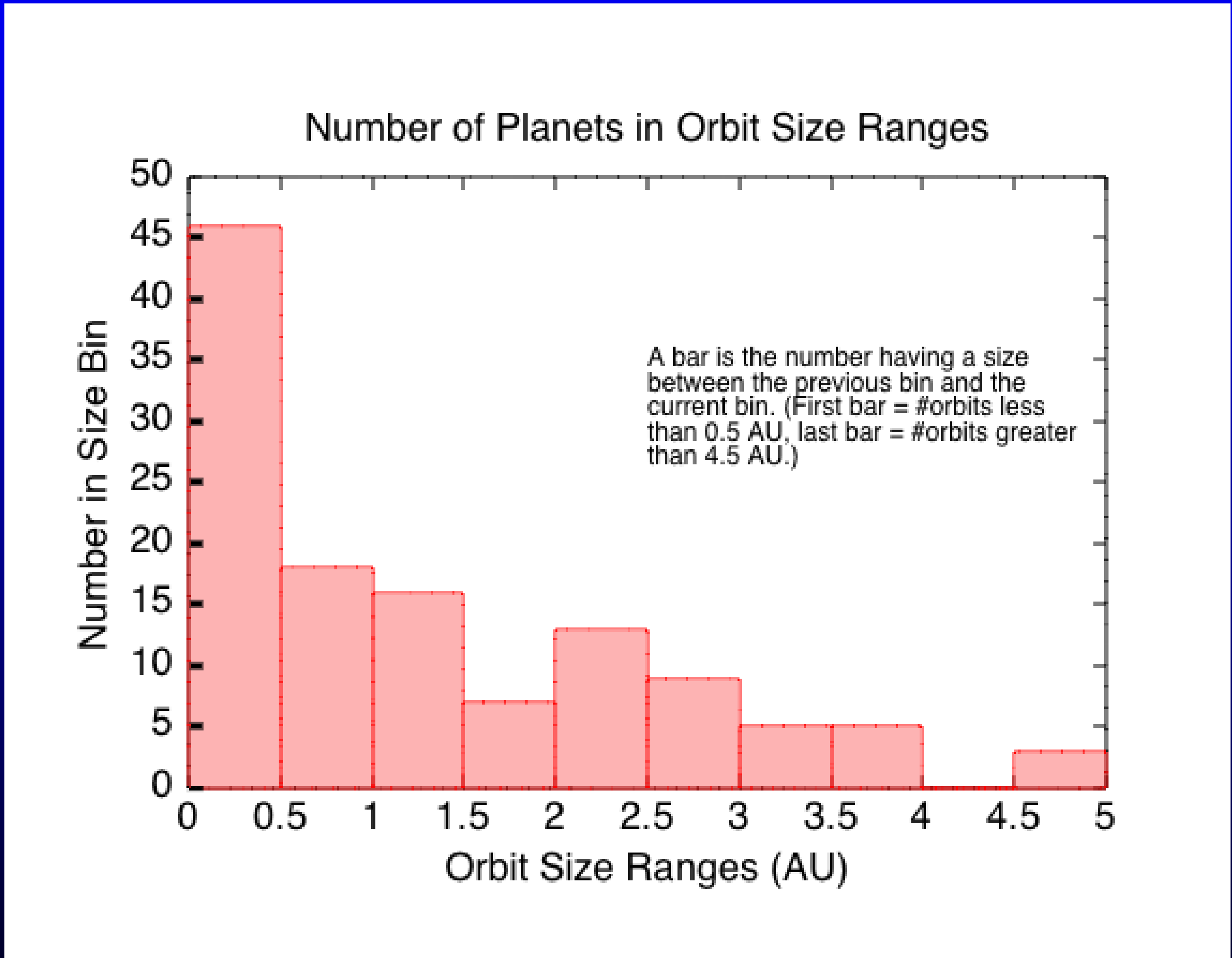

HD46375
HD187123
HD209458
bd-103166
TauBoo
HD75289
51Peg
Ups And
HD217107
HD130322
GJ86
55Cnc
HD195019
HD192263
GJ876
RhoCrB
HD168443
HD16141
HD114762
70Vir
HD52265
HD1237
HD37124
HD134987
HD12661
HD89744
IotaHor
HD177830
HD210277
HD222582
16CygB
47UMa
HD10697
14Her
0.25 M_J
0.53 M_J
0.63 M_J
0.48 M_J
4.1 M_J
0.46 M_J
0.45 M_J
0.68 M_J
1.9 M_J
4.4 M_J
1.2 M_J
1.1 M_J
4.2 M_J
0.93 M_J
3.5 M_J
0.81 M_J
2.0 M_J
0.99 M_J
8.1 M_J
0.21 M_J
10. M_J
7.4 M_J
1.1 M_J
3.4 M_J
1.1 M_J
1.5 M_J
2.8 M_J
7.3 M_J
2.9 M_J
1.2 M_J
1.2 M_J
5.1 M_J
1.6 M_J
2.6 M_J
6.0 M_J
5.4 M_J
0
1
2
3
Orbital Semimajor Axis (AU)

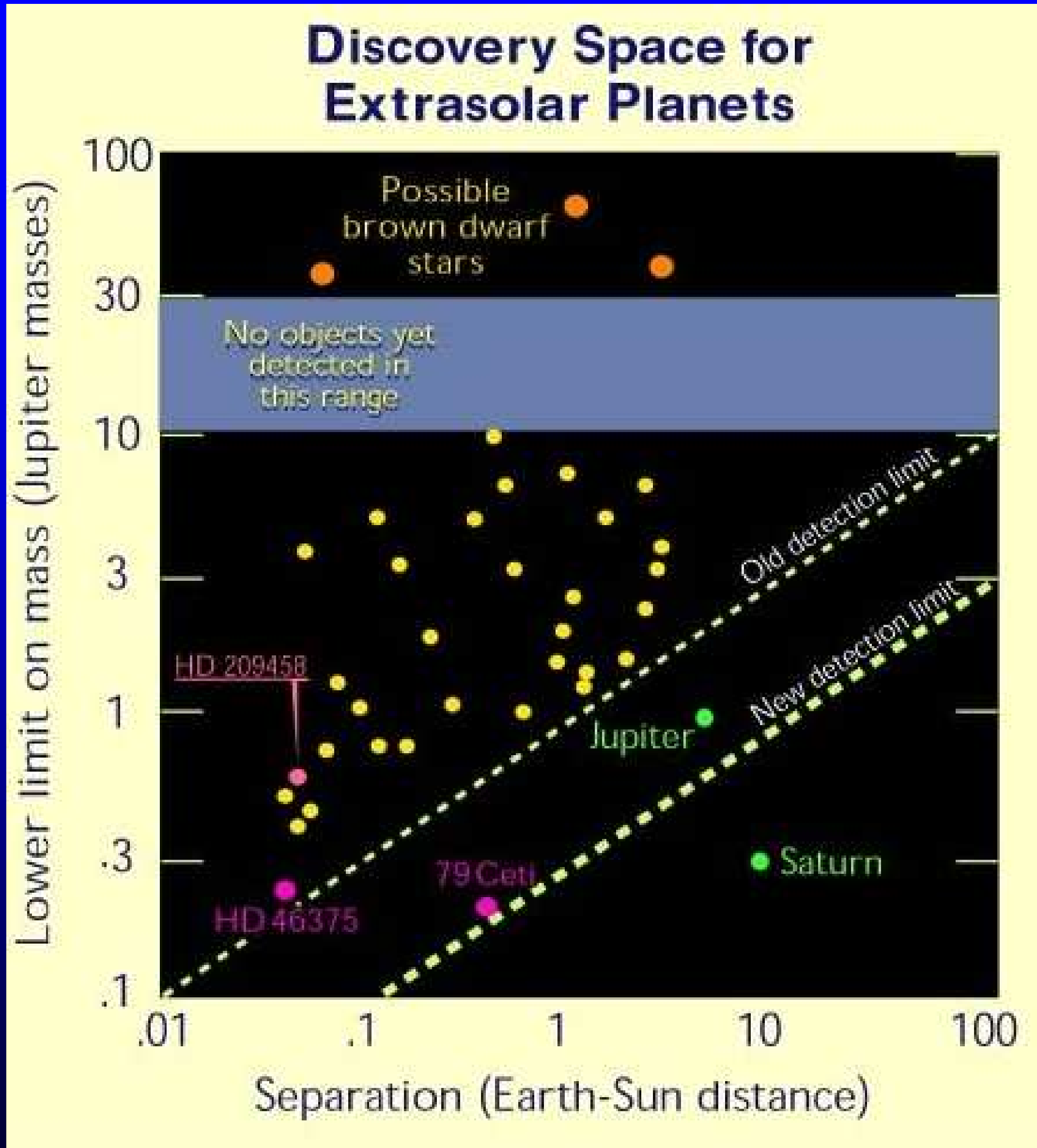
Today

- Notice: planets have now been found out to nearly 6 AU

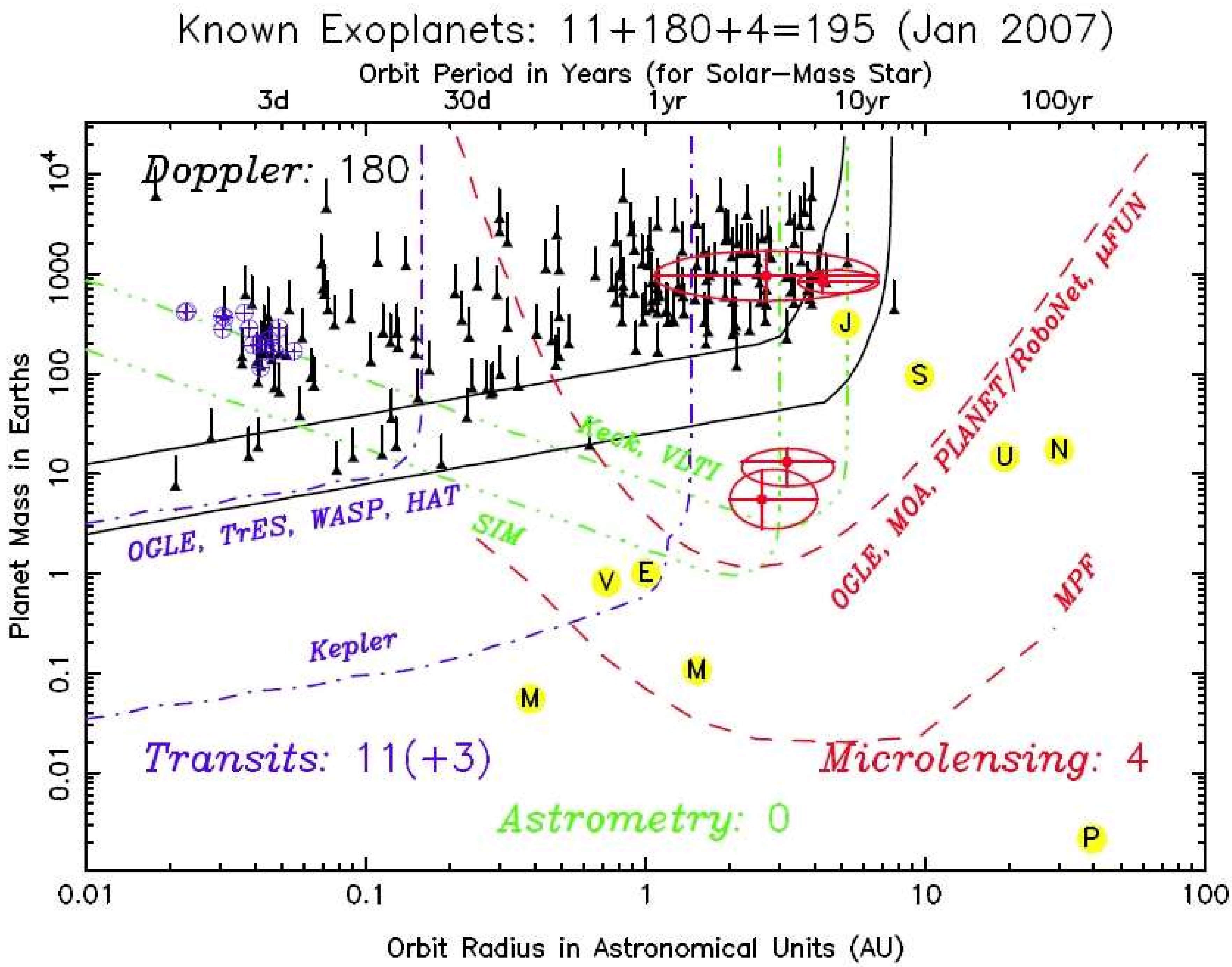


Separation from their Sun





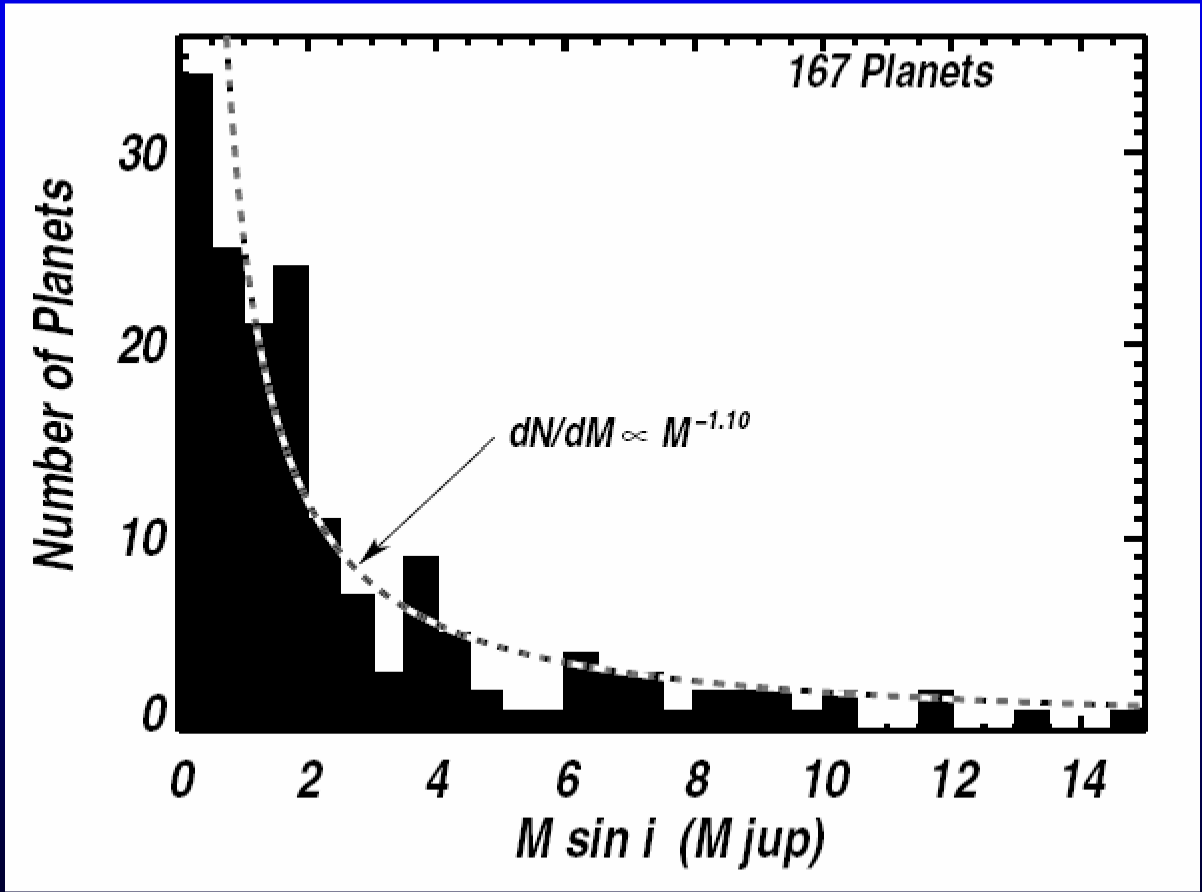
Discovery Space for Extrasolar Planets
Possible brown dwarf stars
No objects yet detected in this range
Old detection limit
New detection limit
HD 209458
Jupiter
79 Ceti
HD 46375
Saturn
Lower limit on mass (Jupiter masses)
100
30
10
3
1
.3
.1
.01
.1
1
10
100
Separation (Earth-Sun distance)



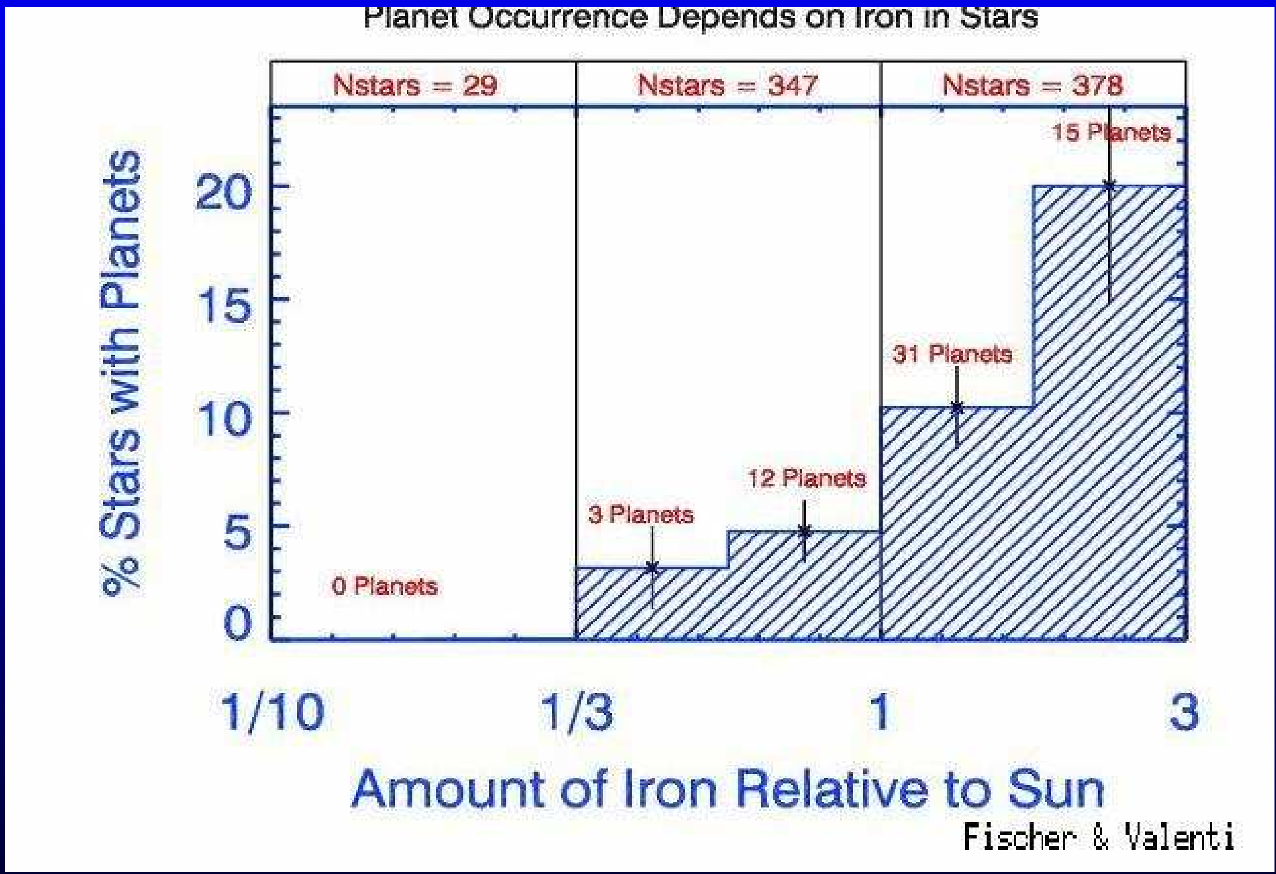
Known Exoplanets: 11+180+4=195 (Jan 2007)
Orbit Period in Years (for Solar-Mass Star)
3d
30d
1yr
10yr
100yr
Doppler: 180
Transits: 11(+3)
Microlensing: 4
Astrometry: 0
OGLE, TrES, WASP, HAT
Kepler
SIM
Keck, VLTI
OGLE, MOA, PLANET/RoboNet, μFUN
MPF
J
S
U
N
V
E
M
M
P
Planet Mass in Earths
10^4
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
100
Orbit Radius in Astronomical Units (AU)

Properties of planets

- Distribution of mass



Properties of planets



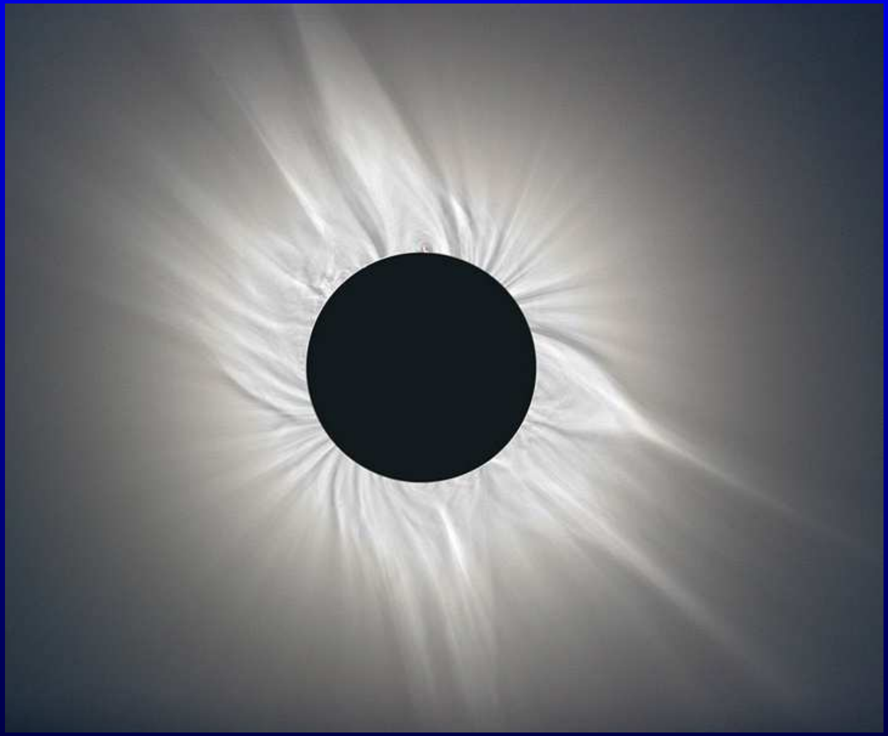
The Future – Direct detection

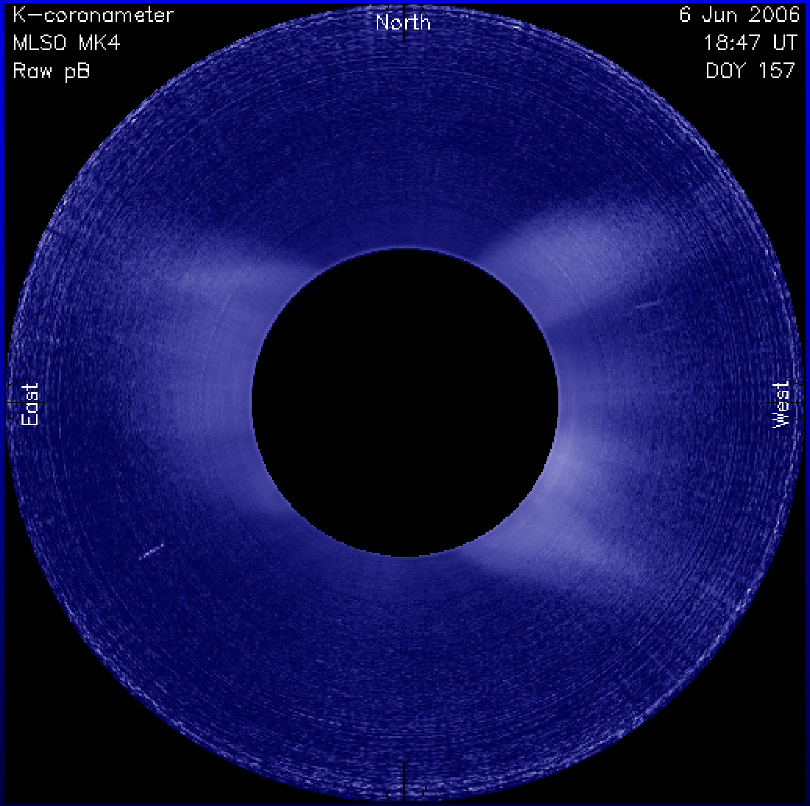
- Must eliminate the overwhelming brightness of the star.
  - 1) Use Infrared as planets are brighter in relation to their Sun.
  - 2) Use a multiple mirror system as an Interferometer - a bit like Young’s Slits – to put a “null” on the stars position.
- Nasa’s Planet Finder
- ESO’s Darwin

Direct Detection: A planet in orbit around a "Brown Dwarf"

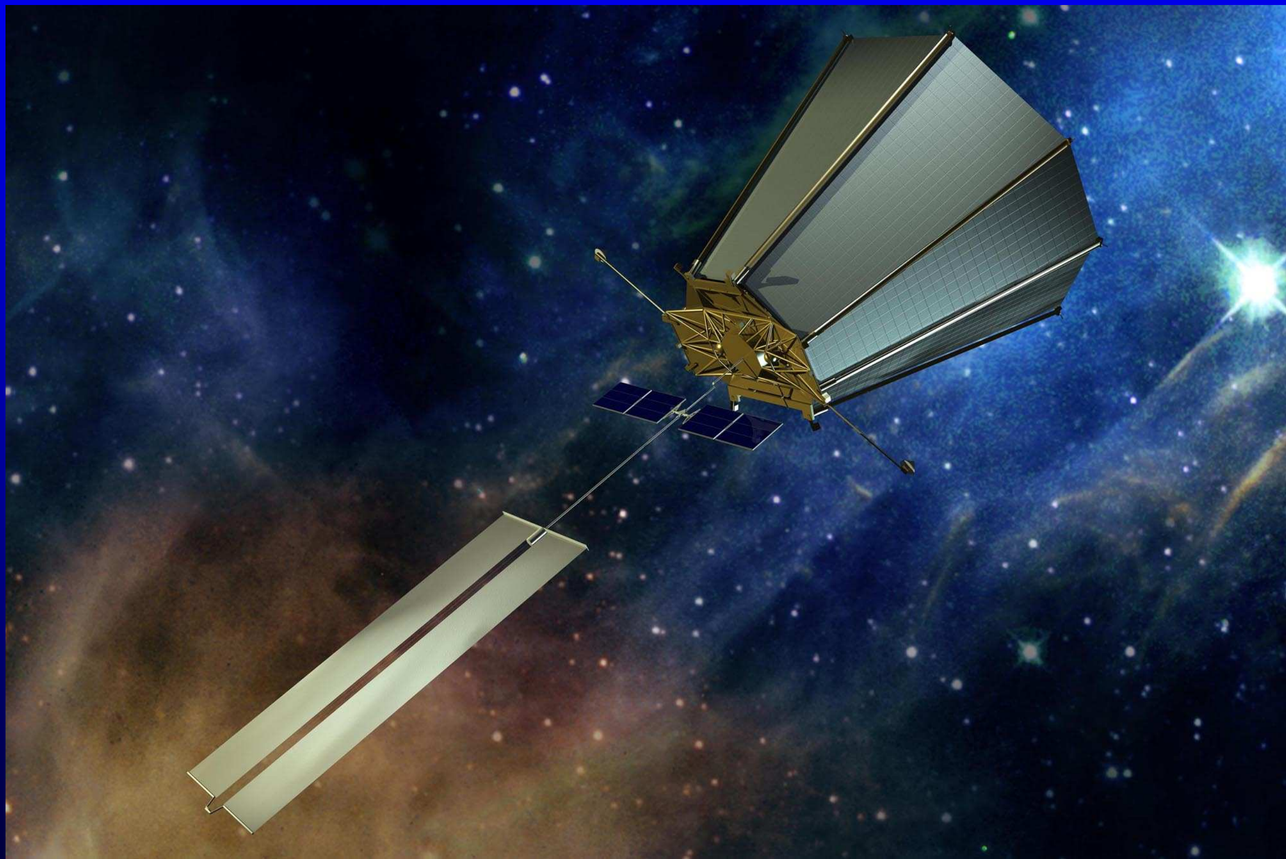
How can we “see” the planet close to its Sun?

1) Occult the Star

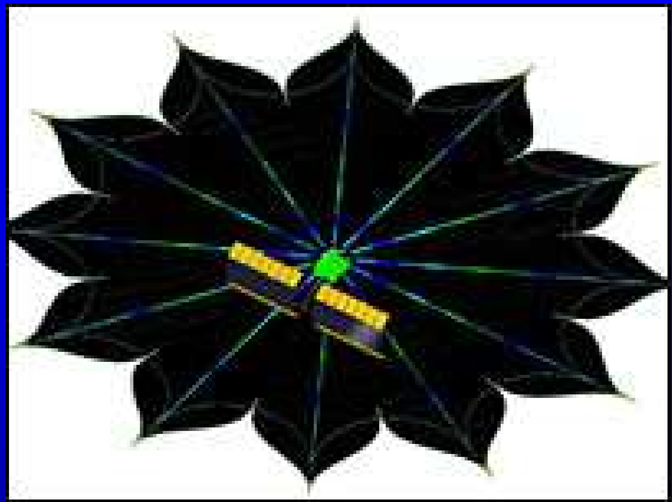




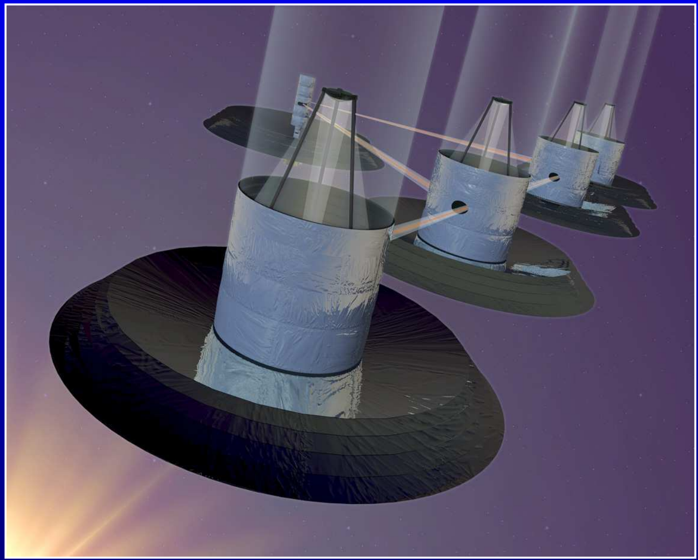
Use a Coronograph



2) Use an “occulter”



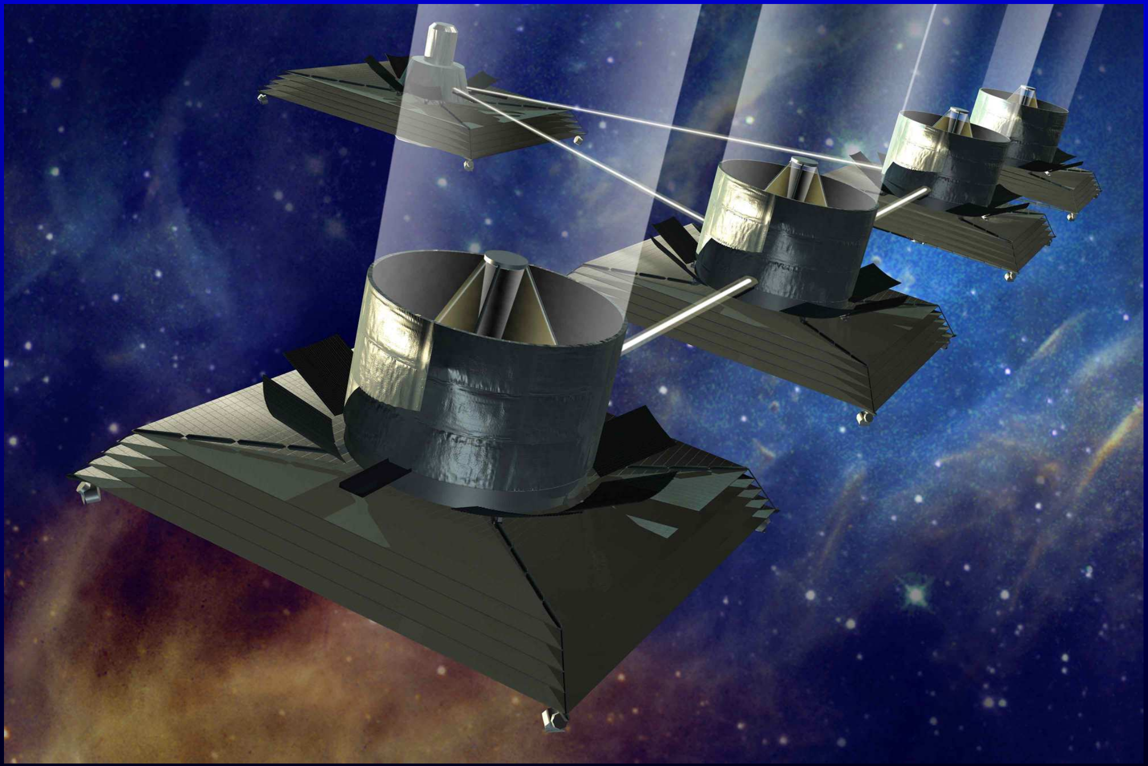
Detecting life



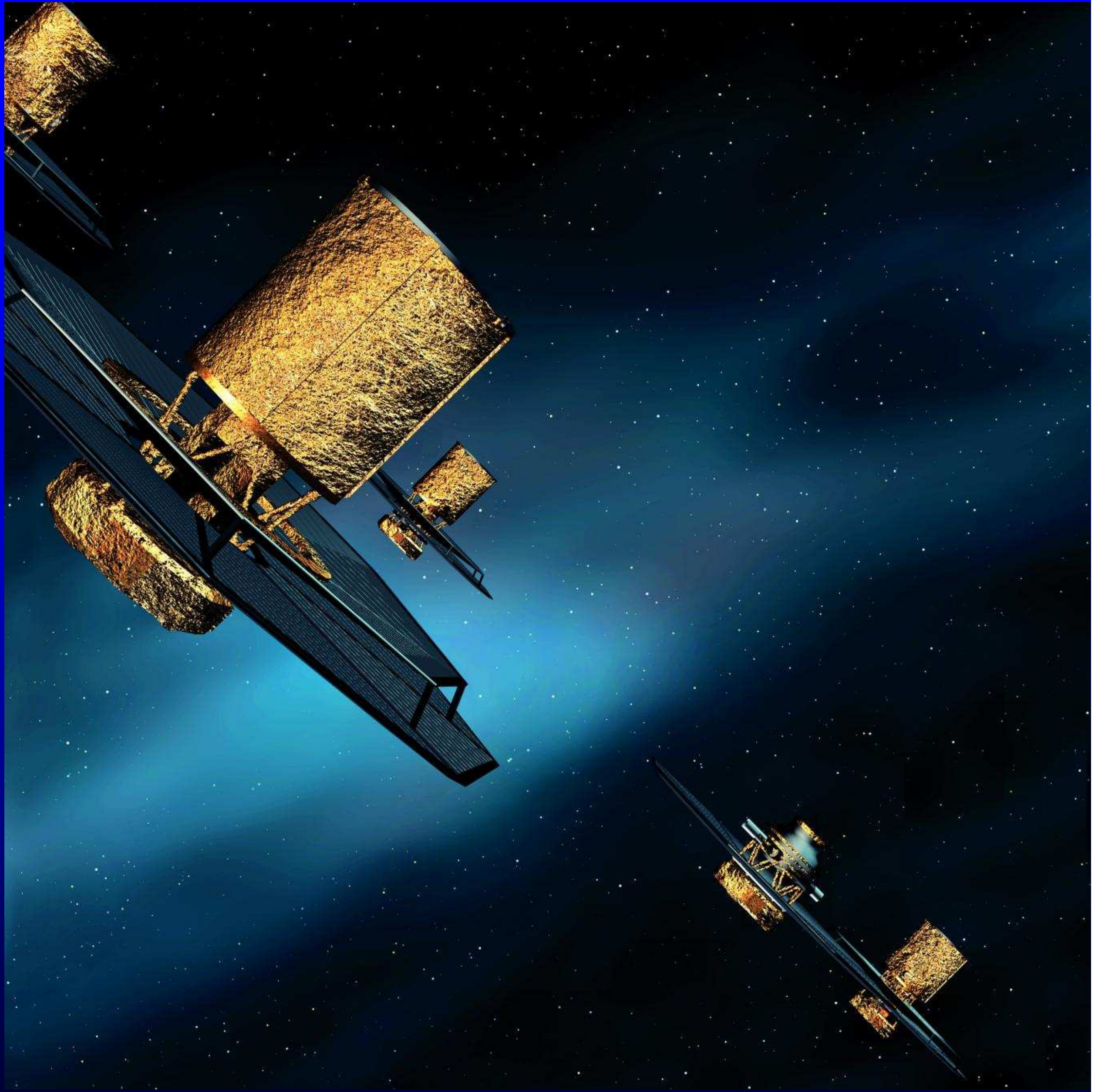
NASA
Terrestrial
Planet
Finder

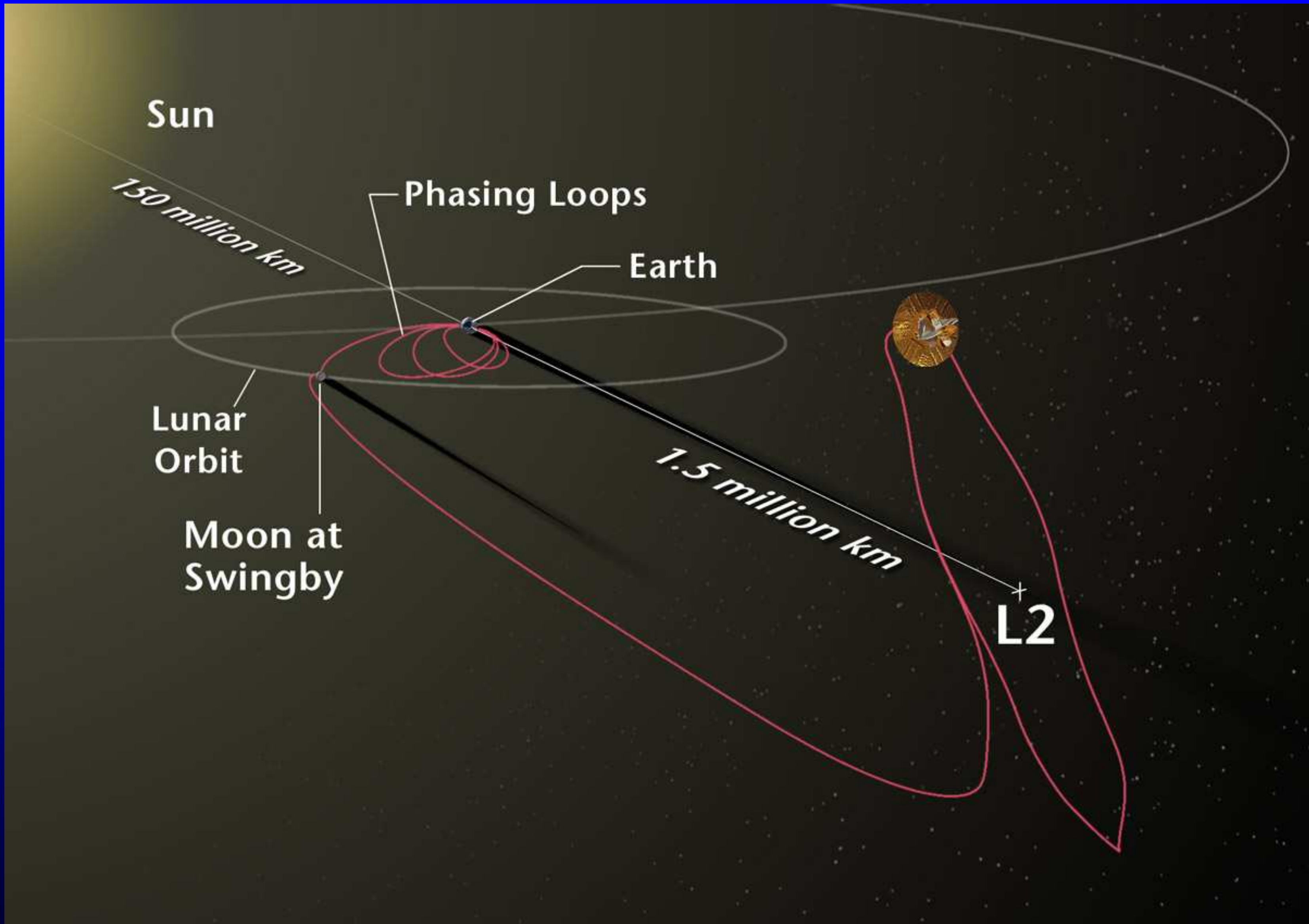
ESA
Darwin

3) Use an Infra-red Interferometer "Terrestrial Planet Finder"



Darwin



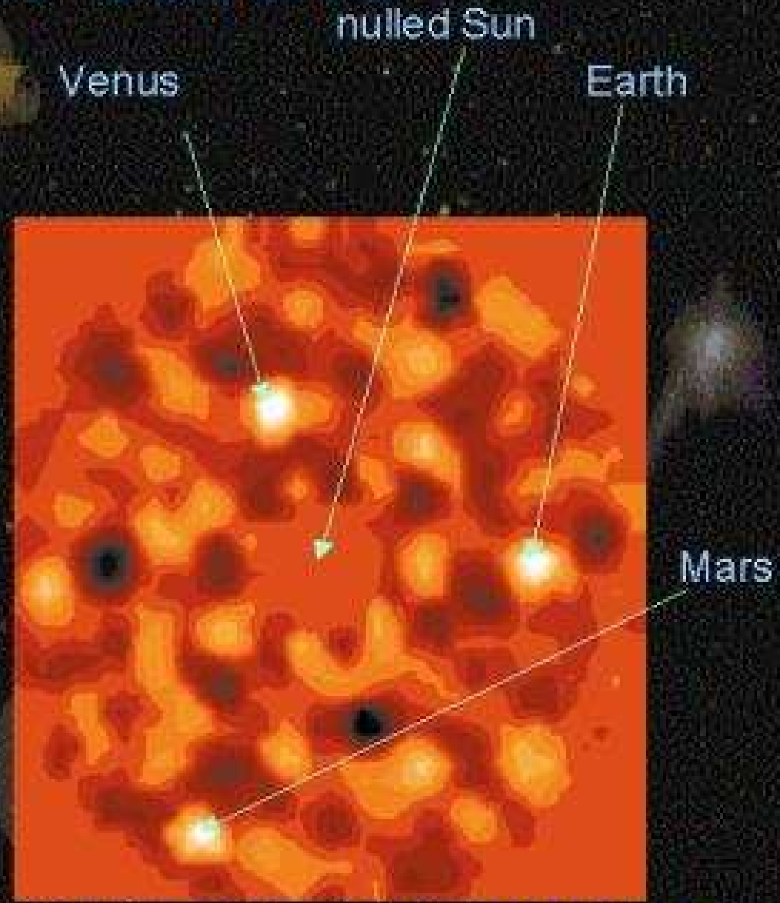


Sun
150 million km
Phasing Loops
Earth
Lunar
Orbit
Moon at
Swingby
1.5 million km
L2

Search for earths

- e.g. reconstruction map by DARWIN of the Solar System ➡
  (planet position at 1st Jan. 2001, orbit seen at 30° inclination)

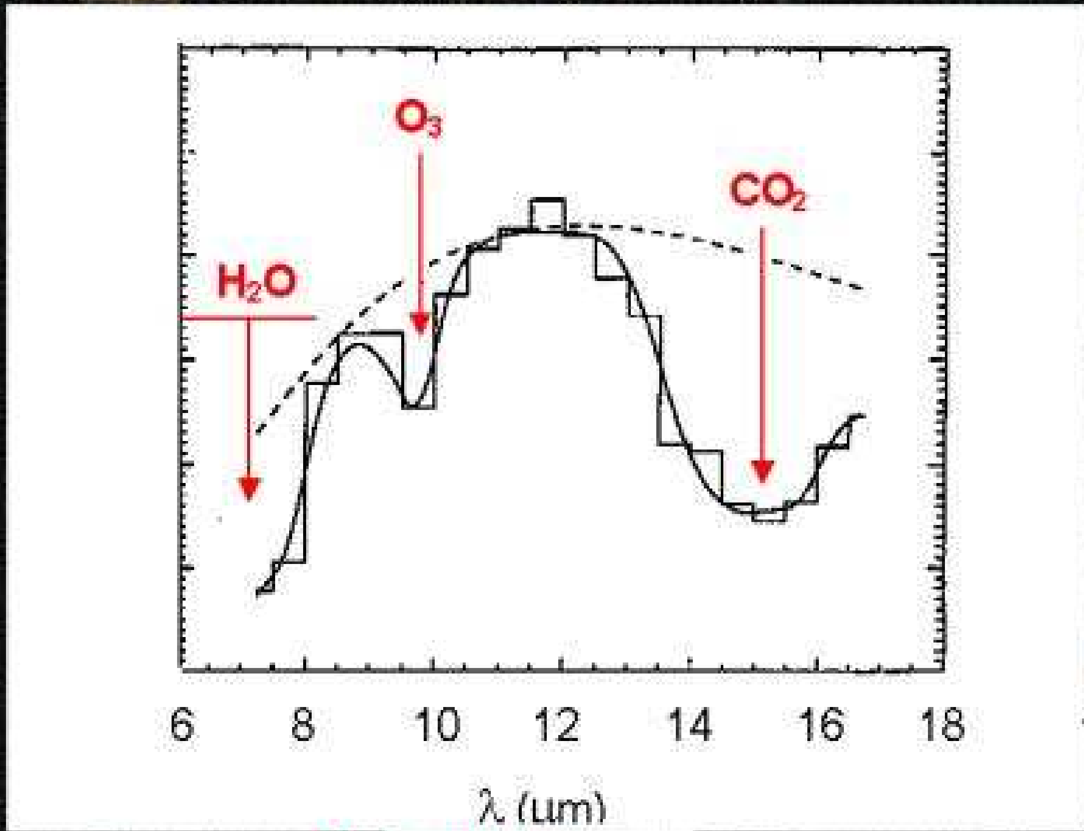
- several observations
  ⇨ **orbital parameters**



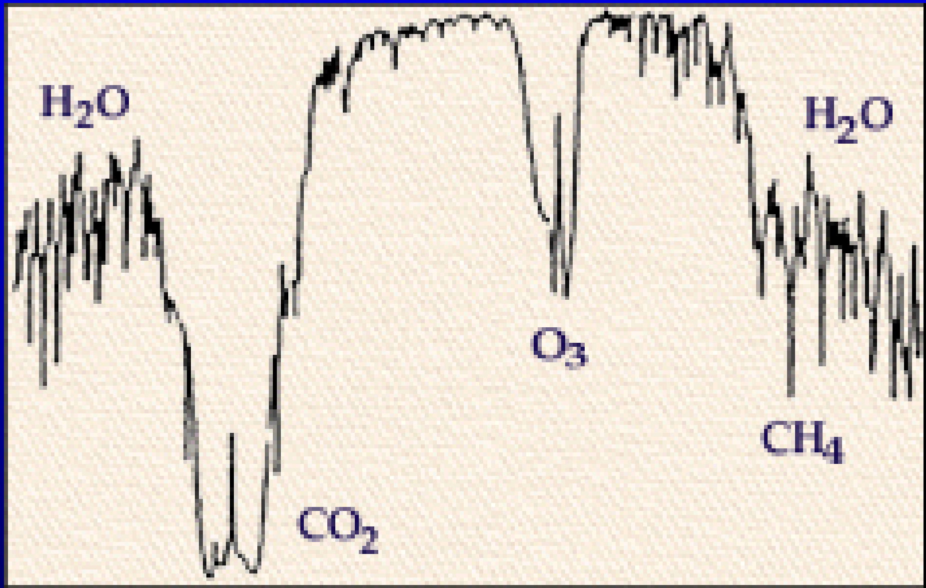
Mennesson and Mariotti (1997)

Spectrum of an earth at 10 pc

by DARWIN: $\lambda / \Delta\lambda = 20$

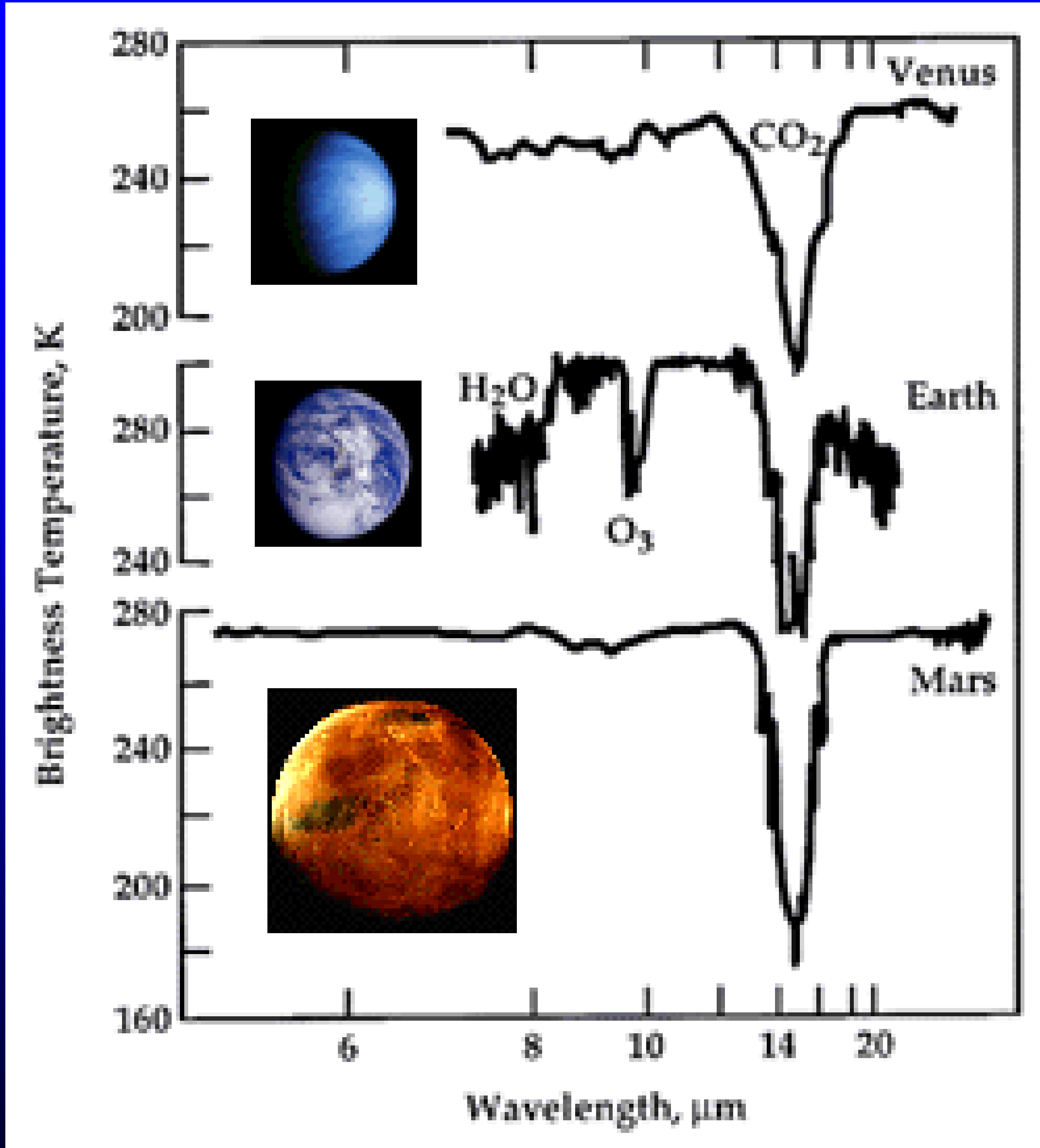


What does it tell us?

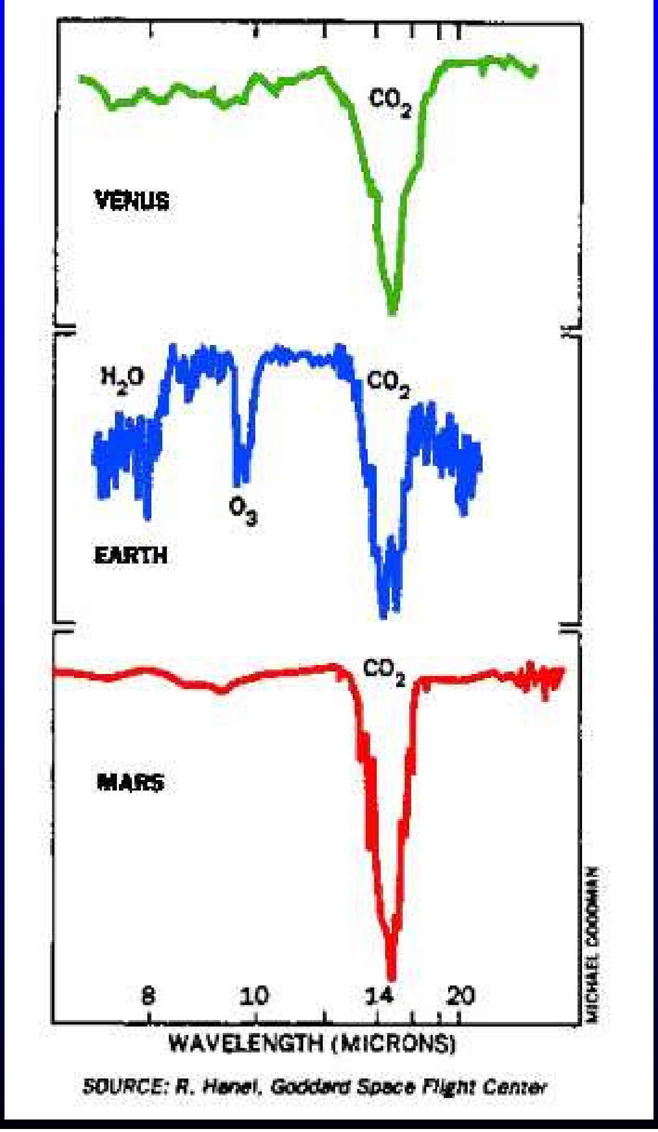


Spectrum - some signs of life:

- The spectral shape shows the temperature of the planet and it is right for water to be liquid
- The strong carbon dioxide band shows we have a planet with an atmosphere
- The ozone band shows plentiful oxygen, probably produced by life
- The spectral features of water show abundant water, indicating a planet with an ocean

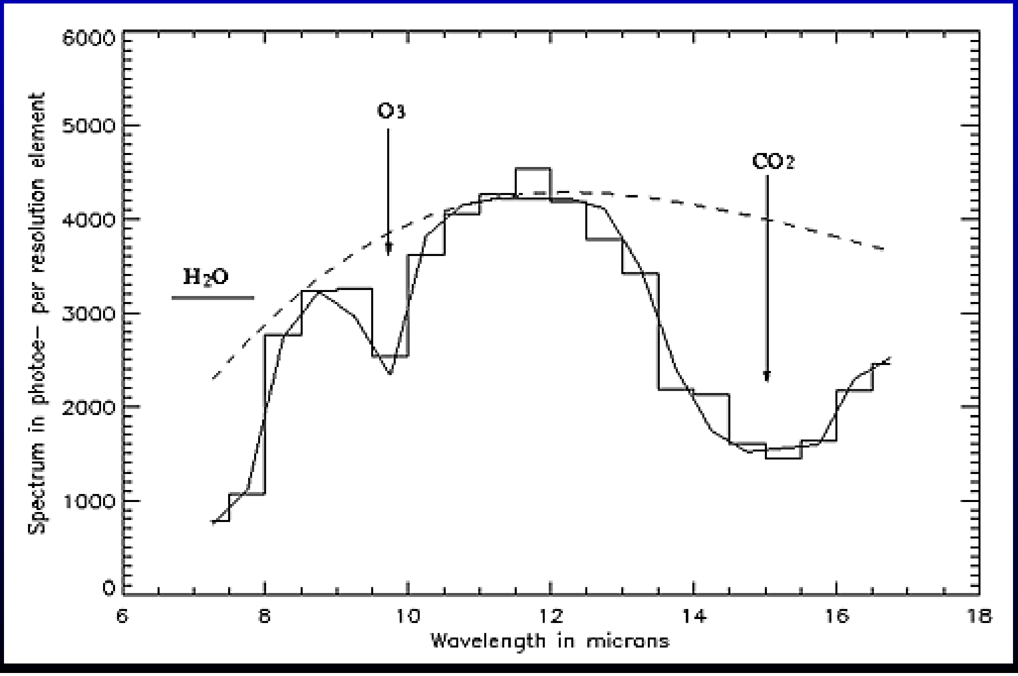

Venus
Earth
Mars
CO2
H2O
O3
Brightness Temperature, K
Wavelength, µm
280
240
200
160
6
8
10
14
20

Detecting life



Water vapour and ozone are signs of lif

Simulated spectrum of Earth at 10pc as seen by Darwin



Exploring extrasolar planets

It’s difficult to go there.

The nearest other star is about 40,000 billion km away.

Some typical speeds and travel times to nearest star:

Supersonic jet	1600 km/hour	3 million years
Space probe (fastest thing we’ve ever built)	60,000 km/hour	75,000 years
Light	1 billion km/hour	4.5 years