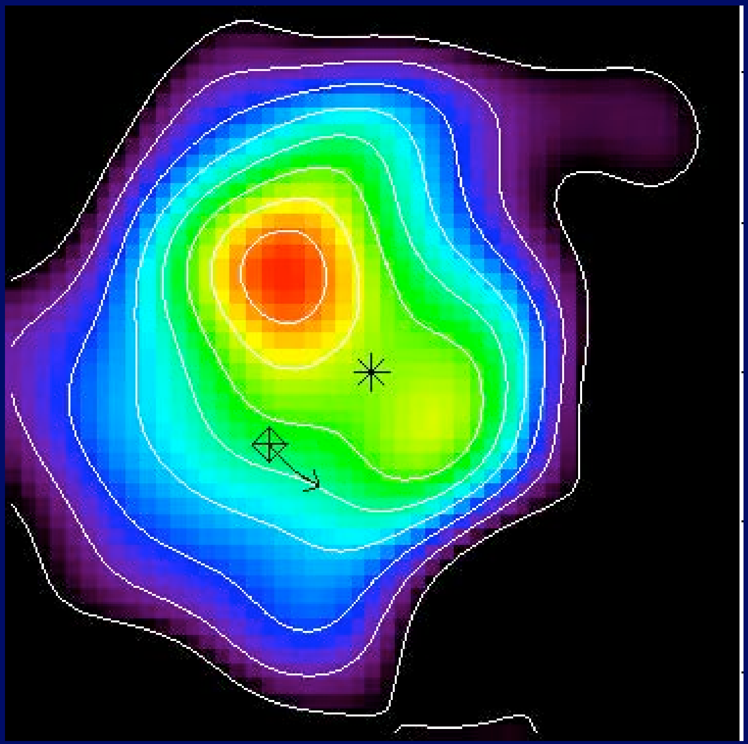
Planet Formation and Detection

Estimating f_p

Planet Formation

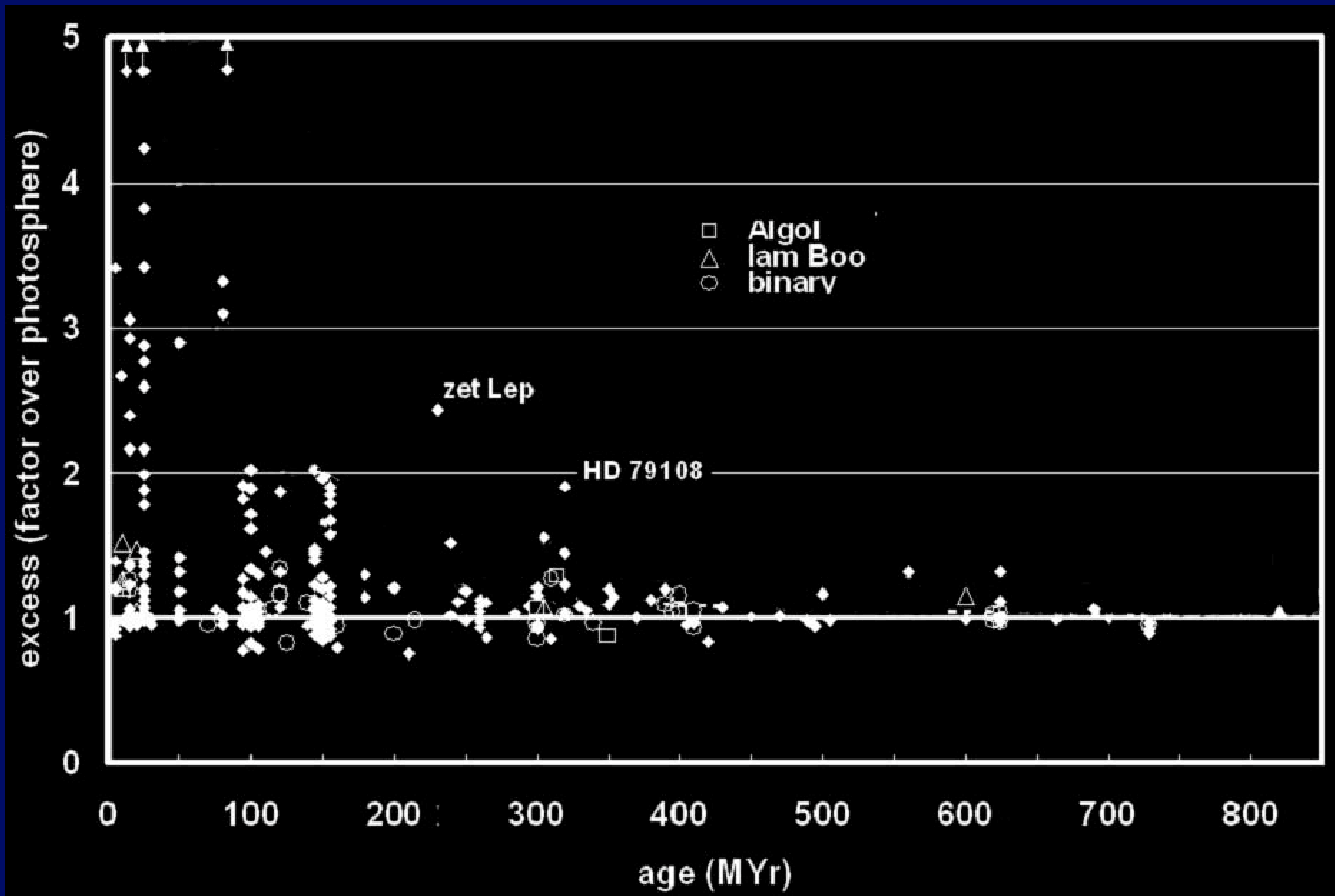


SMM image of Vega shows dust peaks off center from star (*). Fits a model with a Neptune like planet clearing a gap. Can test by looking for motion of clumps in debris disk.

SMM image of Vega
JACH, Holland et al.

Model by Wyatt (2003), ApJ, 598, 1321

Disks versus Age of Star
Evidence for Collisions



Binary Stars

- About 2/3 of all stars are in binaries
  - Most common separation is 10-100 AU
- Can binary stars have disks?
  - Yes, but binary tends to clear a gap
  - Disks well inside binary orbit
  - Or well outside binary orbit

Brown Dwarfs

- Stars range from 0.07 to ~100 M_{sun}
- Jupiter is about 0.001 M_{sun}
- Brown dwarfs between stars and planets
  - Dividing line is somewhat arbitrary
  - Usual choice is 13 $M_{jupiter}$
  - Brown dwarfs rarely seen as companions to stars
  - But "free-floaters" as common as stars
  - Many young BDs have disks
    - Planets around BDs?

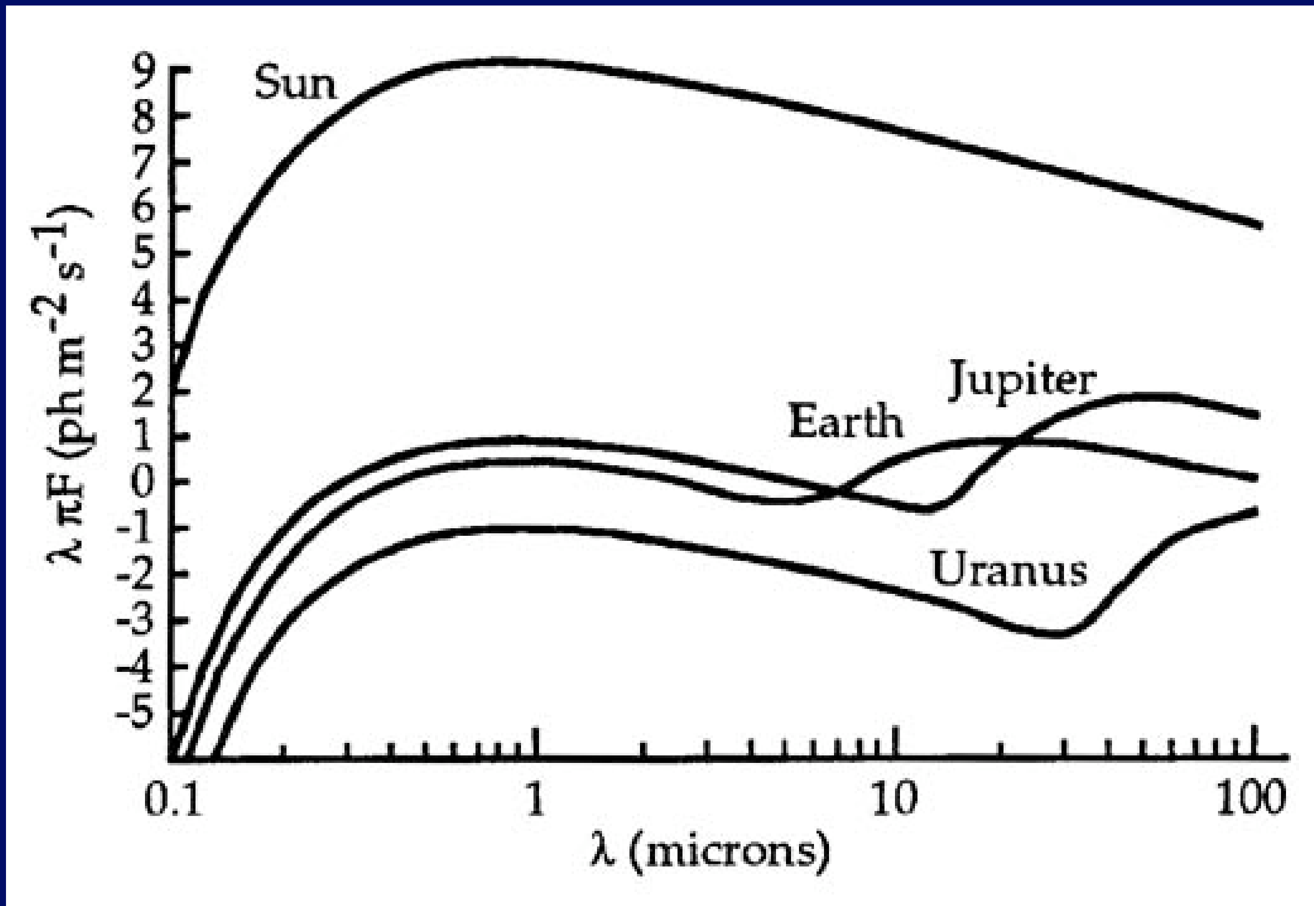
Planet Detection

Methods and Results

Can We See Them?

- Not yet, but there are plans…
- Problem is separating planet light from star light
  - Star is 10^9 times brighter in visible light
  - "Only" 10^6 times brighter in infrared

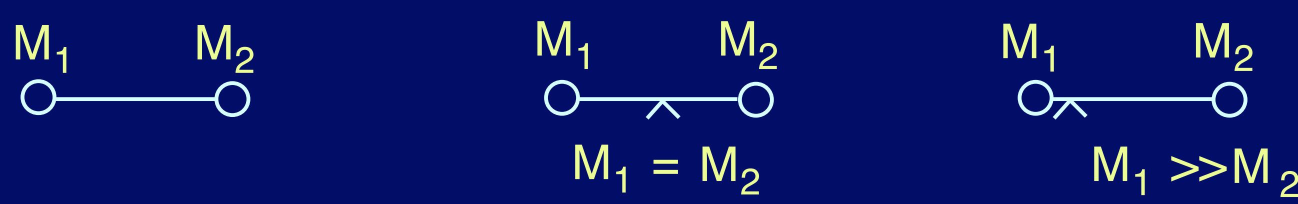
Planet is Much Fainter than Star



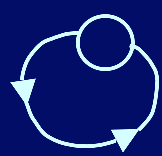
Indirect Detection

Wobbling star

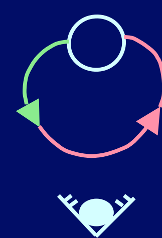
Detect effect of planet on star (both orbit around center of mass)



Large planet will make a star “wobble”



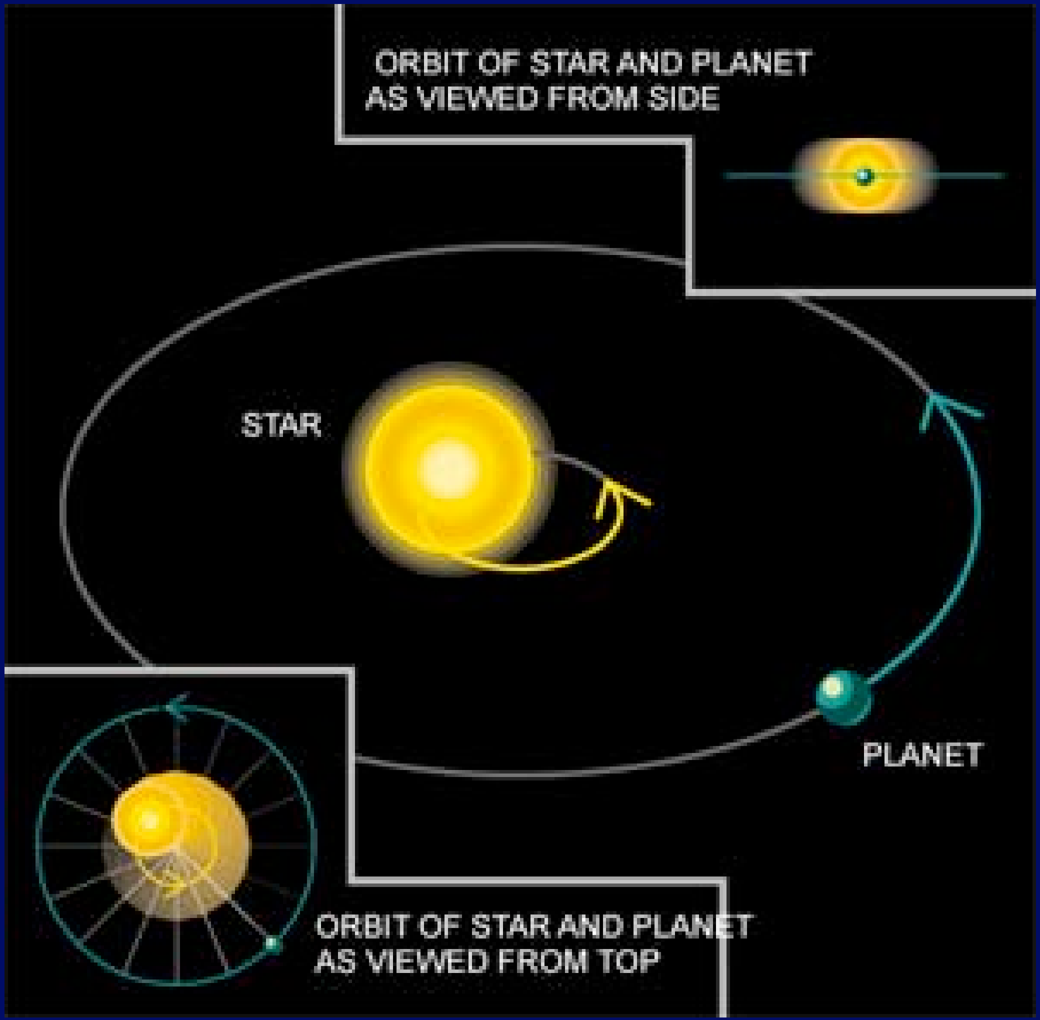
In plane of sky observe position shift

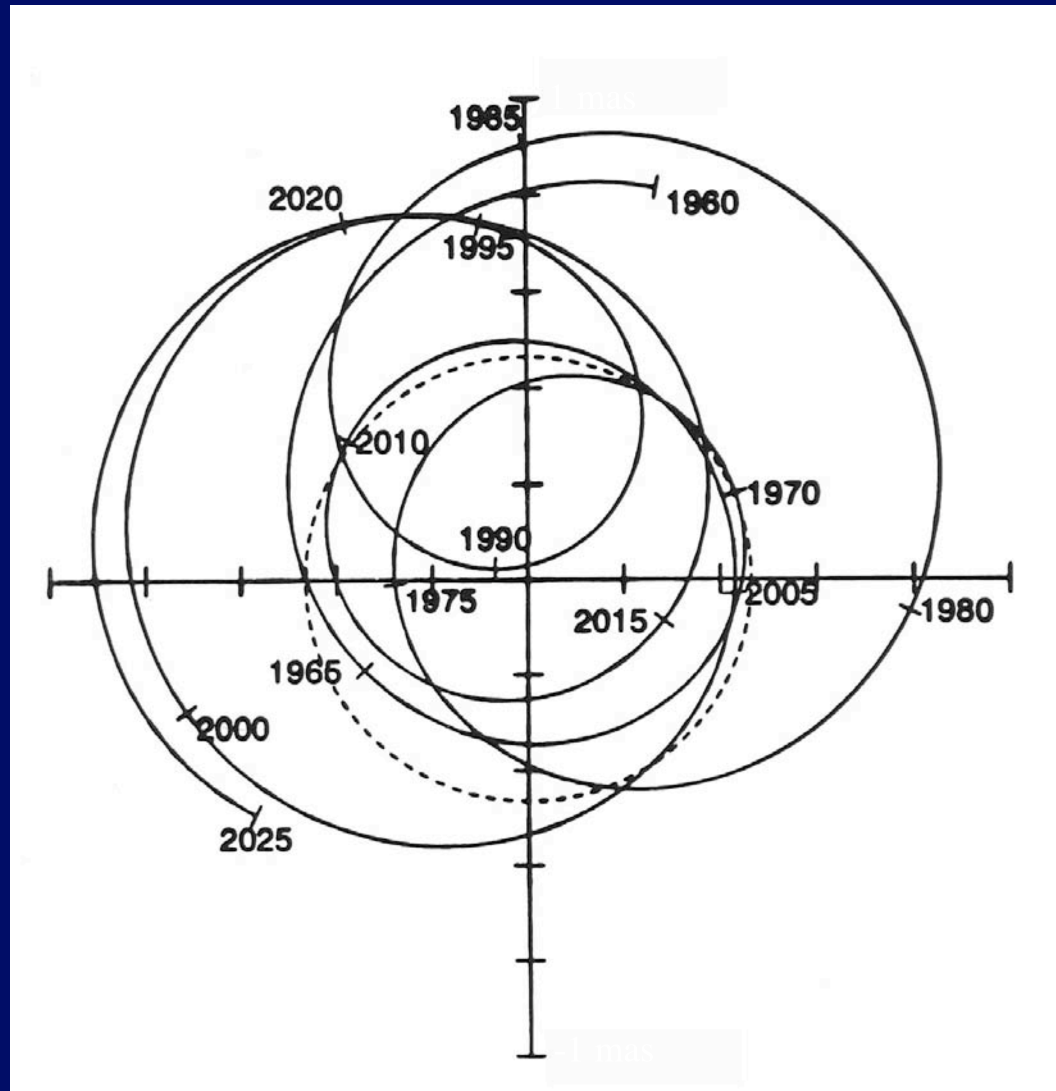


Along our line of sight

Observe Doppler Shift

Star and Planet Orbit Center of Mass



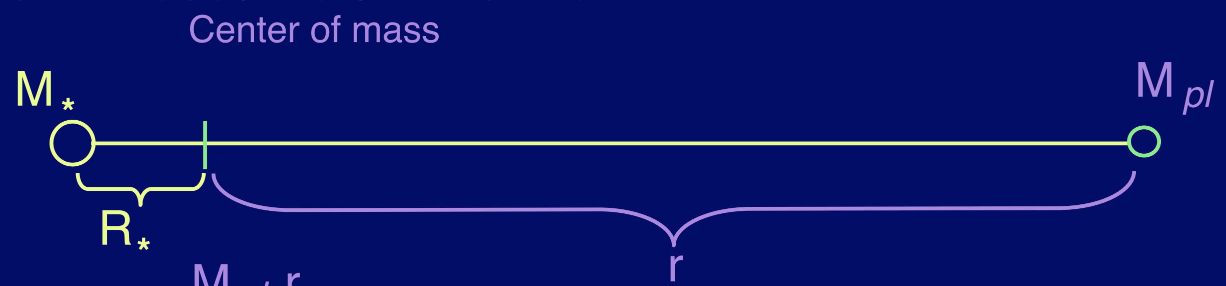


The Sun as viewed from 10 pc (~30 *ly*)

The Astrometric Technique

Measure stellar position (angle) accurately - see wobble compared to more distant stars

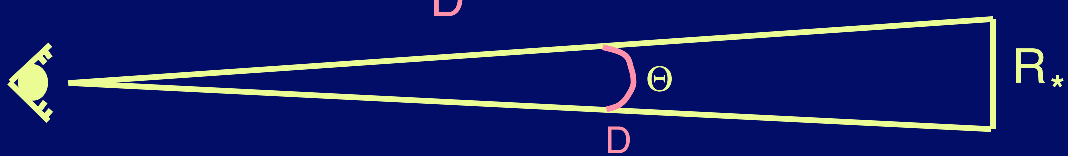
How far does the star wobble?



$$R_* = \frac{M_{pl}\, r}{M_*}$$

We measure angle; for small angles,

$$\Theta = \frac{R_*}{D} \quad \text{in radians}$$



so $$\Theta = \frac{M_{pl}\, r}{M_*} \frac{r}{D}$$

Big planet, big orbit
small star, close to sun

Current limit: 1 mas = 10^{-3} arcsec = 2.8×10^{-6} degrees
= 4.9×10^{-8} radians

e.g. $M_{pl} = M_{Jupiter}$, $M_* = M_\odot$, $D = 15\ ly \Rightarrow \Theta = 1$ mas

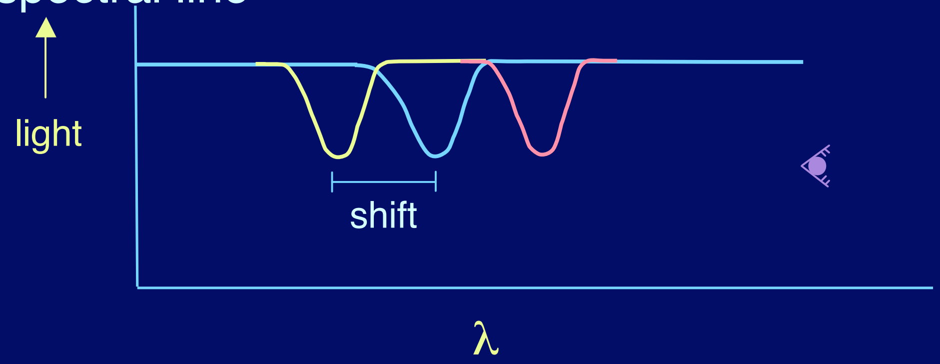
30 *ly*

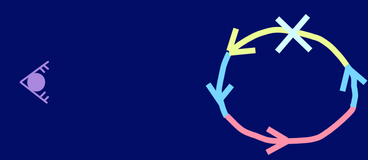
Planet	M_P (M_J)	R (AU)	P (years)	$V_\star$ ($m\,s^{-1}$)	Θ at 10 pc (mas)
Mercury	1.74E-4	0.387	0.241	0.008	6.4E-6
Venus	2.56E-3	0.723	0.615	0.086	1.8E-4
Earth	3.15E-3	1.000	1.000	0.089	3.0E-4
Mars	3.38E-4	1.524	1.881	0.008	4.9E-5
Jupiter	1.0	5.203	11.86	12.4	0.497
Saturn	0.299	9.54	29.46	2.75	0.273
Uranus	0.046	19.18	84.01	0.297	0.084
Neptune	0.054	30.06	164.8	0.281	0.156
Pluto	6.3E-6	39.44	247.7	3E-5	2.4E-5

The Spectroscopic Technique

Measure velocity, not position, of star

Use spectrometer to get Doppler Shift of spectral line





$$\text{Shift} \propto V_* \propto \frac{M_{pl}}{M_*^{1/2}\, r^{1/2}}$$

Big planet, small orbit

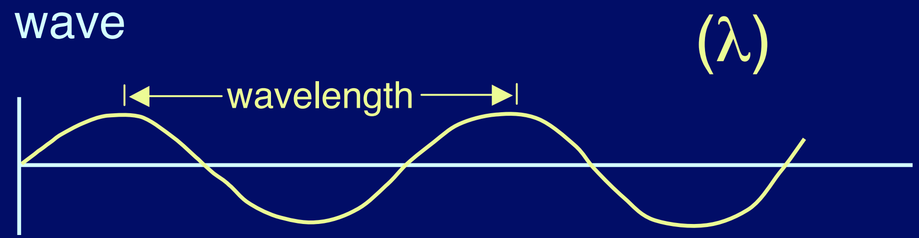
Small star

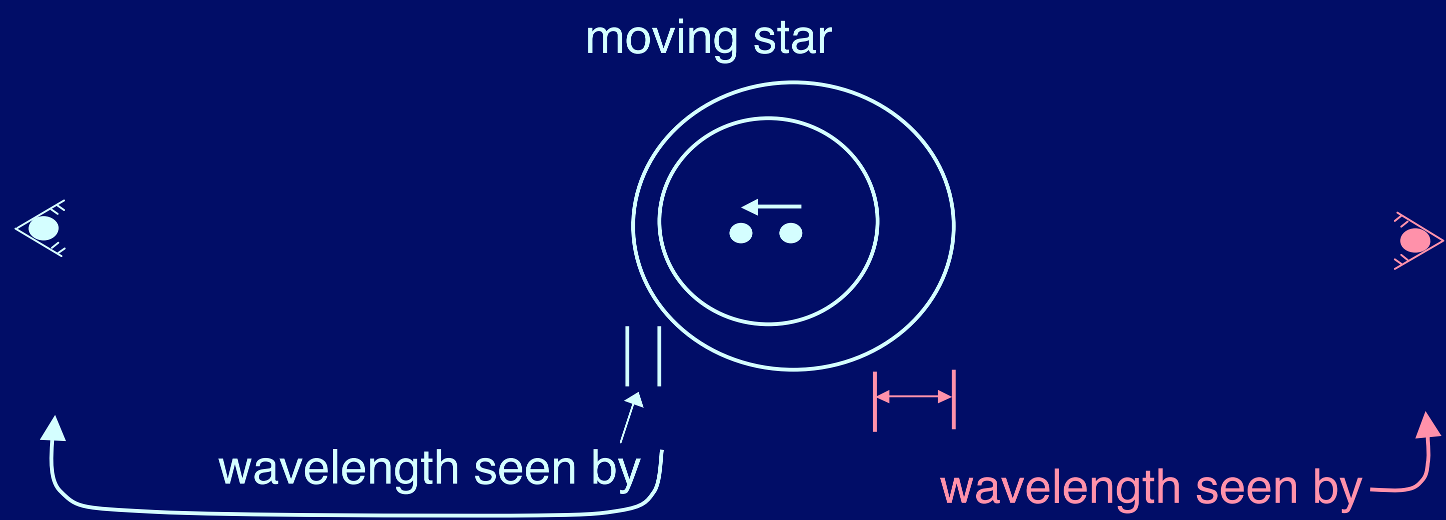
Distance doesn't matter (except for brightness)

Edge - On

The Doppler Shift

Light is a wave





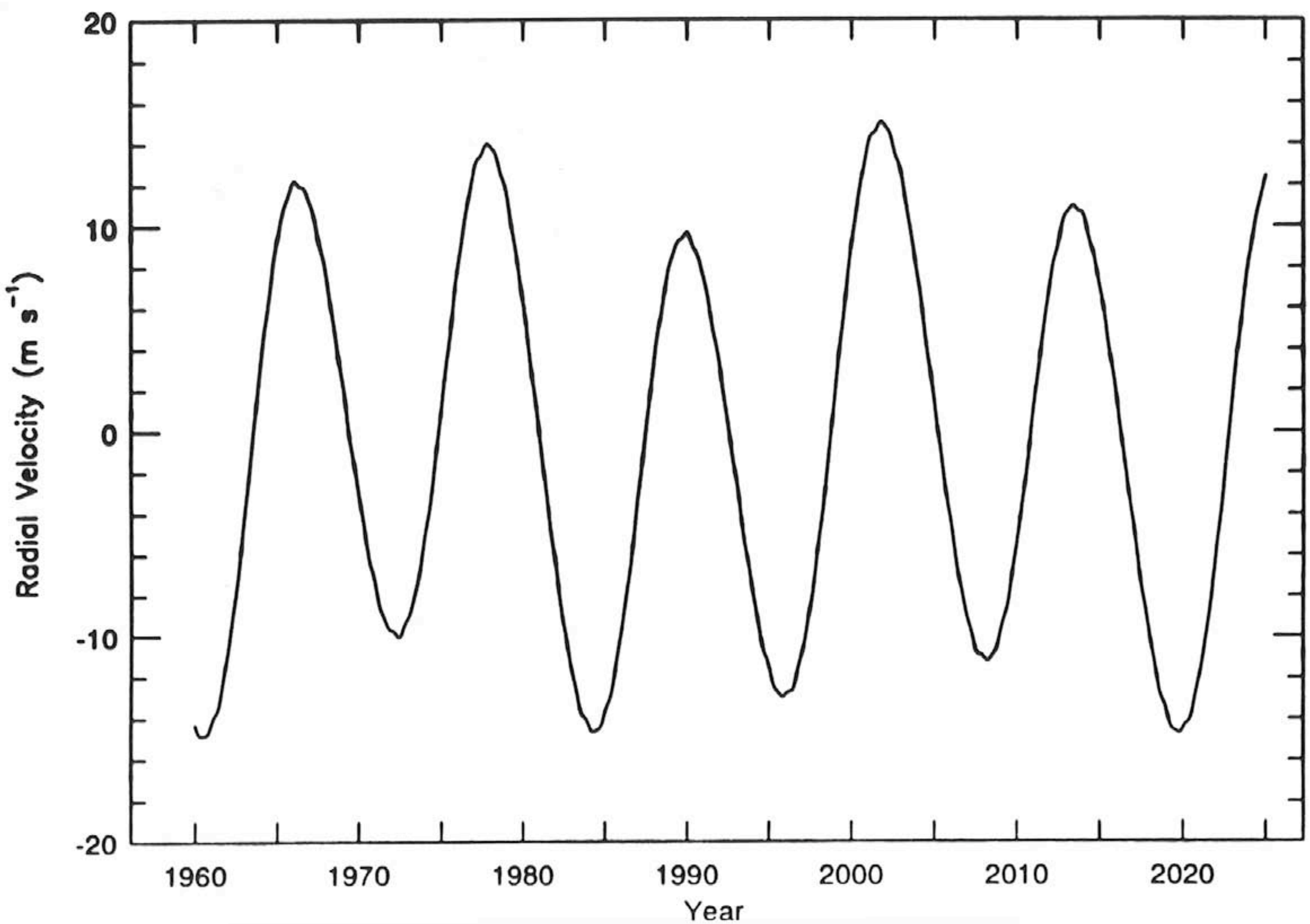
BLUESHIFT

REDSHIFT

$$\frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}} = 1 + \frac{v}{c}$$

Doppler Shift ⟶ Magnitude and direction of velocity

But only along line-of-sight



Motion of the Sun caused by Jupiter, ...

30 *ly*

Planet	M_P (M_J)	R (AU)	P (years)	$V_\star$ ($m\,s^{-1}$)	Θ at 10 pc (mas)
Mercury	1.74E-4	0.387	0.241	0.008	6.4E-6
Venus	2.56E-3	0.723	0.615	0.086	1.8E-4
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Neptune	0.054	30.06	164.8	0.281	0.156
Pluto	6.3E-6	39.44	247.7	3E-5	2.4E-5

What We Can Learn

1. There is a planet

   (If not a mistake)

2. The orbital period (P)

   (The time for pattern to repeat)

3. The orbital radius

   $r^3 \propto M_* P^2$

   (Kepler's Third Law)

4. Lower limit to planet mass (M_{pl})

   Conservation of momentum ⟶

$$M_{pl} \geqslant \frac{M_* V_* P}{2\pi r}$$

= if we see orbit edge-on

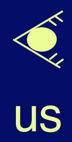
> if tilted

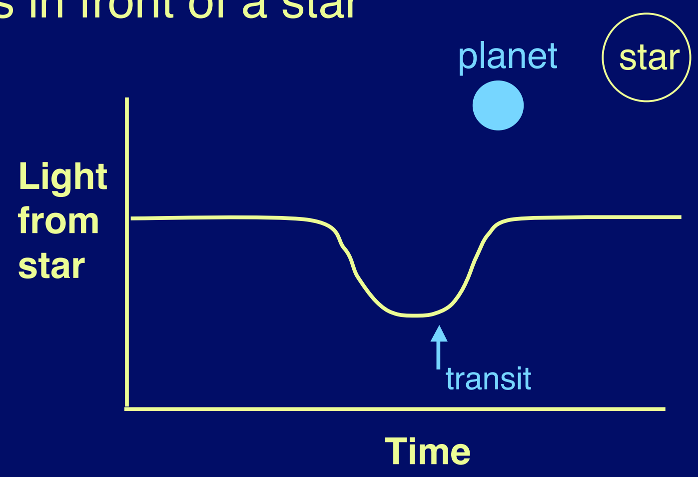
Comparison of Search Methods

	Astrometric	Spectroscopic
Advantages	Big Planet	Big Planet
	Big Orbit	Small Orbit
	Small Star	Small Star
	Nearby Star	--
		Edge-on Orbit

Other Methods

Transits: Planet passes in front of a star



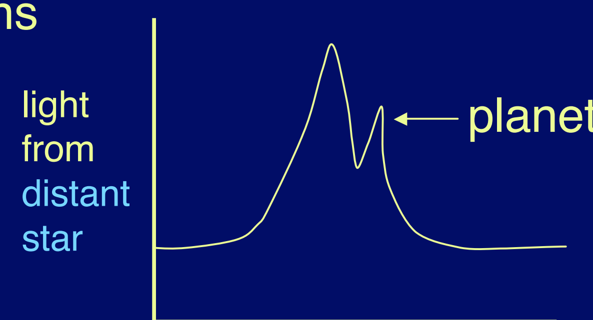


Only about 0.5% of stars with planets will line up

First planet found with this method in January 2003; 5 detected as of January 2005

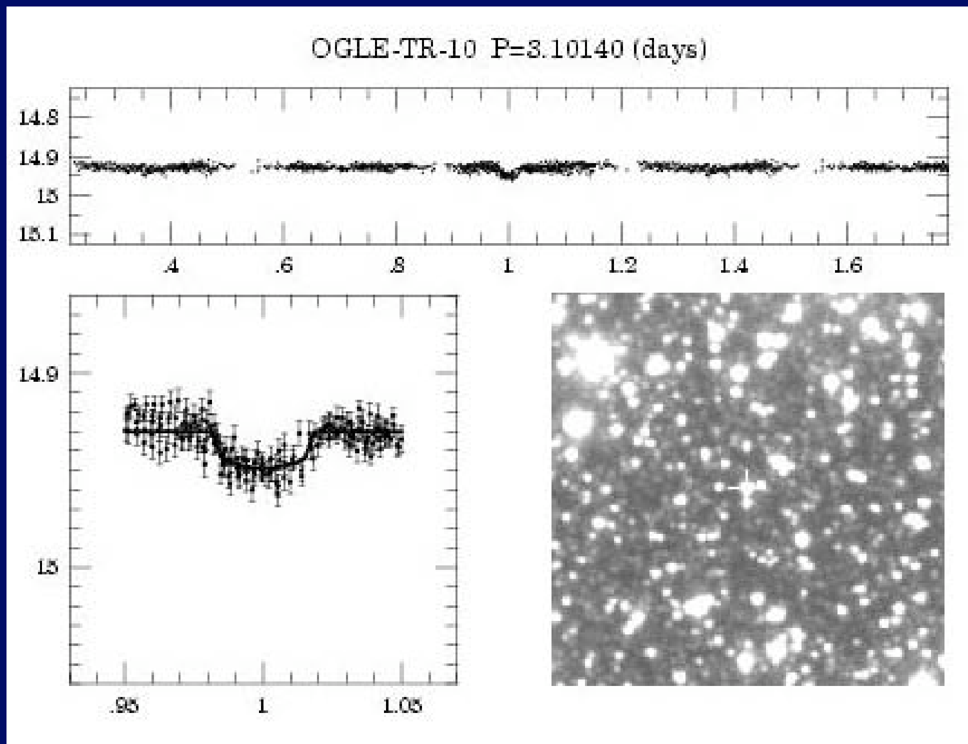
Microlensing: Light from more distant star is focused by gravity of nearer star passing in front

Fortuitous alignment ⇒ brightens



One planet found this way as of January 2005

Planets from the Transit Method

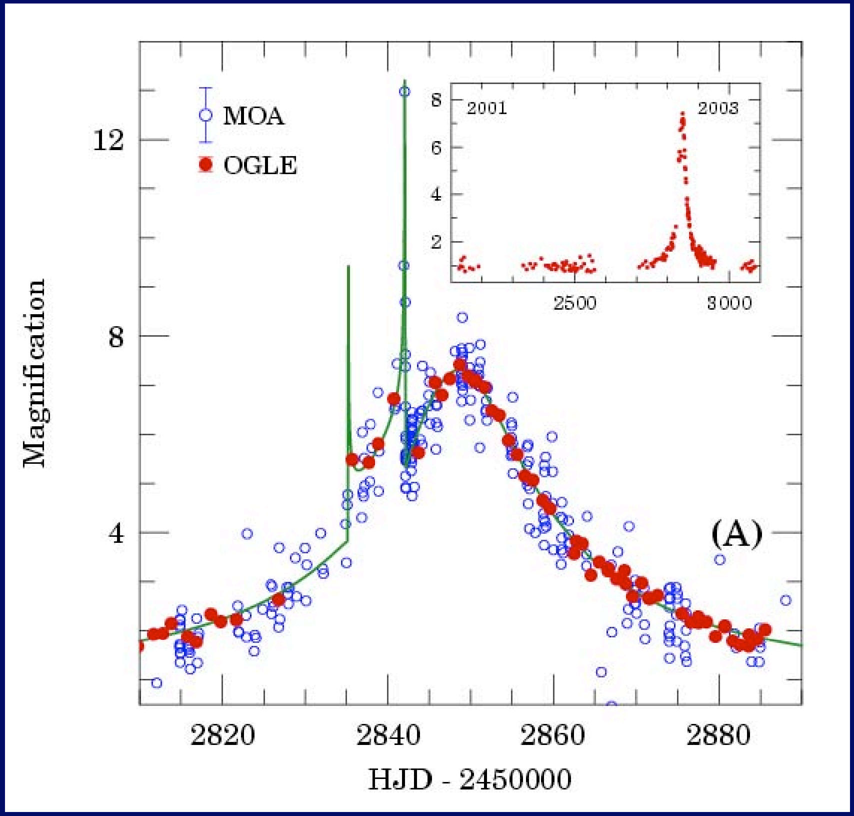


OGLE-TR-10

Light curve

Star field, shows star

Planet Detected by Microlensing



Sharp spikes indicate second lens. Mass of second lens only 0.4% as massive as star. Companion is very likely a planet.

OGLE 2003-BLG-235/MOA 2003-BLG-53

Future Prospects

Direct detection (and study) of Earth-like planets

~ 2015 Terrestrial Planet Finder (TPF)

Darwin (Europe)

Astrometric Method GAIA ~ 2010

M_J Planets out to 600 *ly.*

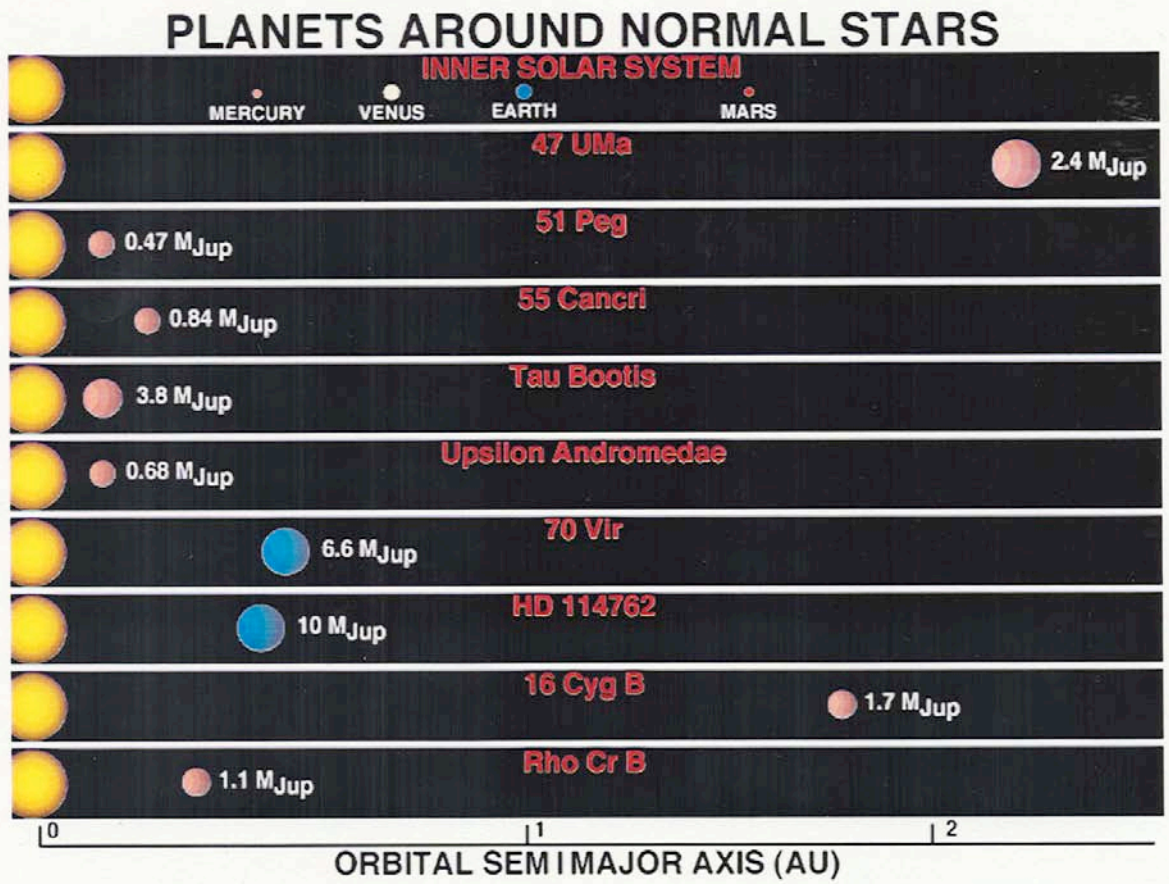
Further Spectroscopic Searches

Transits Kepler (~ 2007)

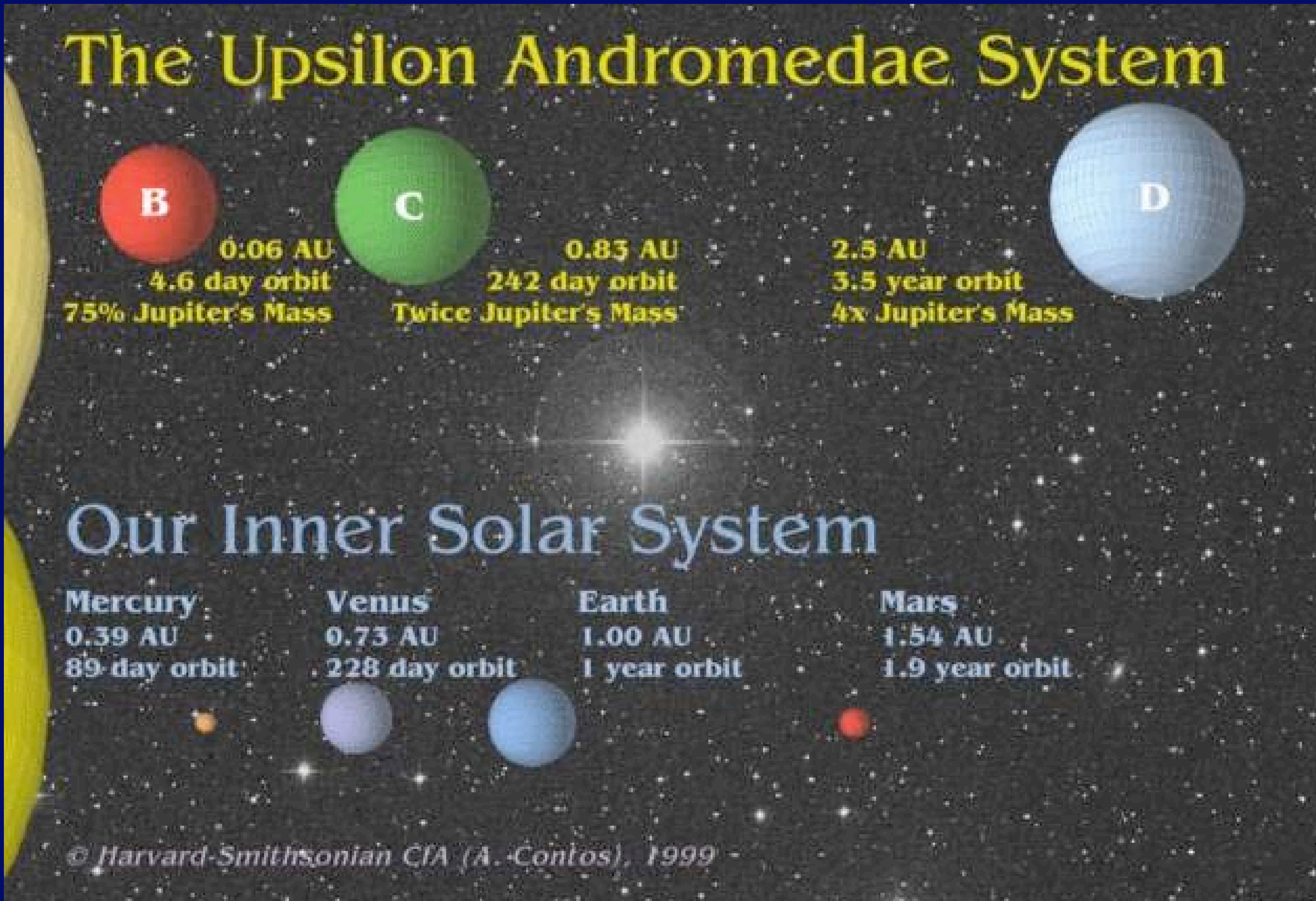
Monitor 100,000 stars for 4 years

“Hundreds of Terrestrial Planets”

Comparative Image of Extrasolar Systems



Courtesy San Francisco State University Astronomy Department

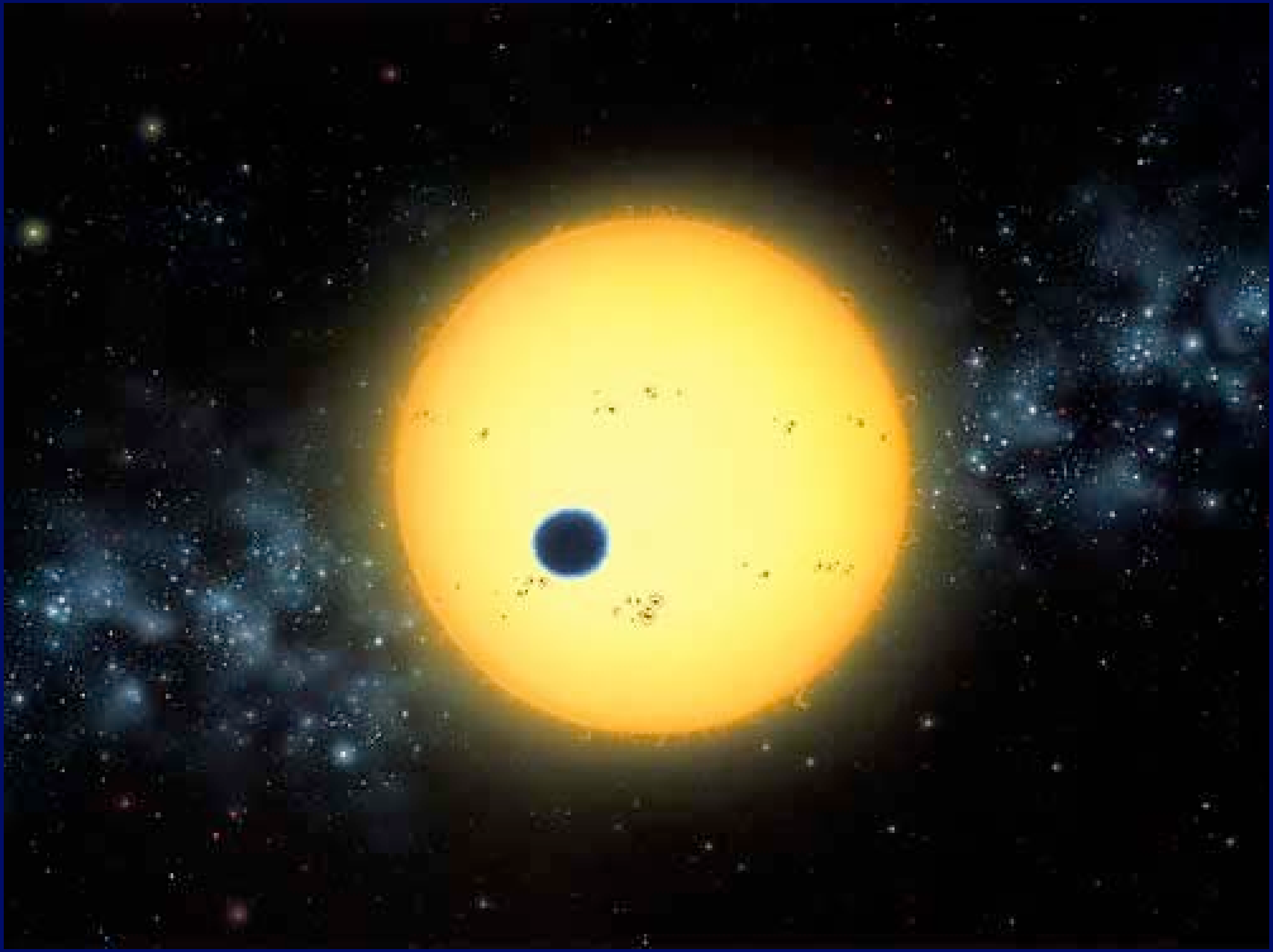


The Upsilon Andromedae System
B
C
D
0.06 AU
4.6 day orbit
75% Jupiter's Mass
0.83 AU
242 day orbit
Twice Jupiter's Mass
2.5 AU
3.5 year orbit
4x Jupiter's Mass
Our Inner Solar System
Mercury
0.39 AU
89 day orbit
Venus
0.73 AU
228 day orbit
Earth
1.00 AU
1 year orbit
Mars
1.54 AU
1.9 year orbit
© Harvard-Smithsonian CfA (A. Contos), 1999

Artist’s conception of the view from the outmost planet of three in Upsilon Andromedae

http://www.extrasolar.spaceart.org

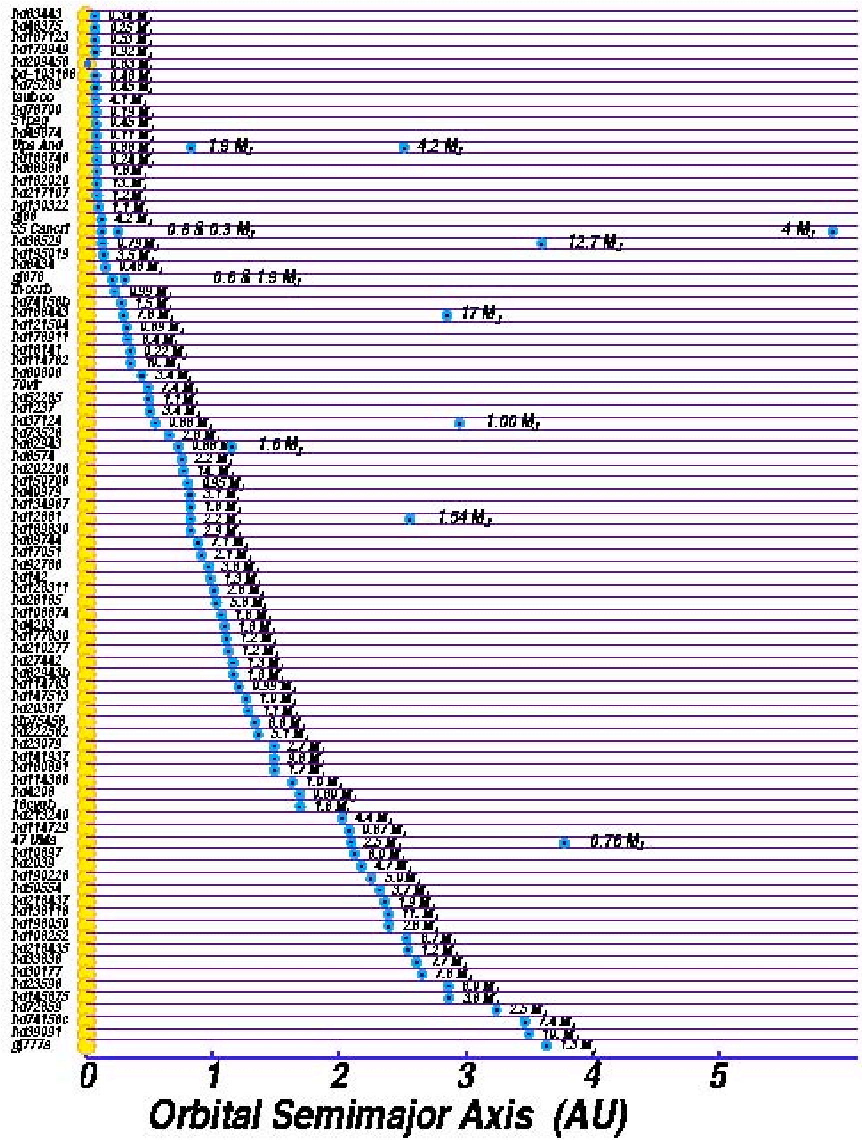
Artist's conception of Transit of HD209458



http://www.extrasolar.spaceart.org

Artist's conception of 47 U ma "view" from Moon of the Second Planet

http://www.extrasolar.spaceart.org


0
1
2
3
4
5
Orbital Semimajor Axis (AU)

Implications of New Planets

Planets more massive than Jupiter can form around stars like the Sun.

Large Planets can form much closer to a star than Jupiter (or move there)

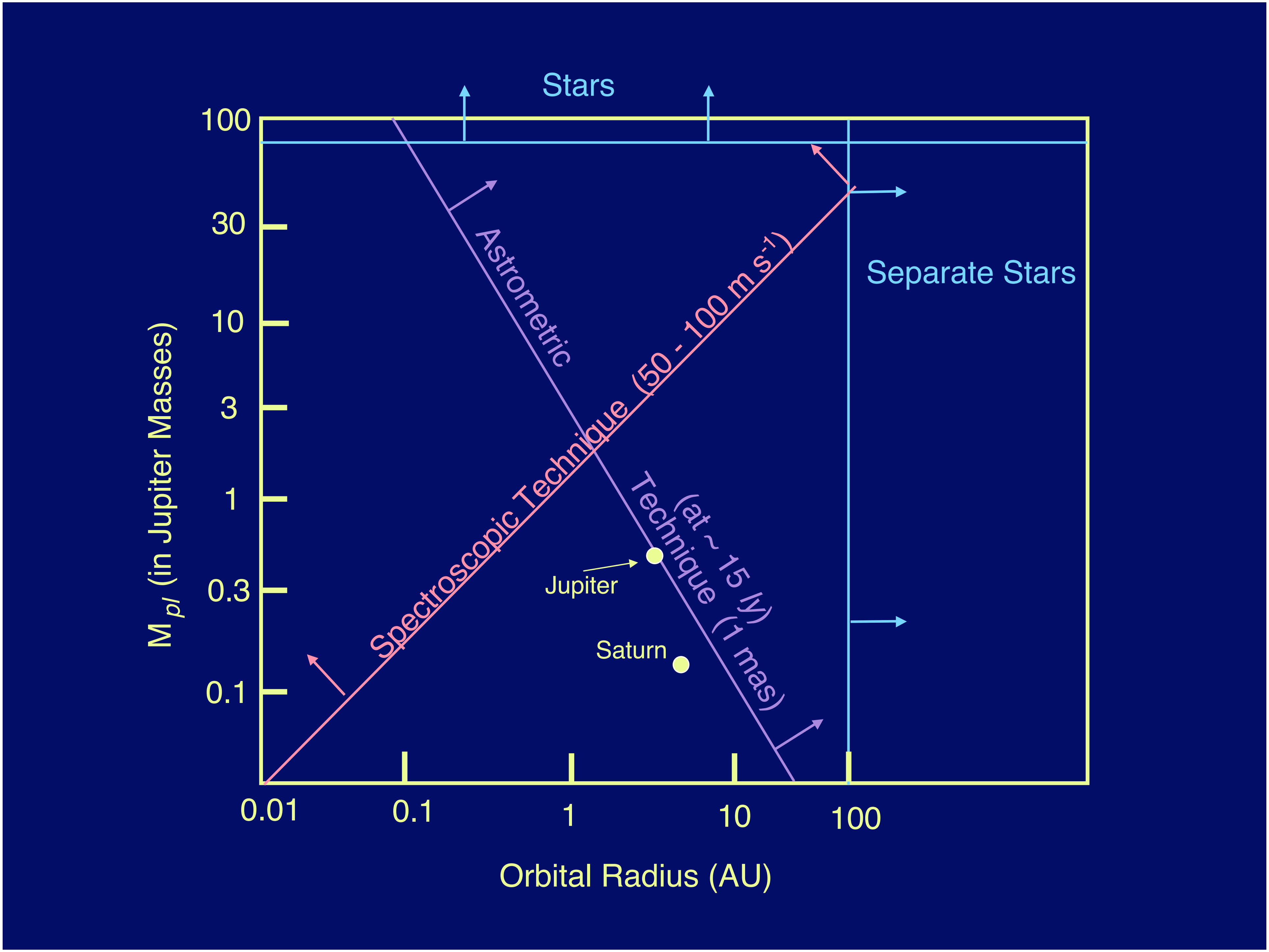
Does this mean we are unusual and our ideas about other planetary systems are just “solar system chauvinism”?

Not necessarily.

The ones found so far are the “easy” ones. (Big planets close to a star)

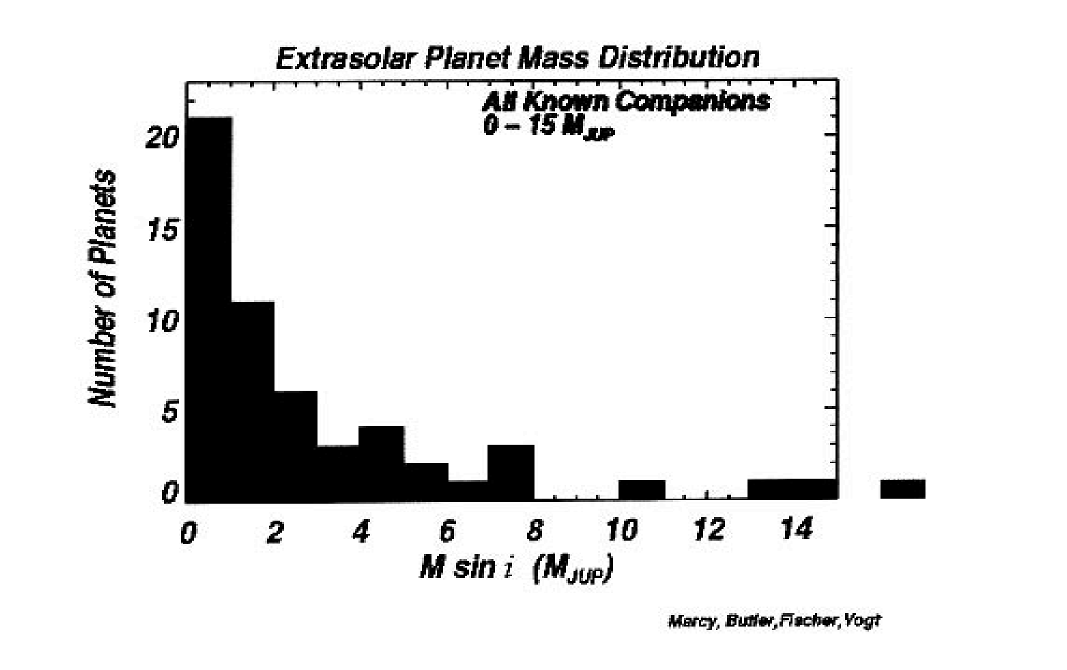
Now there are many more with lower masses than higher masses

Too early to say that we are unusual.



Stars
100
30
10
3
1
0.3
0.1
M$_{pl}$ (in Jupiter Masses)
Separate Stars
Astrometric
Technique (1 mas)
(at ~ 15 ly)
Spectroscopic Technique (50 - 100 m s^{-1})
Jupiter
Saturn
0.01
0.1
1
10
100
Orbital Radius (AU)

- with about 80 extrasolar planet candidates identified:



- more than 1000 stars examined.

Successful Doppler planet search programs:

ELODIE/CORALIE (H.P./La Silla) Mayor, Queloz, Udry, et al. (North/South)

Hamilton/HIRES (Lick/Keck) Marcy, Butler, Fischer, et al. (North)

Cs23 (McDonald 2.7m) Cochran, Hatzes (North)

AFOE (Whipple) Noyes, Brown, et al. (North)

ESO CES (La Silla) Kurster, Hatzes, Endl, et al. (South)

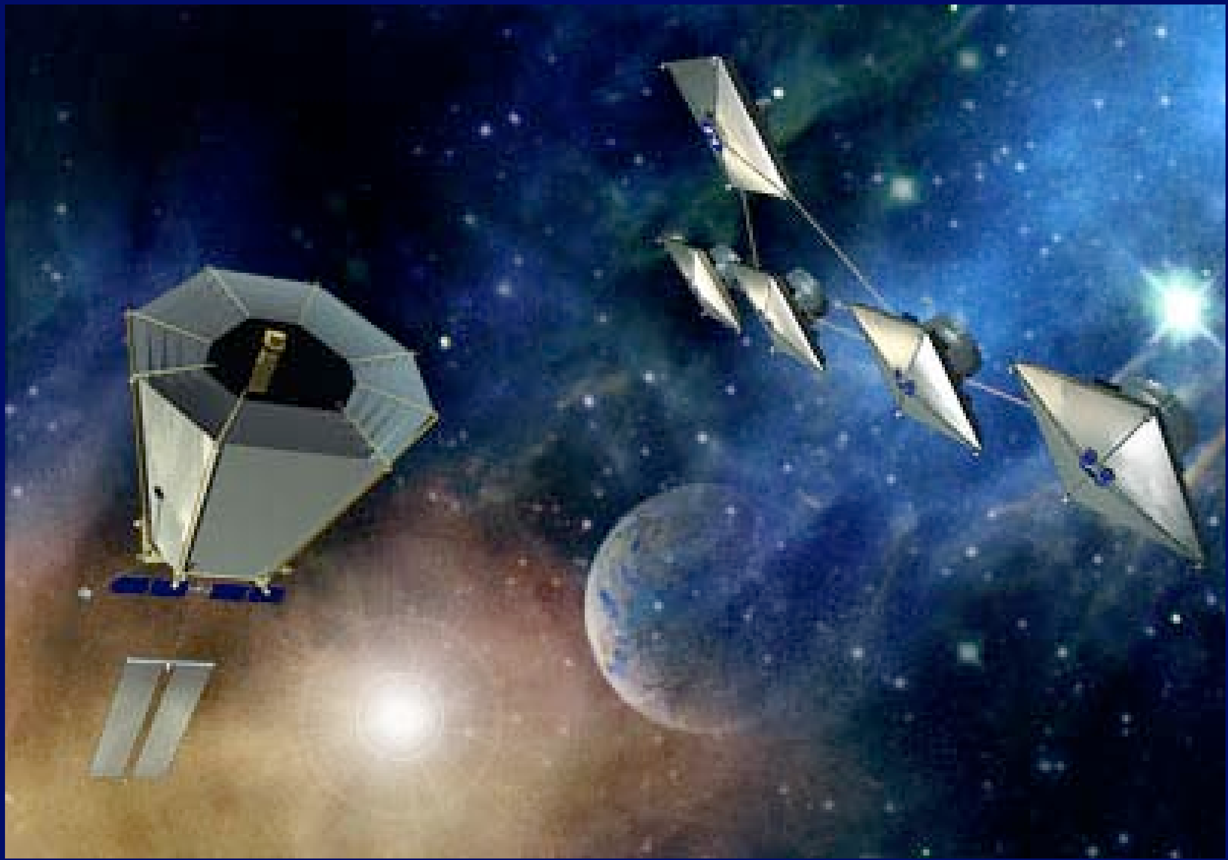
UCLES (AAT) Butler, Tinney, et al. (South)

Direct Detection in Future

- Terrestrial Planet Finder (TPF)/Darwin
  – TPF-C Visible light coronagraph (~2014)
  – TPF-I Infrared interferometer (~2020)
- Goal is to detect earth-mass planets
- And to see what gases in atmosphere
  – Suitable for life?
- http://planetquest.jpl.nasa.gov/TPF/tpf_index.html

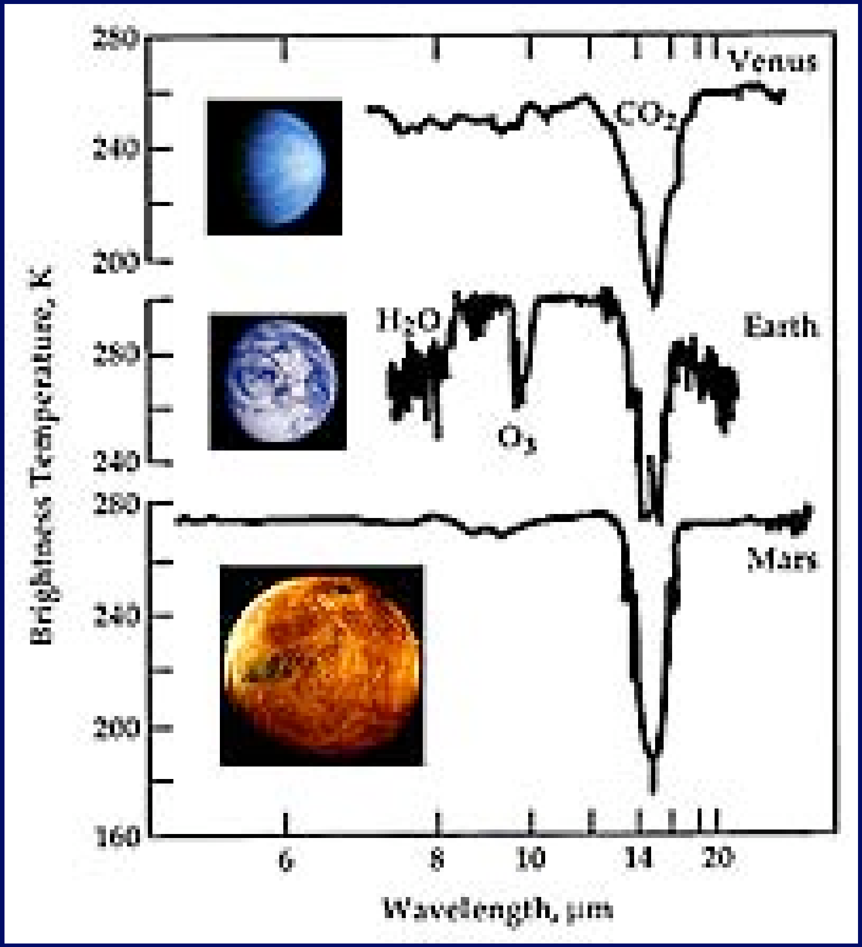
TPF Concepts

TPF-I Infrared Interferometer (2020)



TPF-C Visible light coronagraph (2014)

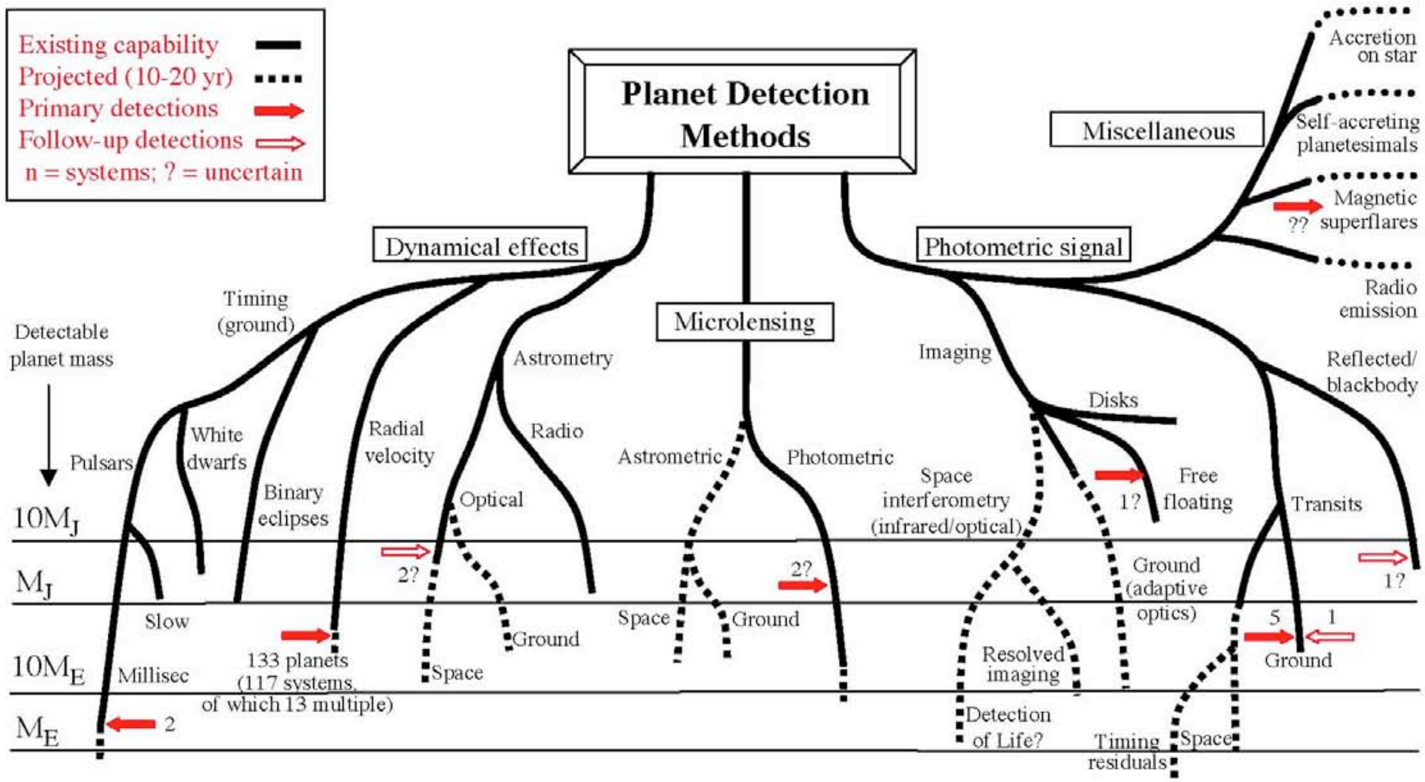
Spectroscopy of atmosphere



Planet Detection Methods

Michael Perryman, Rep. Prog. Phys., 2000, 63, 1209 (updated November 2004)

[corrections or suggestions please to michael.perryman@esa.int]



Brown Dwarfs

Between stars and planets:

$M < 0.07\ M_\odot$ cannot fuse hydrogen

substellar

$M \gtrsim 0.013\ M_\odot \simeq 13\ M_{jup}$ (This boundary is still argued about)

Emit infrared and cool slowly as they release gravitational potential energy

Very few are found as stellar companions

But they appear to be common as “free-floaters”

May have their own planets ??

Implications:

1. Stars and planets form in different ways (no intermediate masses in orbit)
2. There could be free-floating planets
3. Brown dwarfs might have planets (bigger f_p - but suitable for life??)

Current Statistics (Jan. 2005)

- Based on Extrasolar Planets Encyclopedia
  - http://www.obspm.fr/encycl/encycl.html
- 147 Planets in 128 systems
- 15 with multiple planets
- Most planets in one system is 4 (55 Cancri)
- Least massive 0.042 M_{Jup} = 13 M_{Earth}

Estimating f_p

- Maximum? $f_p \sim 1$
  - All young stars may have disks
- Binaries?
  - Can have disks, but planet formation?
  - Even if form planets, orbits may not be stable
  - If reject binaries, $f_p < 0.3$

Estimating f_p

- Minimum?
  - Based on success rate of searches ($n_{found}/n_{searched}$)
  - Estimates now up to 5% ($f_p > 0.05$)
    - Note larger than 0.02 given in book
  - Extrapolate trends to finding
    - Smaller planets, larger orbits, …
  - Estimates range from 0.11 to 0.25
- Allowed range: $f_p = 0.05$ to 1.0
  - Explain your choice!
  - Include/exclude binaries?