Star Formation

Some Details and Rate

Estimate of Average Star Formation Rate (R_*)

$$R_* = \frac{\text{\# of stars in galaxy}}{\text{lifetime of galaxy}} = \frac{N_*}{t_{gal}}$$

N_* : Count them? No

Use Gravity (Newton's Laws)

Sun orbiting center of galaxy at 250 km s^{-1} (155 miles per second)

Kinetic energy = $\frac{1}{2}$ gravitational potential energy

$$\frac{1}{2} M_\odot v^2 = \frac{1}{2} \frac{G M_g M_\odot}{R_g}$$

R_g ← Distance of Sun from center of galaxy

$$\frac{R_g v^2}{G} = M_g$$

Estimate of Average Star Formation Rate (R_*)

$(R_g = 25{,}000 \text{ ly}) \rightarrow M_g = 1.0 \times 10^{11} M_\odot$

Add stars outside Sun's orbit $\rightarrow M_g \simeq 1.6 \times 10^{11} M_\odot$

$$N_* \simeq \frac{M_g}{\text{Avg. mass of star}} = \frac{1.6 \times 10^{11}}{0.4} = 4 \times 10^{11}$$

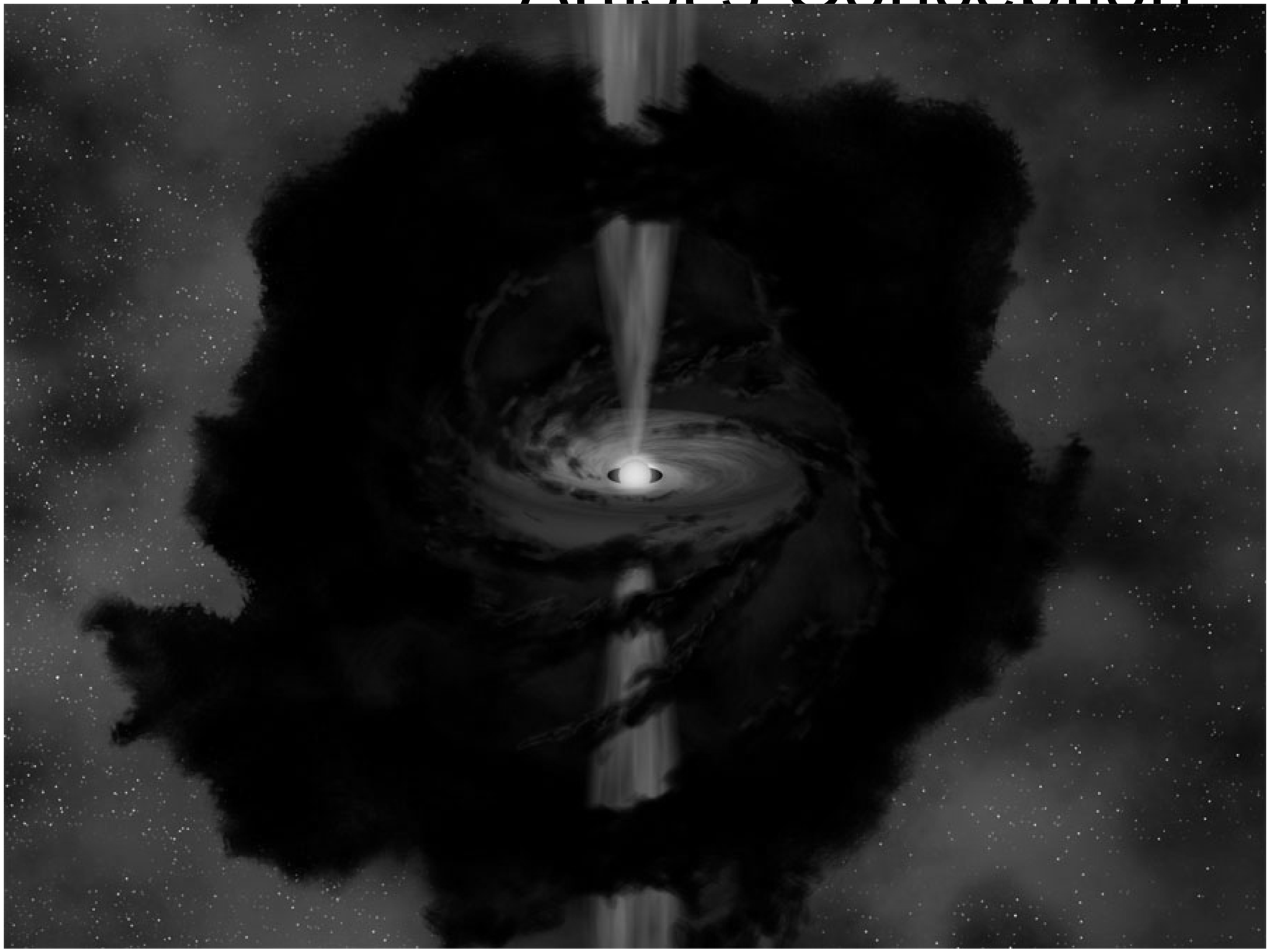
$T_{gal} \simeq 10^{10}$ yr (studies of old stars)

$$R_* \simeq \frac{4 \times 10^{11}}{10^{10}} \text{ stars} = 40 \text{ stars per year} \quad (5 - 50)$$

Current Star Formation

- Occurs in gas with heavy elements
  - Molecules and dust keep gas cool
  - Radiate energy released by collapse
  - Stars of lower mass can form
  - Mass needed for collapse increases with T
- Star formation is ongoing in our Galaxy
  - Massive stars are short-lived
  - Star formation observed in infrared

Artist's Conception



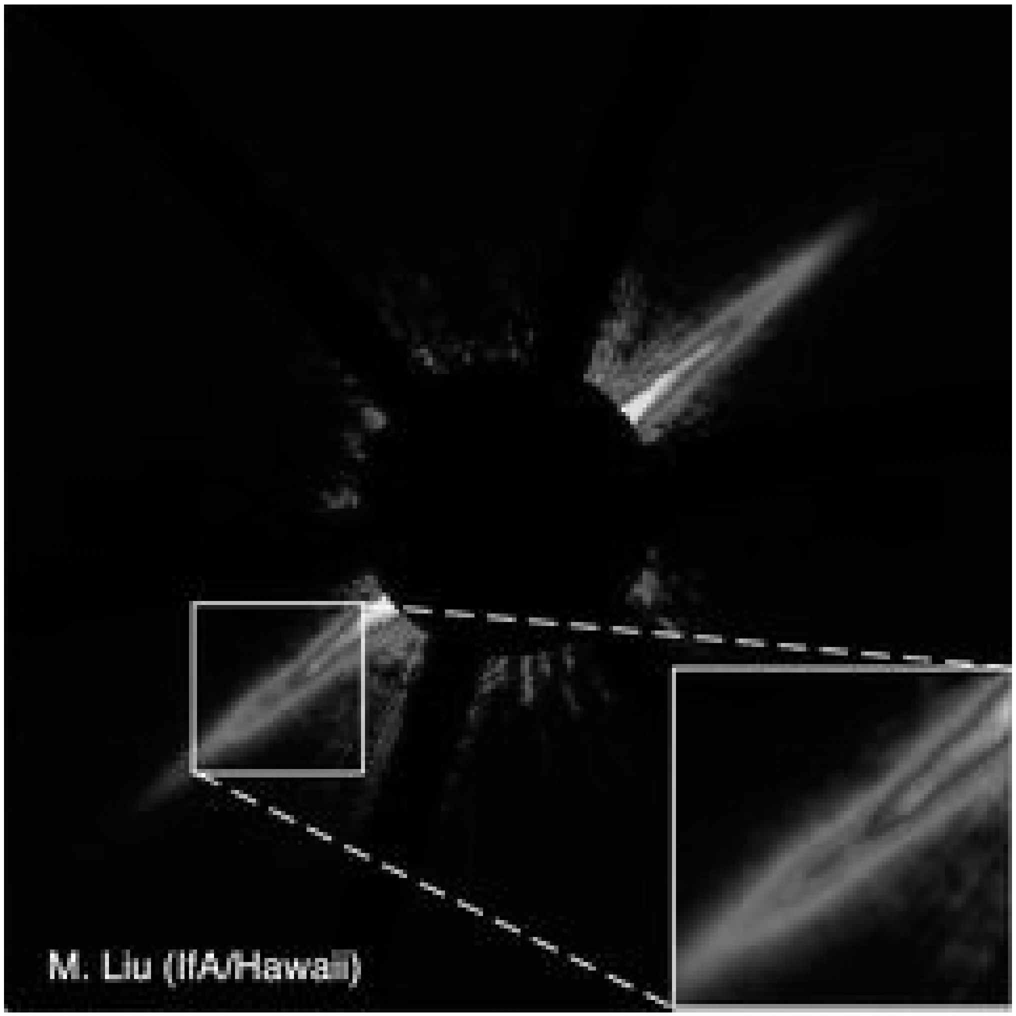
Features:
Dusty envelope
Rotation
Disk
Bipolar outflow

R. Hurt, SSC

The Protostar

- Evolution of the collapsing gas cloud
  - At first, collapsing gas stays cool
  - Dust, gas emit photons, remove energy
  - At $n \sim 10^{11}$ cm^{-3}, photons trapped
  - Gas heats up, dust destroyed, pressure rises
  - Core stops collapsing
  - The outer parts still falling in, adding mass
  - Core shrinks slowly, heats up
  - Fusion begins at $T \sim 10^7$ K
  - Protostar becomes a main-sequence star

The Disk



The Star (AU Mic) is blocked in a coronograph. Allows you to see disk. Dust in disk is heated by star and emits in infrared.

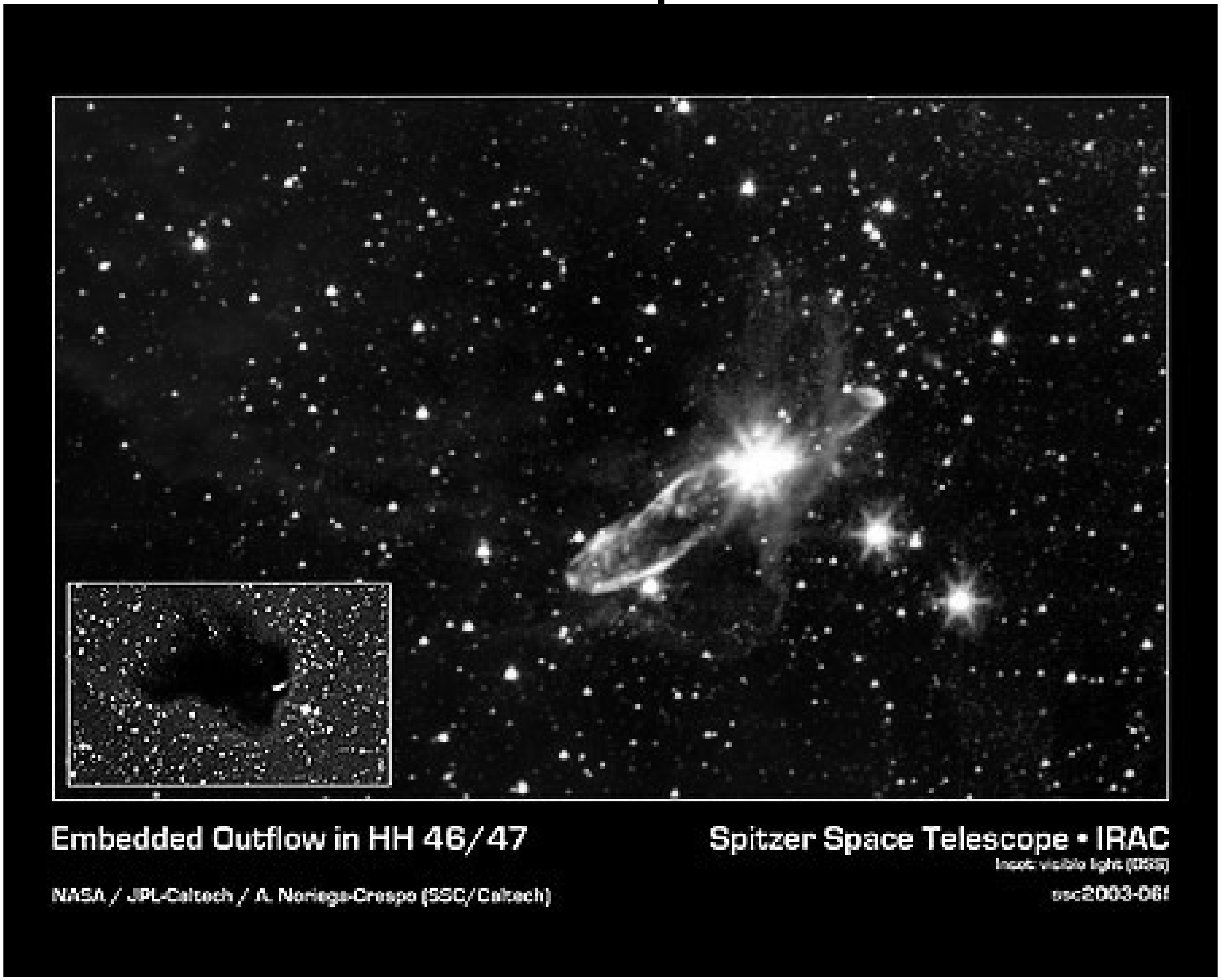
Angular Momentum

- Measure of tendency to rotate
  - $J = mvr$
- Angular momentum is conserved
  - $J =$ constant
  - As gas contracts (r smaller), v increases
  - Faster rotation resists collapse
  - Gas settles into rotating disk
  - Protostar adds mass through the disk

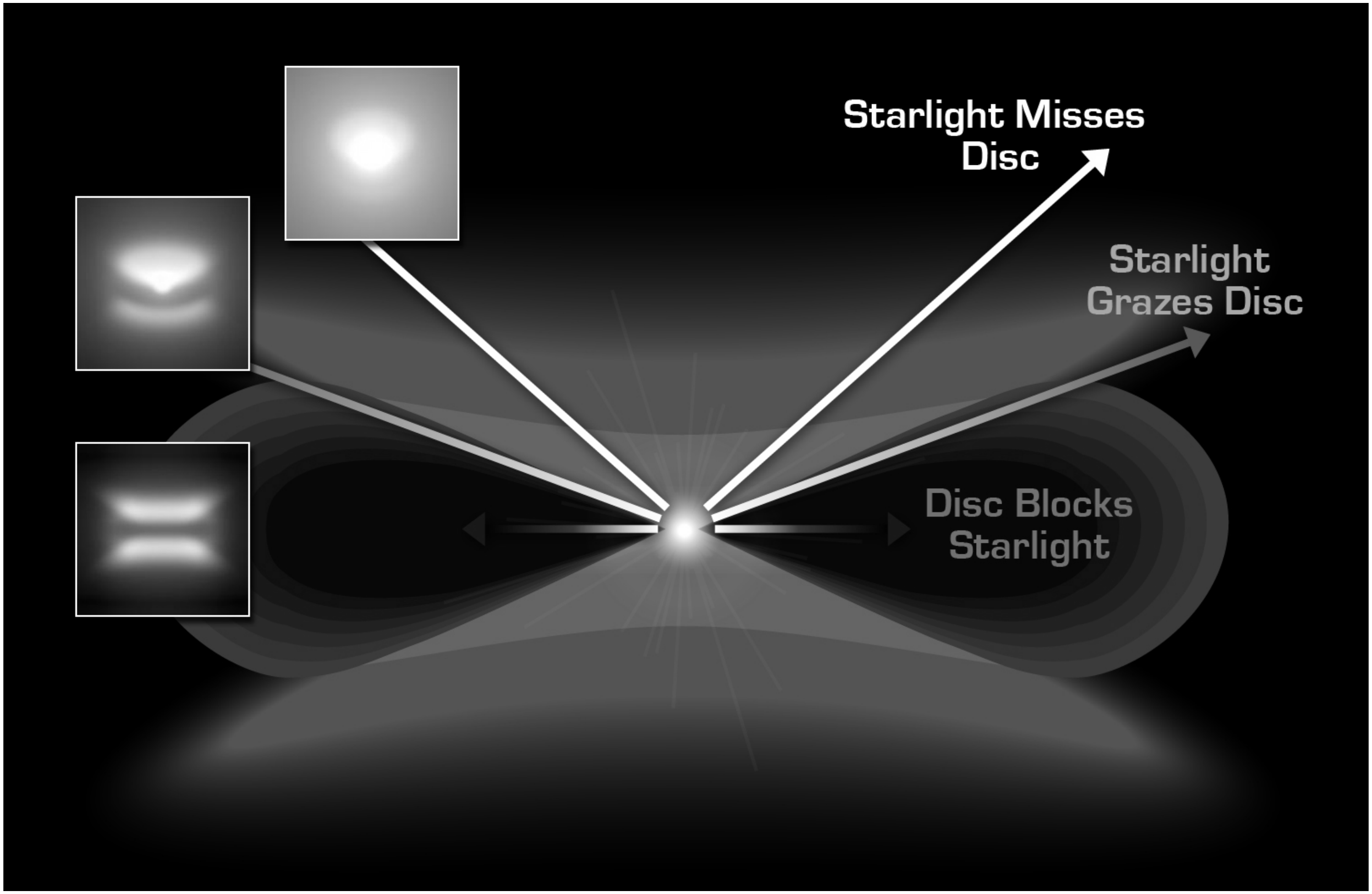
The Wind

- Accretion from disk will spin up the star
  - Star would break apart if spins too fast
- Angular momentum must be carried off
- The star-disk interaction creates a wind
- The wind carries mass to large distances
  - $J = mvr$, small amount of m at very large r
  - Allows star to avoid rotating too fast
- Wind turns into bipolar jet
  - Sweeps out cavity

The Bipolar Jet



Studying the Disk



Robert Hurt, SSC

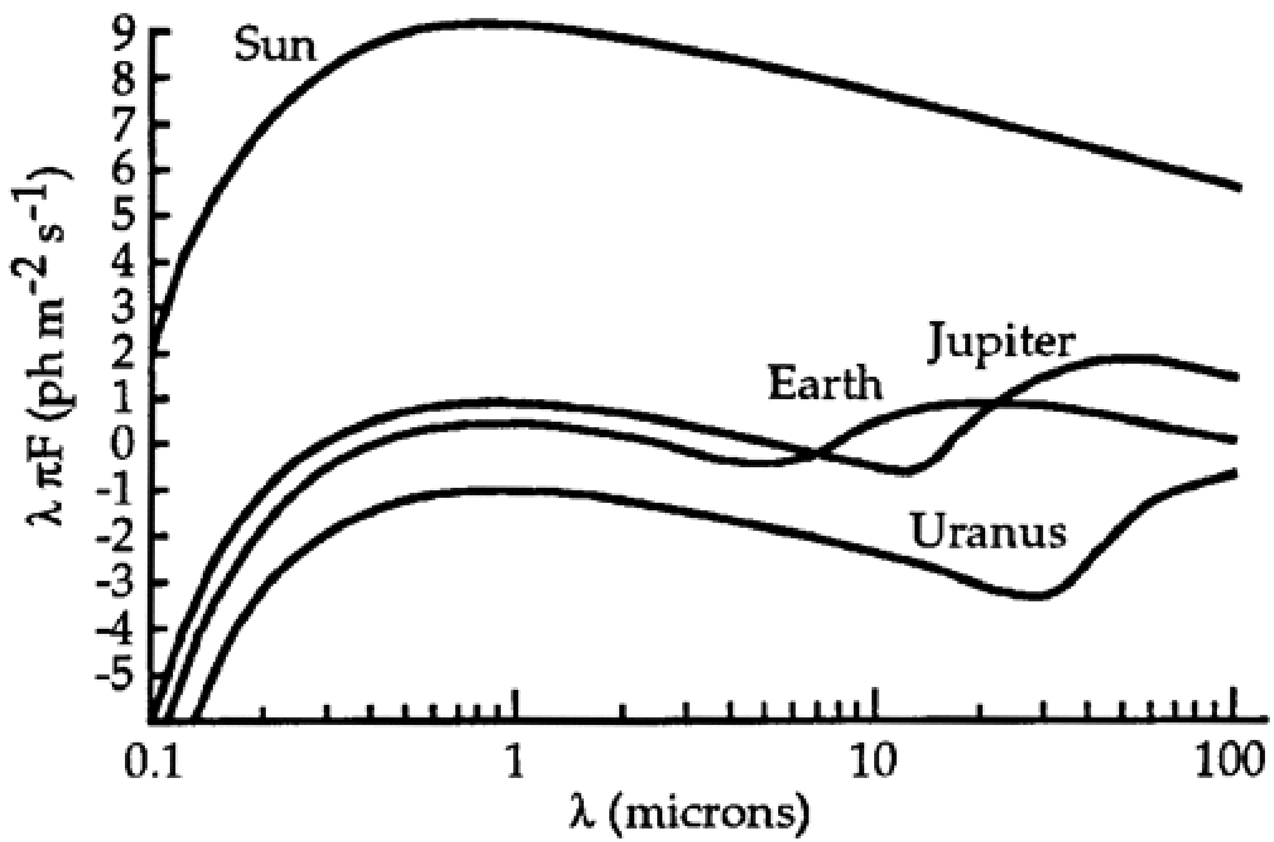
Planet Detection

Estimating f_p

Can We See Them?

- Not yet, but there are plans…
  – 3 recent claims, but planets very far from star, so some doubts
- Problem is separating planet light from star light
  – Star is 10^9 times brighter in visible light
  – “Only” 10^6 times brighter in infrared

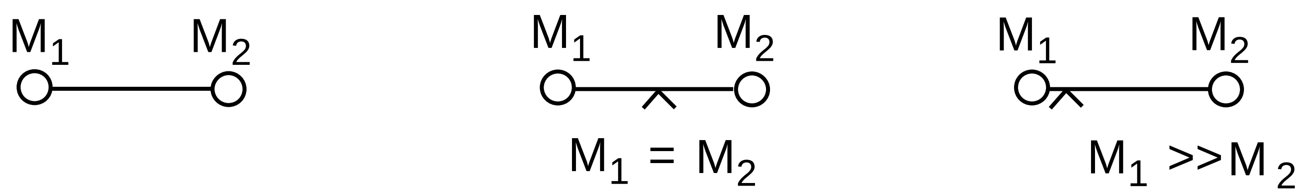
Planet is Much Fainter than Star



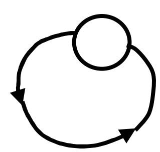
Indirect Detection

Wobbling star

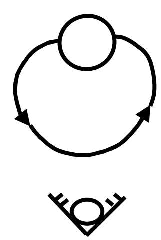
Detect effect of planet on star (both orbit around center of mass)



Large planet will make a star "wobble"



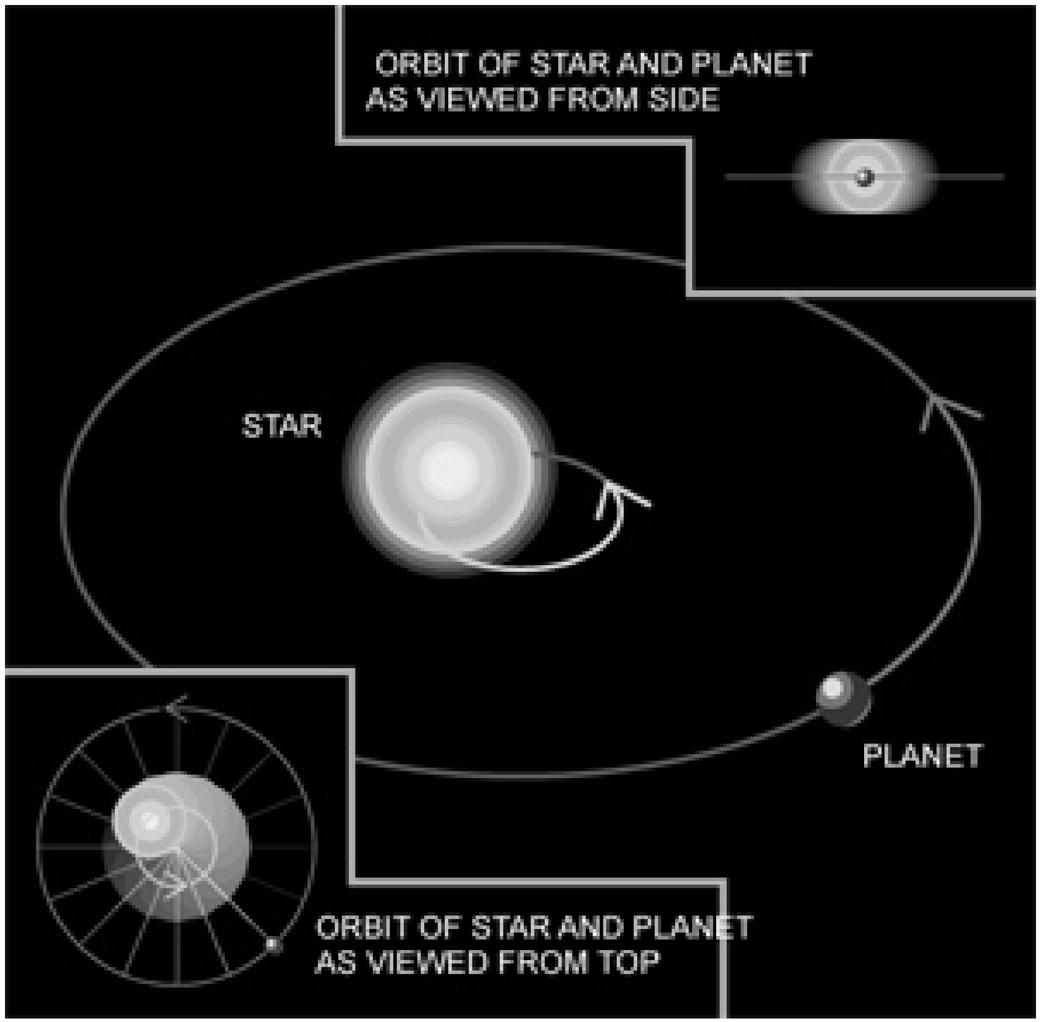
In plane of sky observe position shift



Along our line of sight

Observe Doppler Shift

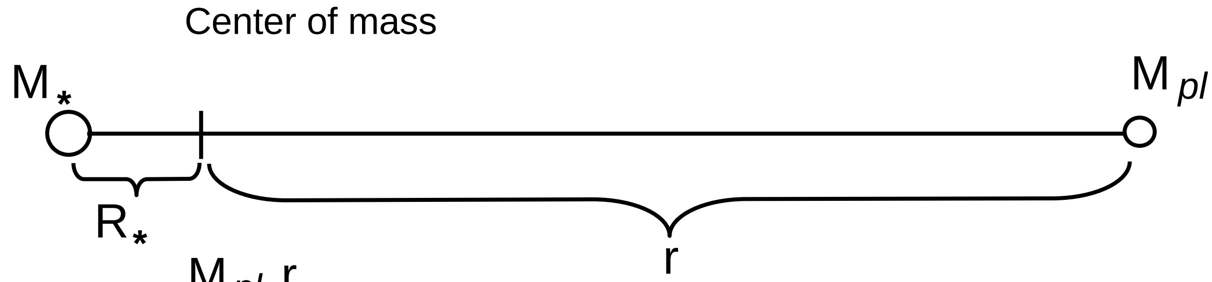
Star and Planet Orbit Center of Mass



The Astrometric Technique

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

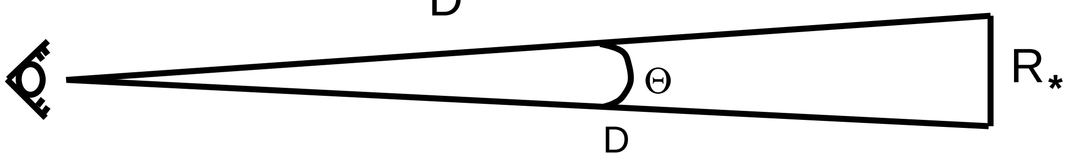
How far does the star wobble?



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

We measure angle; for small angles,

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

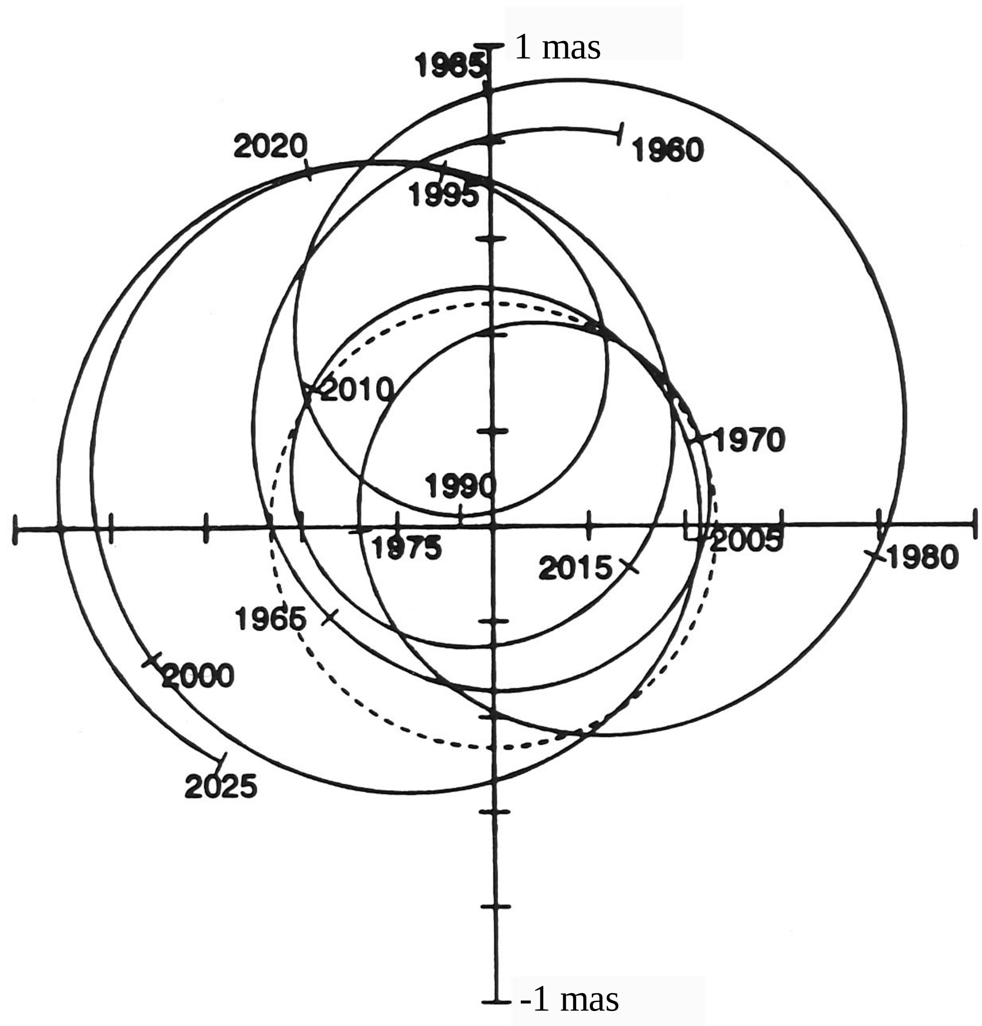


so $$\Theta = \frac{M_{pl}\, r}{M_*} \frac{1}{D}$$

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



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

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

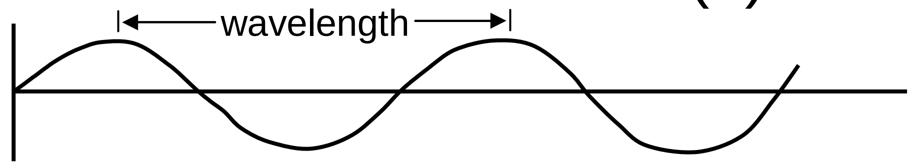
The Spectroscopic Method

- Relies on Doppler Effect
- Motion of star towards and away from us
- Almost all planets around other stars found by this method so far

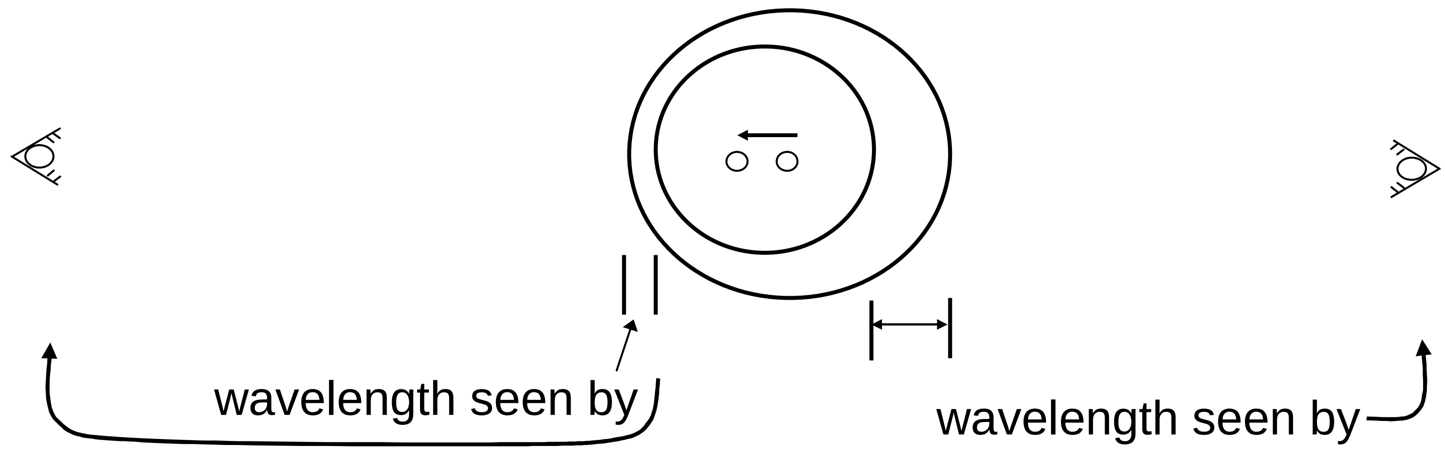
The Doppler Shift

Light is a wave

(λ)



moving star



BLUESHIFT

REDSHIFT

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

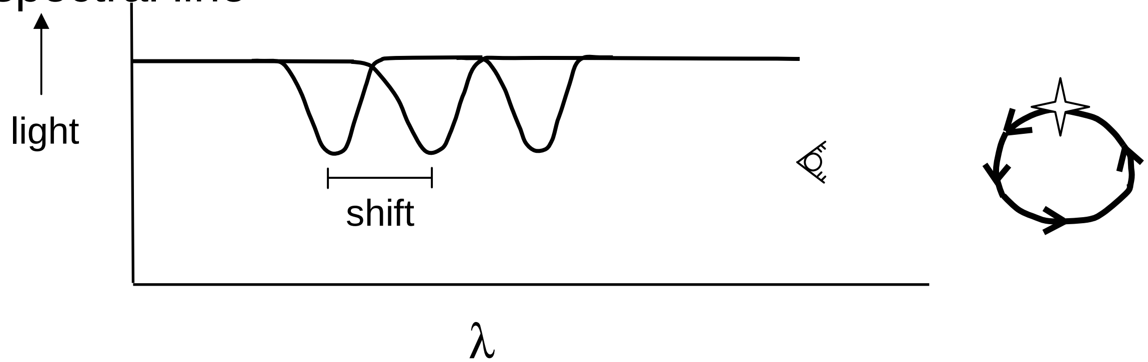
Doppler Shift $\longrightarrow$ Magnitude and direction of velocity

But only along line-of-sight

The Spectroscopic Technique

Measure velocity, not position, of star

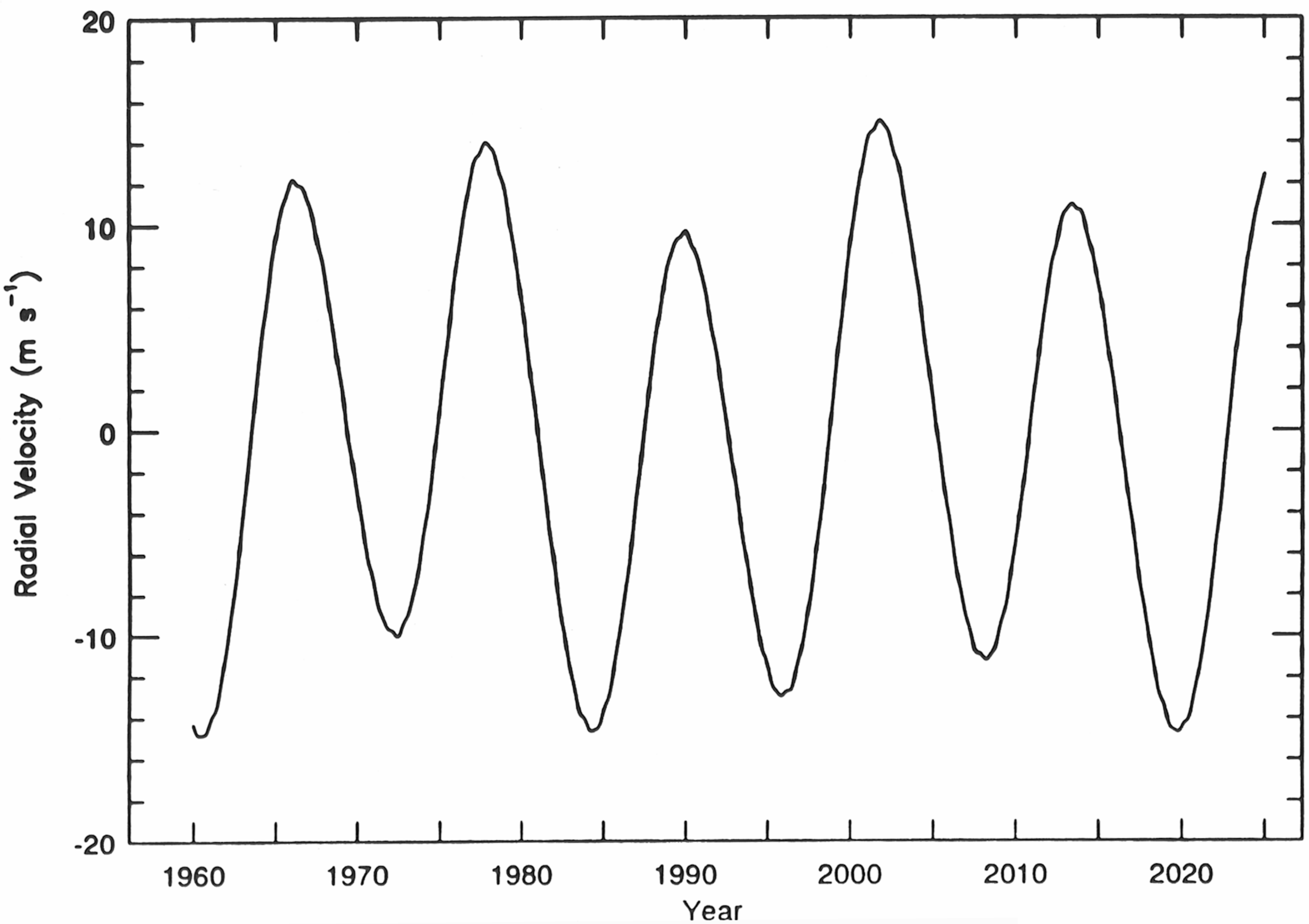
Use spectrometer to get Doppler Shift of spectral line



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

Big planet, <u>small</u> orbit
Small star
Distance doesn't matter (except for brightness)

Edge - On



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
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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_{planet})

   Conservation of momentum $\longrightarrow$

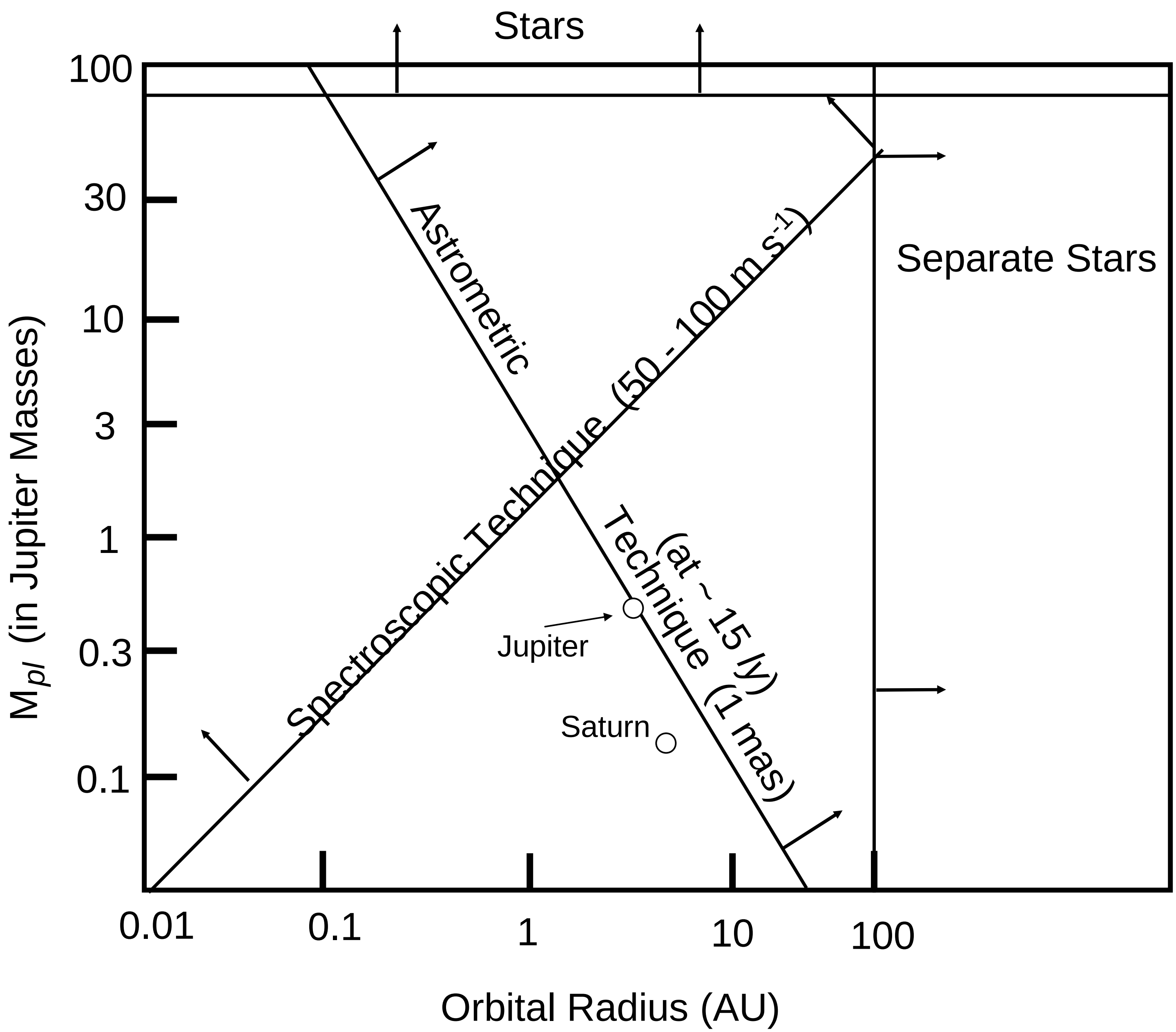
   $$M_{pl} \gtrless \frac{M_* V_* P}{2\pi r}$$

   = if we see orbit edge-on

   > if tilted

Comparison of Search Methods

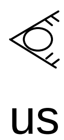
	Astrometric	Spectroscopic
Advantages	Big Planet	Big Planet
	Big Orbit	Small Orbit
	Small Star	Small Star
	Nearby Star	--
		Edge-on Orbit

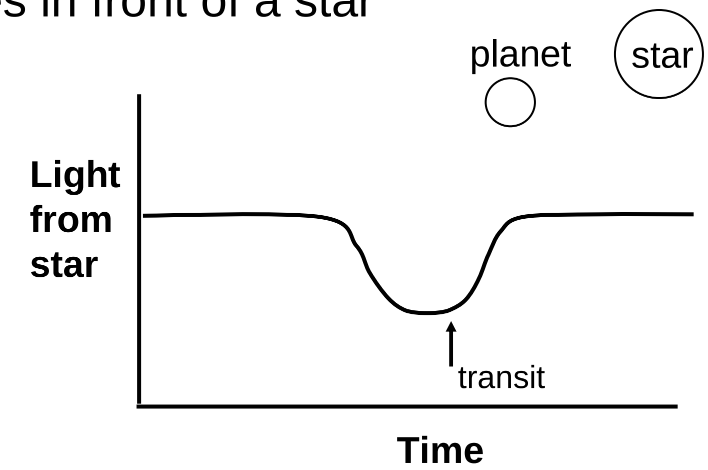


Stars
Separate Stars
Astrometric Technique (at ~ 15 ly) (1 mas)
Spectroscopic Technique (50 - 100 m s-1)
Jupiter
Saturn
100
30
10
3
1
0.3
0.1
0.01
0.1
1
10
100
Mpl (in Jupiter Masses)
Orbital Radius (AU)

Other Methods

Transits: Planet passes in front of a star

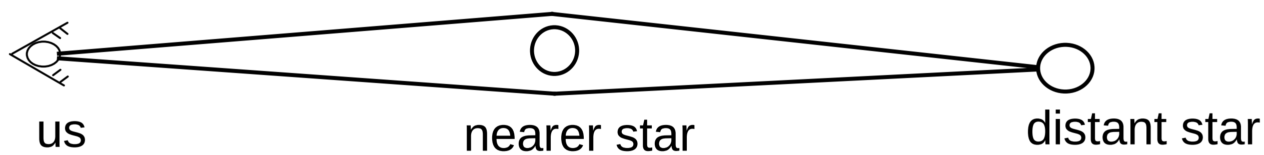




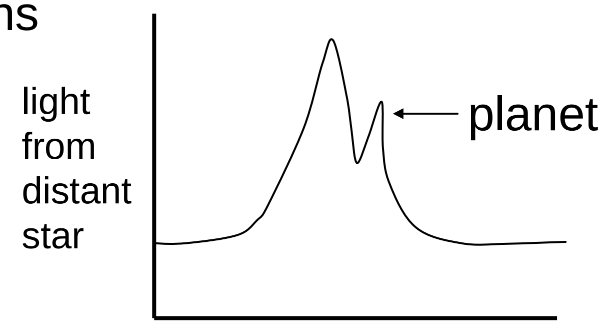
Only about 0.5% of stars with planets will line up

First planet found with this method in January 2003; 9 detected as of January 2006

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



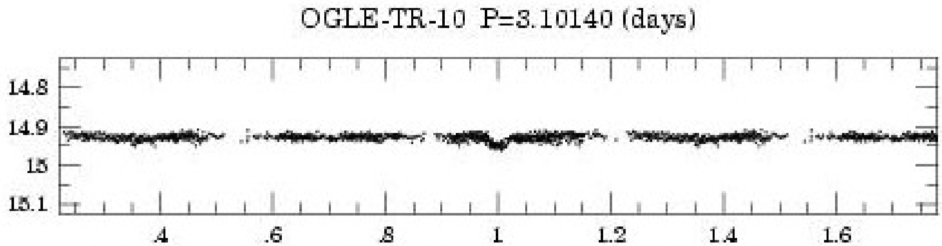
Fortuitous alignment $\Rightarrow$ brightens

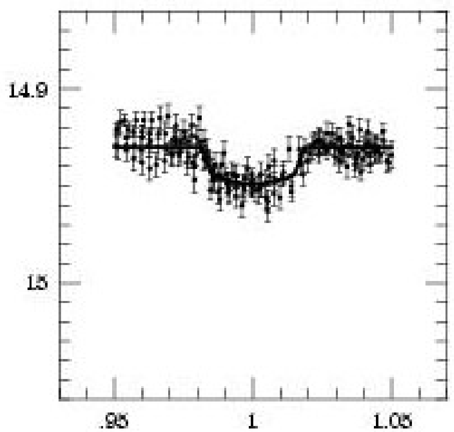


Three planets found this way as of January 2006

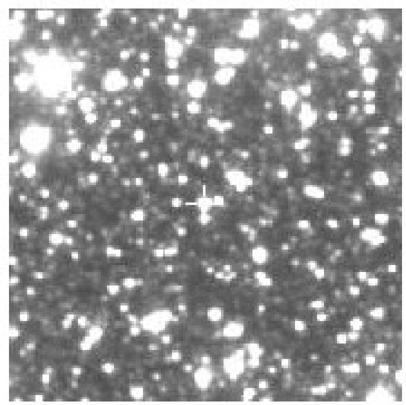
Planets from the Transit Method

OGLE-TR-10



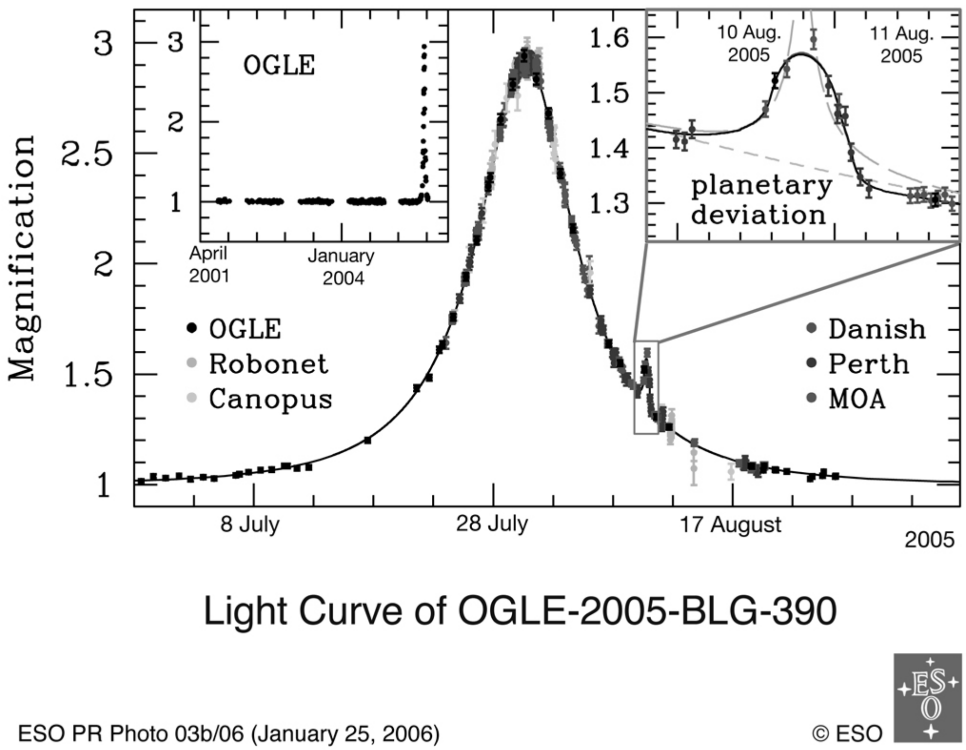


Light curve



Star field, shows star

Planet Detected by Microlensing



Sharp spike indicates second lens. Mass of second lens only 8 x 10^{-5} as massive as star. Most likely mass of planet is 5.5 M_{earth} and separation from star is 2.6 AU. Most likely star is low mass (0.22 M_{sun}).

This method can detect very low mass planets, but they are one-time events. Cannot follow up.

OGLE 2005-BLG-235Lb, announced 1/25/06

http://www.eso.org/outreach/press-rel/pr-2006/pr-03-06.html

Current Statistics (Jan. 2006)

- Based on Extrasolar Planets Encyclopedia
  - http://www.obspm.fr/encycl/encycl.html
- 170 Planets in 147 systems
- 17 with multiple planets
- Most planets in one system is 4 (55 Cancri)
- Least massive
  - $M = 0.023\ M_{Jup} = 7\ M_{earth}$ (Gliese 876)
  - Claim of 5.5 M_{earth} (Microlens 1/25/06)

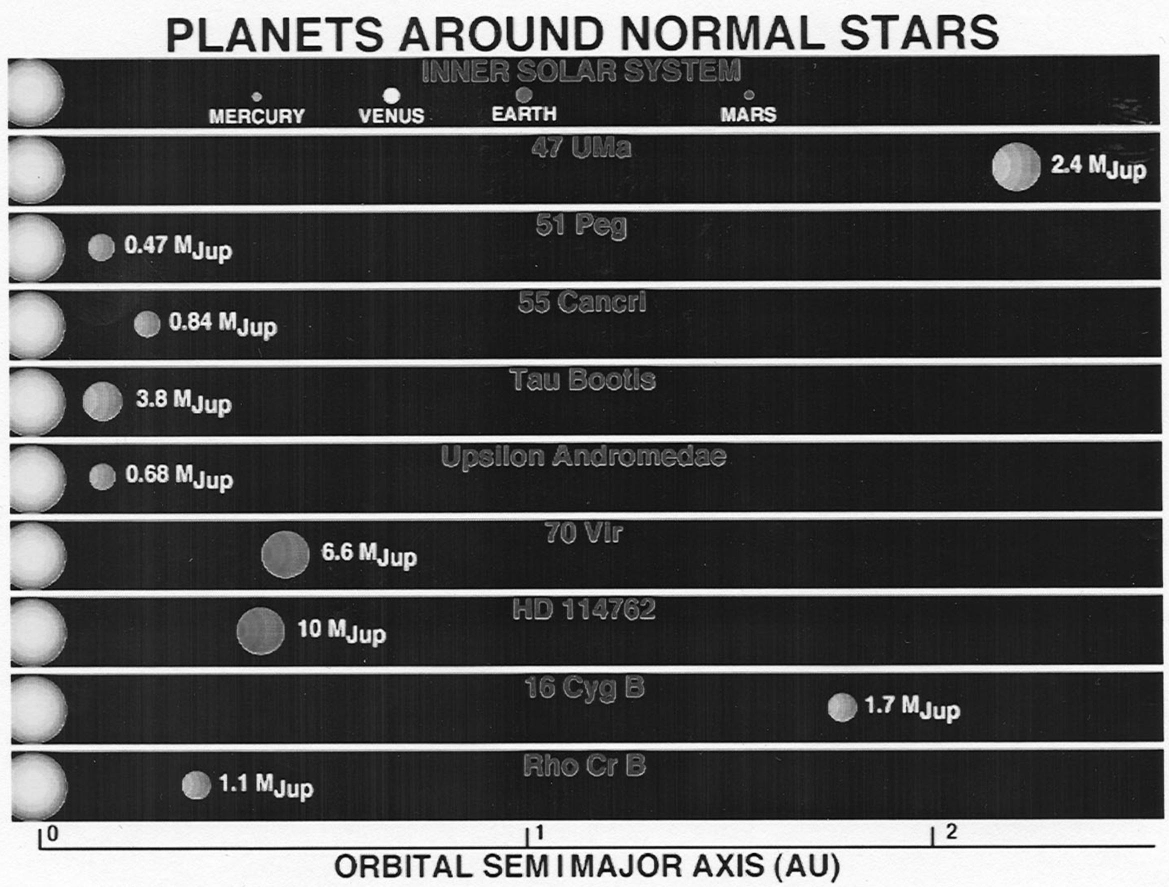
Estimating f_p

- 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, $f_p < 0.3$

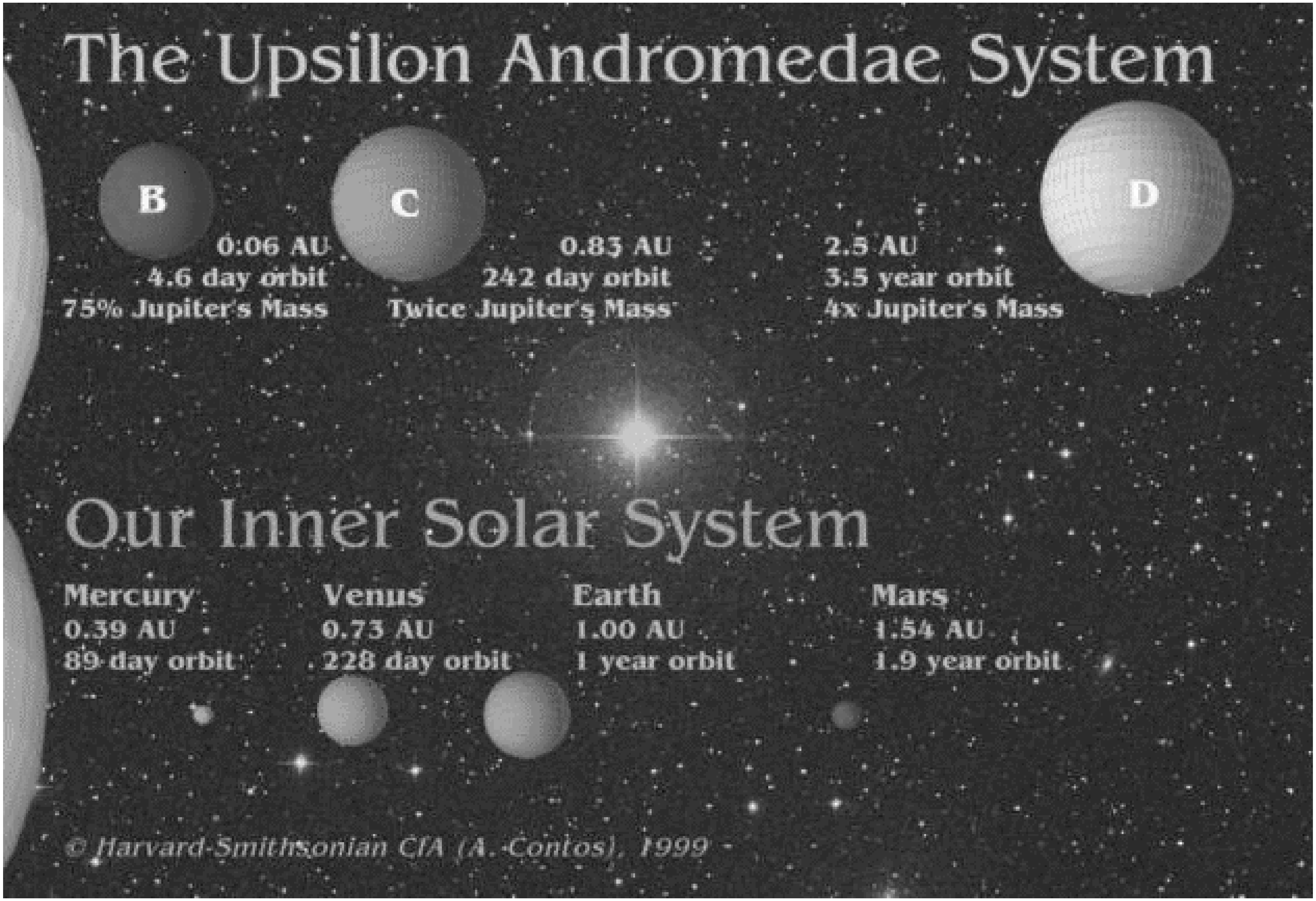
Estimating f_p

- 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?

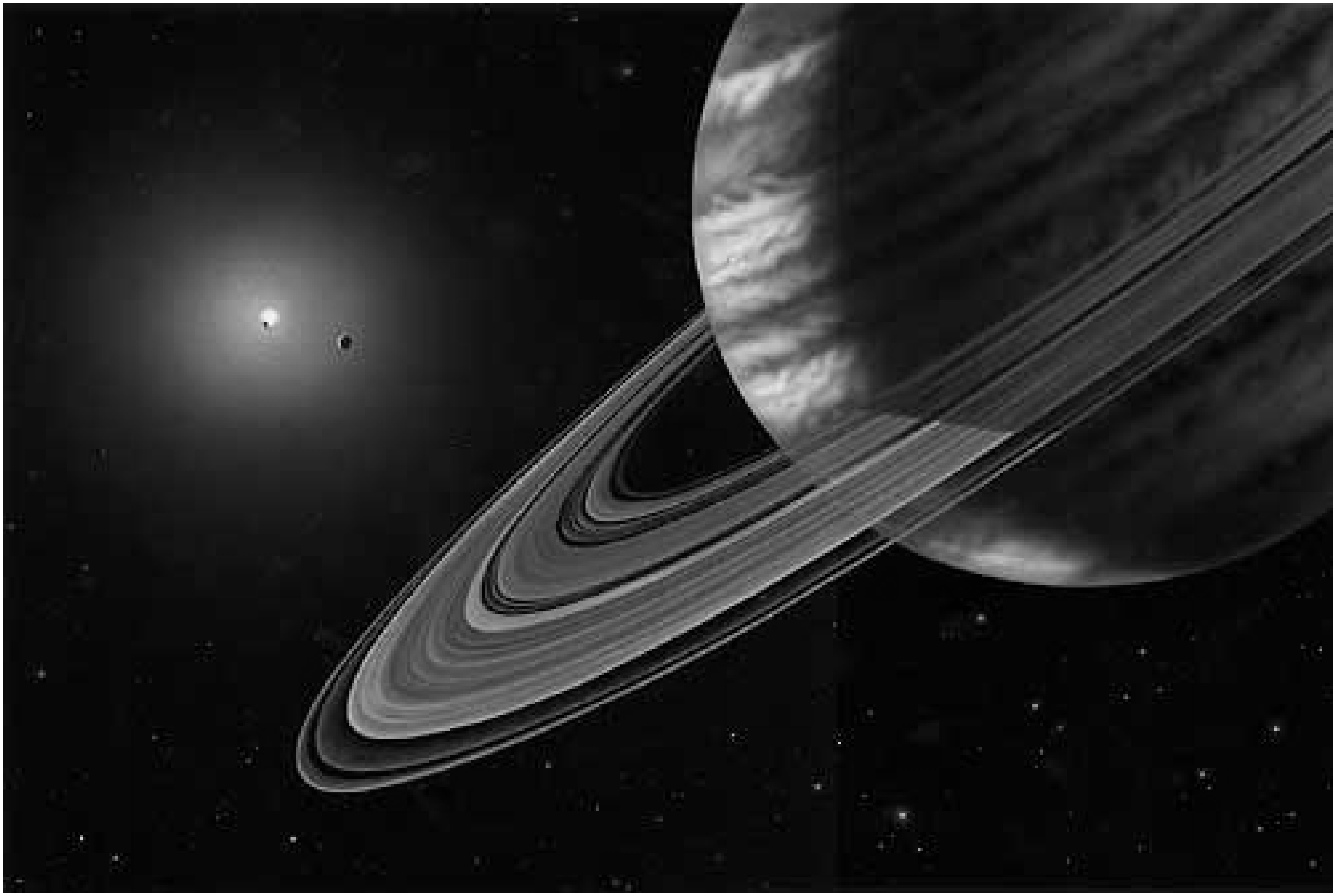
Comparative Image of Extrasolar Systems



Courtesy San Francisco State University Astronomy Department

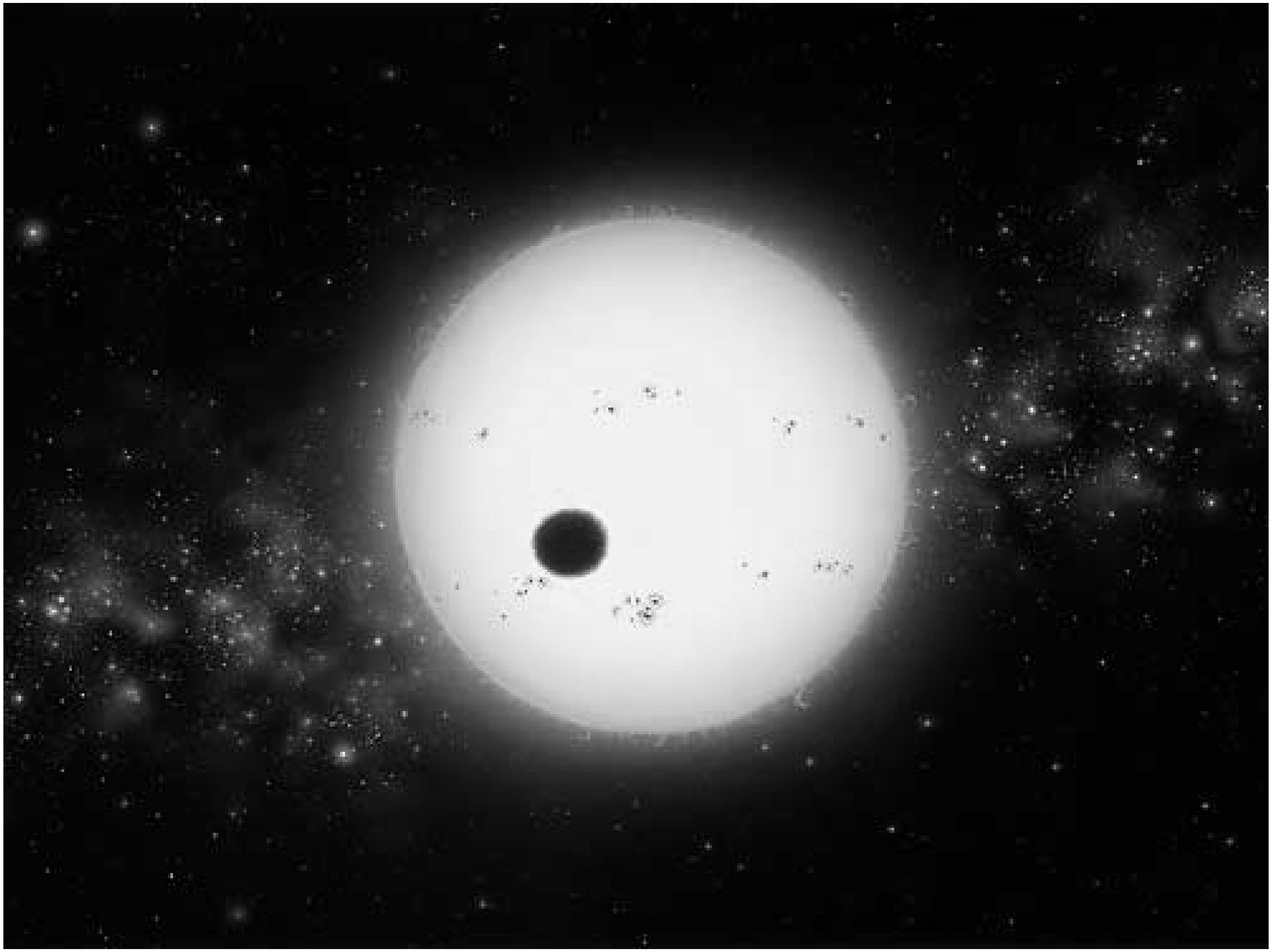

The Upsilon Andromedae System
B
C
D
0.06 AU
4.6 day orbit
75% Jupiter's Mass
0.83 AU
242 day orbit
Twice Jupiter's Mass
2.5 AU
3.5 year orbit
4x Jupiter's Mass
Our Inner Solar System
Mercury
0.39 AU
89 day orbit
Venus
0.73 AU
228 day orbit
Earth
1.00 AU
1 year orbit
Mars
1.54 AU
1.9 year orbit
© Harvard-Smithsonian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

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



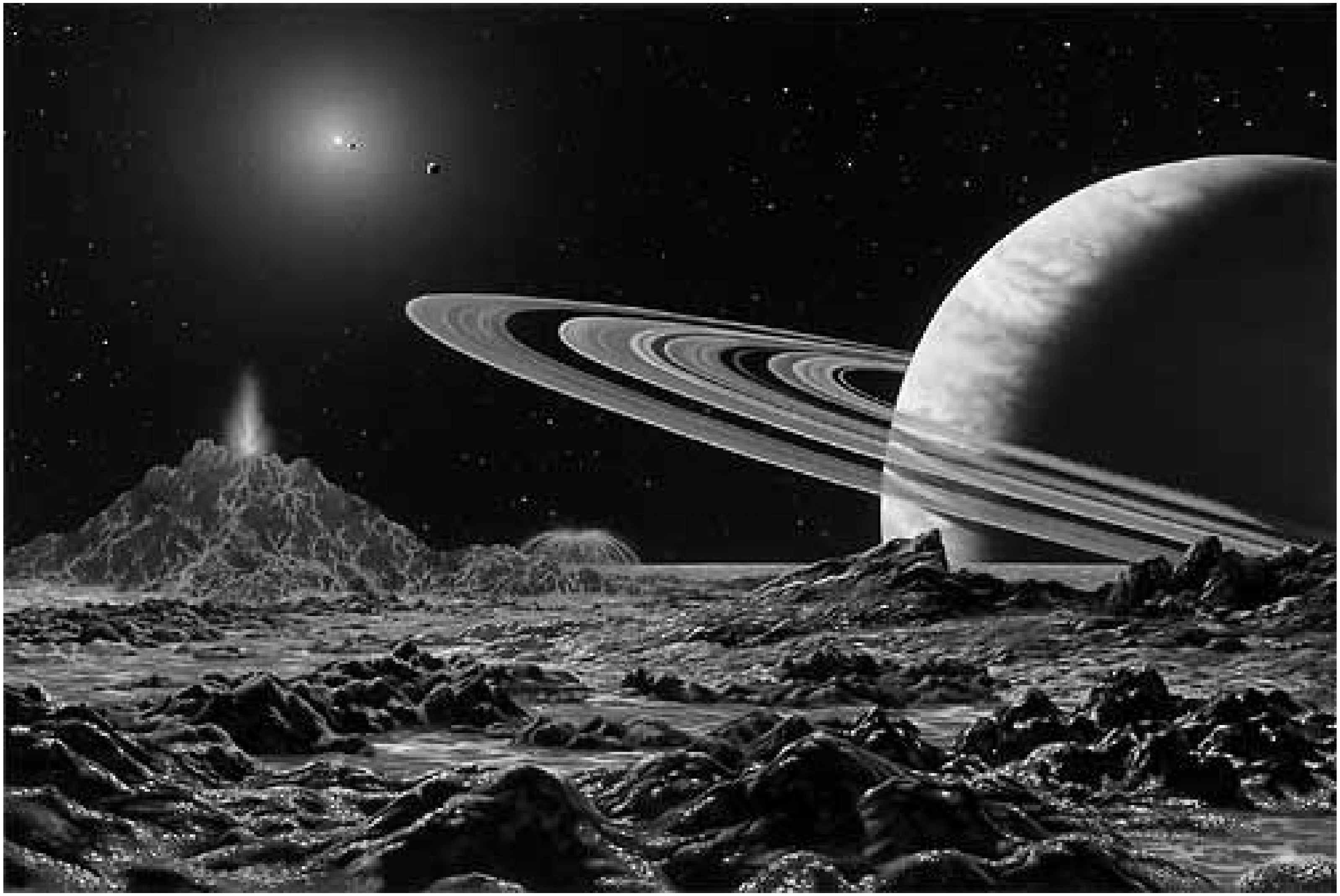
http://www.extrasolar.spaceart.org

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

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”?

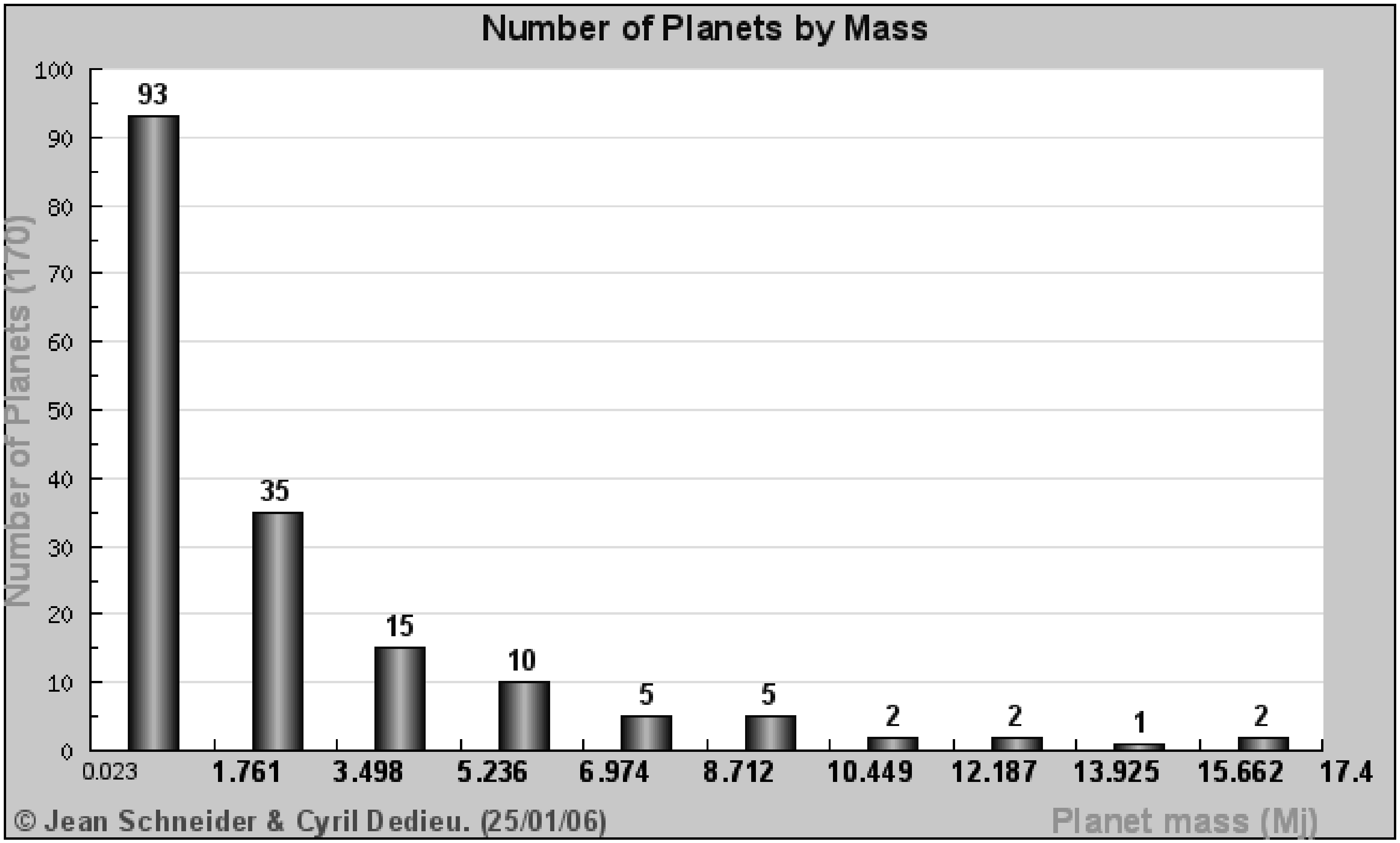
Not necessarily.

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.

Number of planets for different masses



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"

Direct Detection in Future

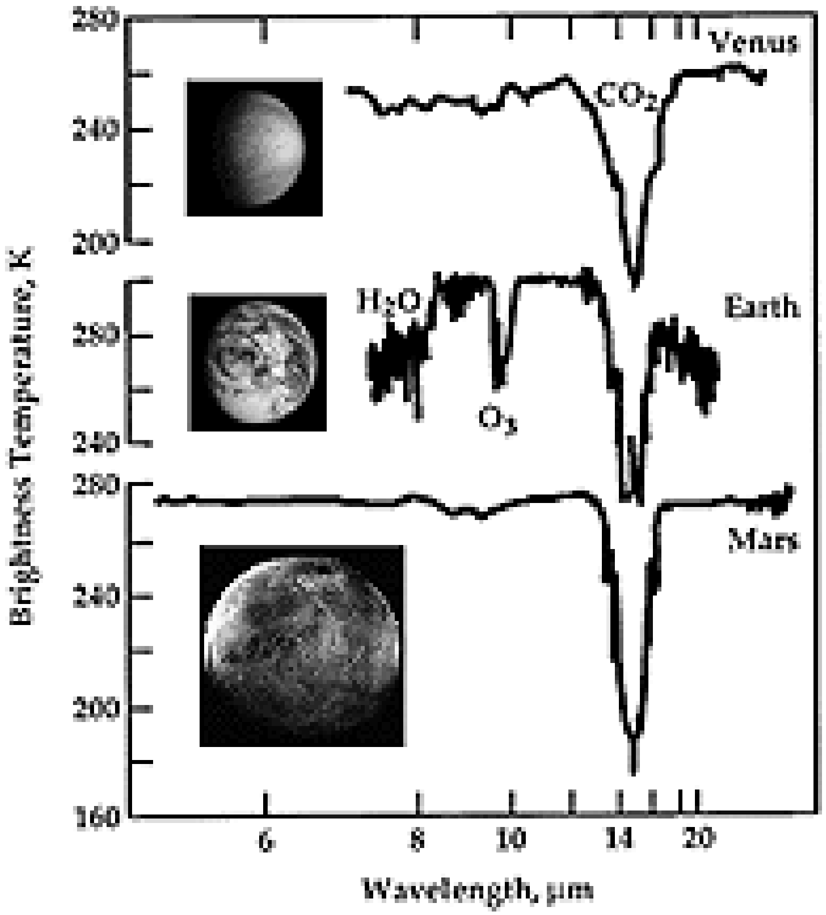
- Terrestrial Planet Finder (TPF)/Darwin
  - TPF-C Visible light coronagraph (~2014)
  - TPF-I Infrared interferometer (~2020)
- Goal is to detect earth-mass planets
- And to see what gases in atmosphere
  - Suitable for life?
- http://planetquest.jpl.nasa.gov/TPF/tpf_index.html

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]