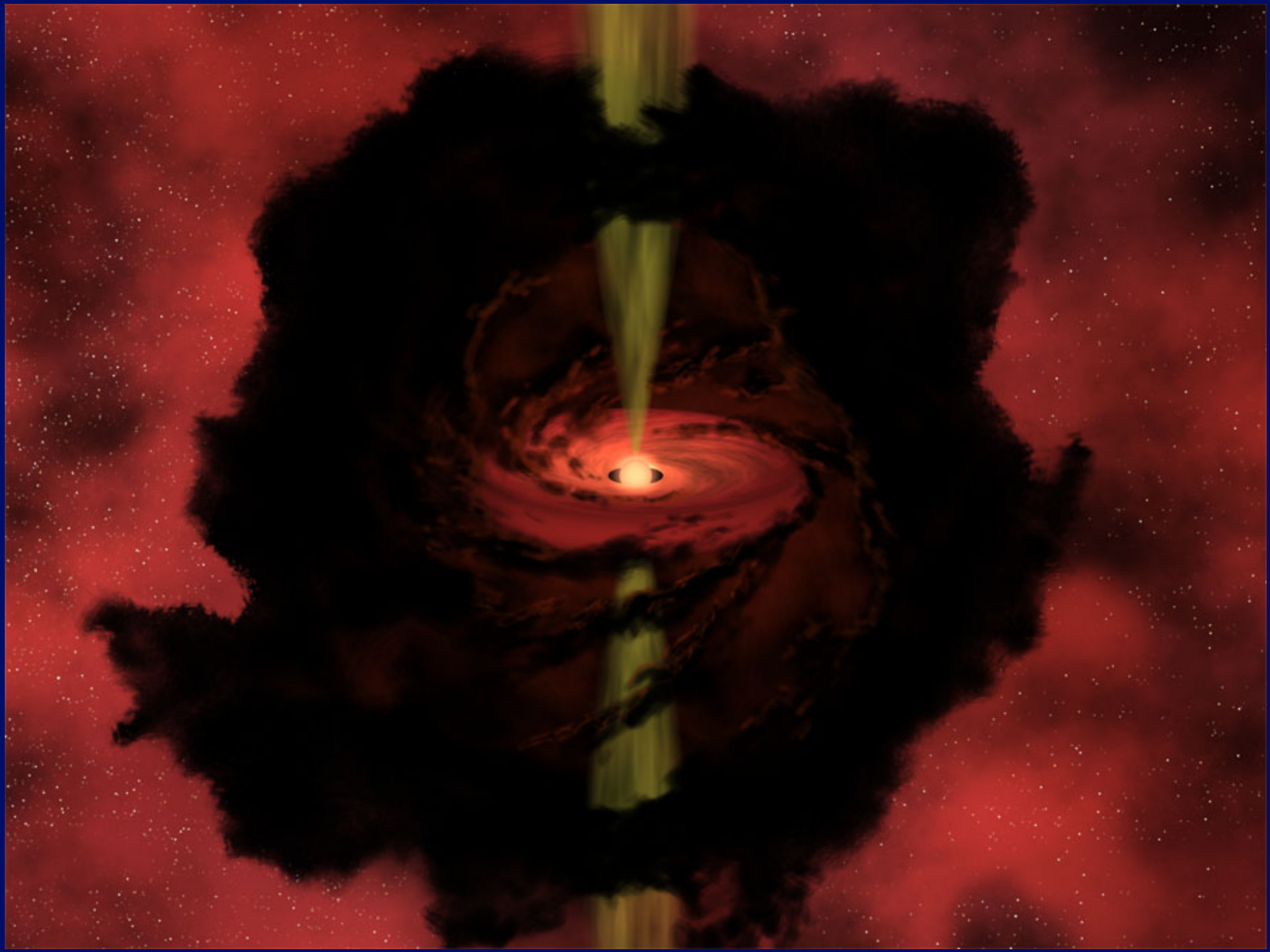
Origin and Detection of Planets

Estimating f_p

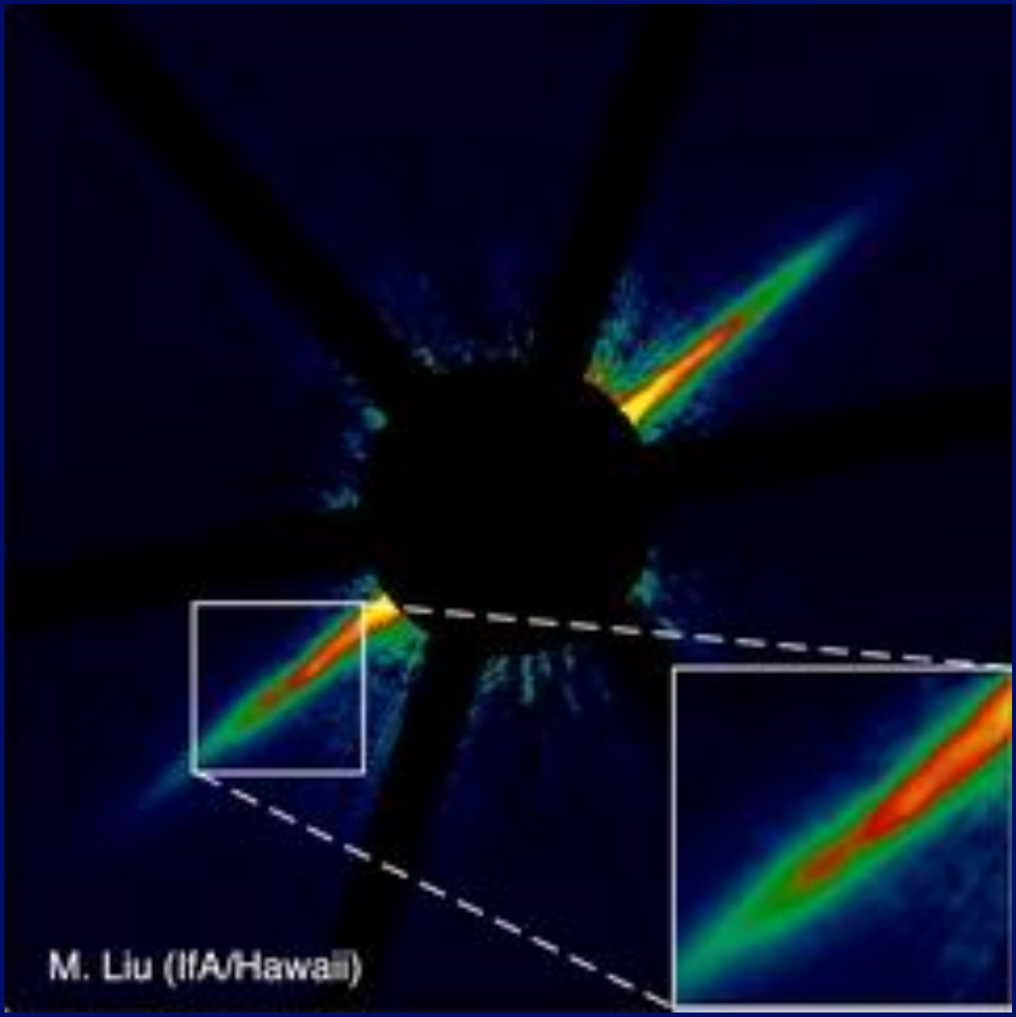
Recall this Picture



R. Hurt, SSC

Features:
Dusty envelope
Rotation
Disk
Bipolar outflow

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.

All young stars appear to form with disks.

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

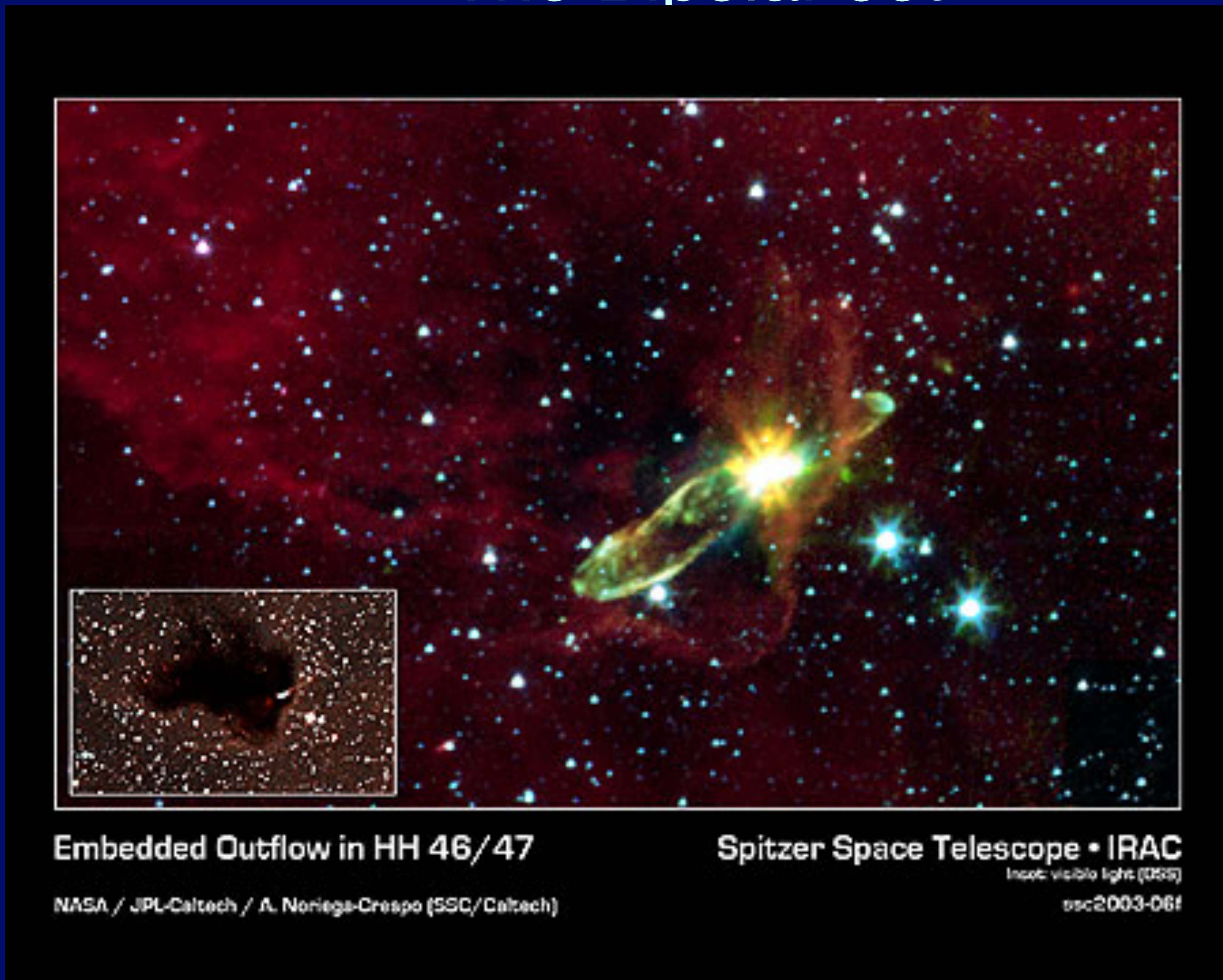
Angular Momentum Example

[Spinning Skater]

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



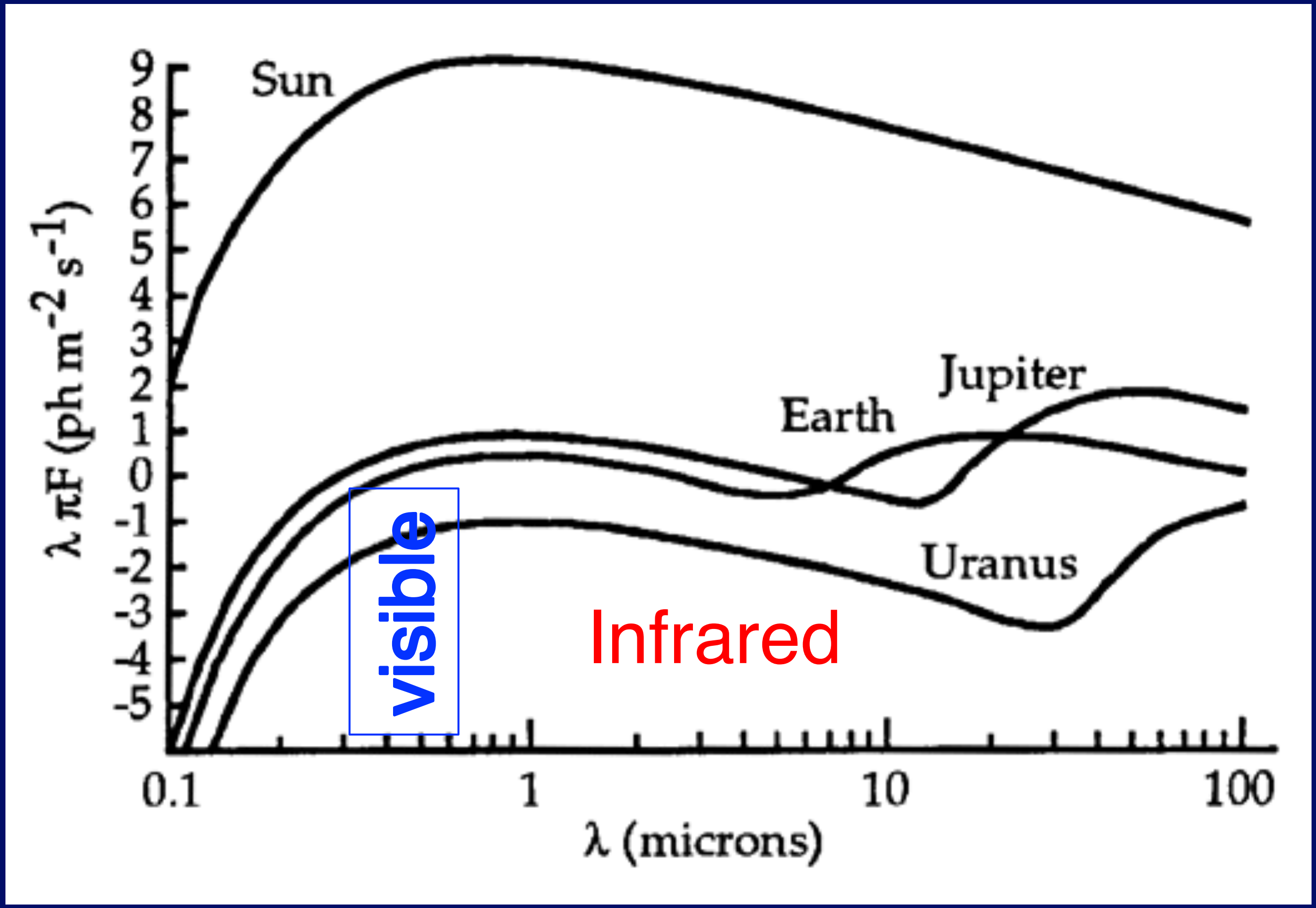
Summary: Disks around forming stars

- Rotating disks form naturally when stars form
- Conservation of angular momentum
- They are observed around almost all young stars
- They are a natural place for planets to form
  - More on this later…
- Now let’s look at what we know about planets around other stars: exoplanets

Can We See Exoplanets?

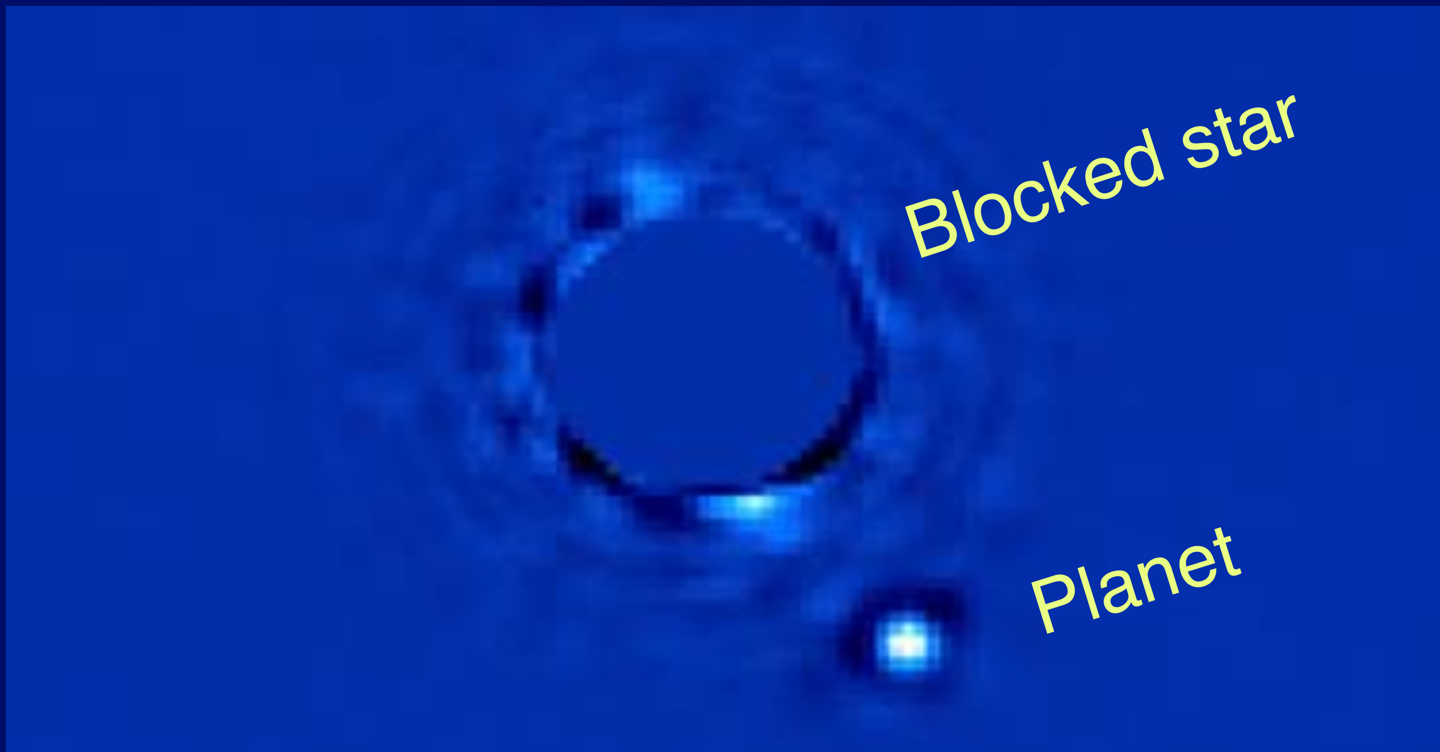
- Not easily
- Problem is separating planet light from star light
  - Star is 10^9 times brighter in visible light
  - “Only” 10^6 times brighter in infrared
- New techniques to block starlight are allowing direct detection

Planet is Much Fainter than Star



Contrast is better in infrared

Image of Planet around Nearby Star β Pic

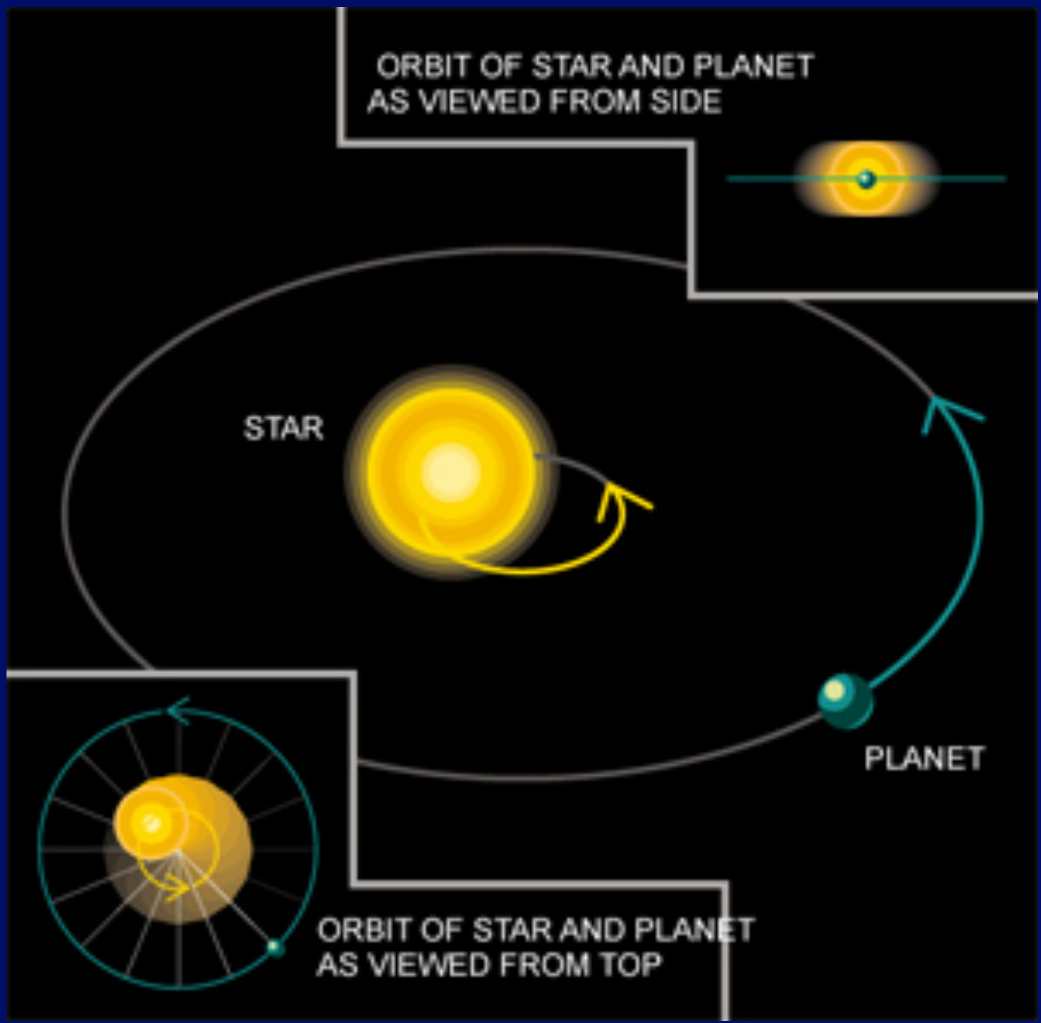


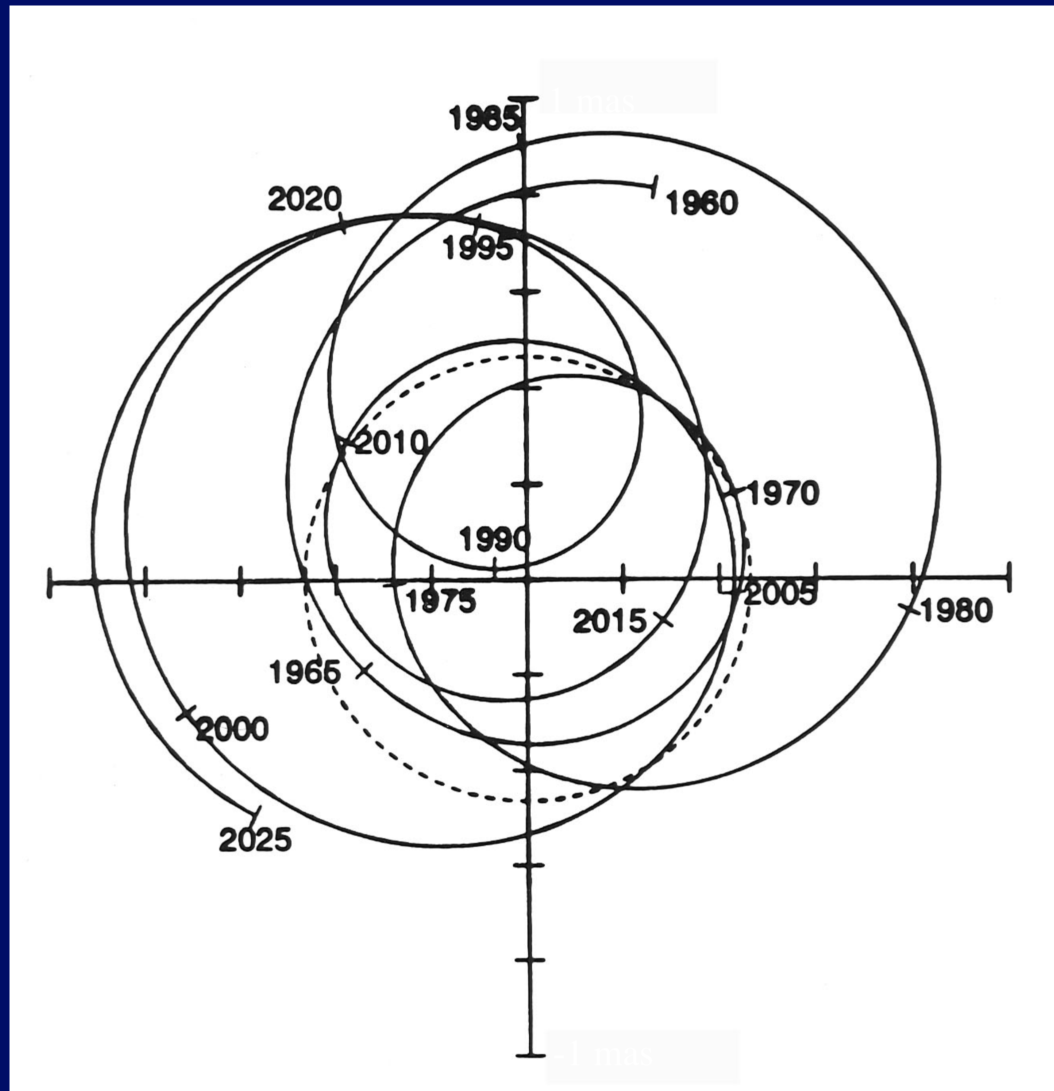
January 2014 from Gemini Planet Imager (GPI)
Works in infrared light

Indirect Detection

- Motion of the star is detected
  - Astrometric
  - Spectroscopic (Doppler)
- Change in light is detected
  - Microlensing
  - Transits

Star and Planet Orbit Center of Mass





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

1 mas = 10^{-3} arcseconds = 1.7 x 10^{-5} arcminutes = 2.8 x 10^{-7} degrees: A VERY small angle!

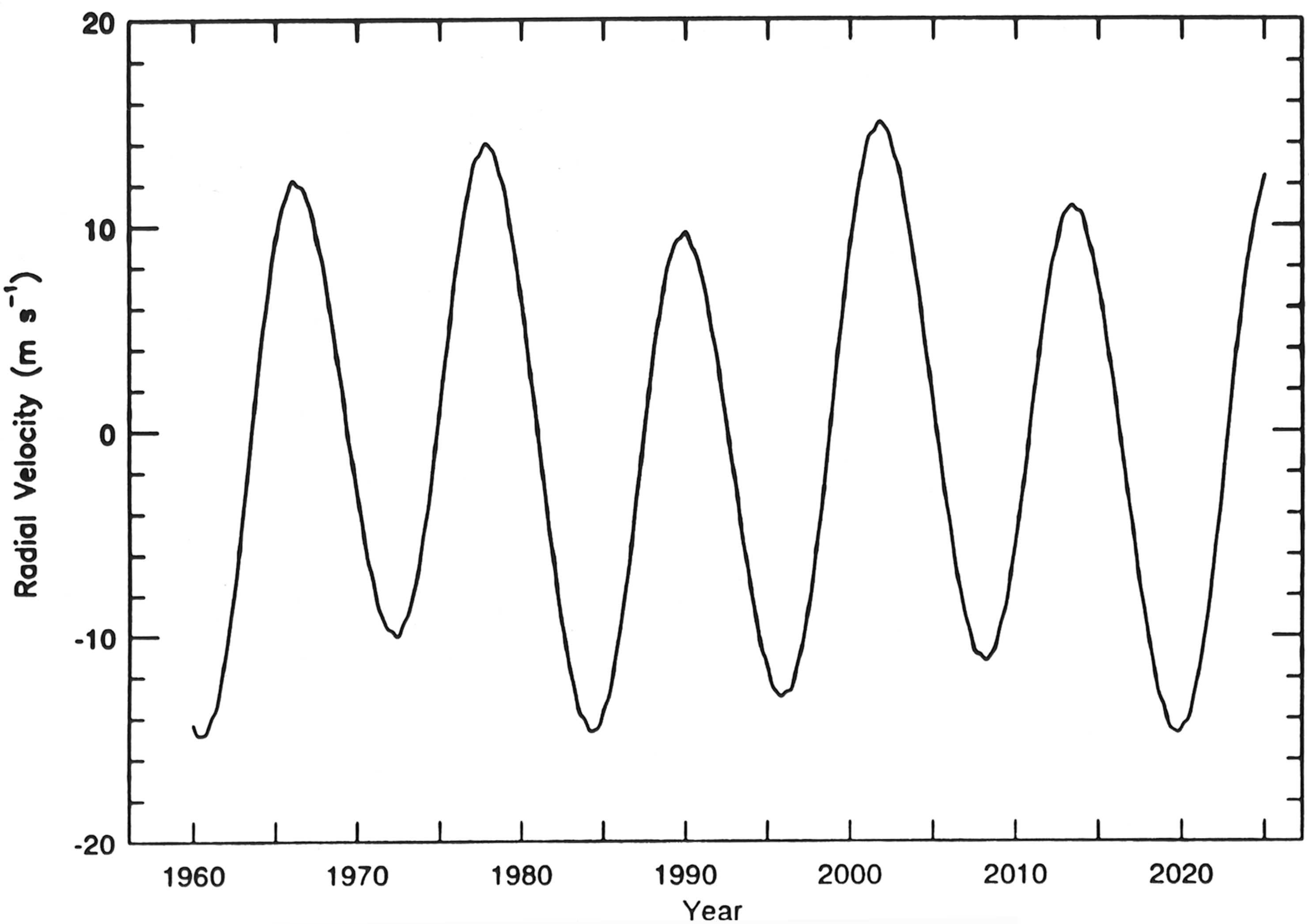
Sun's apparent size would be 0.48 mas at 30 ly

The Spectroscopic Method

- Relies on Doppler Effect
- Motion of star towards and away from us
- Motion across our line of sight does not produce the effect
- We get a lower limit to mass by assuming that the orbit is viewed edge-on

Doppler Demo

- http://www.youtube.com/watch?v=a3RfULw7aAY



Motion of the Sun caused by Jupiter, ...

30 *ly*

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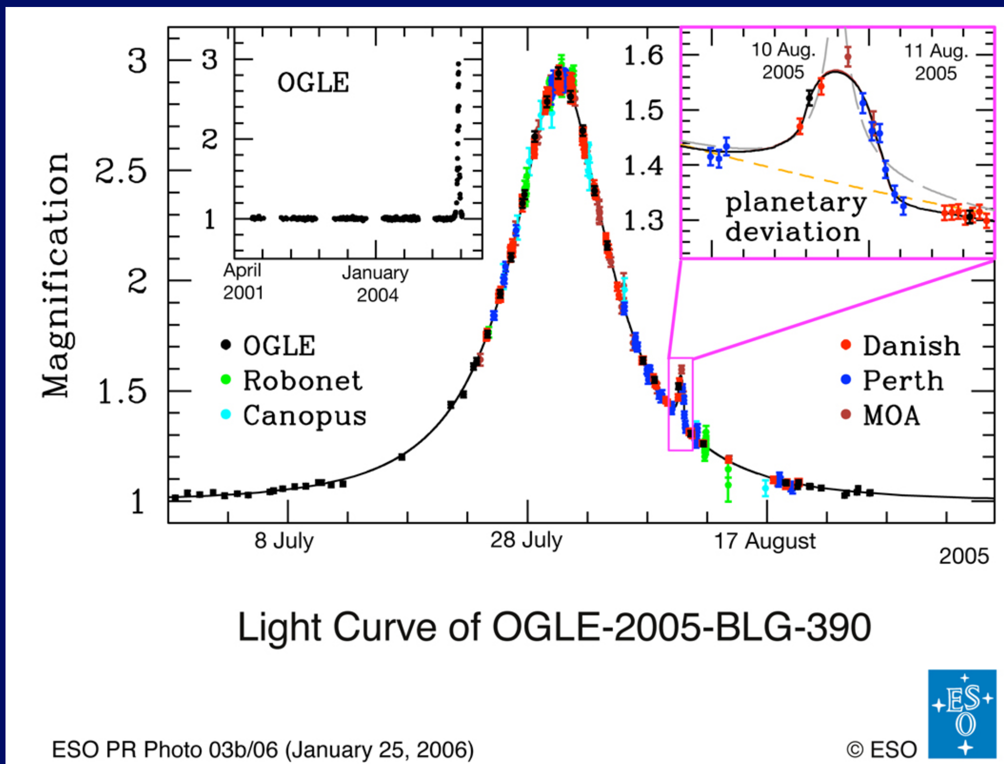
10 m s^{-1} is at level humans can run; stars have much faster motions in atmosphere. Very hard.

Detection by Change in Light

- Microlensing
  - Example of General Relativity
    - Light follows space
    - Space is curved by mass

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.

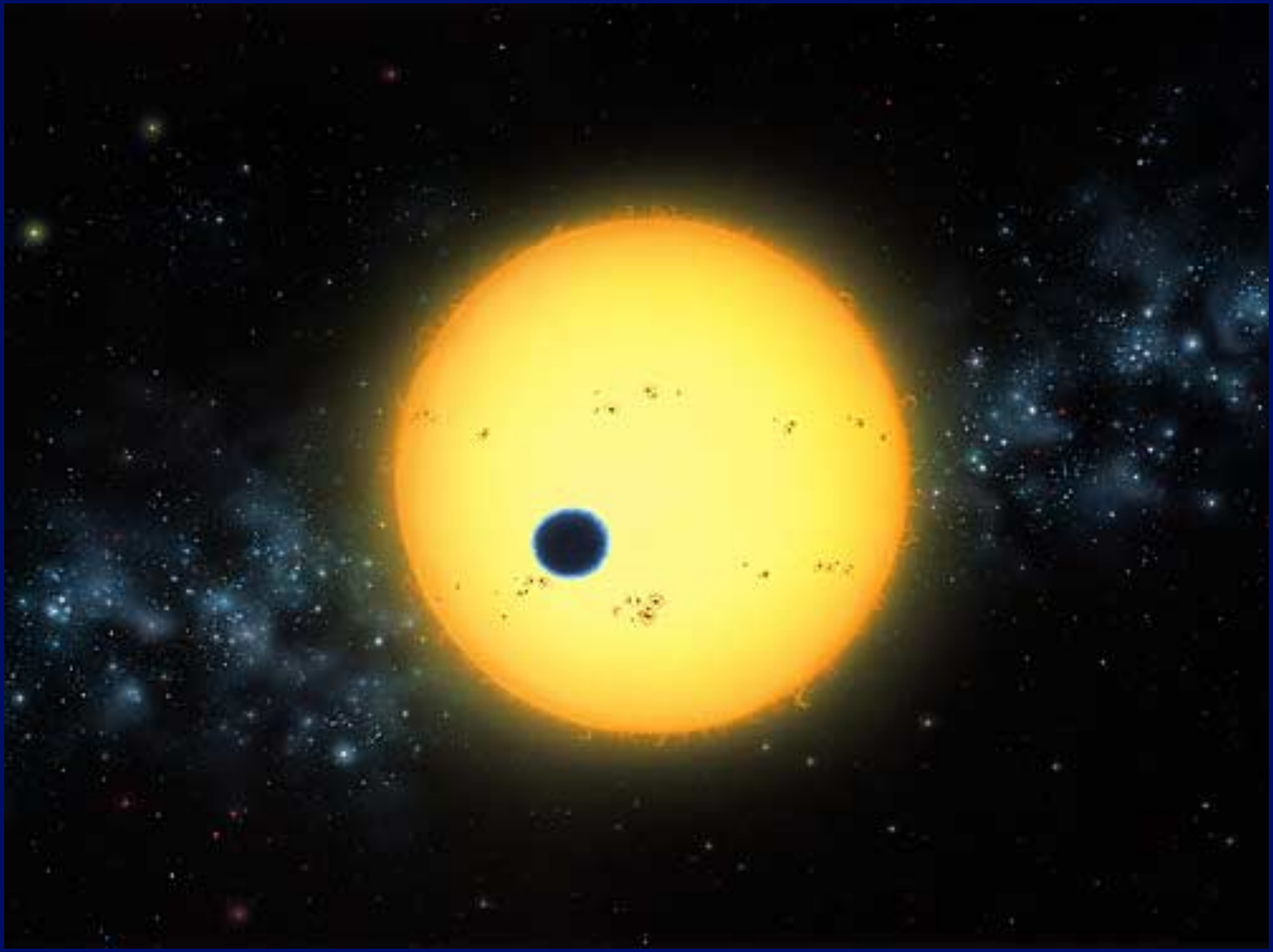
OGLE 2005-BLG-235Lb, announced 1/25/06

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

Transits

- Requires alignment of planet orbit
- Allows determination of size of planet
- Has provided most planet detections recently
- Kepler spacecraft
  - Stared at a patch of sky for several years
  - Found 4706 candidates
  - 1039 confirmed (as of Dec. 2015)

Artist’s conception of Transit of HD209458



http://www.extrasolar.spaceart.org

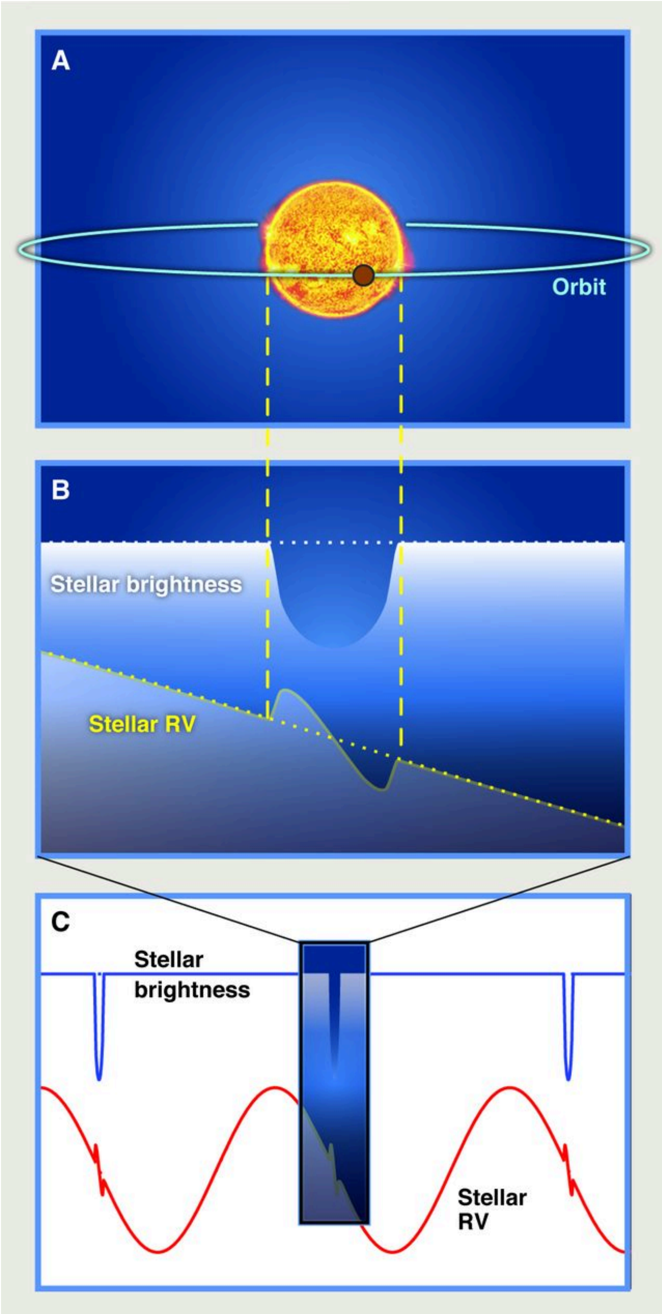


Fig. 1 Schematic illustration of a planetary orbit and the variations in stellar brightness and RV that it causes.
(A) A planet orbits its host star and eclipses ("transits")the star as seen by a distant observer.
(B) The star's light is dimmed by the planet and the observer sees a slight shift in the "velocity" of the star as the different sides of the star are eclipsed, one after the other
(C) A longer view, where one sees multiple transits and distortions of the star's velocity.

A W Howard Science 2013;340:572-576

Science
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Published by AAAS

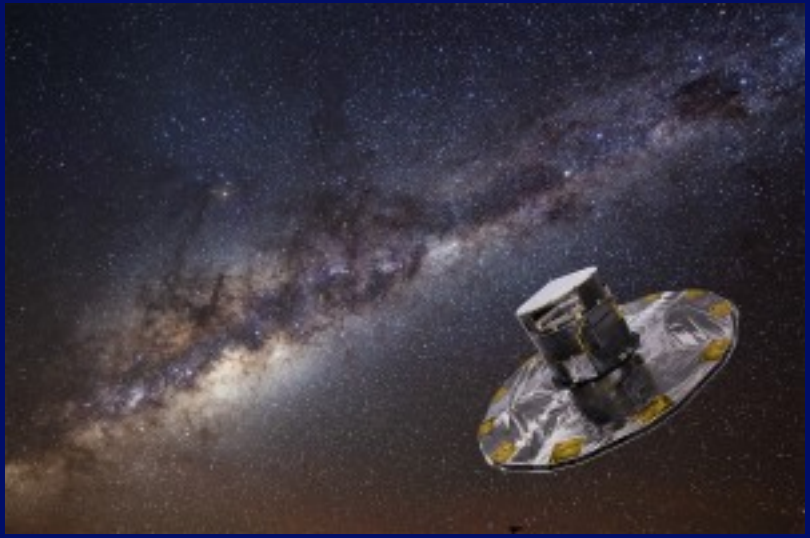
Advantages of Methods

Advantage	Direct	Astrometric	Spectroscopic	Transits	Microlensing
Big Planet	Yes	Yes	Yes	Yes	Yes
Small Star	Yes	Yes	Yes	No	Not important
Big orbit	Yes	Yes	No	No	Yes
Nearby	Yes	Yes	Yes	Not important	No
Edge-on Orbit	No	No	Yes	Required	Not important

Current Statistics (Jan. 2015)

- Based on Extrasolar Planets Encyclopedia
  - http://exoplanet.eu/
- 2052 Planets
- 507 stars with multiple planets
- 3667 Kepler candidates
- Most planets in one system is 5
- Least massive
  - $M = 0.3\ M_{earth}$ (Kepler Object of Interest1843 b)

GAIA: The Revenge of Astrometry



- Launched 19 Dec. 2013
- Five year mission
- Measure star positions with great accuracy (24 micro-arcseconds!)
- Discover ~7000 planets out to 600 ly

An Ongoing Story…

- For Updates:
- http://planetquest.jpl.nasa.gov/

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
- Planets also found around some binaries

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?

How Big can Planets Be?

- Brown dwarfs now found to very low masses
  - Some clearly less than 13 $M_{jupiter}$
    - Can't even fuse deuterium
    - Some people call these rogue planets
    - Some are less massive than known planets
    - Sites for life??
  - Usual definition: planets orbit stars
    - Some brown dwarfs may have "planets"
- Nature does not respect our human desire for neat categories!

Summary

- Detecting planets is hard
- Correcting for that suggests planetary systems are very common
- Binary stars may be less likely sites for planets, but some do have planets
- Many stars have multiple planets
- f_p is fraction of stars with planetary systems
- Probably at least 0.5 and could be 1