Today in Astronomy 106: exoplanets

- The successful search for extrasolar planets
- Prospects for determining the fraction of stars with planets, and the number of habitable planets per planetary system (f_p and n_e).

T. Pyle, SSC/JPL/Caltech/NASA.

Observing exoplanets

Stars are vastly brighter and more massive than planets, and most stars are far enough away that the planets are lost in the glare. So astronomers have had to be more clever and employ the motion of the orbiting planet. The methods they use (exoplanets detected thereby):

- ❑ Astrometry (0): tiny wobble in star's motion across the sky.
- ❑ **Radial velocity** (399): tiny wobble in star's motion along the line of sight by Doppler shift.
- ❑ Timing (9): tiny delay or advance in arrival of pulses from regularly-pulsating stars.
- ❑ Gravitational microlensing (10): brightening of very distant star as it passes behind a planet.

Observing exoplanets (continued)

- **Transits** (69): periodic eclipsing of star by planet, or *vice versa*. Very small effect, about like that of a bug flying in front of the headlight of a car 10 miles away.
- Imaging (11 but 6 are most likely to be faint stars): taking a picture of the planet, usually by blotting out the star.

Of these by far the most useful so far has been the combination of radial-velocity and transit detection.

- Astrometry and gravitational microlensing of sufficient precision to detect lots of planets would need dedicated, specialized observatories in space.
- Imaging lots of planets will require 30-meter-diameter telescopes for visible and infrared wavelengths.

One-stop exoplanet shopping

- ❑ Jean Schneider's encyclopedia of extrasolar planets, updated in real time: exoplanet.eu.
- ❑ Websites of the groups responsible for the discovery of extrasolar planets around ordinary stars:
    - The Geneva group (Michel Mayor, Didier Queloz, *et al*.): exoplanets.eu.
    - The U. California - Carnegie Institution group (Geoff Marcy, Paul Butler, *et al*.): exoplanets.org.

Left to right: Marcy, Butler, Mayor, Queloz

The successful search for extrasolar planets

In the early 1990s, groups in San Francisco and Geneva were gearing up for long searches for giant planets around normal stars by Doppler-velocity techniques.

- The idea: detect the relatively small, but periodic, Dopper shift in the spectrum of a star due to its orbital motion around the center of mass of a star-planet system.
  Click to view the demonstration
- The technology to implement a clever idea for how to do this, had only recently become available.
- The observers thought they were going to detect Jupiters like this, so they were prepared to do observations over the course of many years. (Jupiter's orbital period is 11.9 years.)

The successful search for extrasolar planets (continued)

- So imagine their surprise when they detected their first planet in days, and a couple more within the next two months.

51 Pegasi b: $m \sin i = 0.46 M_J$, $P = 4.2$ days
(Mayor & Queloz 1995, Marcy & Butler 1995)

70 Virginis b: $m \sin i = 6.5 M_J$, $P = 117$ days
(Marcy & Butler 1996)

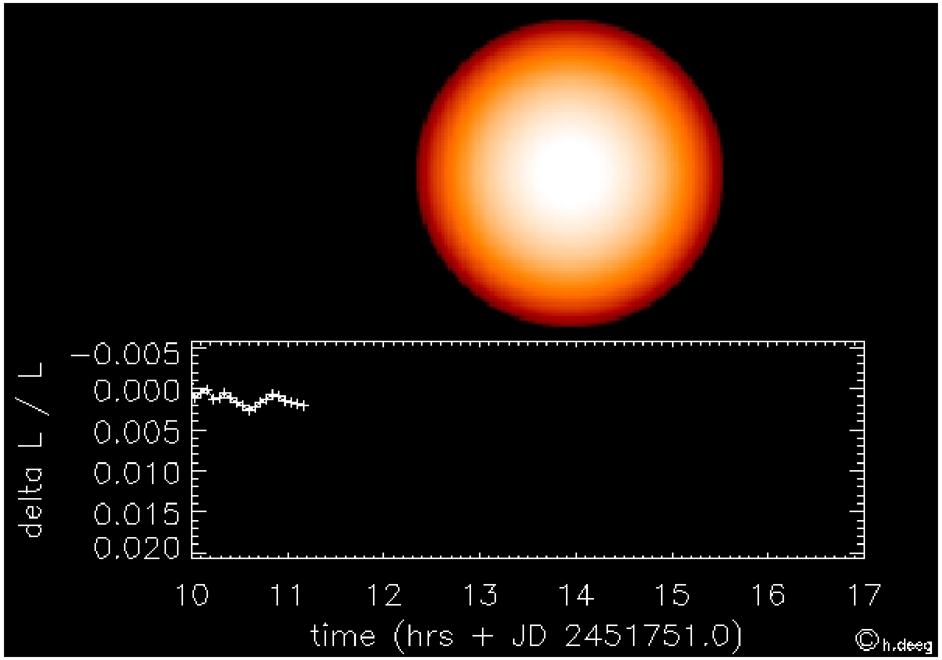
47 Ursae Majoris b: $m \sin i = 2.5 M_J$, $P = 1100$ days
(Butler & Marcy 1996)

Jupiter-size planets, in terrestrial-planet-size orbits (or smaller)? Larger masses if *i* is close to zero (system viewed along rotational axis) in any of the three cases.

The successful search for extrasolar planets (continued)

In 1999, after several more exoplanets had been detected, two more milestones in the search were reached:

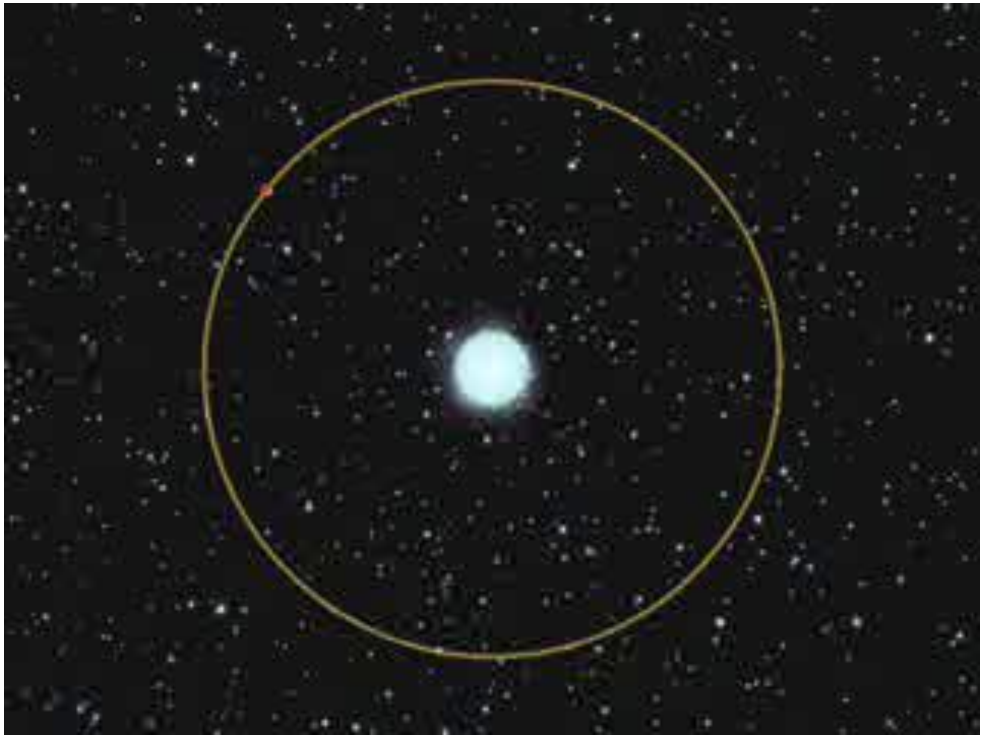
- One planet detected by radial velocity, HD 209458 b, was seen to transit: to eclipse a tiny portion of the star (Henry et al. 2000).
  - Thus its orbit is viewed close to edge on $(i \approx 90°)$ and its mass can be determined precisely: $m = 0.69 \pm 0.05 M_J$.



Deeg and Garrido 2000

The successful search for extrasolar planets (continued)

- Later (in 2005) the Spitzer Space Telescope detected the eclipse of HD 209458b by HD 209458 – meaning that the light from the planet is directly detected at mid-infrared wavelengths when not in eclipse (Deming et al. 2005).

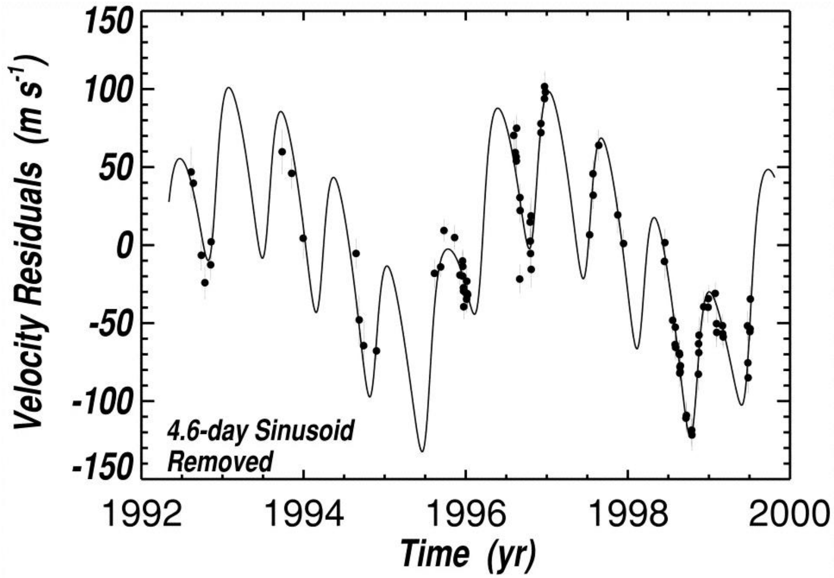


Animation by Robert Hurt, SSC

The successful search for extrasolar planets (continued)

- Also in 1999, the first multiple exoplanetary system was detected: υ Andromedae c and υ Andromedae d (periods 242 and 1275 days), to go with the previously-detected υ Andromedae b (4.6 days).

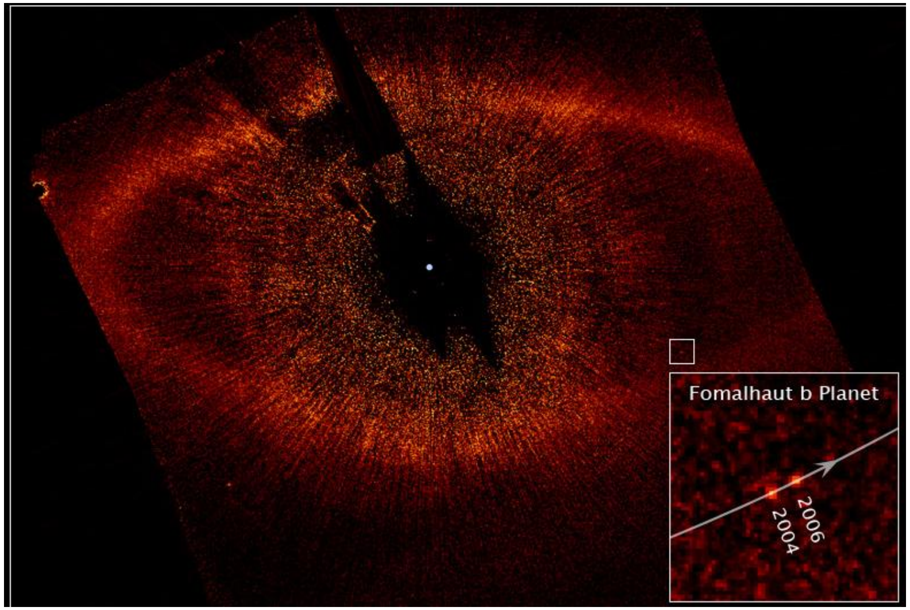
  Top: from Butler et al. 1999
  Bottom: animation by Sylvain Korzennik (CfA)



The successful search for extrasolar planets (continued)

And 2008 saw two historic firsts:

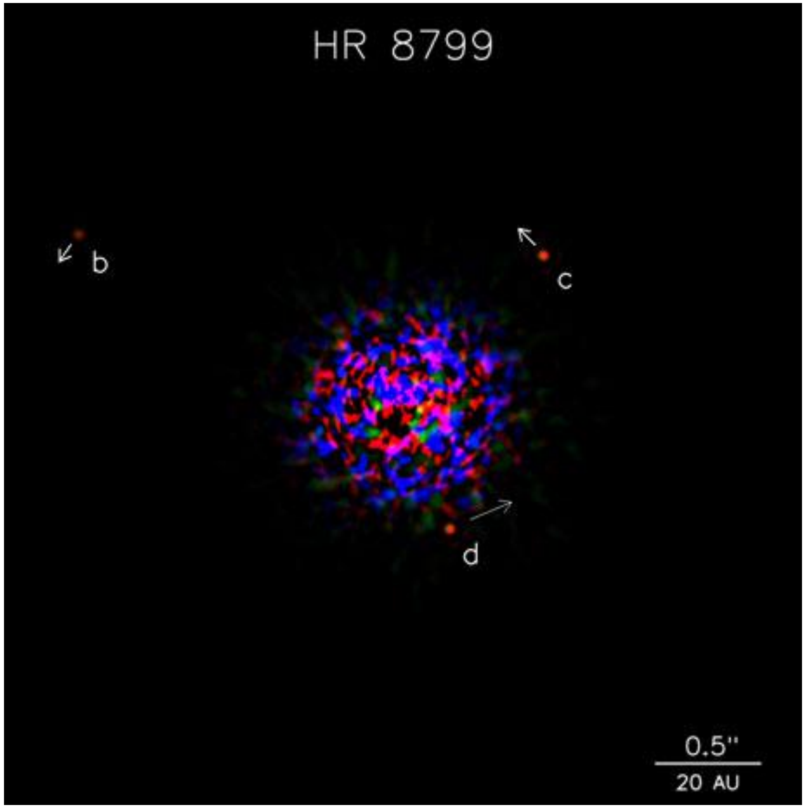
- an image of a planet orbiting the bright, nearby star Fomalhaut, which truncates the remains of the disk from which it formed.
  This planet's orbit was correctly predicted two years earlier (by Alice Quillen, on the basis of the disk truncation) – the first time since Le Verrier (1846, Neptune) that anyone has accomplished such a feat.



Paul Kalas, UC Berkeley/STScI/NASA

The successful search for extrasolar planets (continued)

- and an image of *three* planets in orbit around another bright nearby star, HR 8799.
- HR 8799 was previously known to have two debris belts (Chen et al. 2006), which turn out to lie inside and outside the orbits of the planets. The resemblance to our Solar system's giant planets, asteroid belt and Kuiper belt is striking.



C. Marois and B. Macintosh, Keck Observatory

Mid-lecture Break.

- Exam #1 will be posted on WebWork tomorrow at 10 AM.
  - You have 75-minutes to complete the exam.
  - E-mail with problems or for clarification.
- Any questions can be addressed
  - at the end of class
  - In Office hours today: 1-3PM in B&L 477 or by appointment.

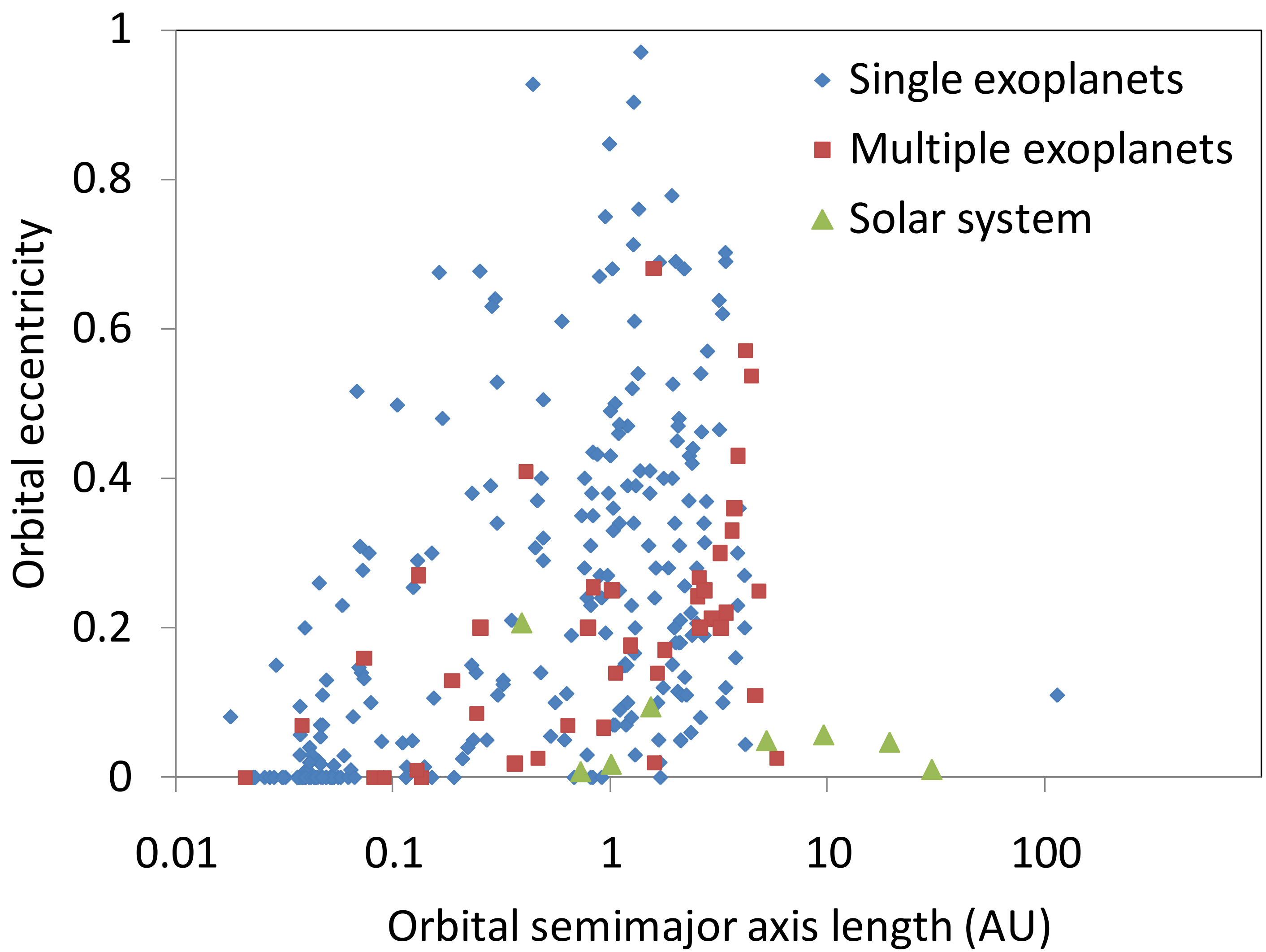
The last launch of the Space Shuttle Endeavor, 16 May 2011. NASA

The successful search for extrasolar planets (continued)

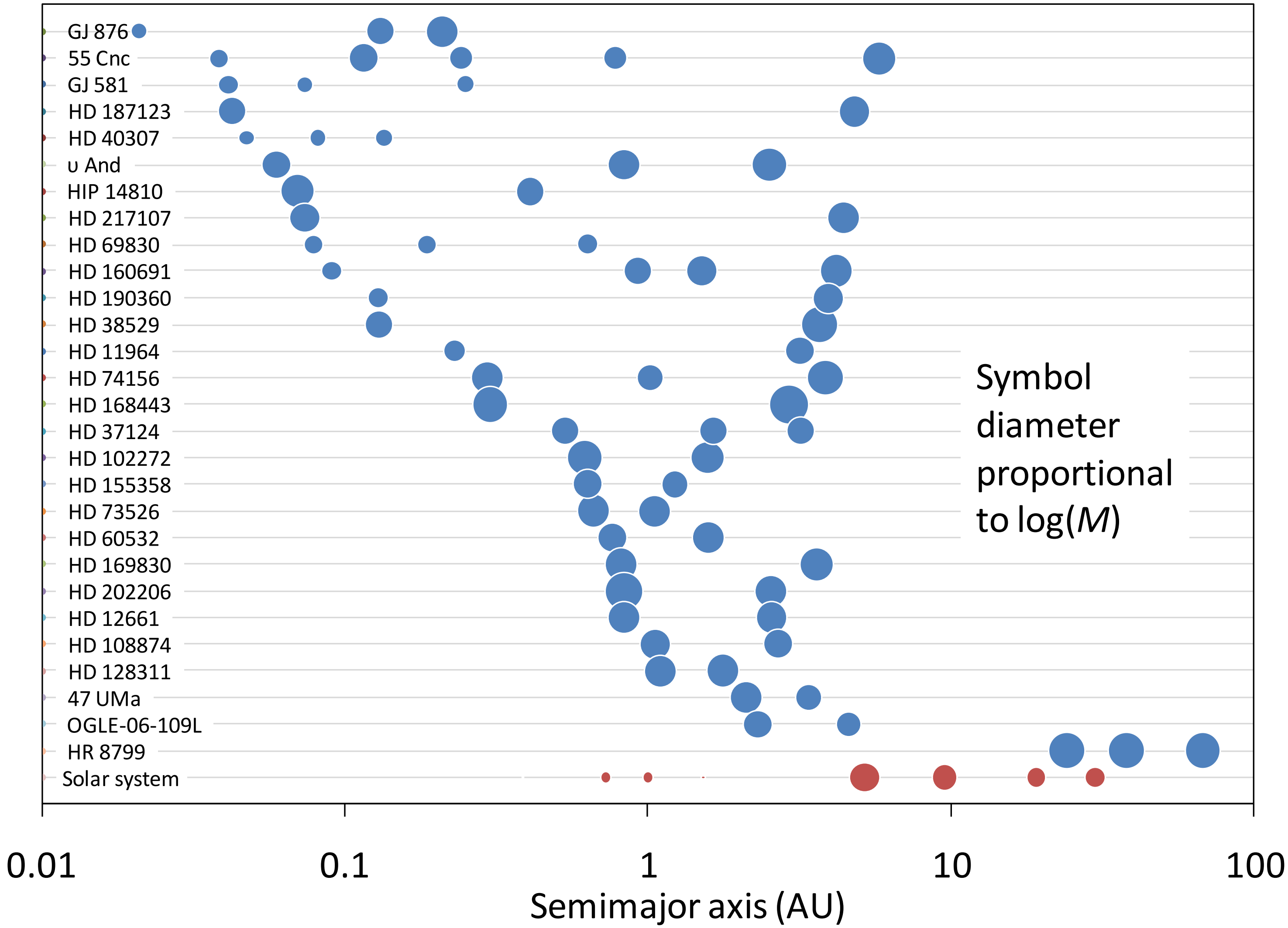
Today there are 551 objects listed as exoplanets. All but 30 were first found by one or both of the two main techniques:

- 131 by both radial velocity and transits. You can take 128 of them to the bank, as we're 100% sure they're of planetary mass.
- 372 others by radial velocity alone. Something like 5-10% of these may prove to be very faint stars or brown dwarfs eventually.
    - These 503 planets live in 422 planetary systems: there are 50 multiple-planet systems detected by radial velocity so far, the most populous being Kepler-11 with six planets.

Orbits of the exoplanets



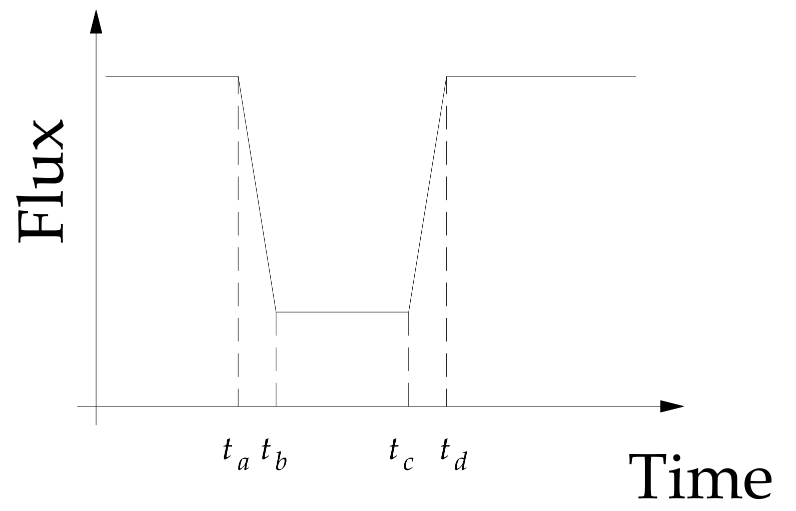
Some of the multiple exoplanetary systems



Exoplanetary transits and eclipses

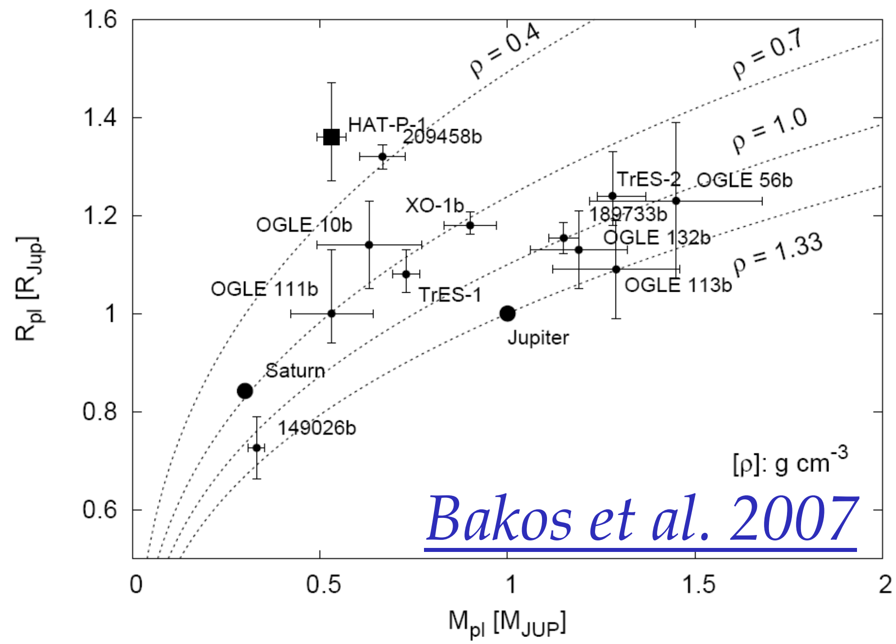
Transits and/or (secondary) eclipses offer opportunities to determine several other properties of exoplanets:

- Because the orbit must be viewed edge-on for transits or eclipses, observation of transits *and* radial velocities allow unambiguous determination of the planetary mass m, not just the lower limit $m \sin i$.
- The duration of the transit offers a measurement of the diameter of the star and/or the precise orbit inclination; the depth of the flux "dip," and time it takes the transit to turn off or on, offer a measurement of the diameter of the planet.



Exoplanetary transits and eclipses (continued)

With each transiting planet's size and mass we get its average **density** (mass per volume), and thus an idea of its internal structure.

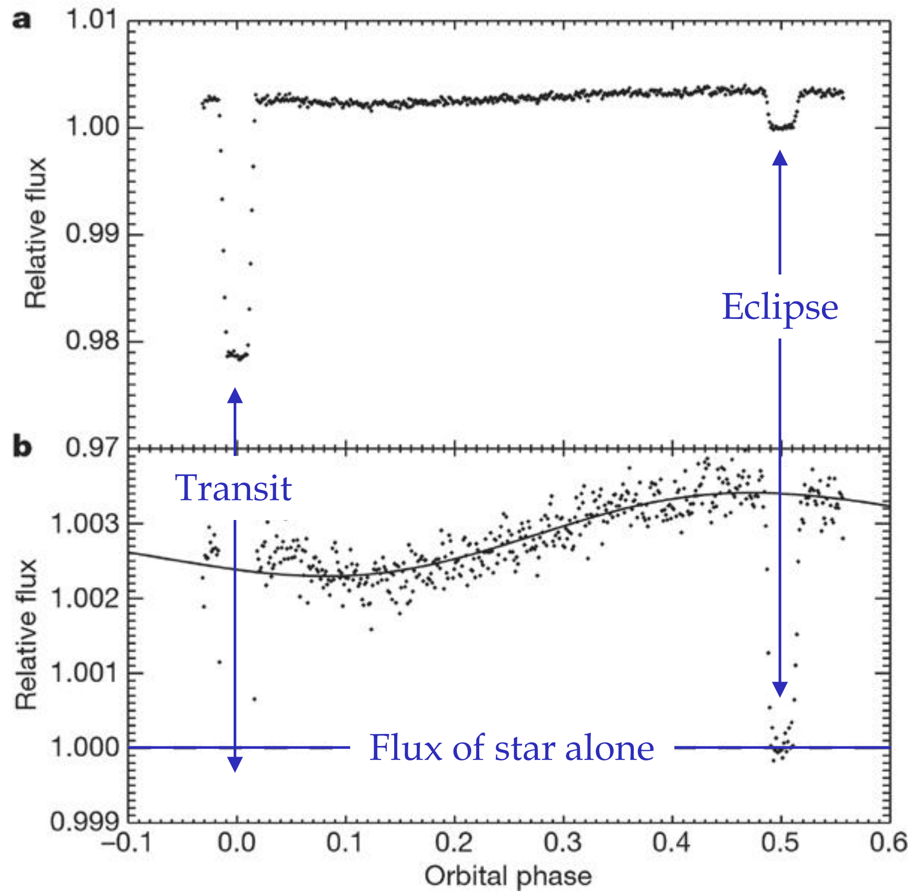


Bakos et al. 2007

- ❑ Most have rather large radii, and correspondingly low density.
- ❑ Example: HAT-P-1b has a density of only $0.28\ \mathrm{gm\ cm^{-3}}$.
- ❑ But COROT-Exo-7b ($5.6\ \mathrm{gm\ cm^{-3}}$) is even denser than Earth, at $5.5\ \mathrm{gm\ cm^{-3}}$ the densest in the Solar system.
- ❑ And GJ1214b ($1.3\ \mathrm{gm\ cm^{-3}}$), warm but not a gas giant, might be made mostly (75%!) of water: a Waterworld.

Exoplanetary transits and eclipses (continued)

- At mid-infrared wavelengths (at least with an observatory as sensitive and stable as the Spitzer Space Telescope), the difference between transit, eclipse and points in between enables one to isolate flux from the planet, and even to "map" the emission from the planet's surface, as in HD 189733b at right.



HD 189733 at λ = 8μm; [Knutson et al. 2007](#).

Hot Neptunes and Jupiters

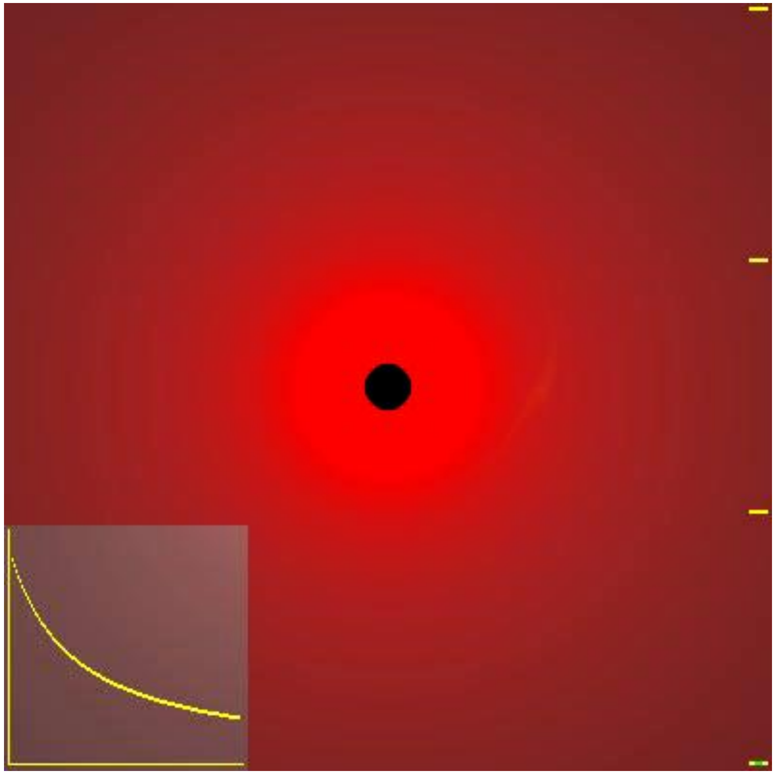
Unexpected features of today's exoplanets:

- ❑ 162 of the 429 exoplanets have orbits with semimajor axes smaller than Mercury's, and all lie well inside their planetary system's snow line. 139 are Neptune size or larger; 93 are more than ten times Neptune's size.
  - These are gathered under the new title of **hot Neptunes** or **hot Jupiters**.
- ❑ Those for which the radii are known tend to be unexpectedly large and low in density.
- ❑ Except for the ones with the smallest orbits, their orbits tend to be eccentrically elliptical– very different from the Solar system.

Hot Neptunes and Jupiters (continued)

Nobody thinks it's likely that the hot Neptunes and Jupiters formed in the locations at which we observe them.

- There isn't really enough mass in the inner parts of proto-planetary disks to make them.
- More likely: they were formed further away from the star (~10 AU) and subsequently had their orbits perturbed by the outer disk, thus **migrating** to their present positions.



(Phil Armitage, U. Colorado)

Habitable exoplanets?

Hardly any of today's exoplanets lie anywhere near the habitable zone, and only recently have exoplanets have been found that are small enough possibly to be terrestrial rather than gas-giant. The best case is GJ 581 $(0.3 M_{\odot}, 0.013 L_{\odot})$:

- Two of its three planets are super-Earth in size: GJ 581c and GJ 581d, with $m \sin i = 5.0 \text{ and } 7.7 M_{\text{Earth}}$.
- The habitable zone for A = 0.39 and GJ 581 lies at

$$r = \left(\frac{T_0}{T}\right)^2 \sqrt{(1-A)L}$$

$$\approx 0.05 - 0.09 \text{ AU (fast) or } 0.10 - 0.19 \text{ AU (slow)}.$$

The orbital radii are 0.073 and 0.25 AU (c,d), and the planets are probably tidally locked (slow rotators) but not resonantly locked (so no tidal heating).

Habitable exoplanets? (continued)

- GJ 581c will have a hot side and a cold side. If it has an atmosphere with good circulation it could be habitable (Chylek and Perez 2007), but this does not seem likely (von Bloh et al. 2007). If its atmosphere doesn't circulate well, it will all freeze out on the cold size.
- GJ 581d would need all this and a substantial greenhouse effect to be habitable (Chylek and Perez 2007), and this is only barely possible (von Bloh et al. 2007).
- Maybe that's just as well; on the surfaces of these planets the gravitational acceleration would be at least 1.7-1.9*g*, which would take some getting used to.

f_p and n_e

The current score for the Drake-equation quantities:

- ❑ 100% of stars are born with enough material around them to make multiple planets of all sorts.
- ❑ Today we have *detected* planets around 14% of nearby stars. But we're much better at detecting large planets than small ones: this result probably means that 14% of stars have gas-giant planets, and **f_p is at least 0.14**.
- ❑ The smallest exoplanet is four Earth masses, and no exoplanet clearly lies in the habitable zone. We don't know how many habitable moons there are around giant planets *further from the star* than the habitable zone. So our evidence is still the Solar system: **$n_e = 1 \pm 1$.**

More and better exoplanets

The radial-velocity searches will continue at their present frantic pace, and the search for transits have received a big boost:

- **CoRoT** (CNES, France), launched 27 December 2006, is working very well and has discovered a string of transiting planets, including the “hot super-Earth” planet COROT-Exo-7b which we discussed on the first day of class.

More and better exoplanets (continued)

- *Kepler* (NASA, USA), launched on 6 March 2009 and to last 3.5 years thereafter, will be sensitive enough to detect transiting planets in the habitable zones around a few tens of thousands of stars, down to about Mercury's mass; it's designed to measure our Drake-equation quantities f_p and n_e quite precisely.

Ball Aerospace/NASA