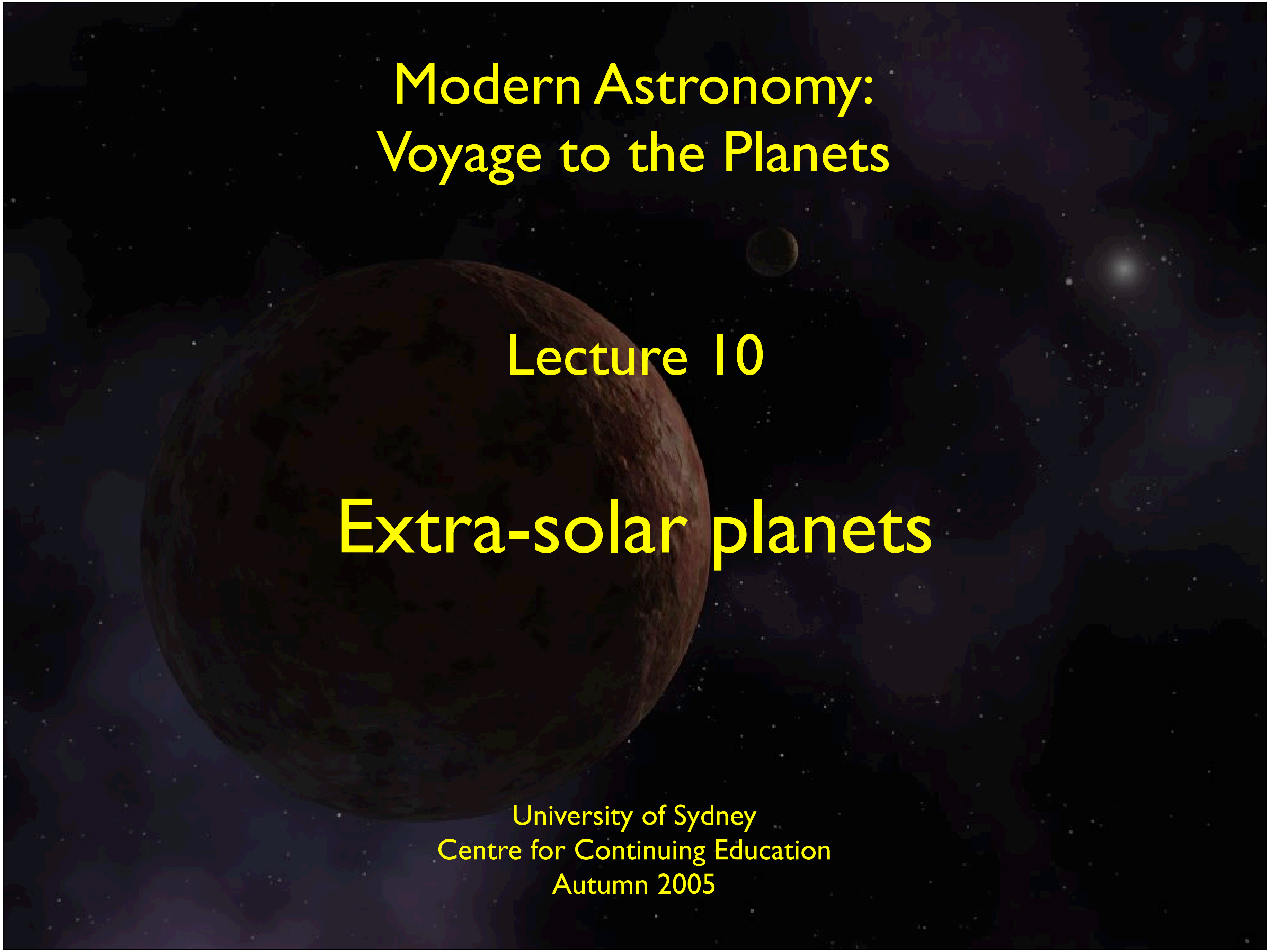
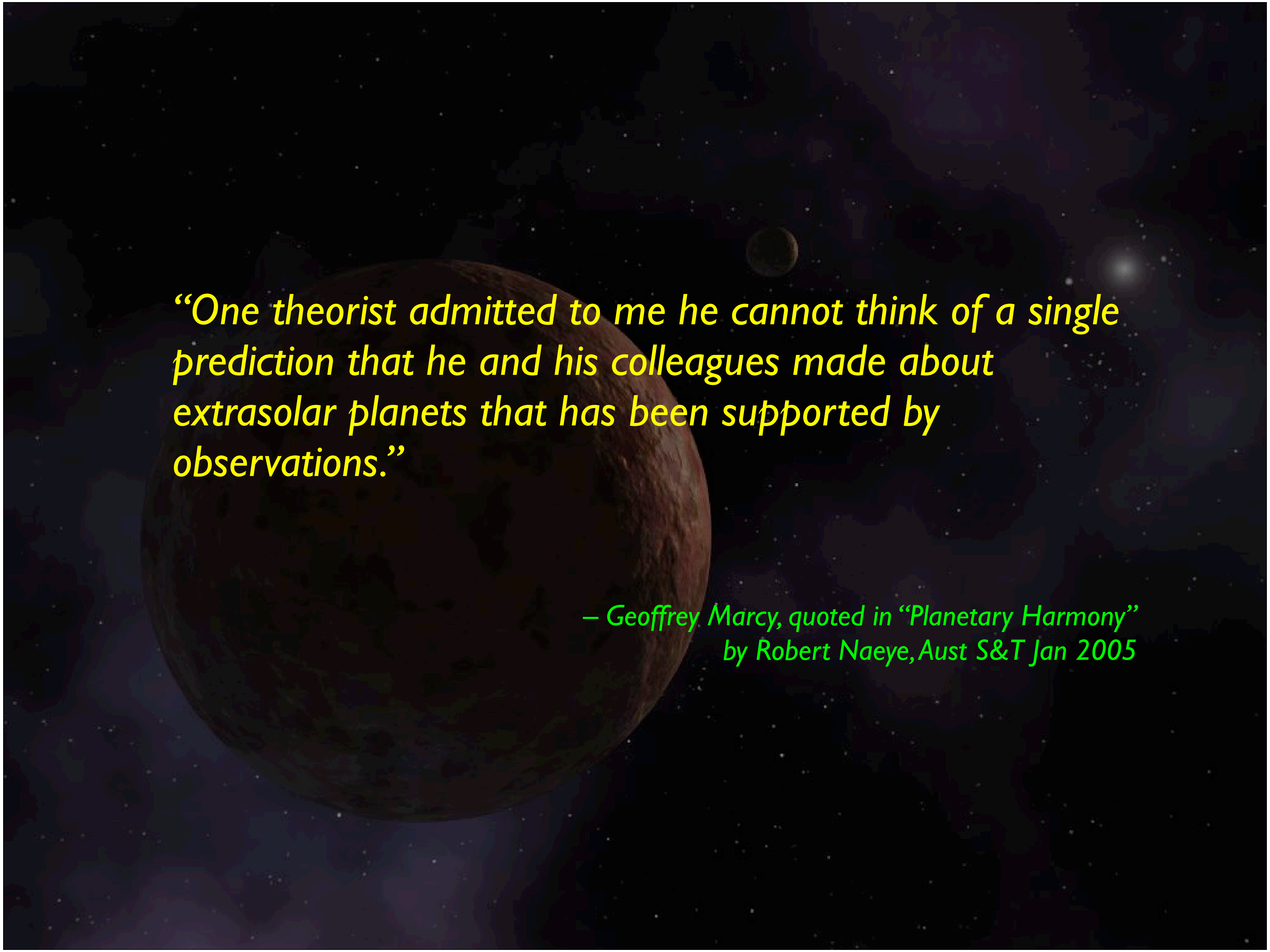


Modern Astronomy: Voyage to the Planets

Lecture 10

Extra-solar planets

University of Sydney
Centre for Continuing Education
Autumn 2005

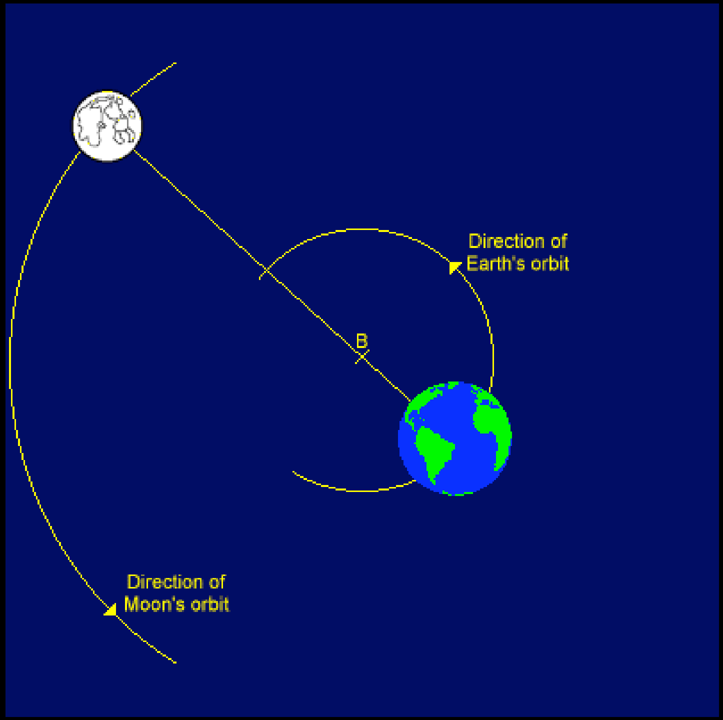

"One theorist admitted to me he cannot think of a single prediction that he and his colleagues made about extrasolar planets that has been supported by observations."
– Geoffrey Marcy, quoted in "Planetary Harmony"
by Robert Naeye, Aust S&T Jan 2005

Tonight:

- How to find a planet
- What we found
- What does it mean?
- Where next?

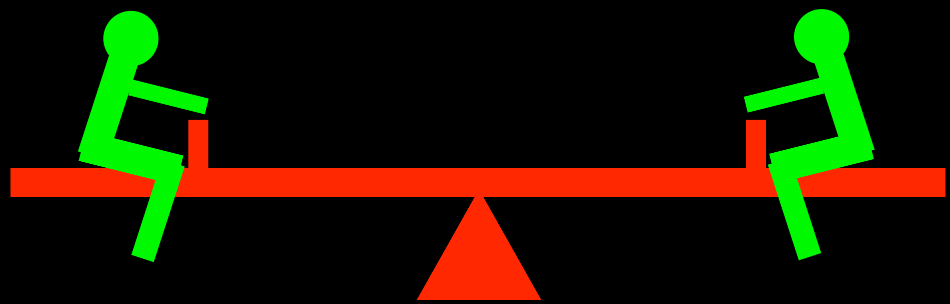
Orbits

We talk about planets orbiting the Sun, but in fact both planet and Sun move. Two bodies in orbit each move about the *centre of mass* (or *barycentre*).



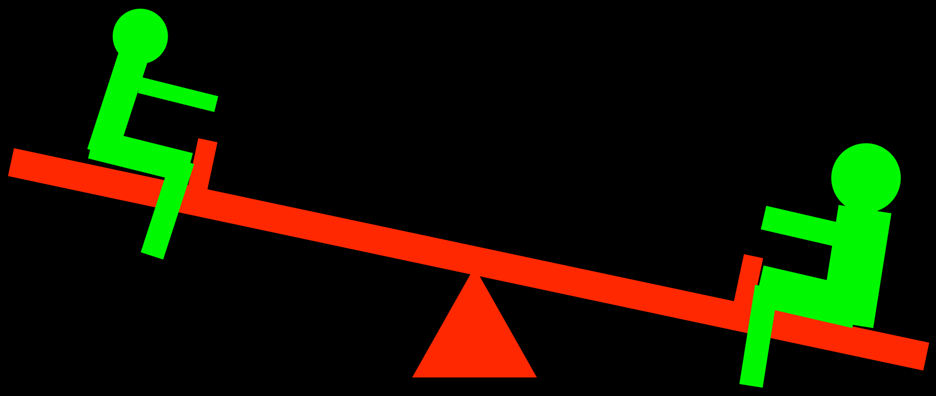
The centre of mass is always directly between the two objects, and where it is depends on their masses.

Just like a see-saw, where the fulcrum has to be placed closer to the heavier child.



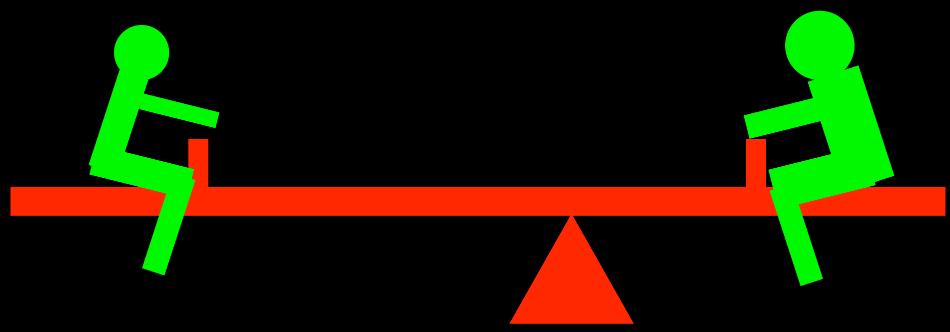
The centre of mass is always directly between the two objects, and where it is depends on their masses.

Just like a see-saw, where the fulcrum has to be placed closer to the heavier child.

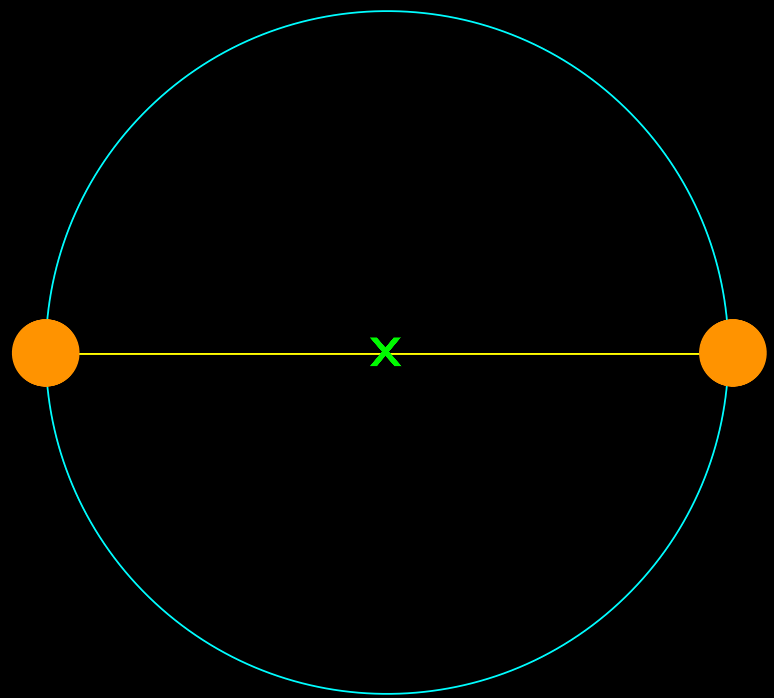


The centre of mass is always directly between the two objects, and where it is depends on their masses.

Just like a see-saw, where the fulcrum has to be placed closer to the heavier child.

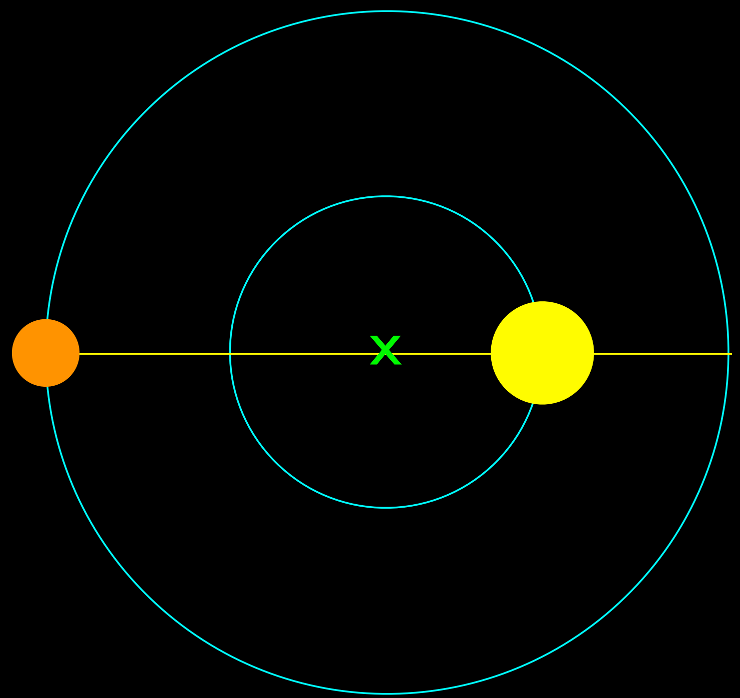


Two objects of equal mass will orbit with the centre of mass exactly halfway between them.



Two objects of equal mass will orbit with the centre of mass exactly halfway between them.

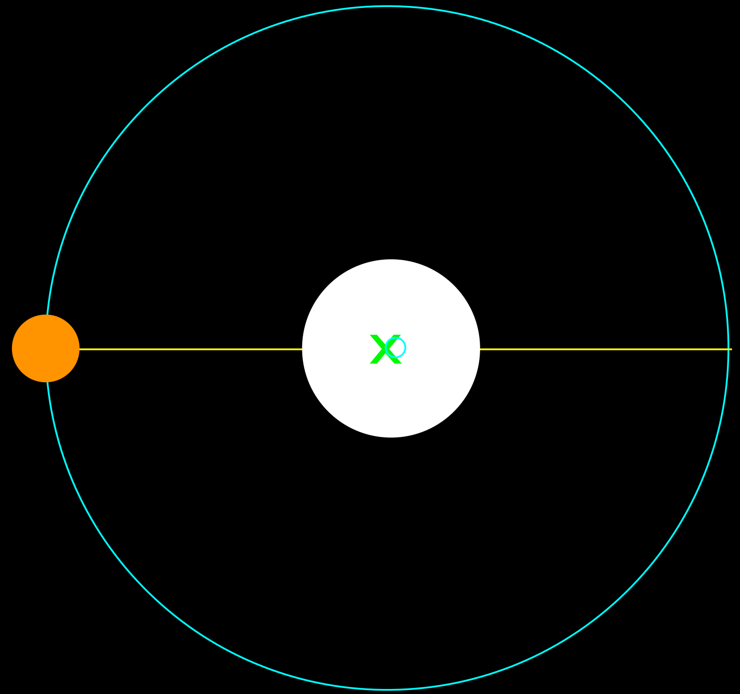
If one object is twice as massive as the other, the centre of mass will be twice as close to it.



Two objects of equal mass will orbit with the centre of mass exactly halfway between them.

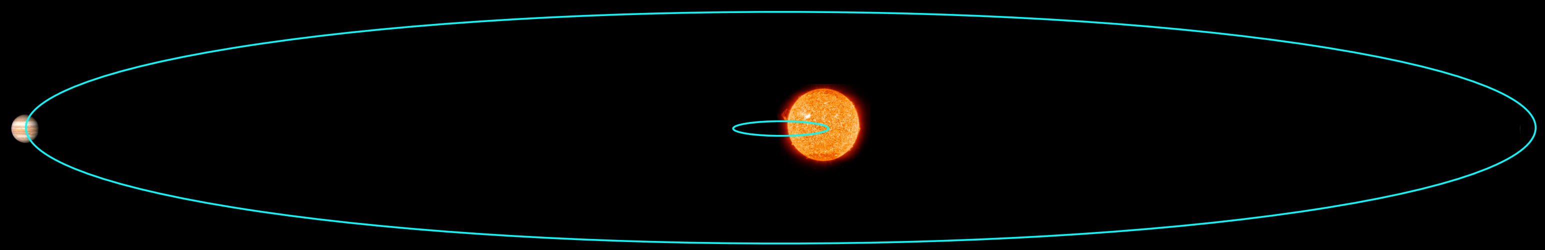
If one object is twice as massive as the other, the centre of mass will be twice as close to it.

If one object is one hundred times as massive as the other, the centre of mass will be one hundred times as close to it.



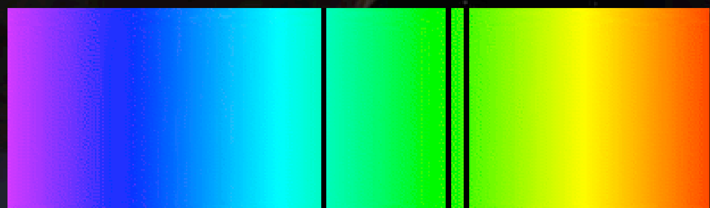
The ratio of the mass of the Sun to the mass of Jupiter is 1000, so the centre of mass is 1000 times closer to the Sun than it is to Jupiter.

The radius of the Jupiter's orbit is just over 1100 times the radius of the Sun, so its barycentre with the Sun lies just above the Sun's surface. Thus as Jupiter executes its 12 year orbit, the Sun executes a much smaller ellipse, wobbling just over one solar diameter.



Stars are much too far away to detect this wobbling in space. However, we can detect *velocities* very easily, because of the Doppler shift.

As the star wobbles to and fro, we see lines in its spectrum moving first to the red, and then to the blue. Measuring the size of this shift allows us to determine the velocity of the star, and hence (from Kepler's law) the mass of the companion.



The Sun moves about the Sun–Jupiter barycentre at about 12 metres per second, so if we can measure a regular change in a star’s velocity of 12 m/s over 12 years, then we can detect a Jupiter-sized planet in a Jupiter-sized orbit.

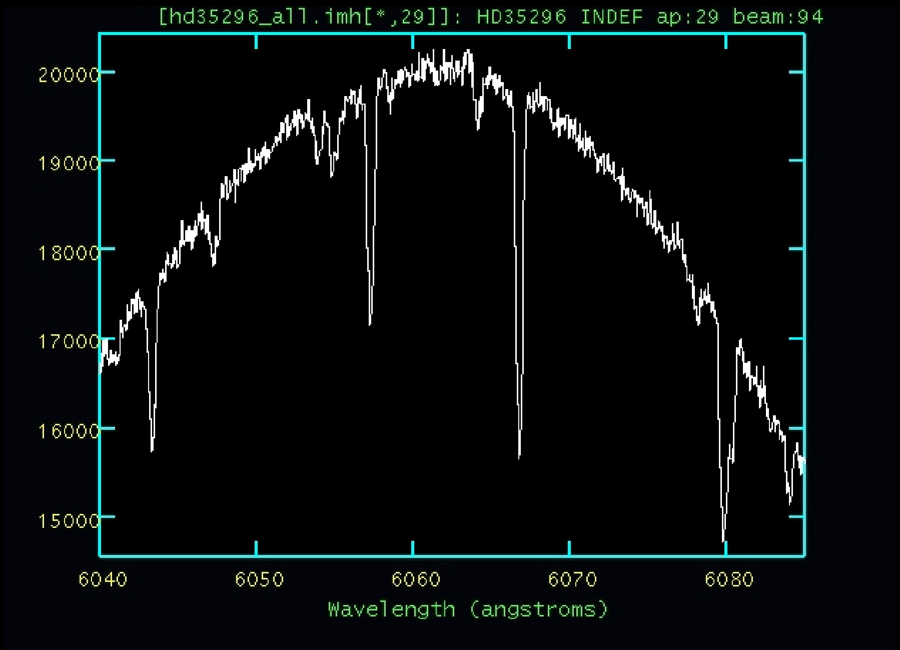
However, this means we have to be able to measure shifts in velocity to 12/300,000,000, or a precision of 4 in a *billion*.

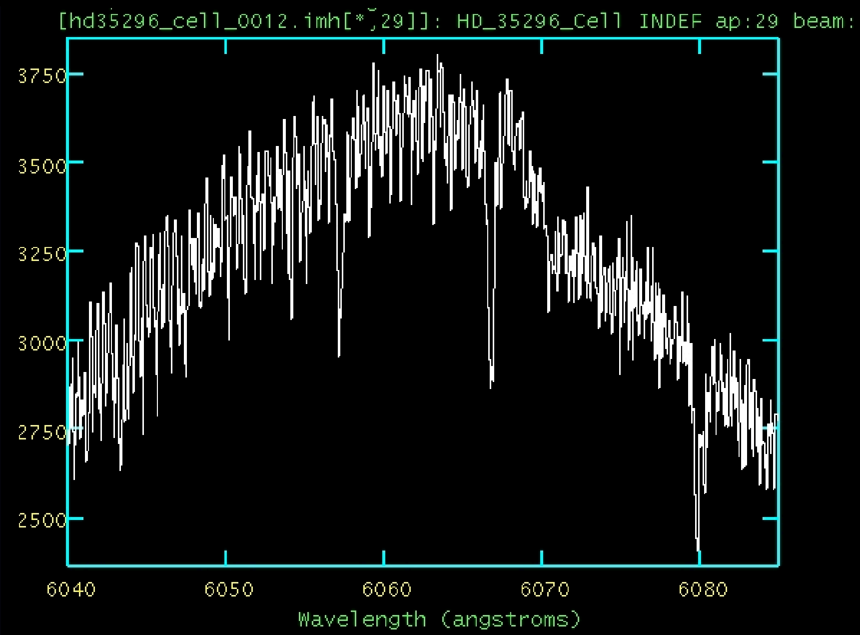
This places extraordinary demands on the stability of the instrument used to make the measurement. We need to spread the light out a long way to measure the tiny shifts, but also have a very stable reference system.

Solution: pass the light from the star through an iodine cell, which superimposes a large number of reference absorption lines on the star's spectrum.

The iodine cell used in the Anglo-Australian planet search.

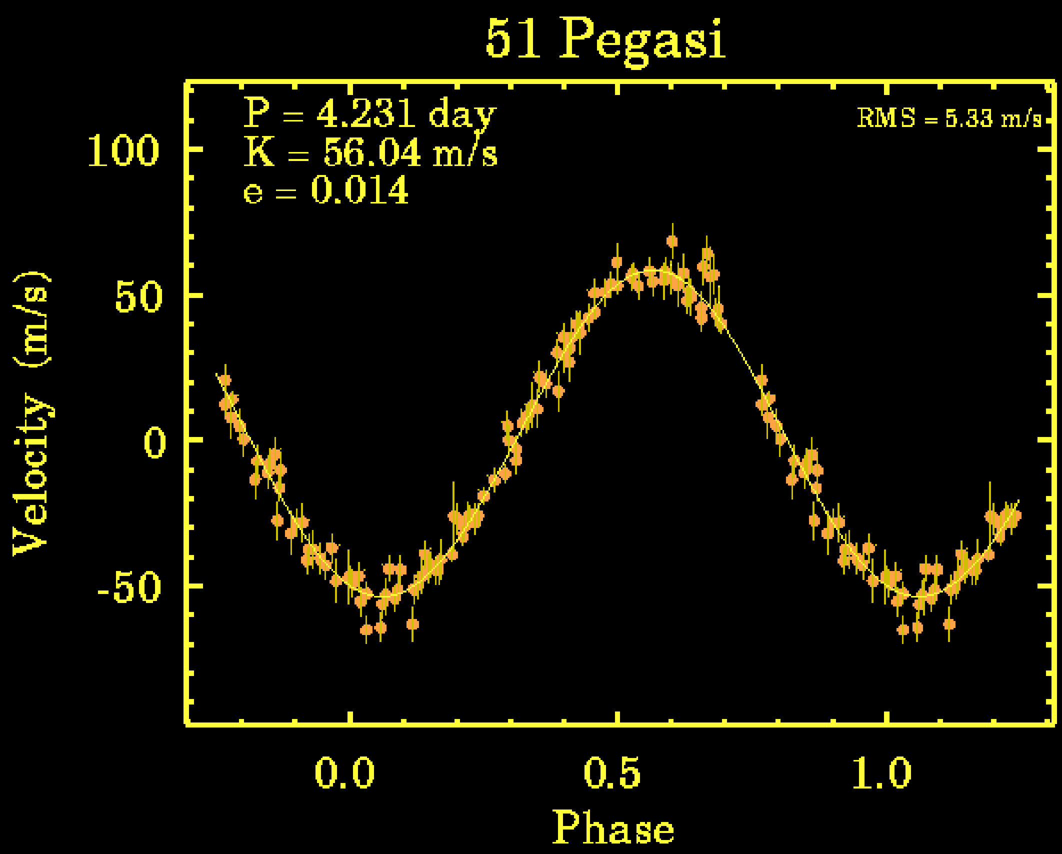
Here is the spectrum of a nearby F dwarf, by itself, and with the light sent through an iodine cell. Each of the wiggles is a sodium line, which allows very precise wavelengths to be measured.





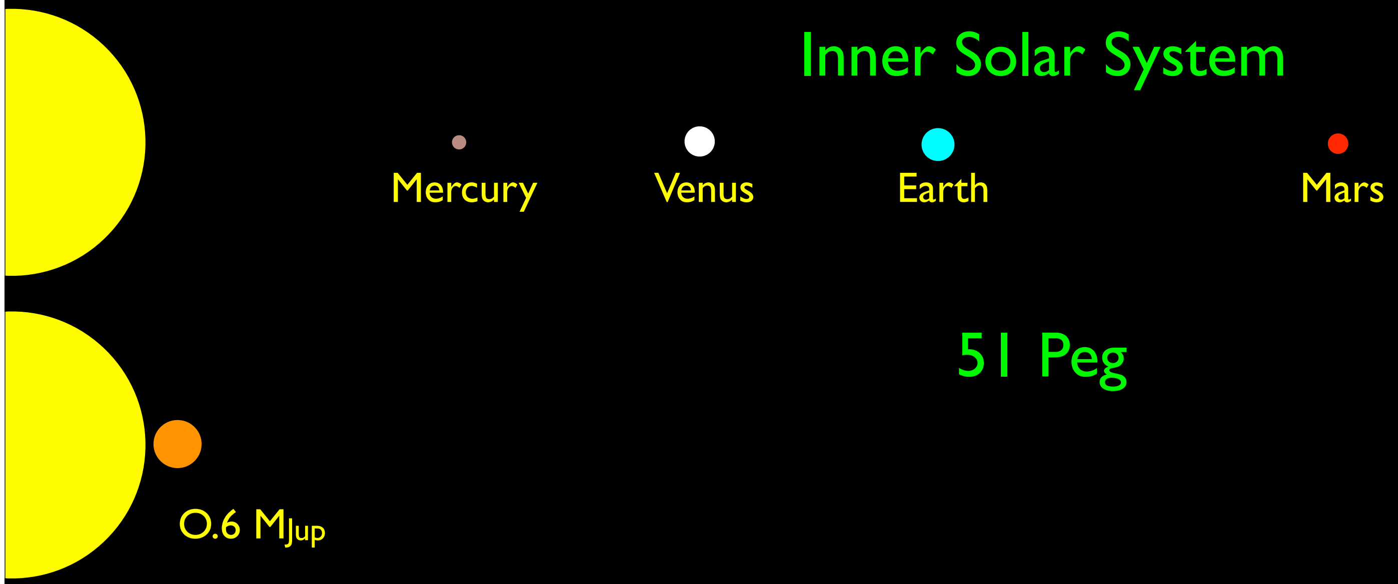
In 1995, Mayor and Queloz, from the Geneva Observatory, announced the discovery of the first extra-solar planet. They had found a regular oscillation of the star 51 Pegasi, a G5 dwarf, very similar to our own Sun, at a distance of 42 lightyears.

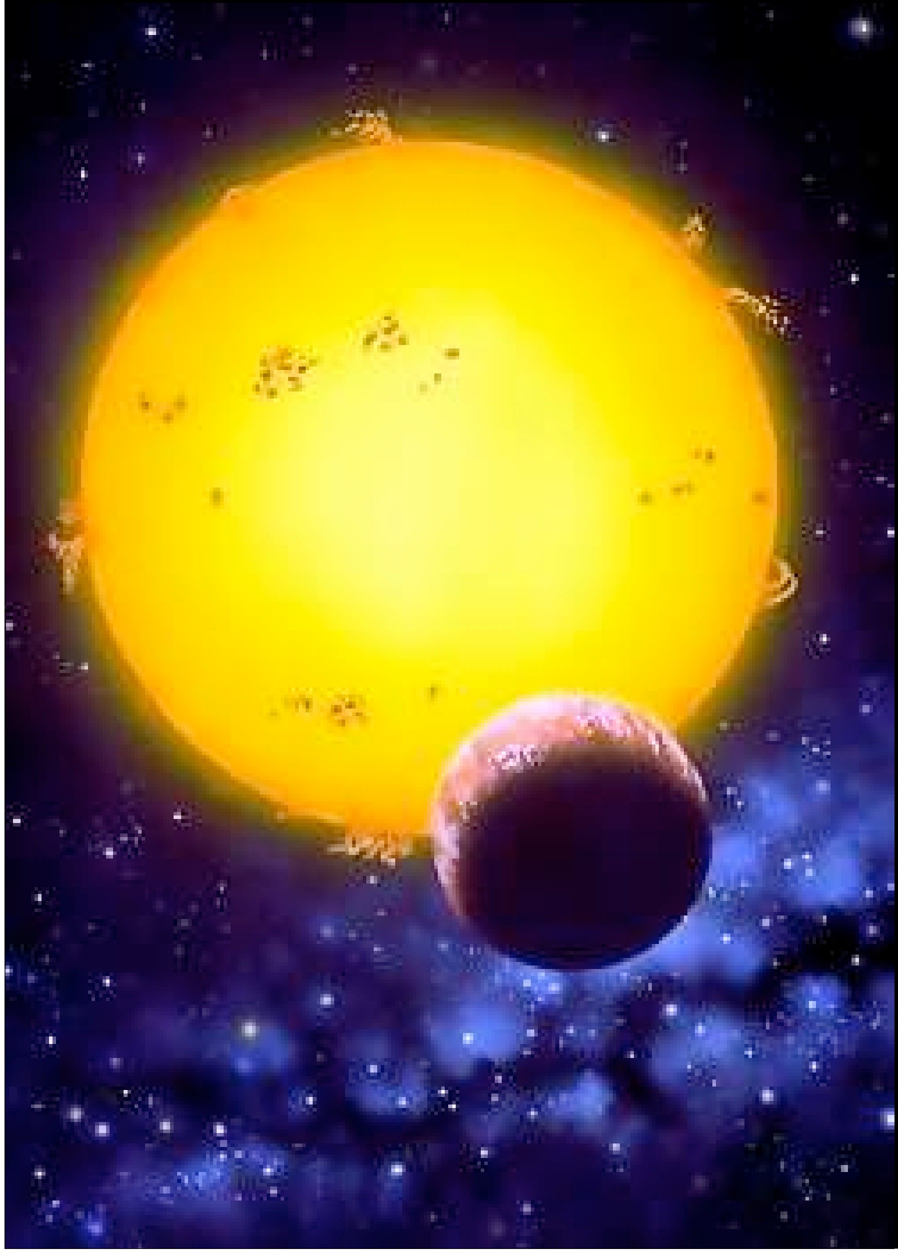
Most astonishingly, the period was only *4.2 days*.



They had found a planet which was 60% as massive as Jupiter, in an orbit much smaller than Mercury's (0.05 AU): a Jovian-mass planet in a sub-Mercurian orbit.

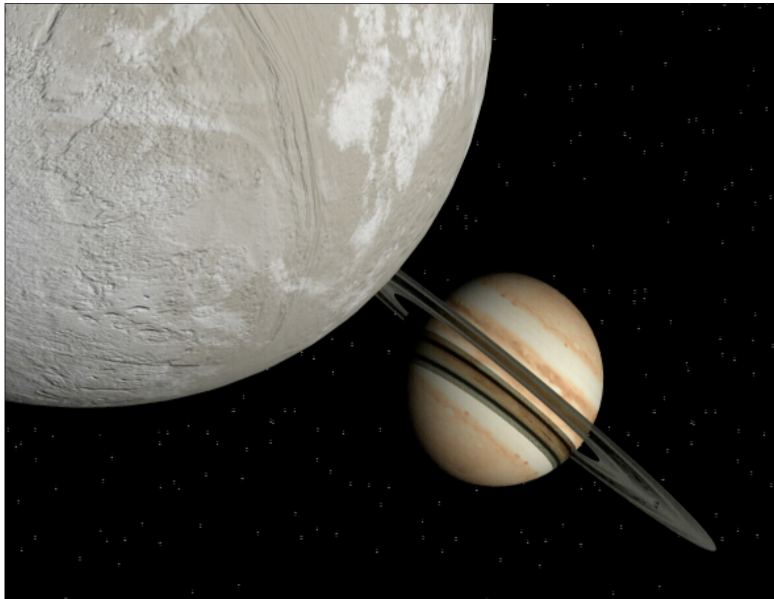
What is such a planet (a gas giant? a giant rocky planet?) doing so close to its star?





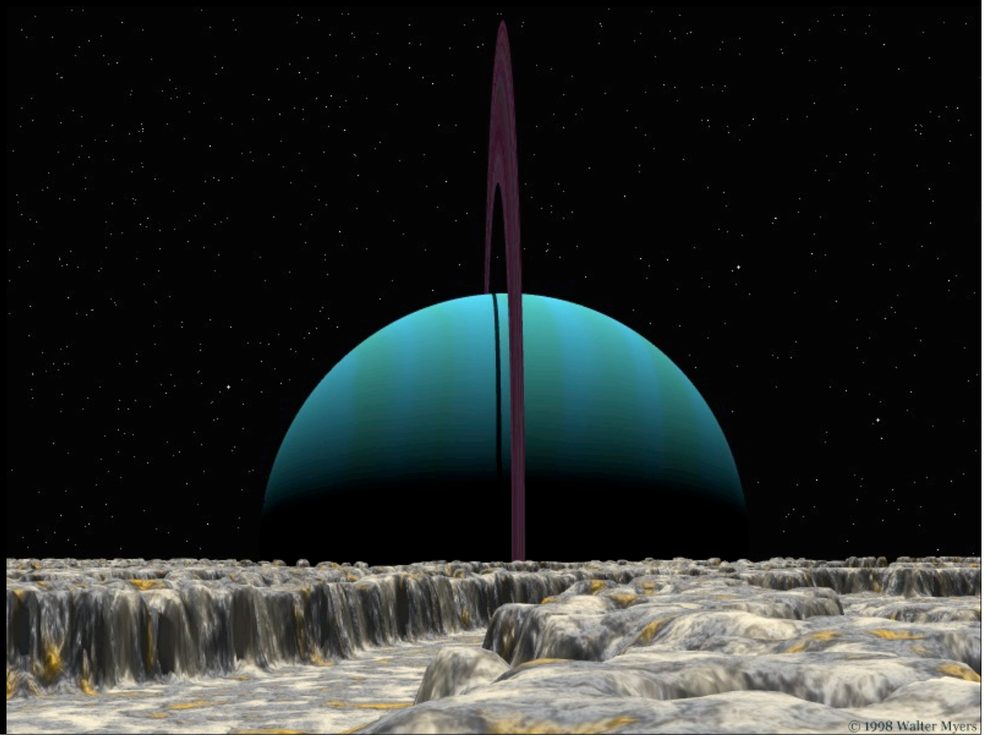
The unlikelihood of forming a massive planet so close to a star could only mean one thing: several people immediately suggested that planets *might not stay put where they were made*.

Artist's impression of the planet around 51 Pegasi.



Almost immediately, two new planets were announced, one around 47 Ursa Majoris and one around 70 Virginis, which, at 7.4 M_{Jup}, is still one of the most massive planets found.

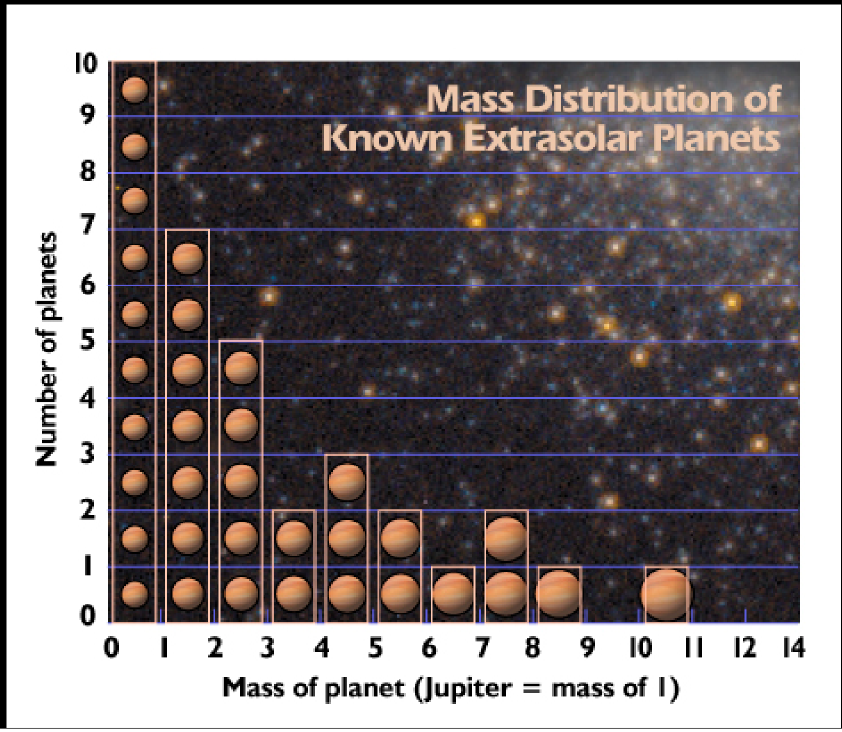
After that, they started arriving at an enormous rate.



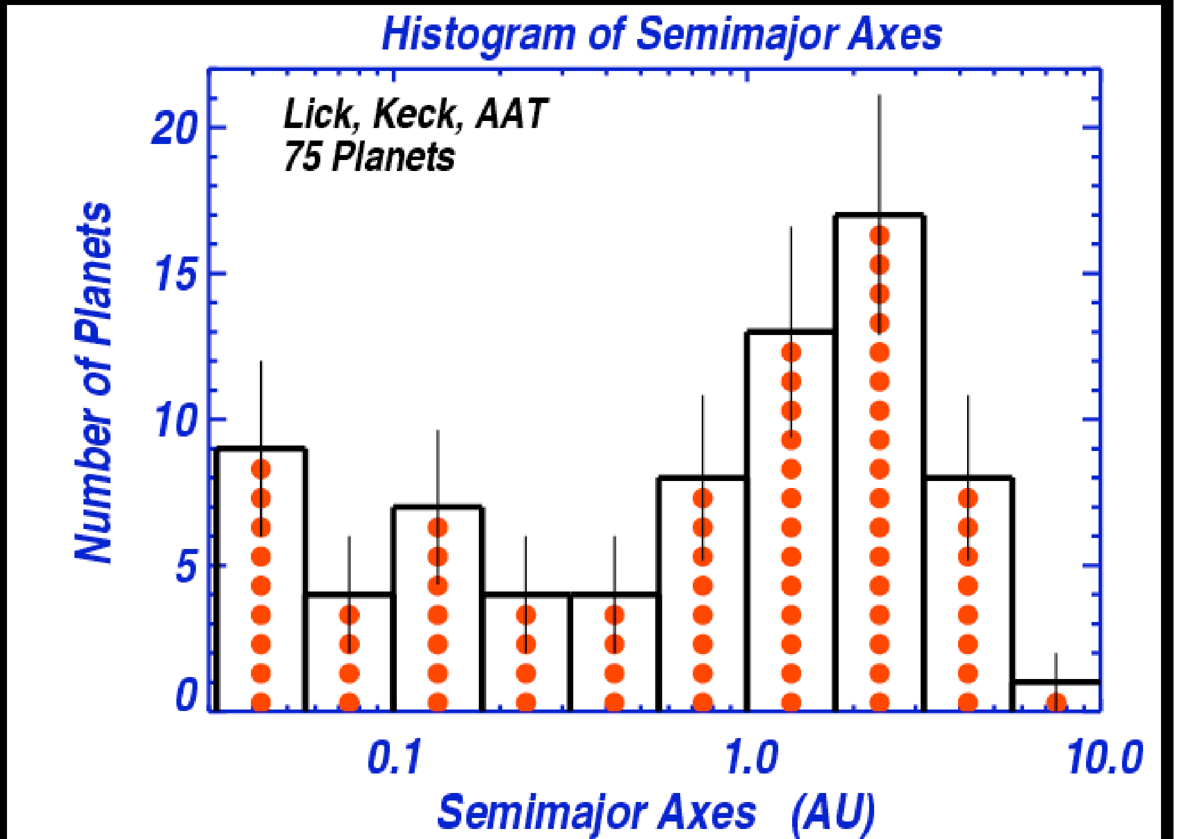

As of 23 May 2005, we know of 155 planets around 136 stars.
None of them look anything like what we were expecting.

With so many planets found, we can start finding some patterns.

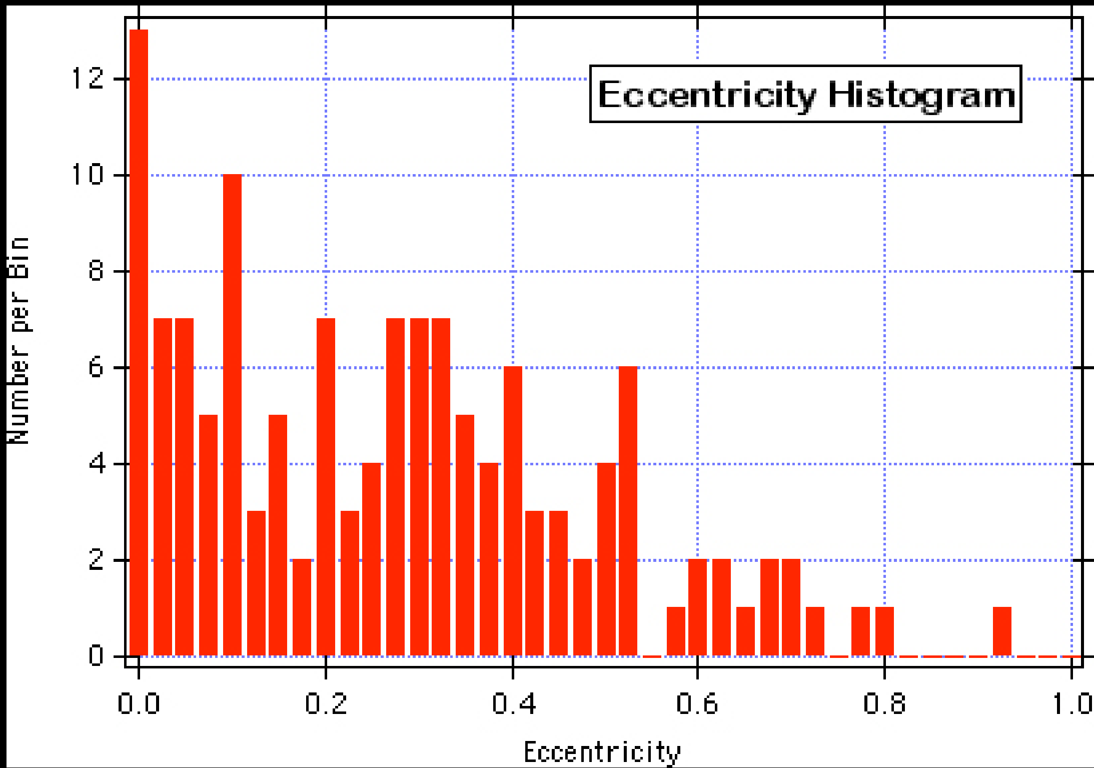
- The masses range between 15 M_{Earth} and about 15 M_{Jup}. There seems to be a real gap between masses of about 12M_{Jup} and 80M_{Jup} – the “brown dwarf desert”.



- A large fraction of the discovered planets look like 51 Peg-b: the so-called *hot Jupiters*: massive planets which orbit very close to their sun.

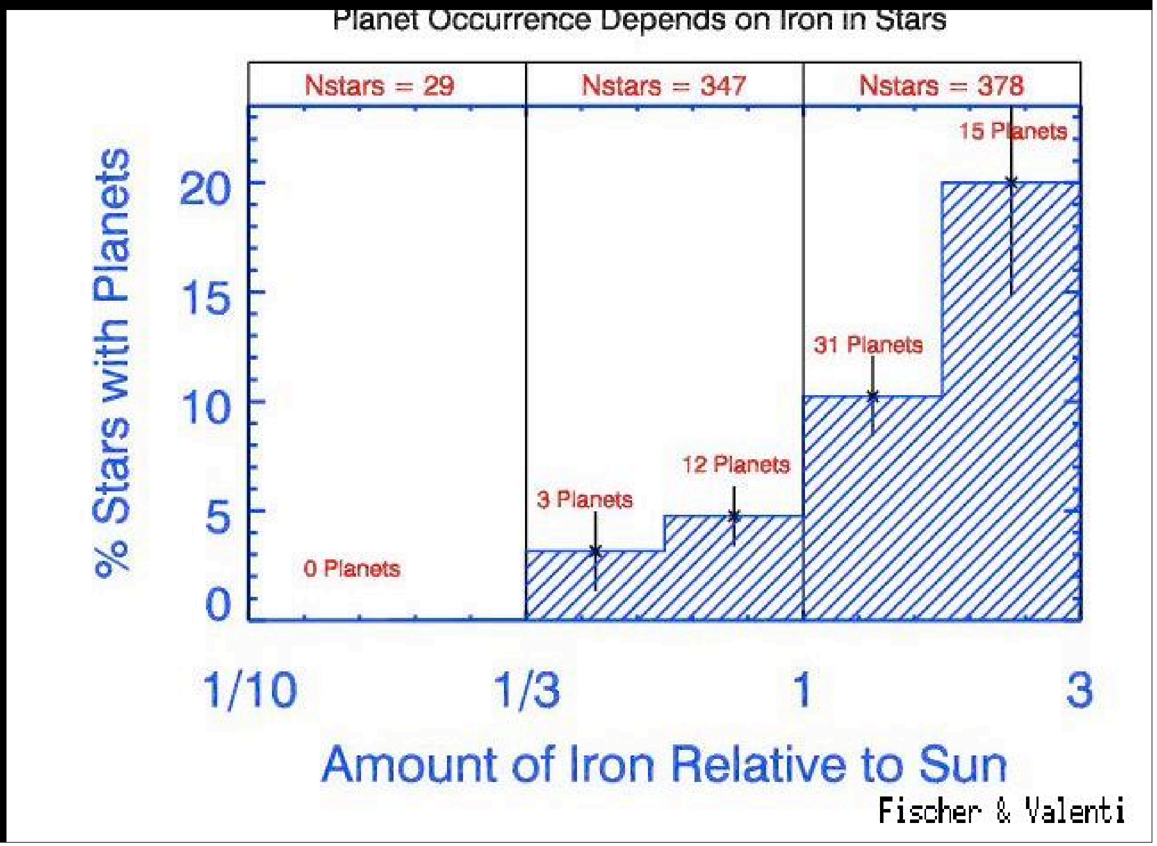


- Most of the planets have eccentric orbits: the mean eccentricity is about 0.25 (compared with Jupiter's orbital eccentricity of 0.094, or Earth's of 0.017). Planets very close to their sun have almost circular orbits, while planets further away can have any eccentricity.

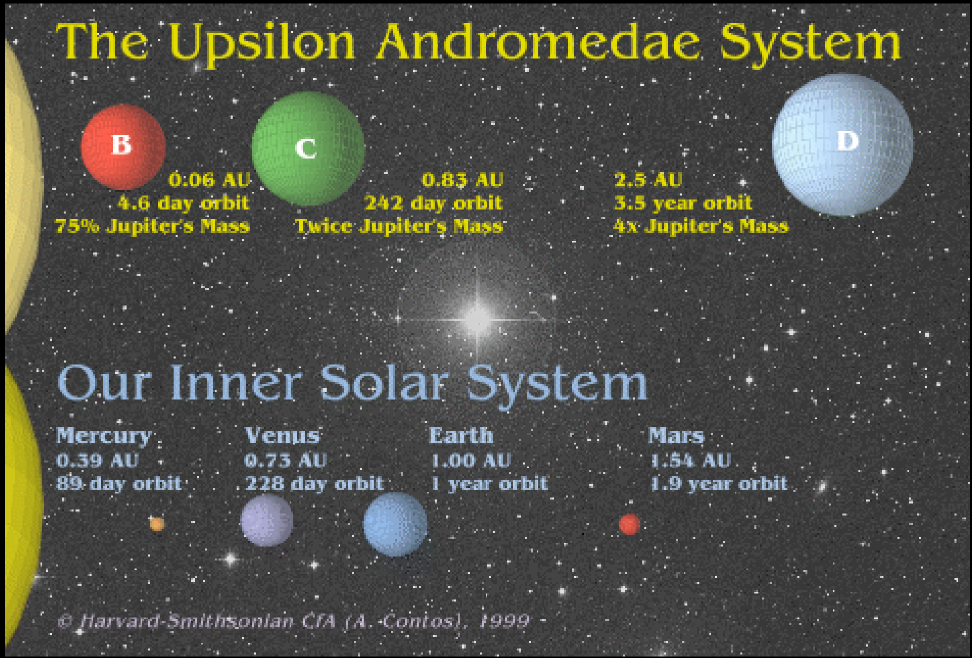


About 7% of nearby G, F and K stars have at least one giant planet within 5 AU.

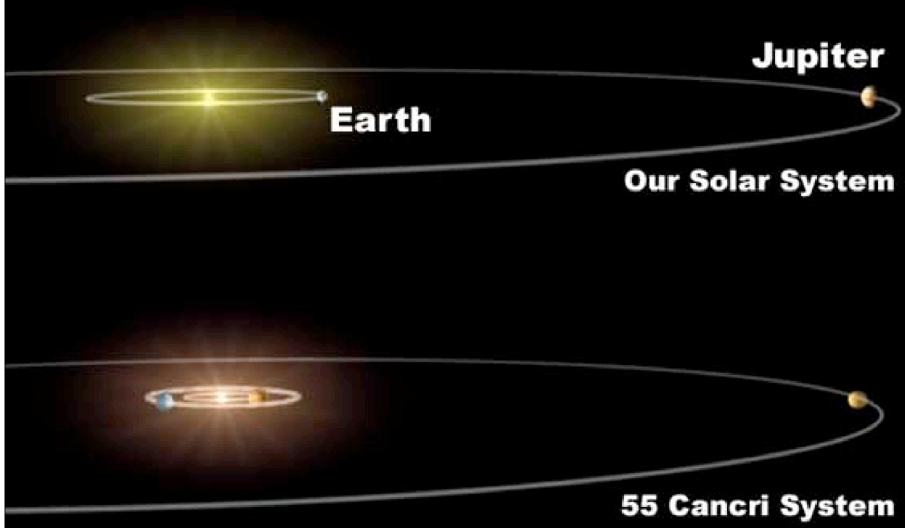
The *chance* of having a planetary companion depends on the metallicity of the star: stars with higher metal content have significantly more planets.



In 1999, the first multiple-planet system was found, around Upsilon Andromedae. All three planets are massive, with the innermost orbiting extremely close to the star.



We now know of 14 multiple planet systems: the system around 55 Cancri has four planets.



What does it mean?

So far, *none* of the discovered systems look much like the Solar System (though we're at least getting closer).

So what are the problems so far?

- *How do you form "hot Jupiters"?*

In the model of planet formation we discussed last week, it's very difficult:

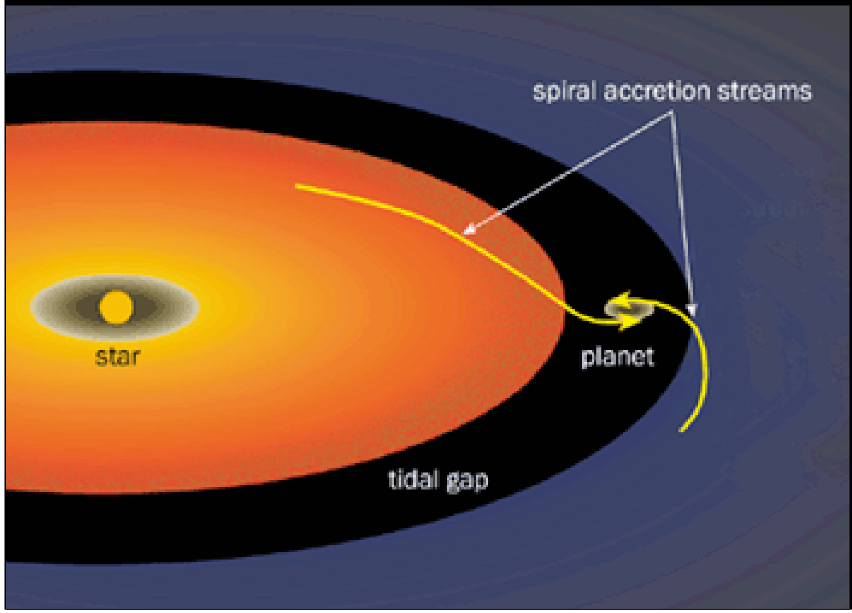
– too hot
– too little material
– too little gas to form envelope

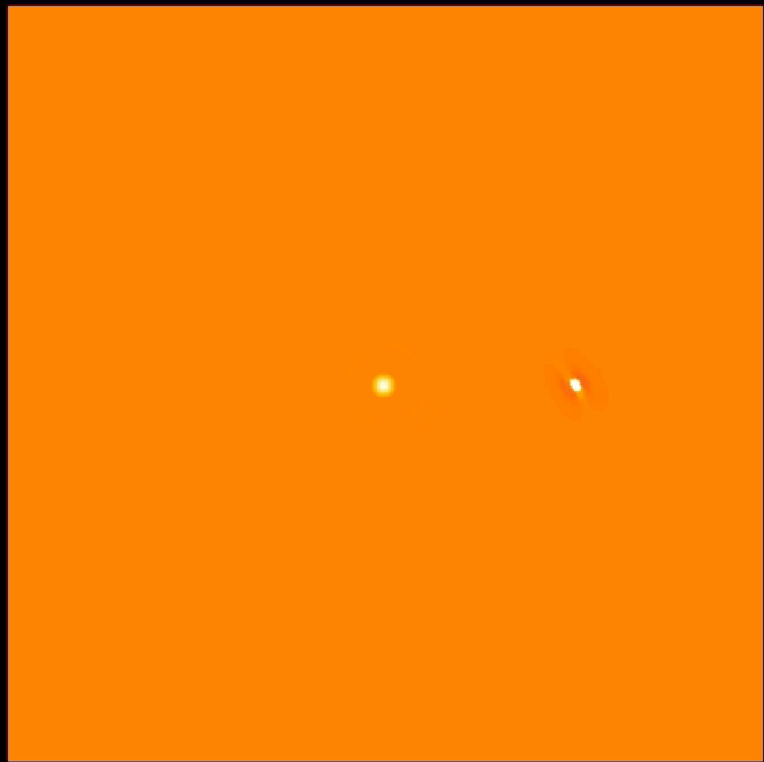
Require: *planetary migration*.

You remember that the giant planets accreted gas directly from the disk. We discussed how they had to complete their accretion before the proto-Sun blew the gas away. What we didn't stress was that there must have been a period when the giant proto-planets were embedded in the disk.

What effect does this have?

Simulations have shown that tidal interactions with the disk force the planet to migrate inwards.





Simulation of a proto-planet growing from 10 Earth masses to 1.5 Jupiter masses

So why does it stop? Why doesn’t it plunge into the star?

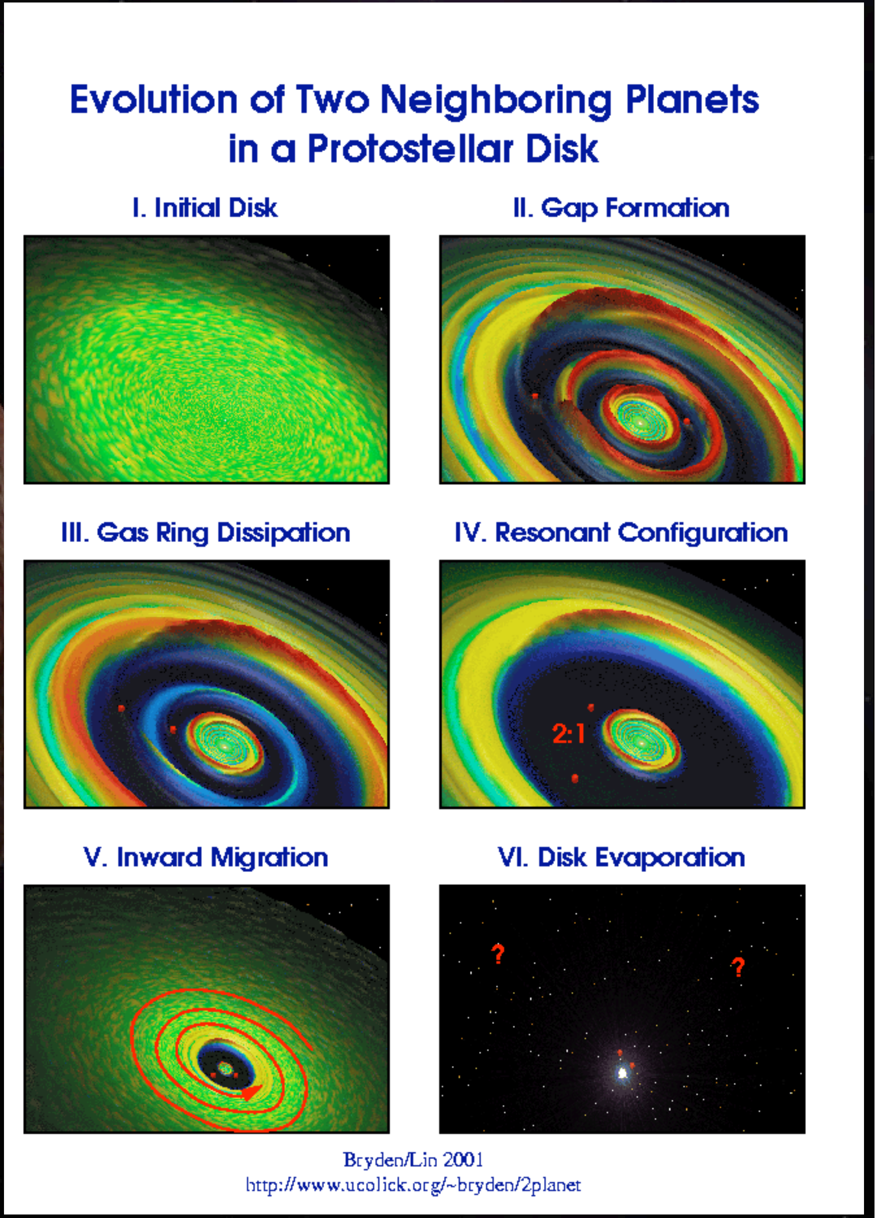
- It reaches the inner edge of the disk? (cleared by the star’s magnetic field, perhaps?)
- Tidal interactions with the star?
- Planet fills its Roche lobe and recedes from the star?
- Orbit stabilised by resonant interactions with other planets?
- Perhaps they didn’t stop: the visible planets are merely the survivors from a long chain of planets which spiralled into the star...

Resonances between planet orbits are looking as though they may be very important in many systems. Seven of the multiple-planet systems show resonances.

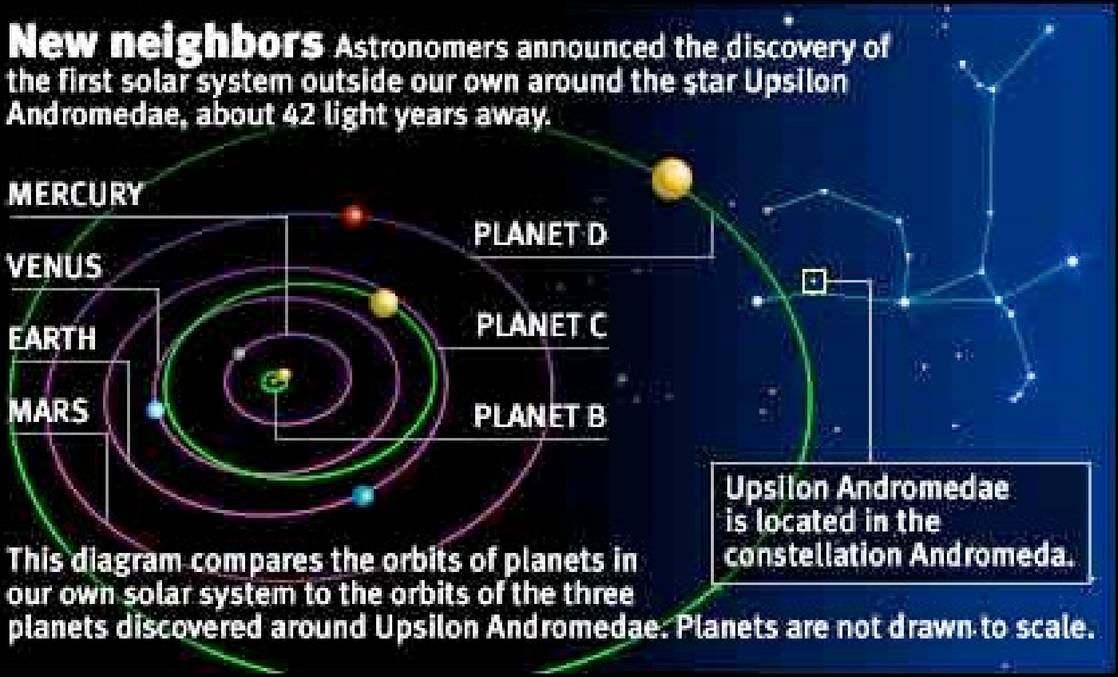
System	*N*	Resonance type
Gliese 876	2	Planets in a tight 2:1 mean-motion resonance and a secular resonance
Upsilon Andromedae	3	Planets c and d in a secular resonance
55 Cancri	4	Planets b and c probably in a 3:1 mean-motion resonance
HD 82943	2	Planets in a 2:1 mean-motion resonance
HD 12661	2	Planets in a secular resonance, but anti-aligned
HD 37124	2	Planets probably in a 5:1 mean-motion resonance
HD 128311	2	Planets in a 2:1 mean-motion resonance and a secular resonance

The existence of so many resonances is giving many clues into how these systems form and evolve.

Here is a model for the 2:1 orbital resonance of Gliese 876's two planets.



The idea that planet-planet interactions are important received confirmation from the peculiar system around Upsilon Andromedae. The two outer planets have highly elliptical orbits ($e \sim 0.3$) which interact on timescales of 10,000 years, and whose combined effect circularises the inner planet's orbit every 7000 years.



The Upsilon Andromedae orbits compared to the inner Solar System.

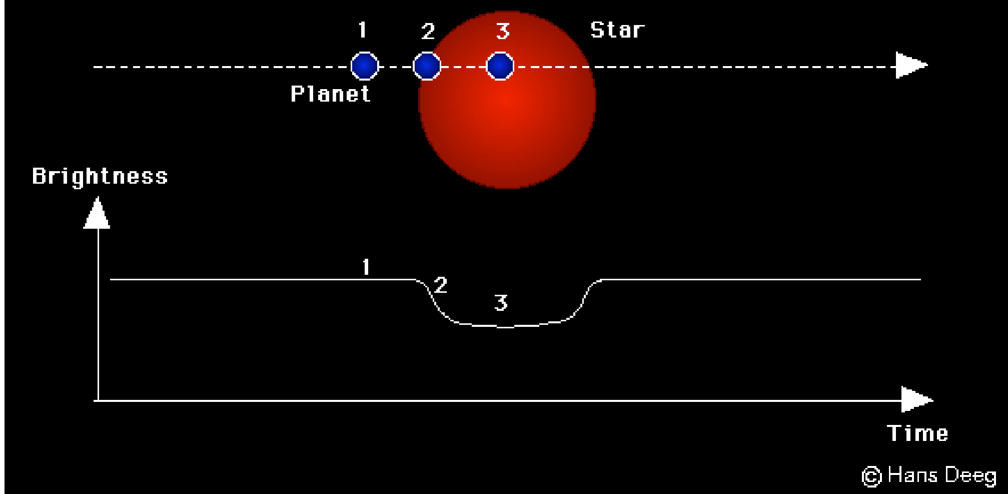
Recent work suggests this is the result of interactions with another giant planet had a close encounter with the outermost planet, and was then ejected from the system, leaving the middle two planets in eccentric orbits.

A Simulation of
Planet-Planet Scattering in the
Upsilon Andromedae
Planetary System

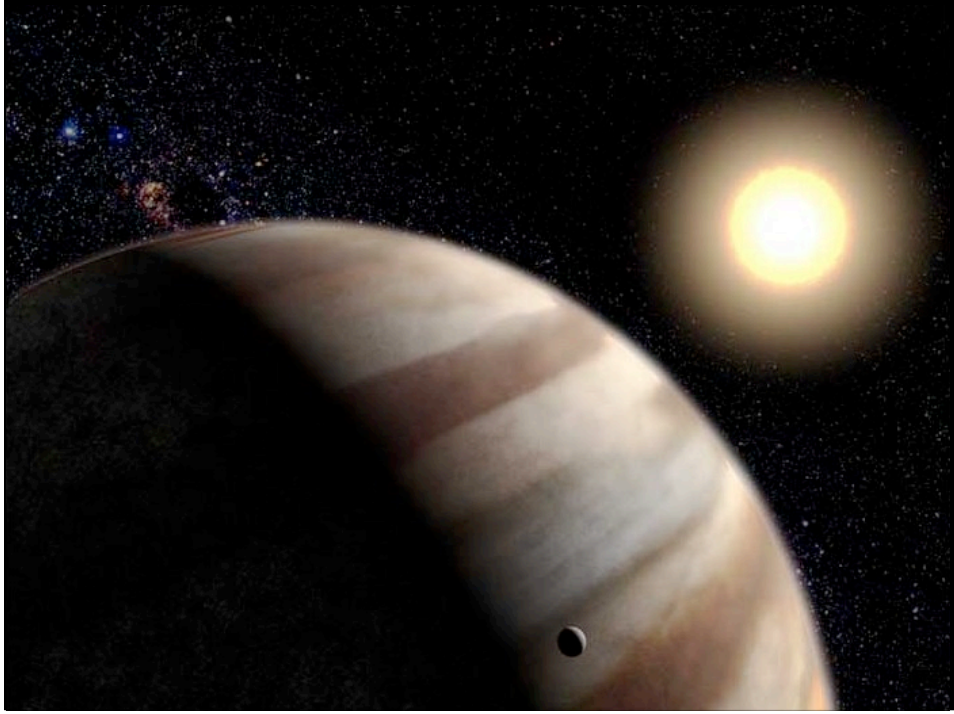
Diameters of planets have been
greatly exaggerated for visibility

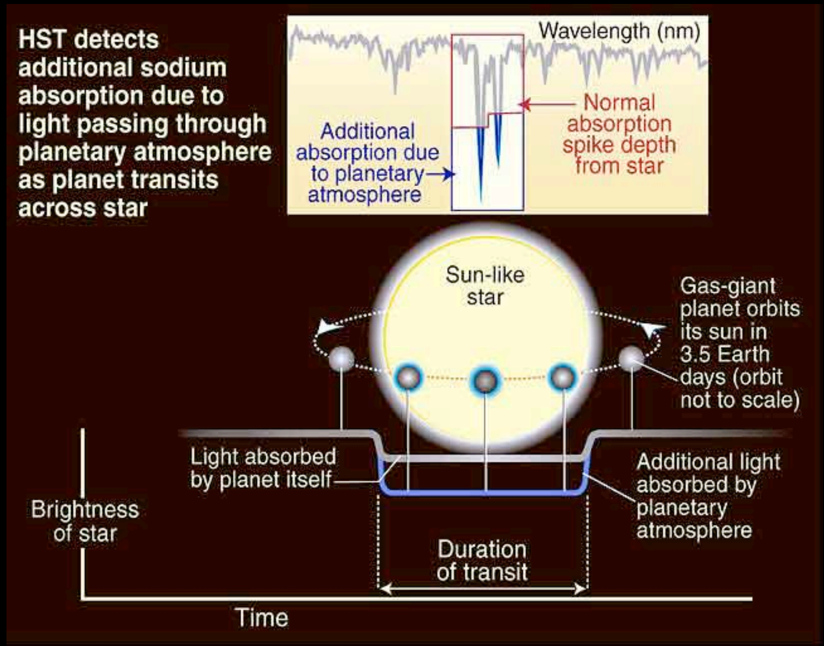
Latest news

Planets are now starting to be detected using *transit observations*: where the dimming of the light from the star caused by a planet moving in front is recorded.

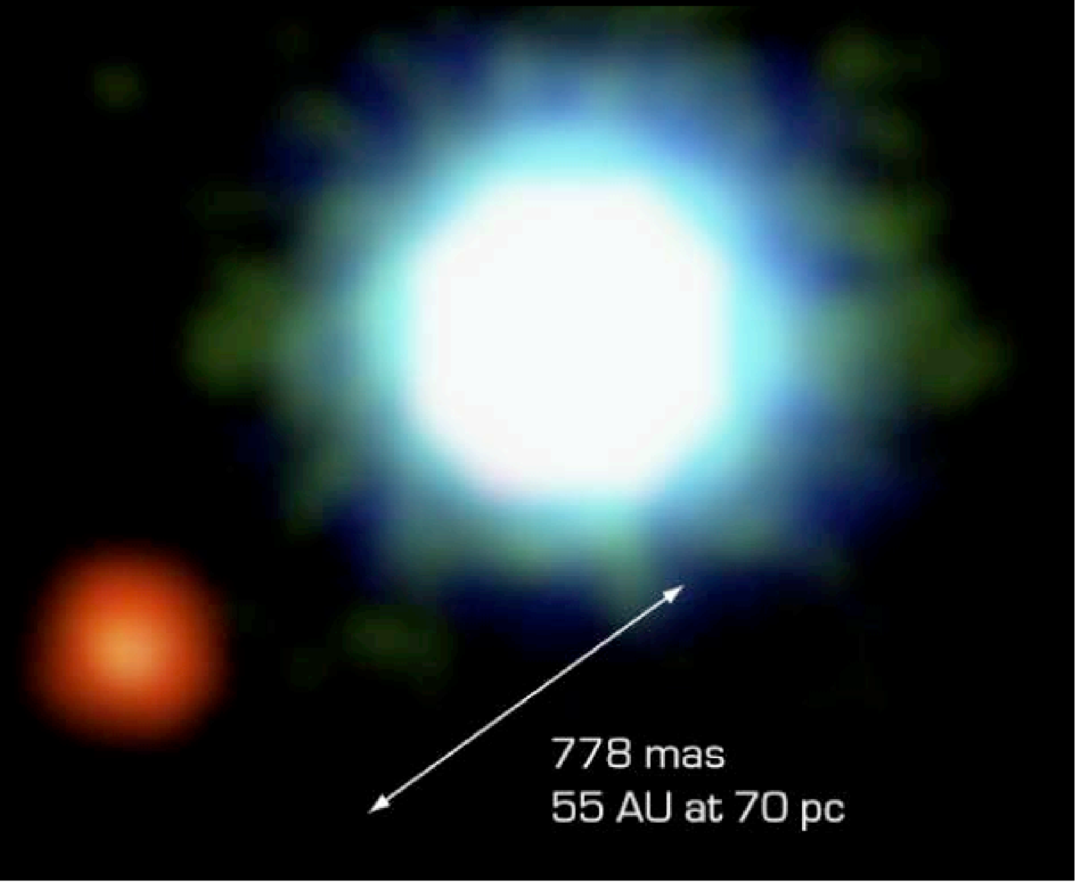


In 2001, Hubble detected an atmosphere around an extrasolar planet for the first time, detecting sodium in the atmosphere of a $0.7M_{Jup}$ mass planet orbiting HD 209458 in just 3.5 days.





Infrared images from the VLT provide the first direct image of an extra-solar planet, around a brown dwarf. The companion is about 5 Jupiter masses, and shows strong spectral signatures of water.



Where next?

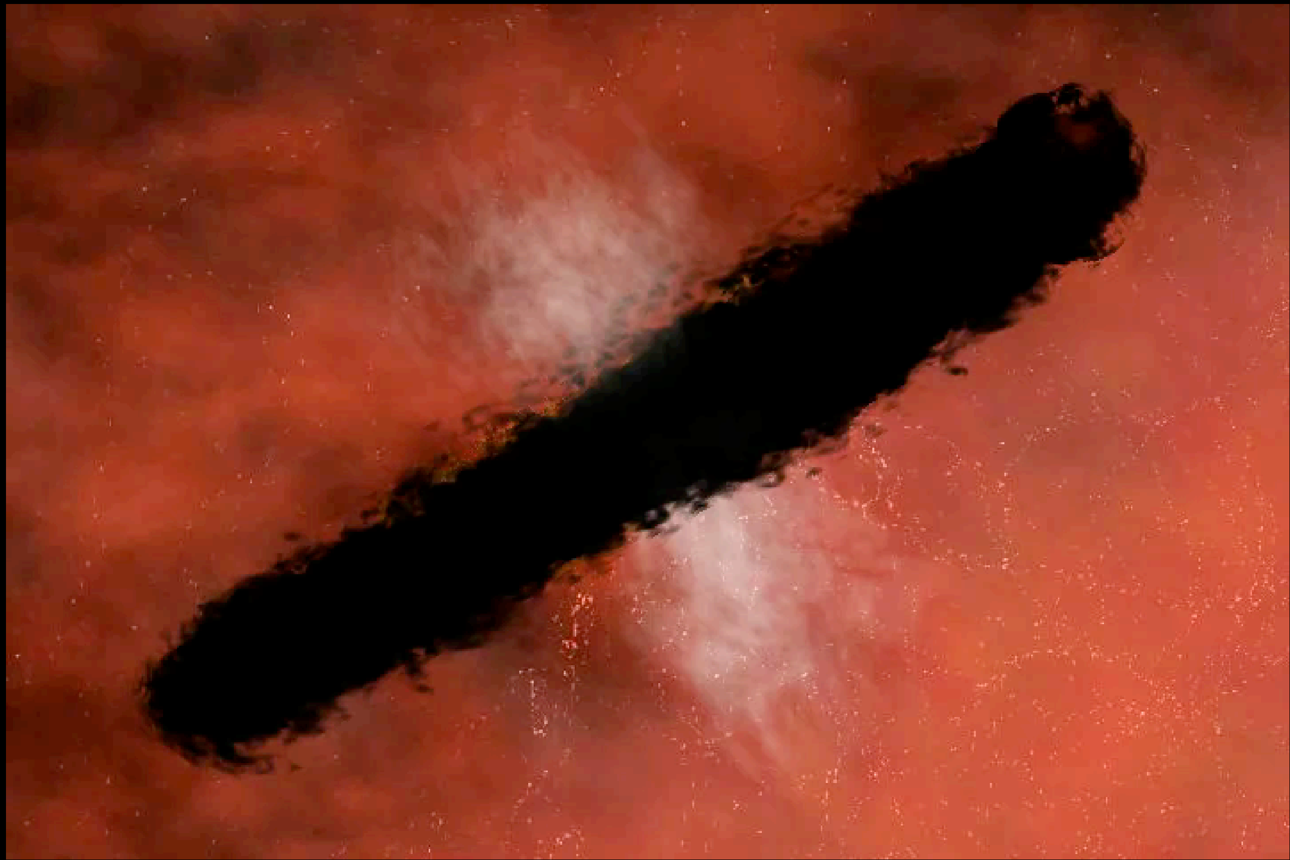
The new planets have raised enormous numbers of questions. Some of the biggies:

- *How do giant planets get eccentric orbits?*
- *How do hot Jupiters form, and what stops their migration?*
- *Why didn't Jupiter migrate?*
- *How common are systems like the Solar System?*

The next few years are going to be exciting times for planetary astronomy.

The big radial velocity searches have been going for about 12 years now; only now can they start seeing orbital periods as long as Jupiter's.

Chandra recently saw huge flares from young stars in the Orion nebula. It is possible these may disrupt the planet-forming disks and prevent planets from plummeting into the star.



Animation of X-ray flares from a young sun affecting a planet-forming disk.

Then there's the technique known as *microlensing*: detecting a planet because it bends the light of a background star, making it increase in brightness in a predictable way.

Last Update: Tuesday, May 24, 2005. 11:35am (AEST)   Print   Email

Aust astronomers help spot new planet

The Canopus Observatory telescope was involved in the planet's discovery. (Photo courtesy of University of Tasmania)

A new planet has been discovered in the Milky Way with the help of a team of Tasmanian astronomers.

The gassy planet is about 1,000 times the size of earth and is located halfway to the centre of the galaxy - about 25,000 light years away.

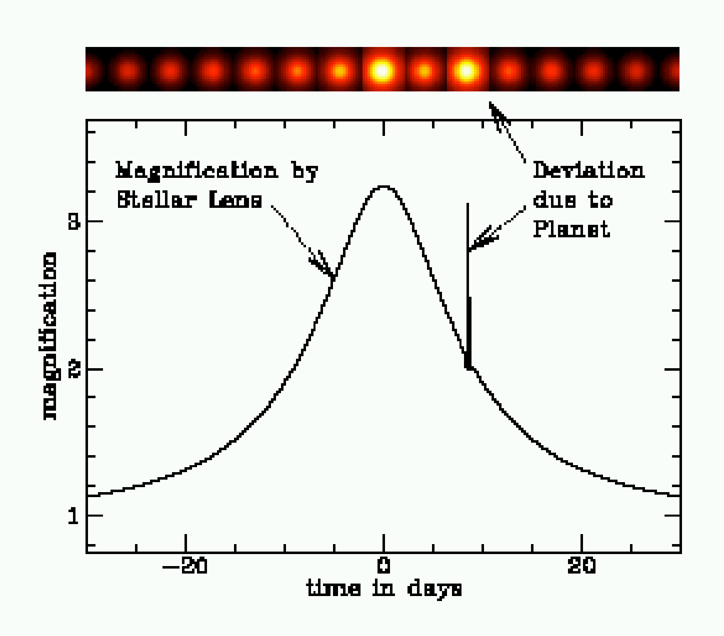
The Paris Institute for Astrophysics is coordinating the project; four Southern Hemisphere telescopes, including the University of Tasmania's Canopus Observatory, were involved in the discovery.

The university's Stefan Dieters says they used a little-known technique called "micro-lensing" to identify the planet.

"It's the only method around at the moment that can detect earth-mass planets," he said.

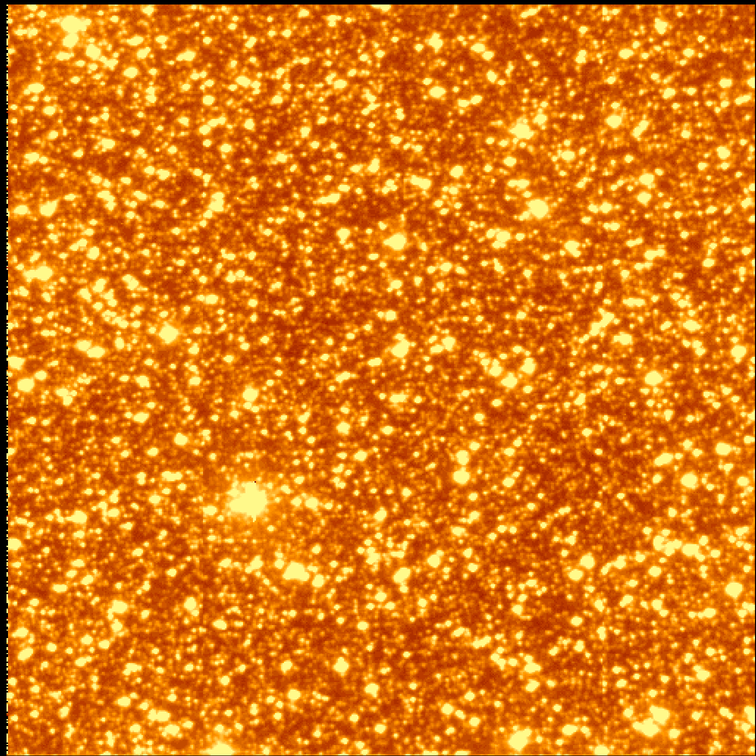
"So with this discovery we are now very confident we can detect an earth-mass planet, if we get a little bit of luck."

Article from ABC News, 24 May 2005

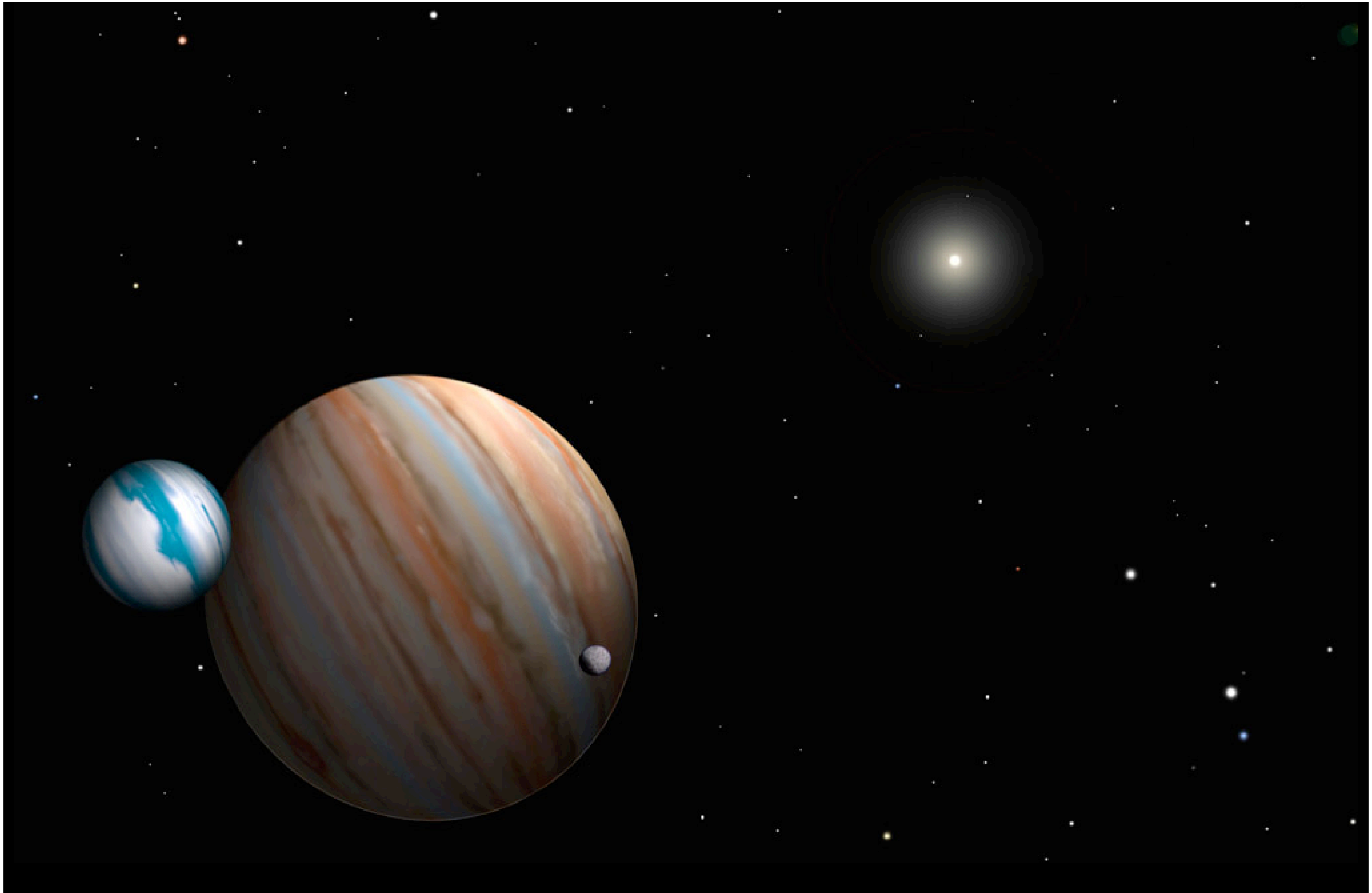


The technique has the advantage that it is sensitive to even quite small planets. Unfortunately, the events never repeat, so it is impossible to study individual systems.

However, microlensing can be used as a tool for studying the *statistical* properties of planetary systems.

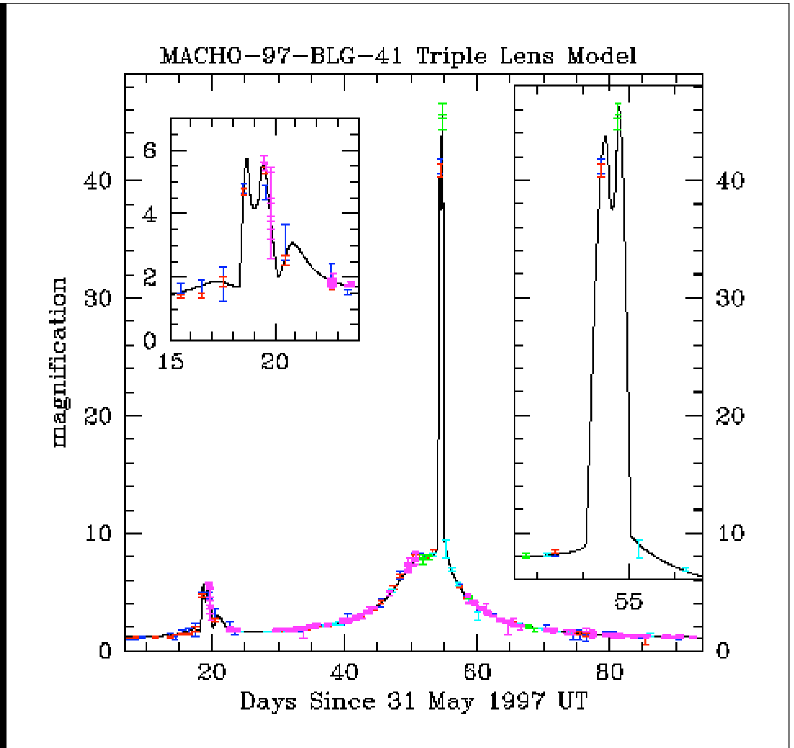


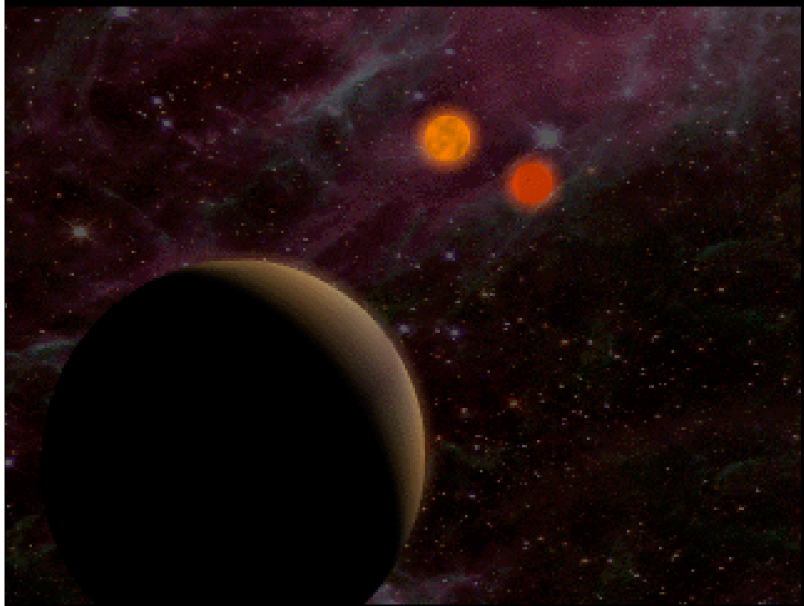
A typical field being monitored for micro-lensing events: the brightness of each of these stars is measured.



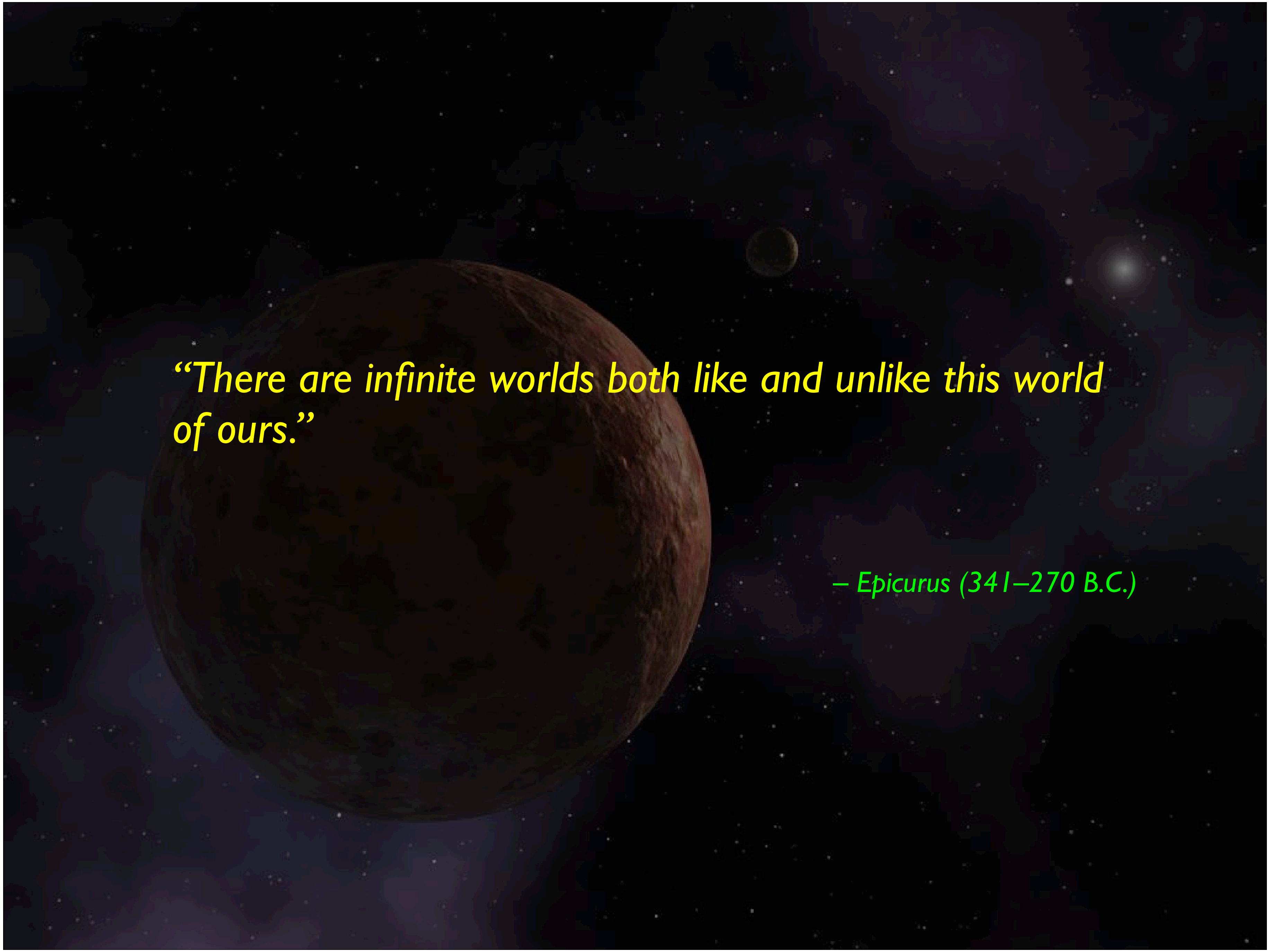
This artist's conception shows the second planet to be found using gravitational microlensing. It weighs about three times as much as Jupiter and orbits a sun-like star located approximately 15,000 light-years from the Earth. Credit: David A. Aguilar (CfA)

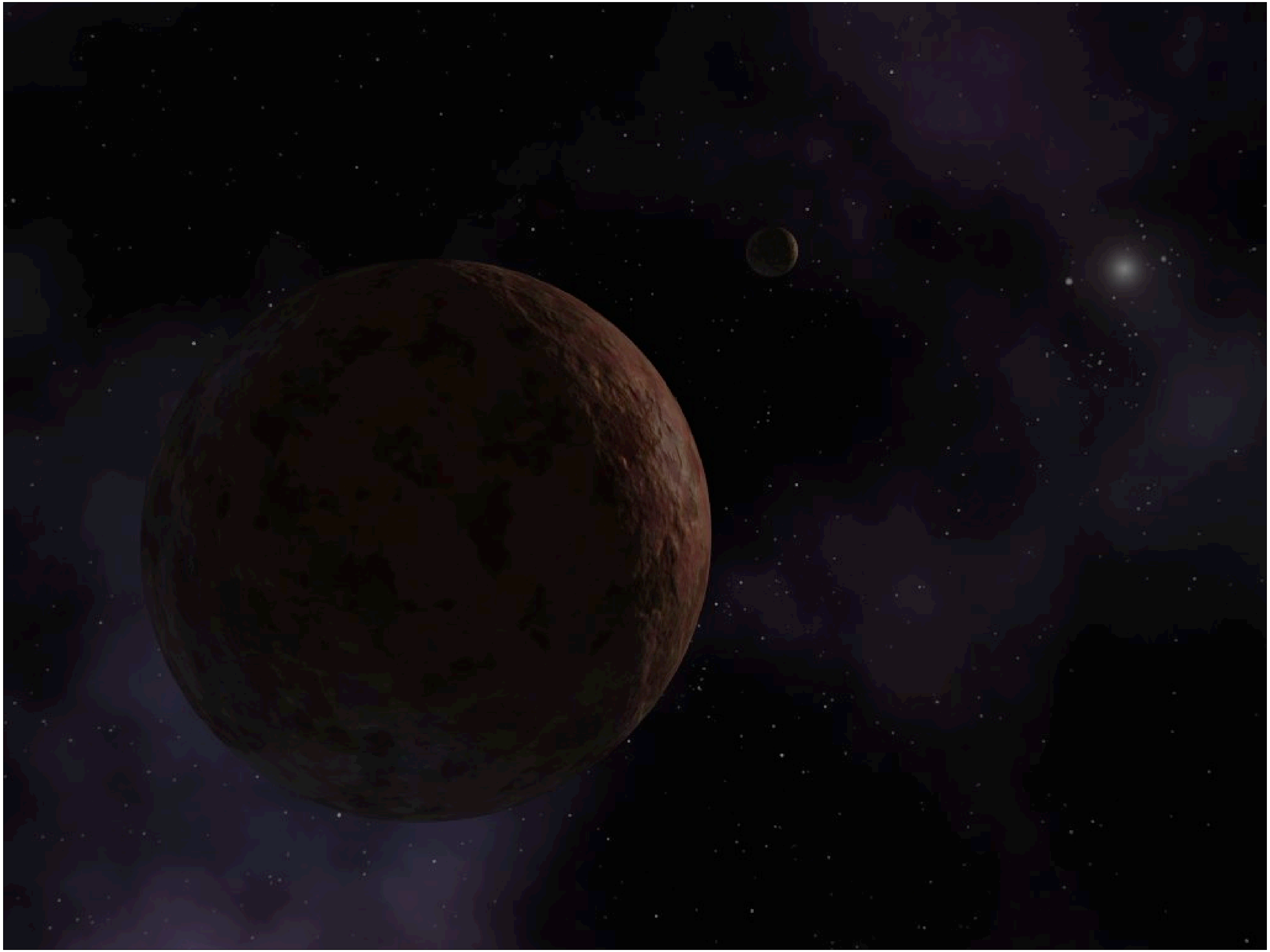
In 1999, observations from Mount Stromlo detected a microlensing event which was probably due to a planet orbiting a binary





The stars are probably a K dwarf and an M dwarf with a separation of about 1.8 AU, orbited by a $3M_{Jup}$ object at a distance of about 7 AU.


“There are infinite worlds both like and unlike this world of ours.”
– Epicurus (341–270 B.C.)



Future astronomy courses

- Spring 2005:

  Stars and Galaxies

  (with Geraint Lewis)

  A general introduction to the most important concepts in astronomy

- Autumn 2006:

  Lives of the Stars

  A more detailed look at how stars live and die; follows on from Stars and Galaxies

- Spring 2006:

  Topics in Modern Astronomy

  Guest speakers talk about their research

Further reading

Quite a few books have been written in recent years about the discovery of planets outside our solar system, but unfortunately most of them seem to have been written immediately after the first few were found in 1996, so are now seriously out of date, less than a decade later!

- One of the ones I read was **"Looking for Earths: The race to find new solar systems"** by Alan Boss (John Wiley, 1998). He has a good description of the early years, and the many failures and retractions of planets before eventual success. The last part of the book spends far too long on NASA acronyms of projects that don't exist yet, and the tentative suggestions about distinguishing between planets and brown dwarfs are now very out of date.
- Michel Mayor, co-discoverer of the first planet, has a book called **"New Worlds in the Cosmos: The discovery of exoplanets"** by Michel Mayor and Pierre-Yves Frei, transl. Boud Roukema (Cambridge UP, 2003). It's much more up-to-date, and has a good description of what people are now thinking about how to make these planets. Doubtless it too will look very dated in a few short years!
- Web-sites can at least stay up-to-date, even if they're less readable. A couple of good ones:
  - The California and Carnegie Planet Search, http://exoplanets.org/
  - The Extrasolar Planets Encyclopaedia, http://cfa-www.harvard.edu/planets/
- The cover story of the first issue of *Australian Sky and Telescope* was all about planet resonances: **"Planetary Harmony"** by Robert Naeye, AS&T January 2005

Sources for images used:

- Background image: Artist's conception of Sedna, from Spitzer Press Release 15 March 2004, http://www.spitzer.caltech.edu/Media/releases/ssc2004-05/index.shtml
- Iodine cell: from The Anglo-Australian Planet Search, http://www.aao.gov.au/local/www/cgt/planet/aat.html
- Example spectrum through iodine cell: from TLS Tautenburg: Coudé Echelle Spectrograph, http://www.tls-tautenburg.de/coude/echelle_spectrograph.html
- 51 Pegasi figures: from Niel Brandt, Astro 1, http://www.astro.psu.edu/users/niel/astro1/slideshows/class44/slides-44.html
- 47 Ursa Majoris: artist's impression by John Whatmough, from Astronomy Picture of the Day 1997 October 5, http://antwrp.gsfc.nasa.gov/apod/ap971005.html; 70 Virginis, image by Walter Myers, http://www.arcadiastreet.com/cgvistas/exo_020.htm
- Mass distribution: from Niel Brandt, http://www.astro.psu.edu/users/niel/astro1/slideshows/class44/slides-44.html
- Semi-major axis distribution: from California and Carnegie Planet Search, http://exoplanets.org/semimajor_axes.html
- Eccentricities: from Extra-Solar Planet Data Trends, http://home.cwru.edu/~sjr16/advanced/esol_trends.html
- Upsilon Andromedae: artist's impression by Lynette Cook, from Astronomy Picture of the Day, 16 April 1999, http://antwrp.gsfc.nasa.gov/apod/ap990416.html; orbital diagram, from http://cfa-www.harvard.edu/cfa/hotimage/upsAnd_hotimage.html
- Spiral accretion streams: from http://www.pd.infn.it/~mbarbier/research/esp/
- Planetary migration movie: from Pawel Artymowicz: Planetary systems and their changing theories, http://www.astro.su.se/~pawel/planets/movies.html
- Resonance table: from "Planetary Harmony" by Robert Naeye, Australian S&T January 2005
- Upsilon Andromedae orbits: from http://exobio.chez.tiscali.fr/newsavril99.htm. Simulation: from Planet-Planet Scattering in Upsilon Andromedae, http://www.astro.northwestern.edu/rasio/UpsAndPR/
- Transit: from http://www.iac.es/proyect/tep/fig1moda.gif
- Atmosphere around HD 209458: from Hubble Site News Release, November 27 2001, http://hubblesite.org/newscenter/newsdesk/archive/releases/2001/38/. Sodium absorption: from space.com, First Detection Made of an Extrasolar Planet's Atmosphere, http://www.space.com/scienceastronomy/astronomy/extrasolar_atmosphere_011127-1.html
- Brown dwarf planet: from ESO press release 12/05, http://www.eso.org/outreach/press-rel/pr-2005/pr-12-05-p2.html

- X-ray flares from Orion: Chandra press release, 10 May 2005, http://chandra.harvard.edu/press/05_releases/press_051005.html
- Microlensing simulation: from the Microlensing Planet Search Project, http://www.nd.edu/~srhie/MPS/
- Artist's conception of latest microlensed planet: from CfA Press Release, 23 May 2005, http://cfa-www.harvard.edu/press/pr0514.html
- Binary microlens: from http://bustard.phys.nd.edu/MPS/97-BLG-41/97blg41.html