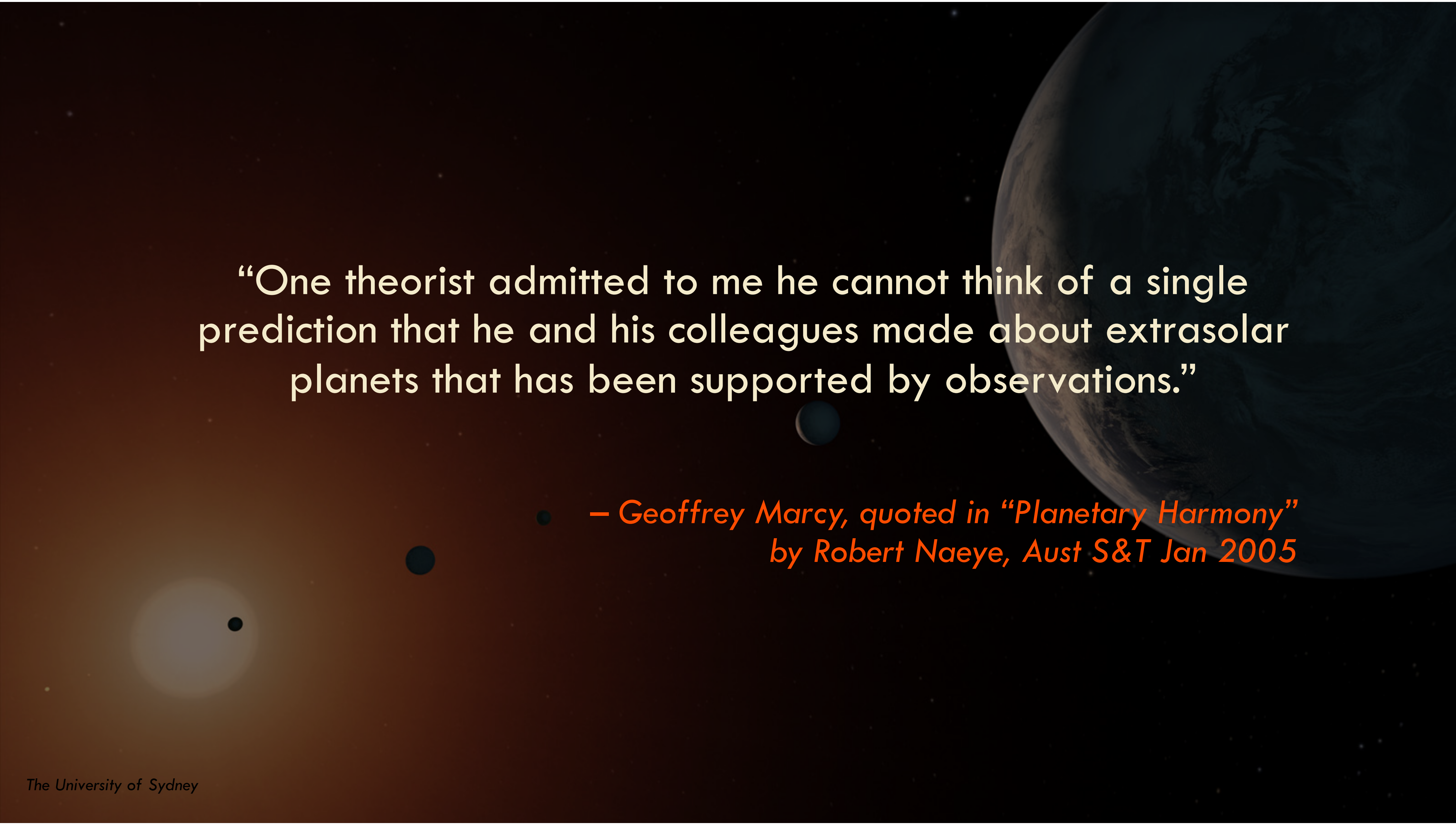
Voyage to the Planets
Lecture 10:
Extra-solar planets

Presented by

Dr Helen Johnston
School of Physics

Spring 2017

THE UNIVERSITY OF SYDNEY



“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.”

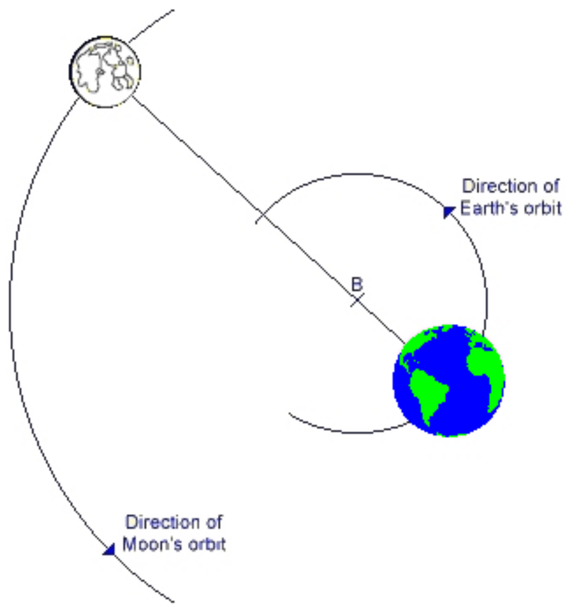
– Geoffrey Marcy, quoted in “Planetary Harmony” by Robert Naeye, Aust S&T Jan 2005

Tonight

- How to find a planet
- What we found
- The *Kepler* mission
- What does it mean?

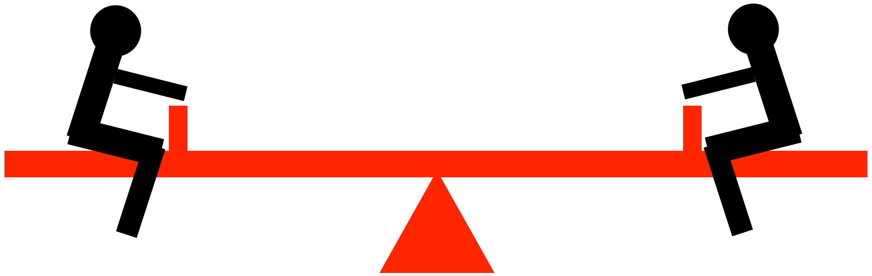
Orbits

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.



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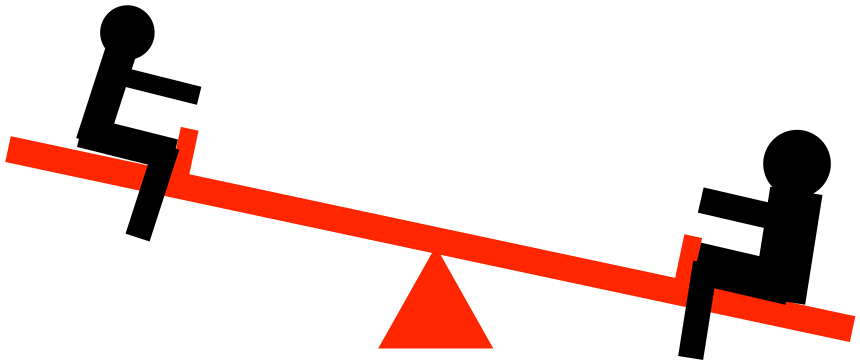

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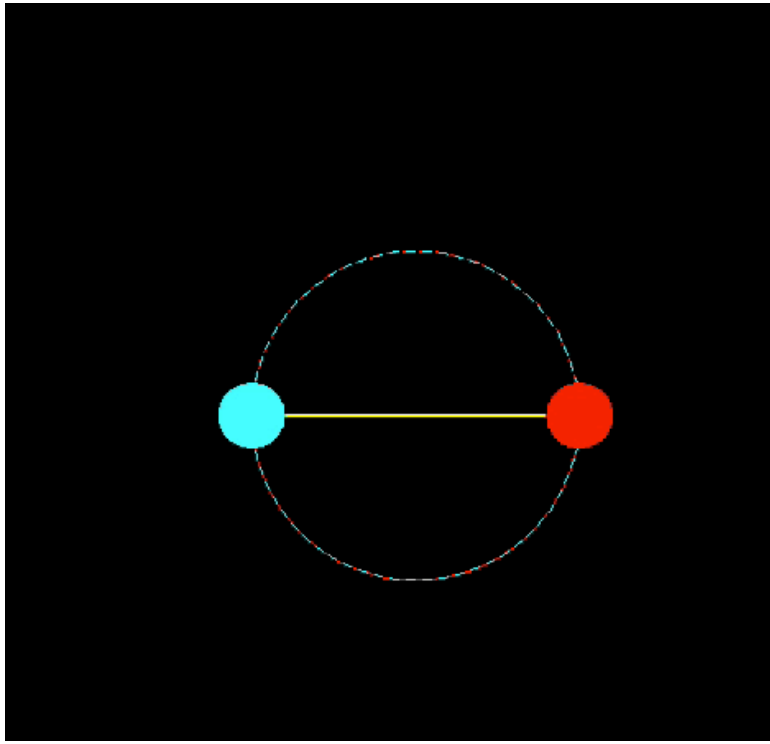
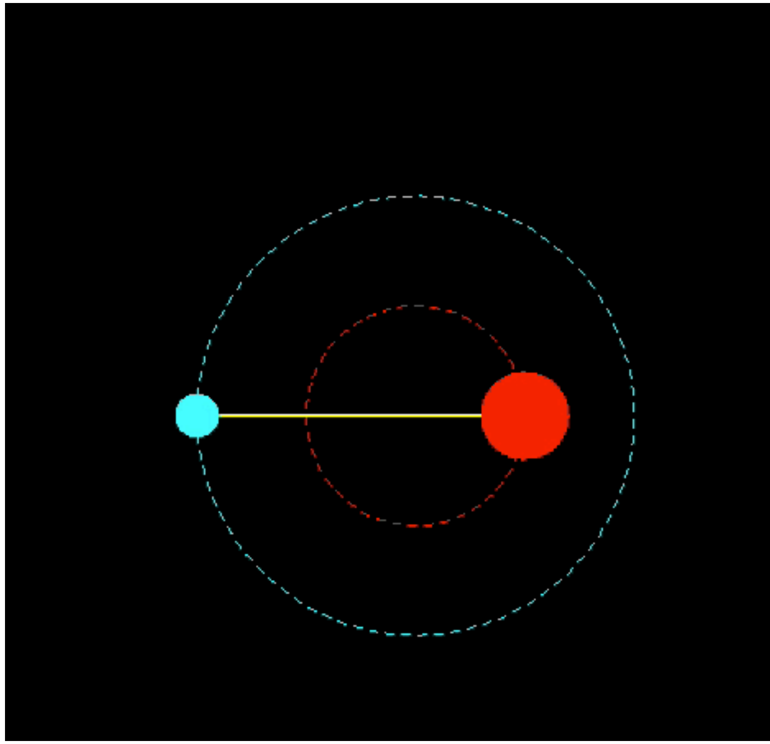
Two objects of equal mass will orbit with the centre of mass exactly halfway between them.



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

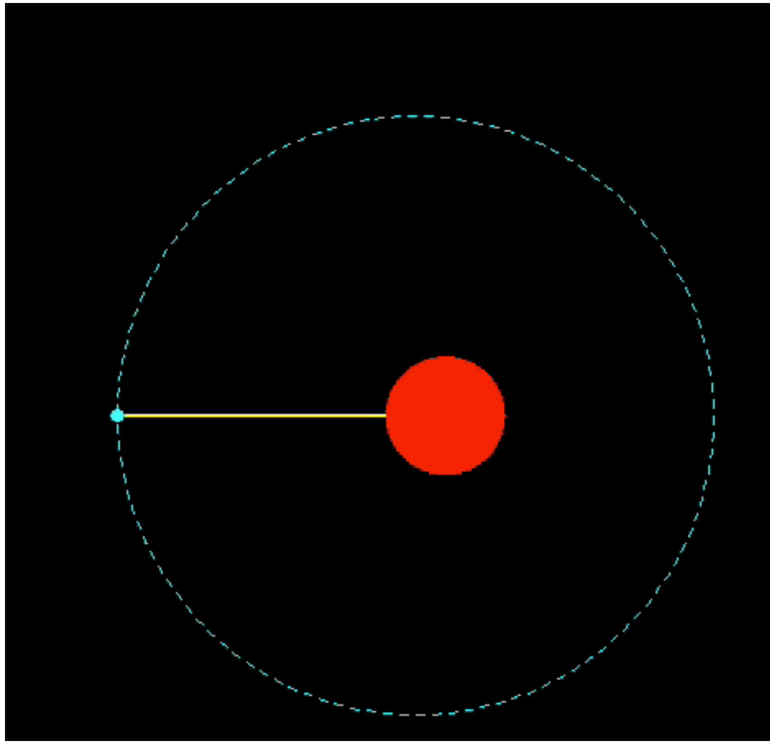
If one object is twice as massive as the other, the centre of mass will be twice as close to it.



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

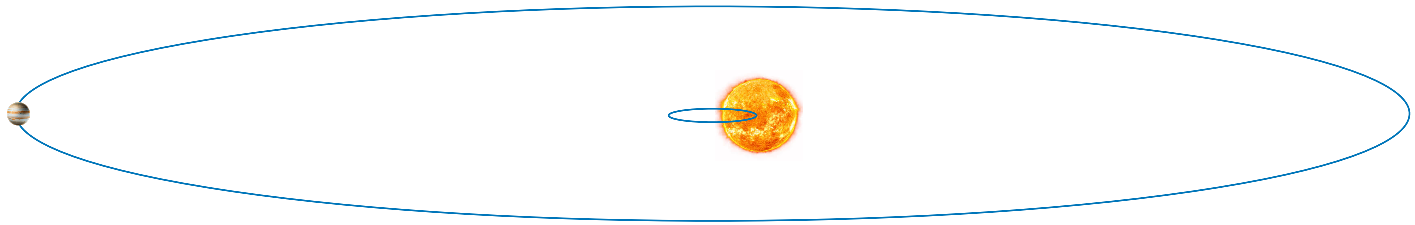
If one object is twice as massive as the other, the centre of mass will be twice as close to it.

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.



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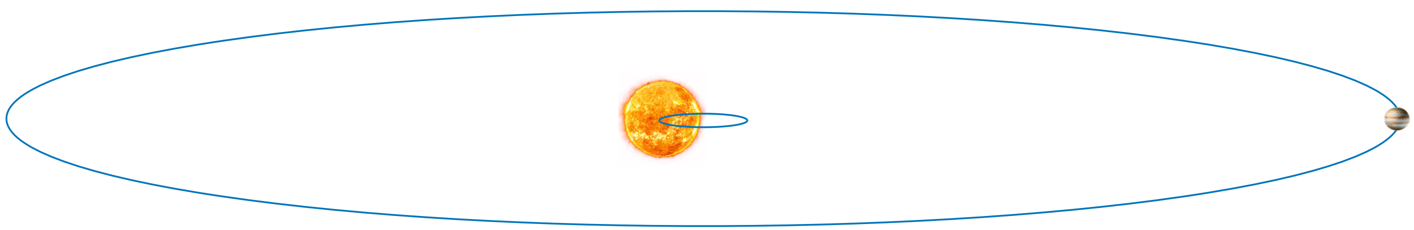
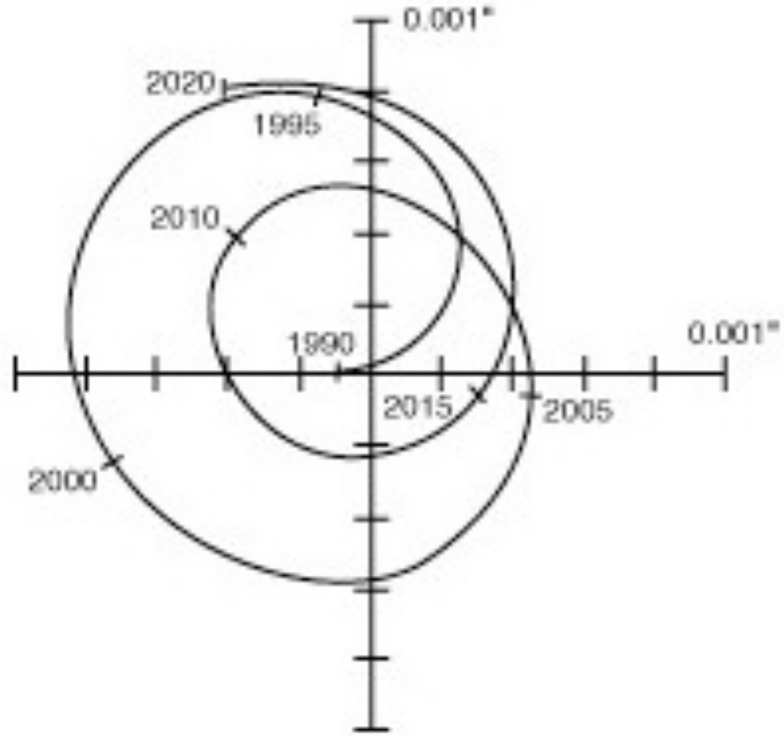


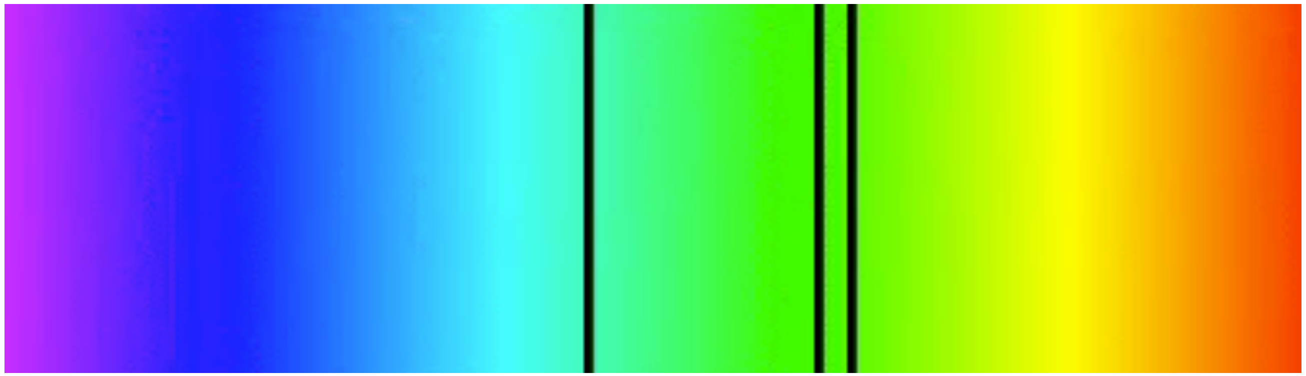
The motion of a star due to a planet is tiny in the extreme: no planets have yet been detected this way, though the next generation of space missions will change that.



Astrometric displacement of the Sun due to Jupiter as at it would be observed from 10 parsecs, or about 33 light-years.

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.

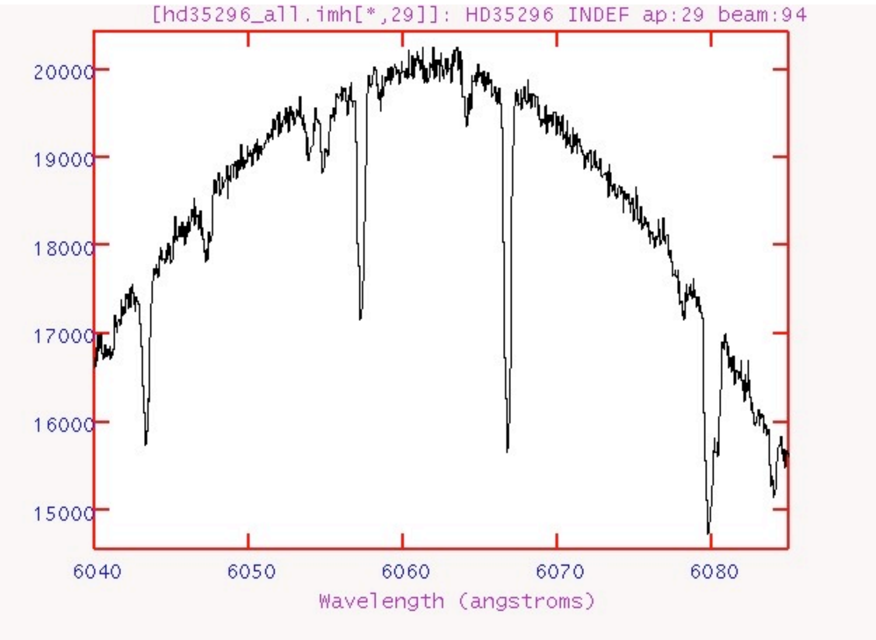
However, this means we have to be able to measure shifts in velocity to 12/300,000,000, or a precision of 4 parts per *billion*.

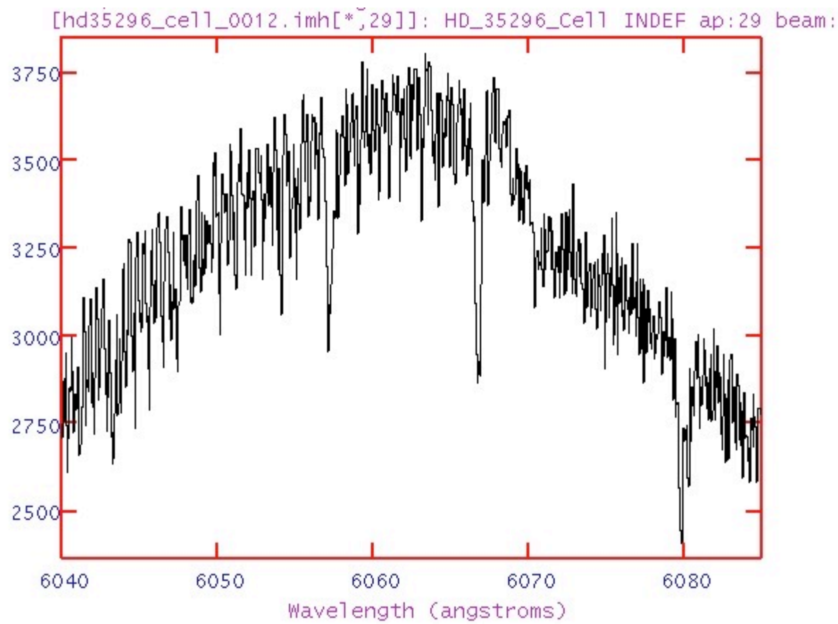
This places extraordinary demands on the stability of the instrument used to make the measurement. We need to spread the light out a long way to measure the tiny shifts, but also have a very stable reference system.

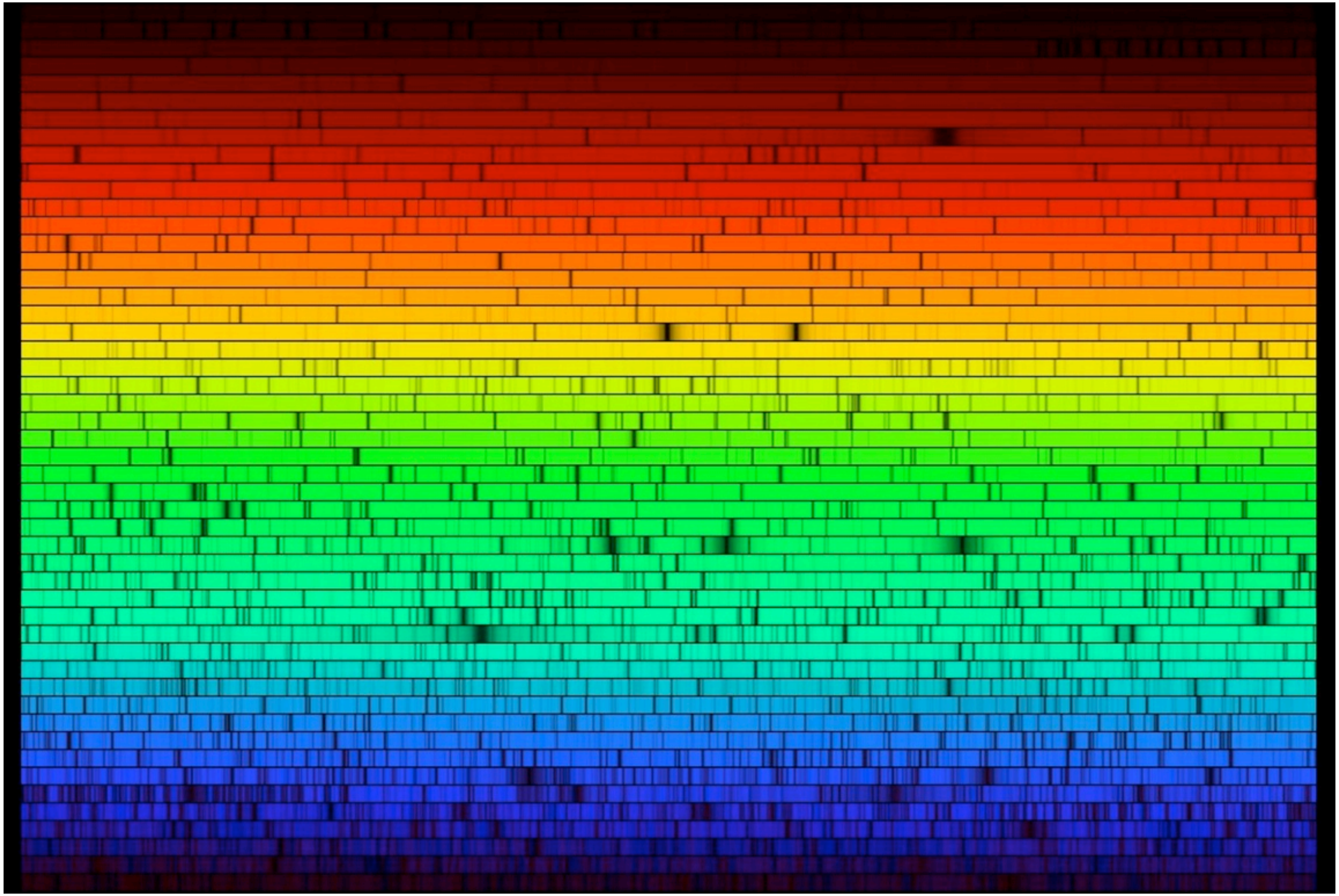
Solution: pass the light from the star through an iodine cell, which superimposes a large number of reference absorption lines on the star's spectrum.

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.



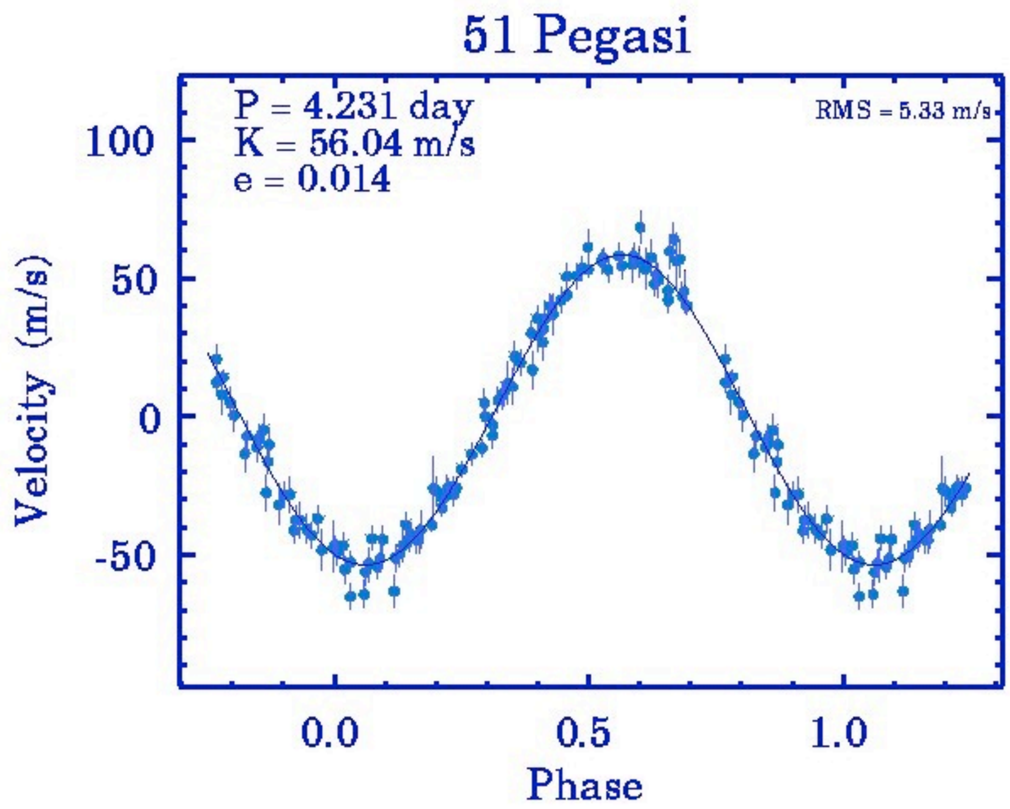




Example echelle spectrum from the Keck HIRES instrument

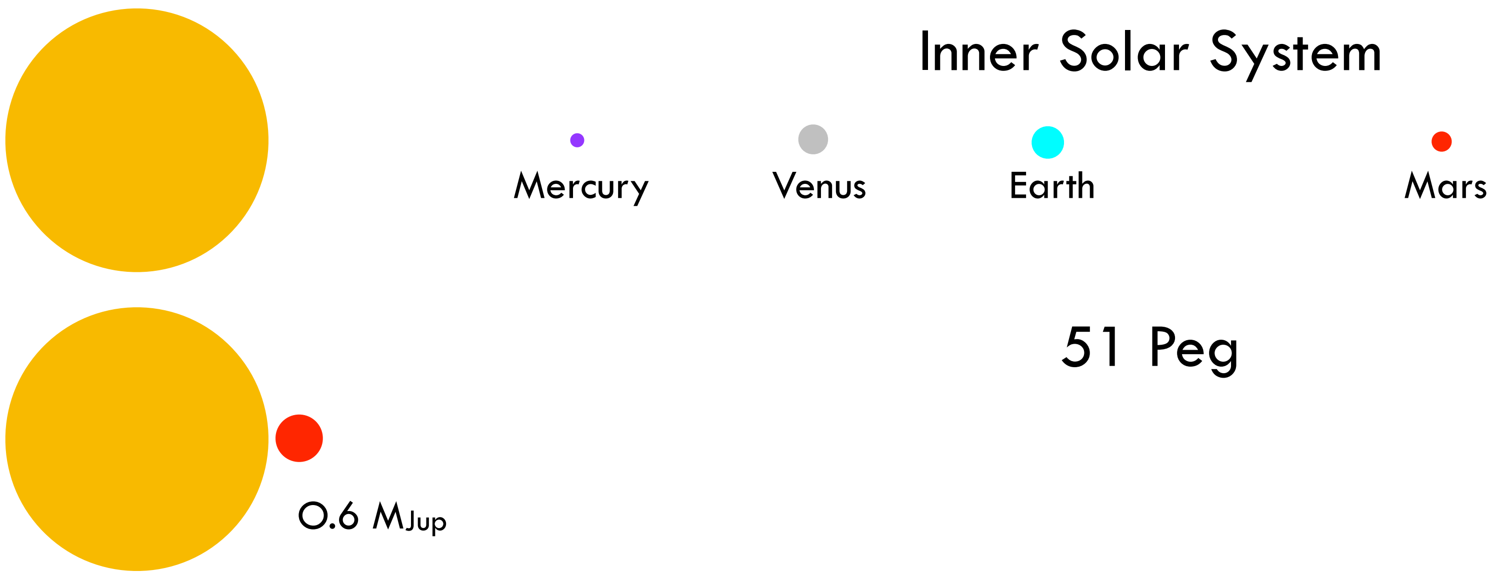
In 1995, Michel Mayor and Didier Queloz, from the Geneva Observatory, announced the discovery of the first extra-solar planet. They had found a regular oscillation of the star 51 Pegasi, a G5 dwarf, very similar to our own Sun, at a distance of 42 lightyears.

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

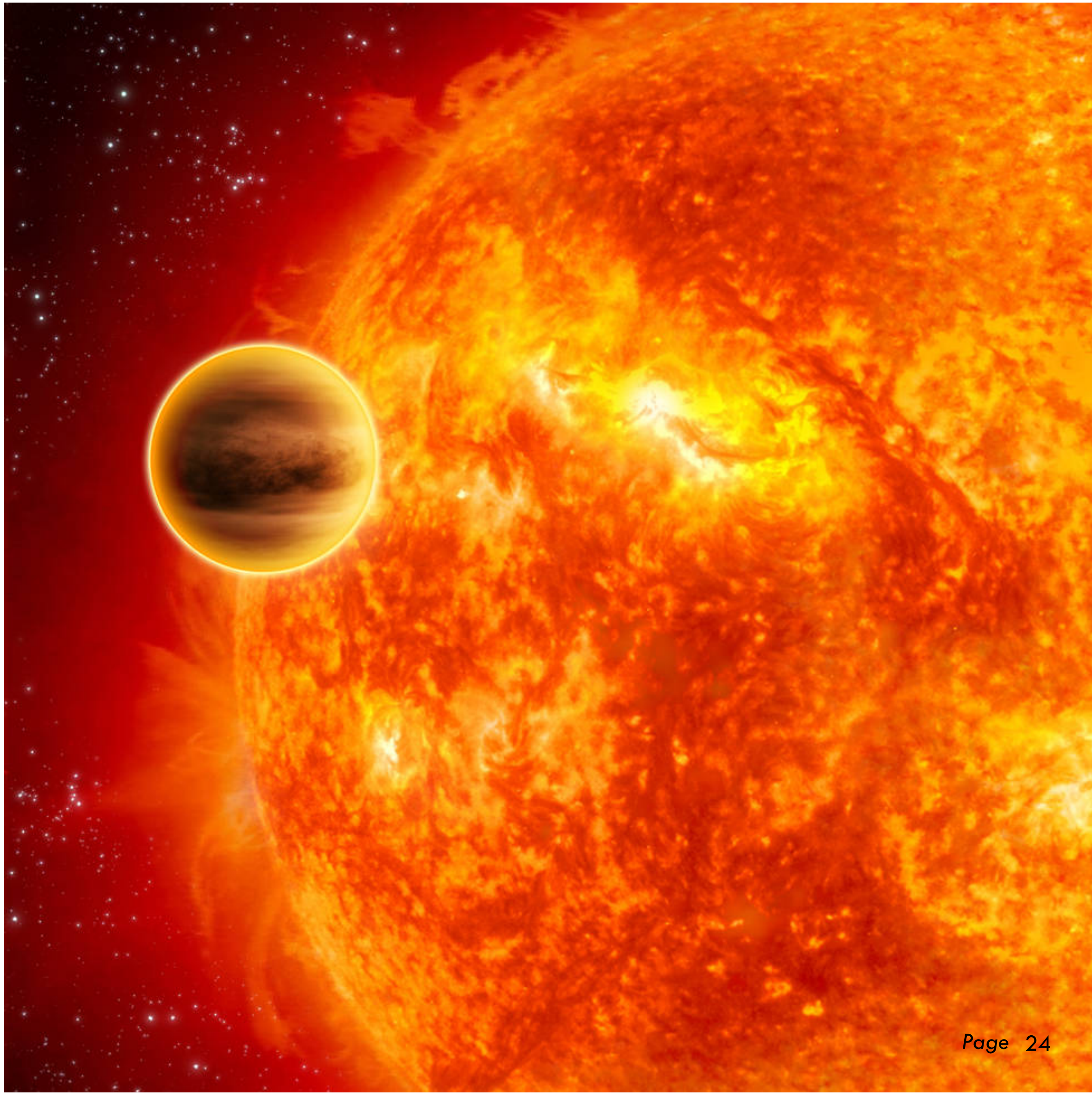


They had found a planet which was 60% as massive as Jupiter, in an orbit much smaller than Mercury’s (0.05 AU): a Jovian-mass planet in a sub-Mercurian orbit.

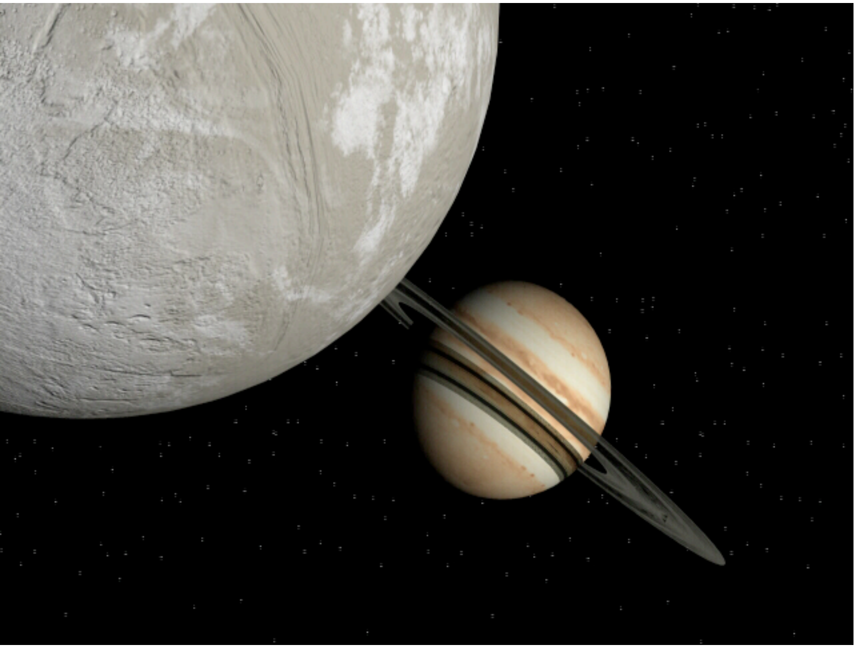
What is such a planet (a gas giant? a giant rocky planet?) doing so close to its star?



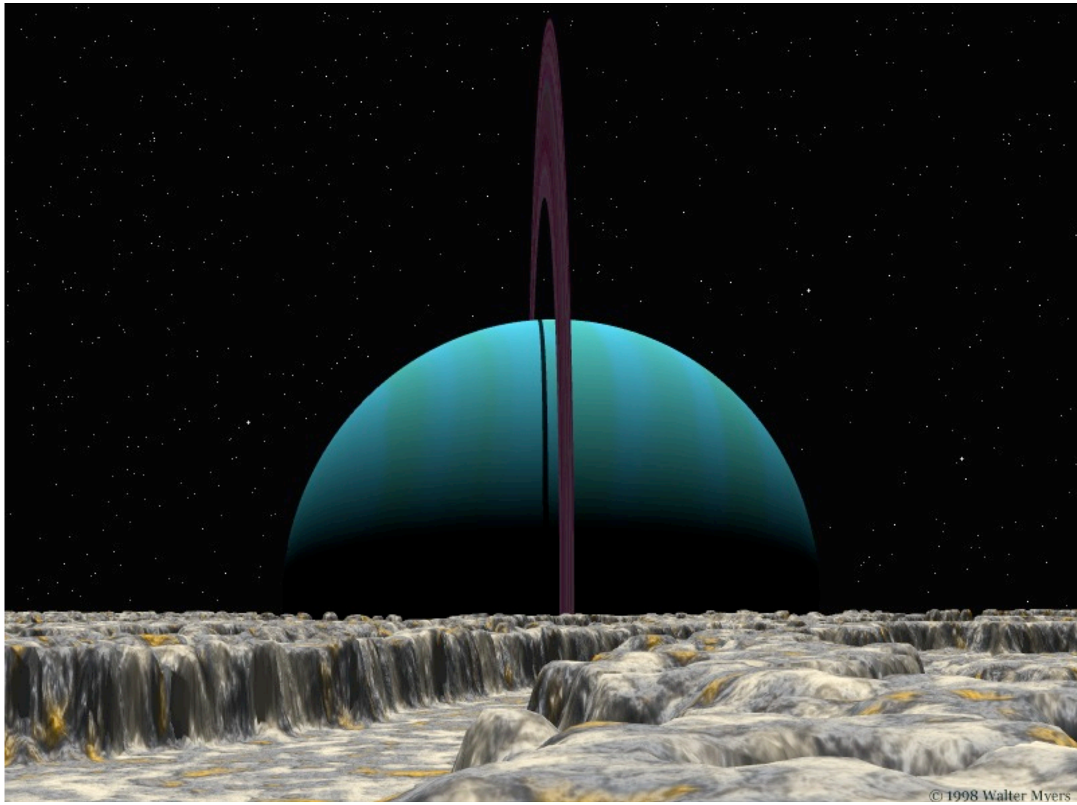
The unlikelihood of forming a massive planet so close to a star could only mean one thing: several people immediately suggested that planets *might not stay put where they were made*.



Artist's impression of the planet around 51 Pegasi.

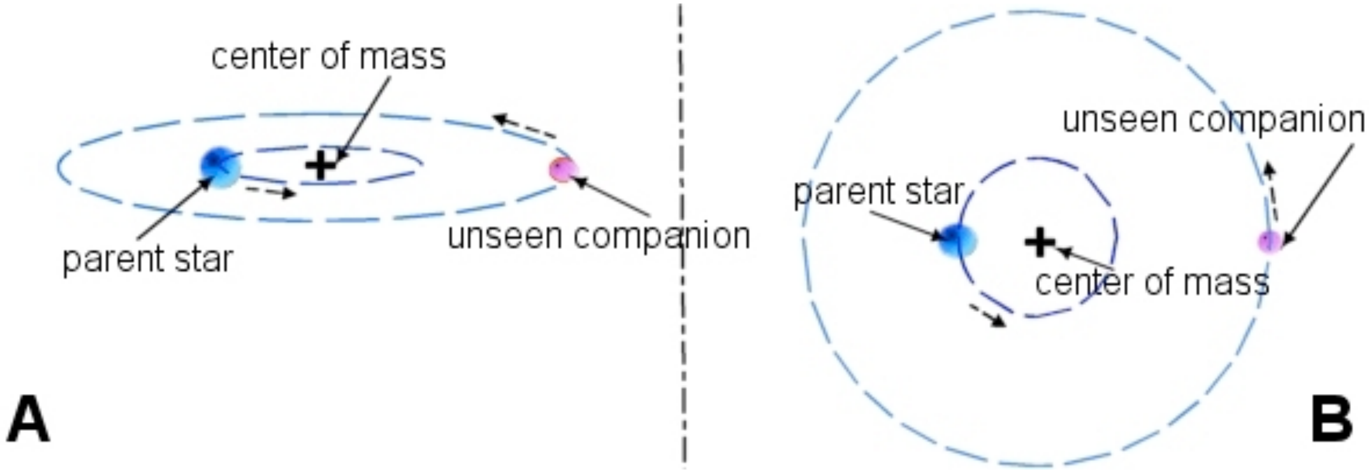


Almost immediately, two new planets were announced, one around 47 Ursa Majoris and one around 70 Virginis, which, at 7.4 M_{Jup}, is still one of the most massive planets found.



After that, they started arriving at an enormous rate.

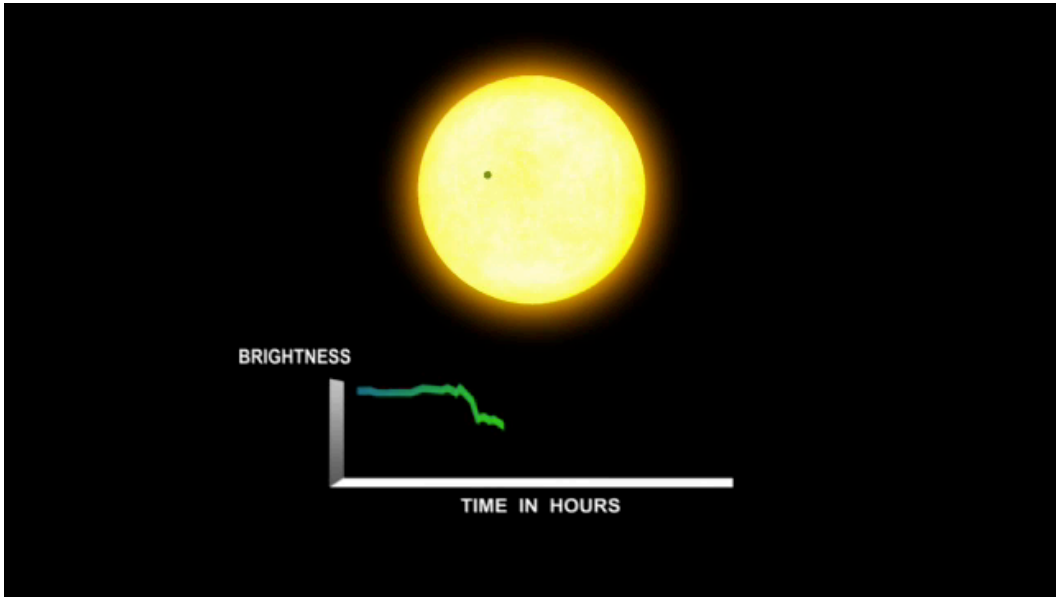
Radial velocity searches are biased towards finding *massive* planets in *small* orbits (maximises velocity variation). We can only measure the velocity along our line of sight, so if the orbit is tilted, the velocity we measure is less than the true velocity, so our mass estimate is only a lower limit.



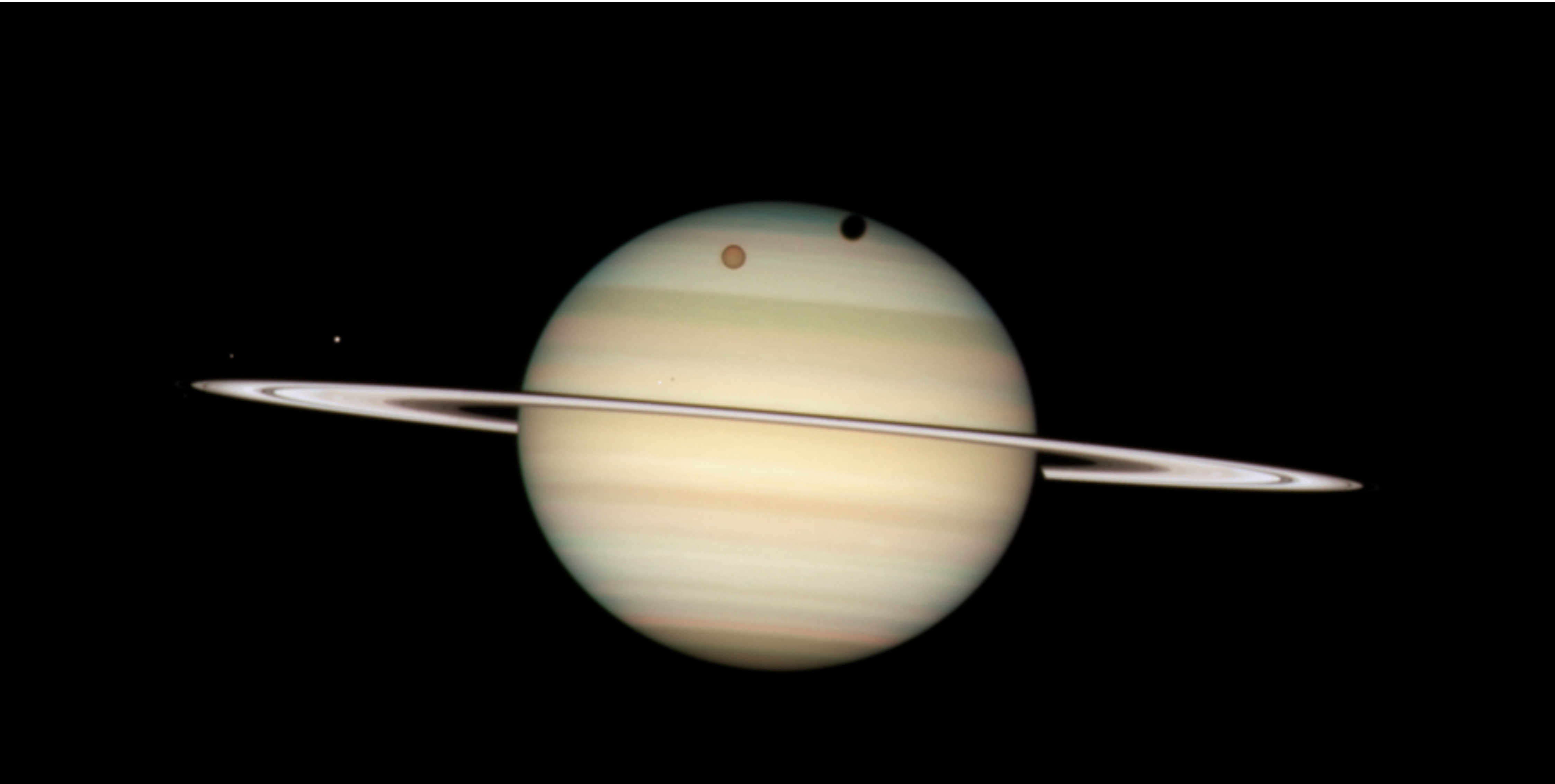
Large orbits also have long orbital periods, which means you have to observe for much longer to see a whole orbit.

Transits

If the orbit of a planet around a star happens to be edge-on, then once during every revolution, the planet will pass in front of its star in a *transit*. This can be detected by recording the star's brightness very accurately and looking for dips.

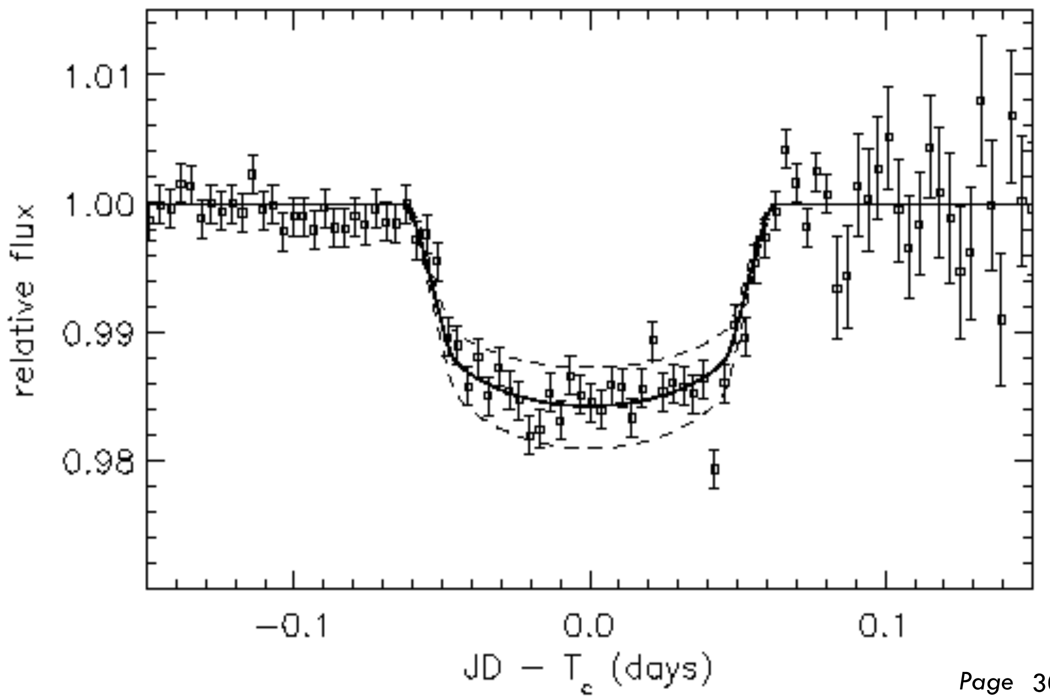


This can only work if the viewing geometry is favourable, and is biased towards finding *large* planets in *small* orbits. The 2012 transit of Venus showed that terrestrial planets don't cause much of a decrease in the light from the star!



Hubble image of Titan transiting across Saturn, taken in February 2009

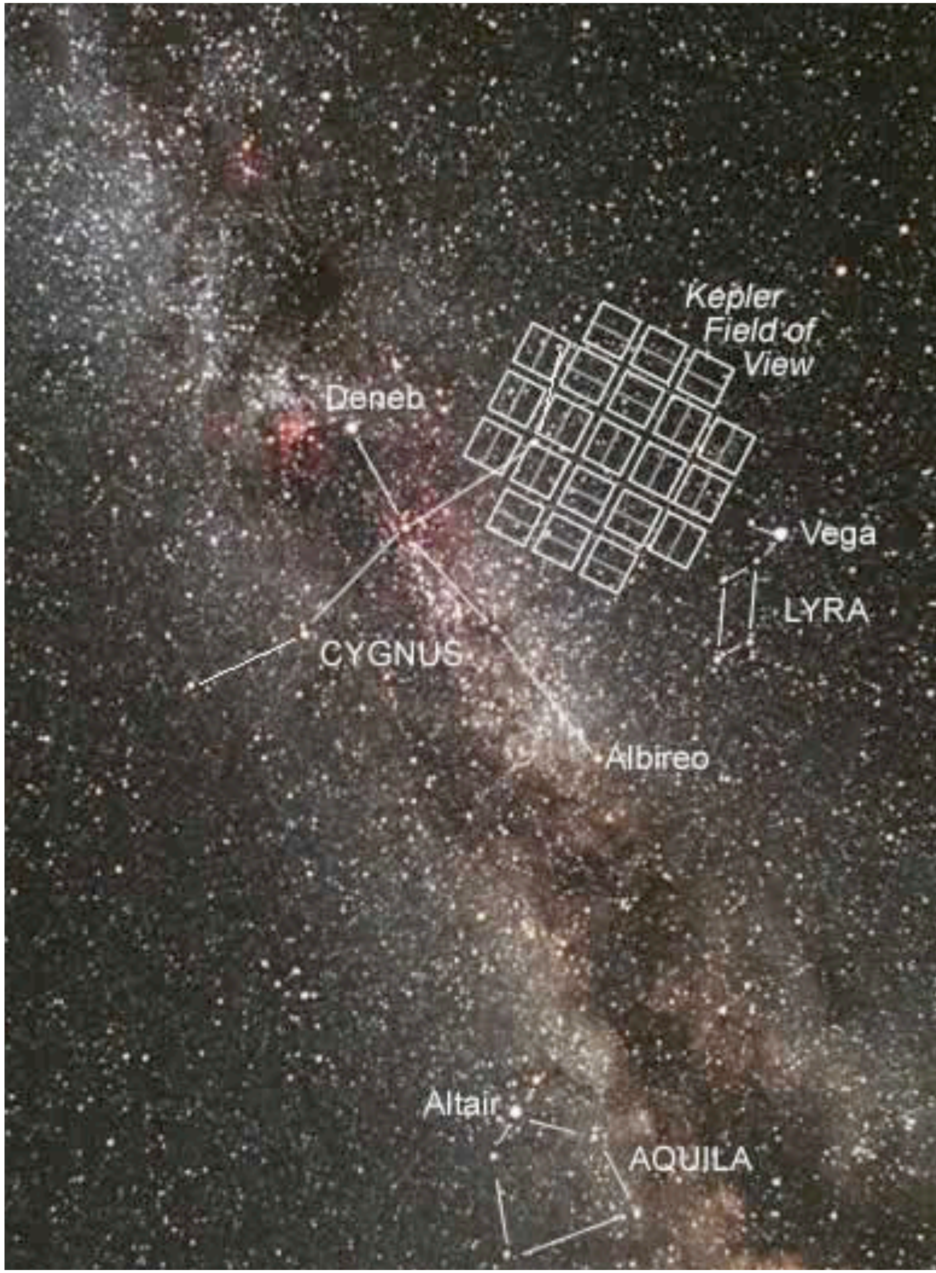
Measuring transits of planets which have been detected via velocity variations is particularly valuable because this enable both the *mass* and the *size* of the planet to be determined exactly (not just lower limits).



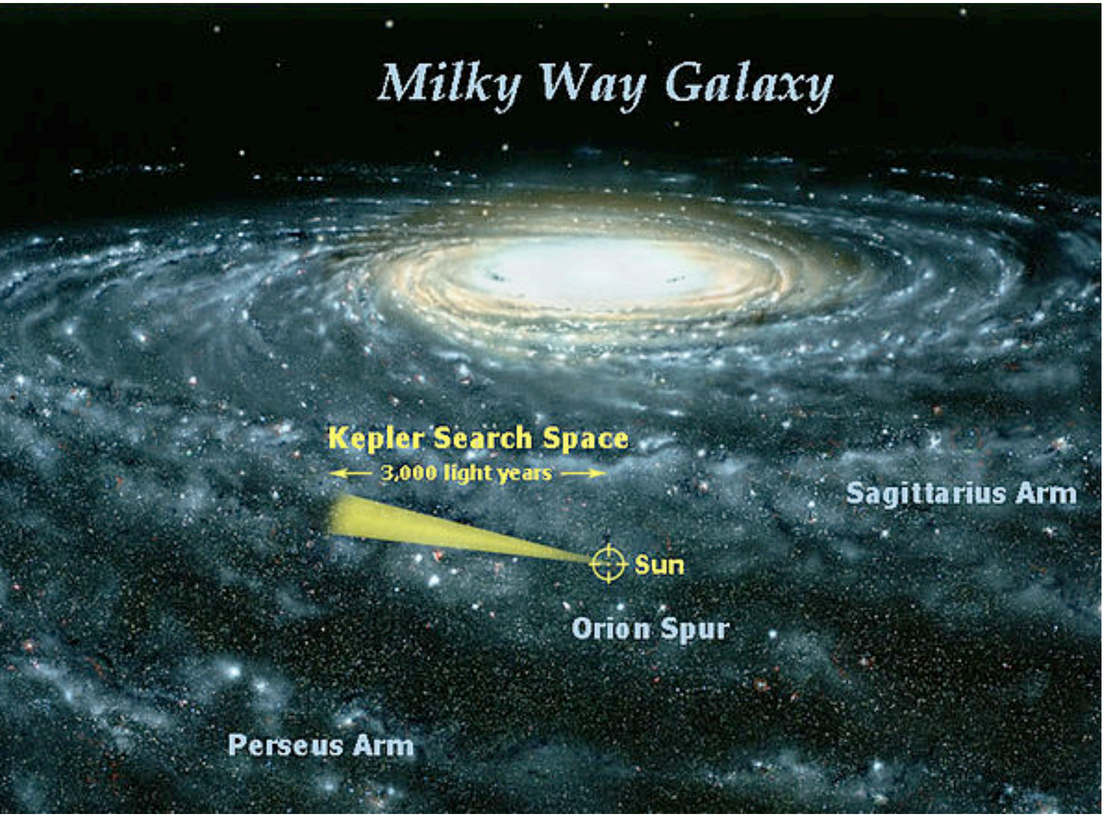
Light curve of HD 209458, which was already known to have a planet via the radial velocity technique.

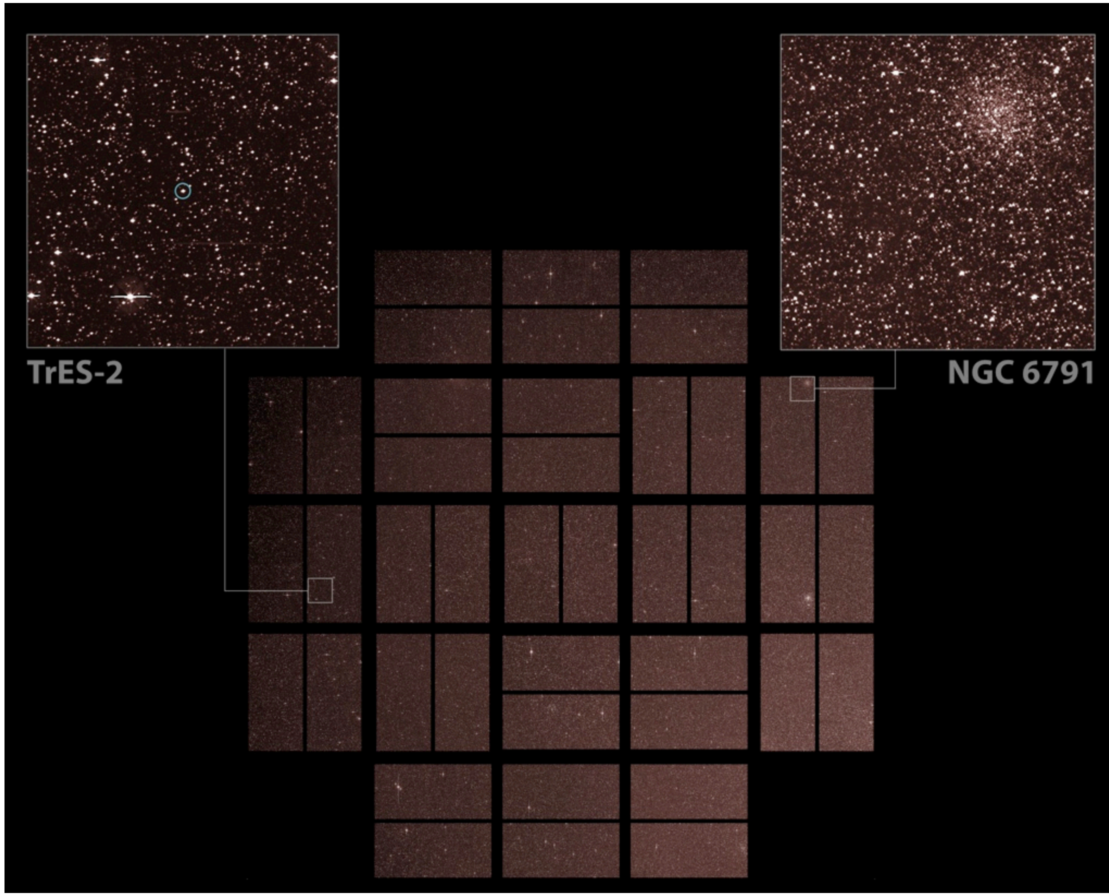
The *Kepler* mission to find transiting planets was launched in March 2009. It was designed to observe 155,000 stars in a single field in Cygnus, observing continuously (every 30 min) for 3.5 years.

To detect the transit of an Earth-like planet, it needs to detect brightness changes of 1/10,000 when an Earth-sized planet on an Earth-like orbit makes a ~12-hour passage in front of a Sun-sized star.



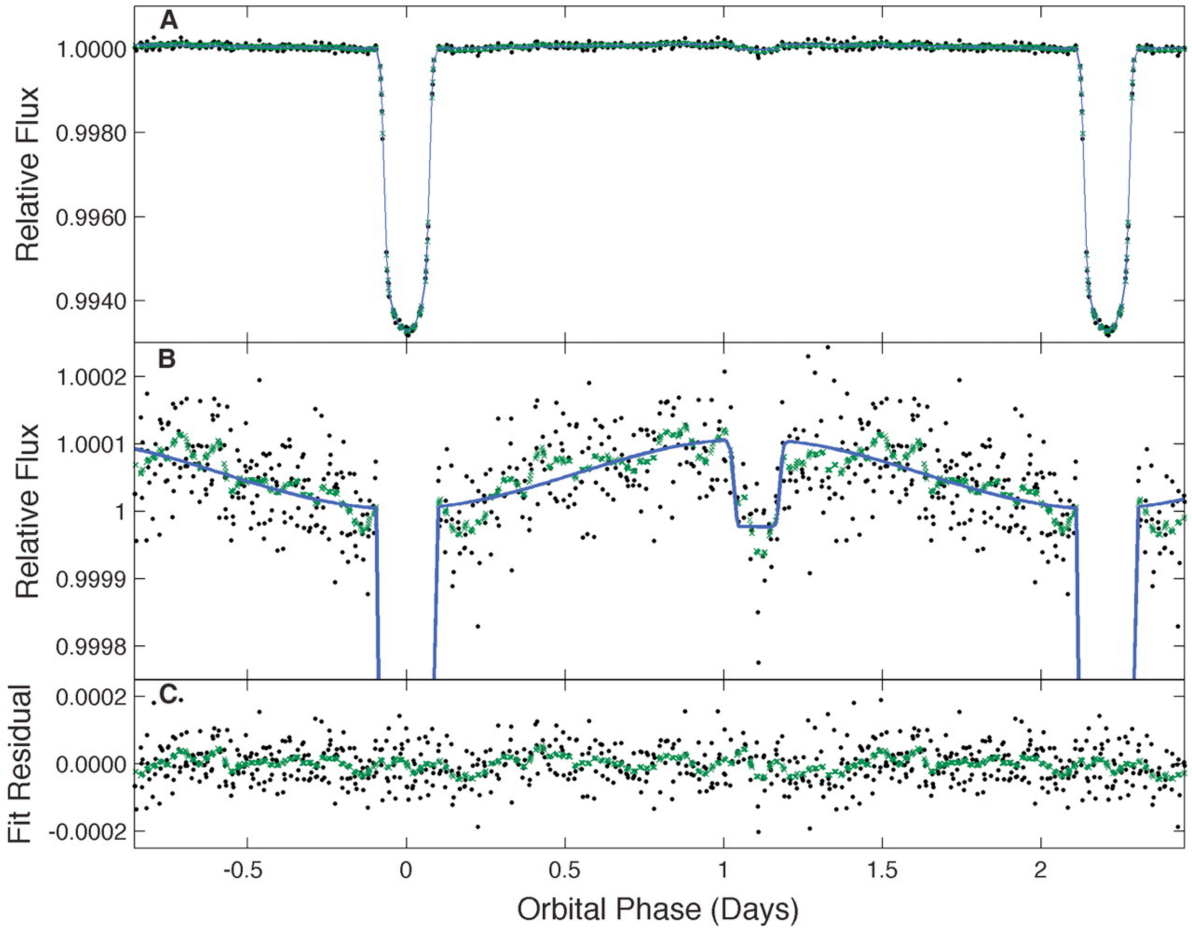
Kepler was placed in a heliocentric, Earth-trailing orbit, falling gradually further behind the Earth. It pointed to a region in the Orion arm, in the direction of the Sun's motion around the Galaxy.

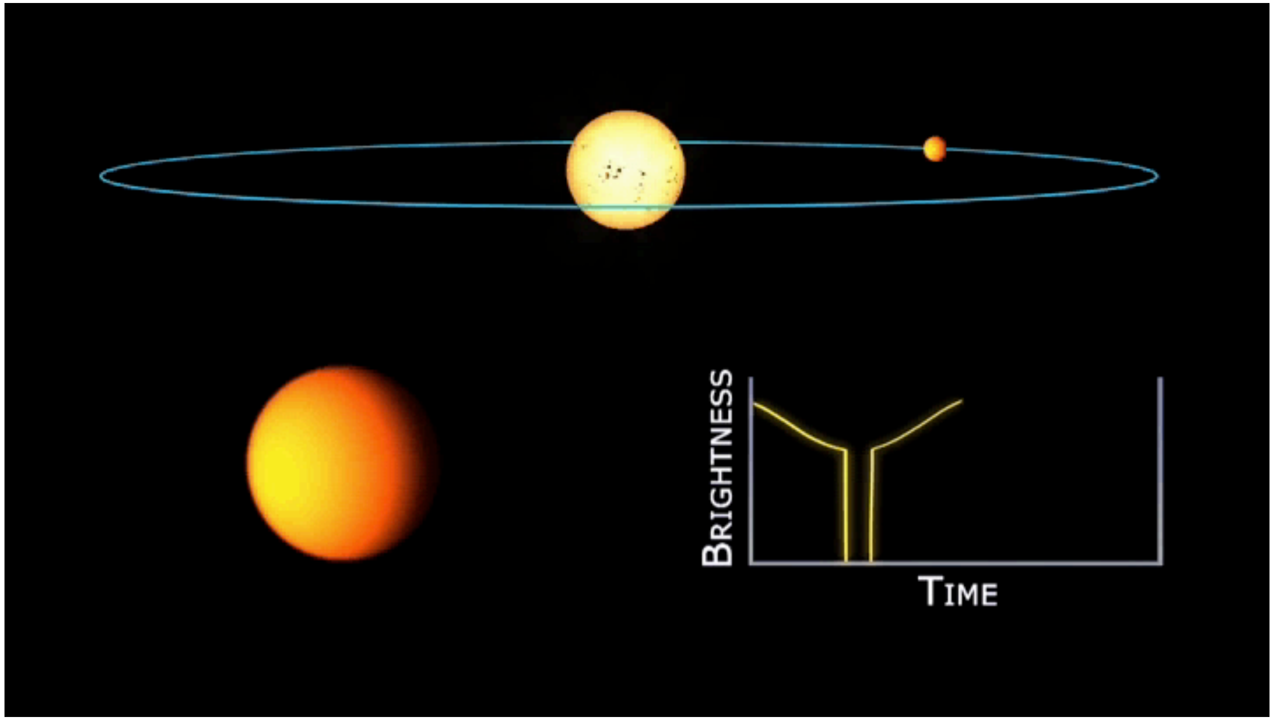




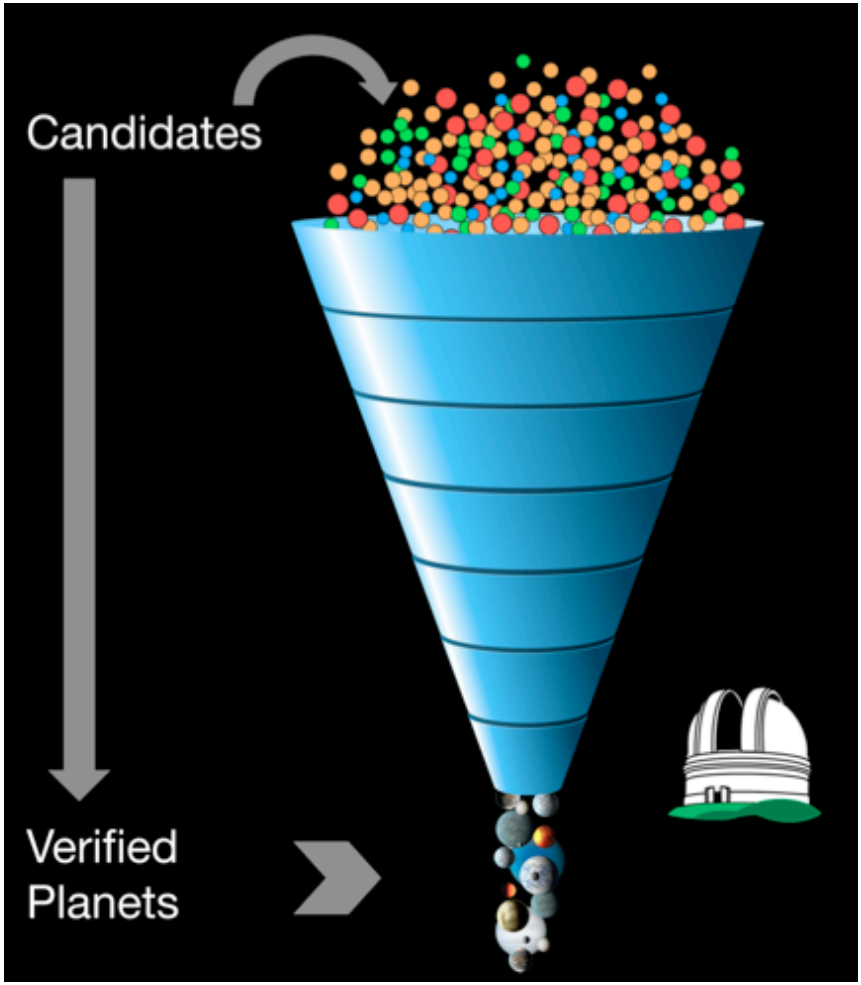
First images from Kepler, showing the whole field of view, and an open cluster and a star with a transiting planet

From its first 10 days of commissioning data, *Kepler* detected a previously known giant transiting exoplanet, HAT-P-7b



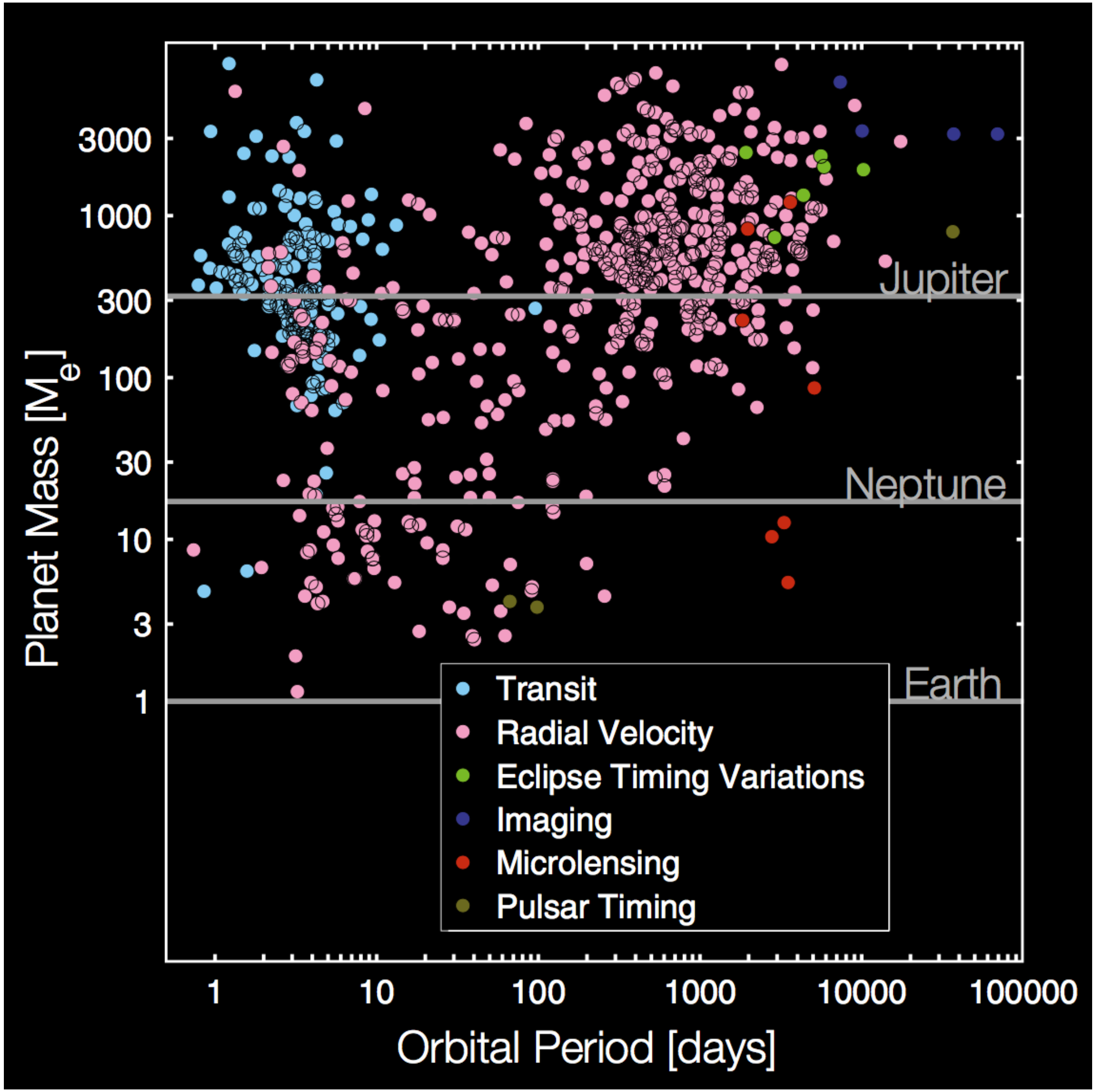

BRIGHTNESS
TIME

Since then, Kepler spent four years finding planets. Planetary candidates are only confirmed when large ground-based telescopes have detected the radial velocity variations due to the planet. There are so many candidate planets that these confirming observations are now the limiting step.

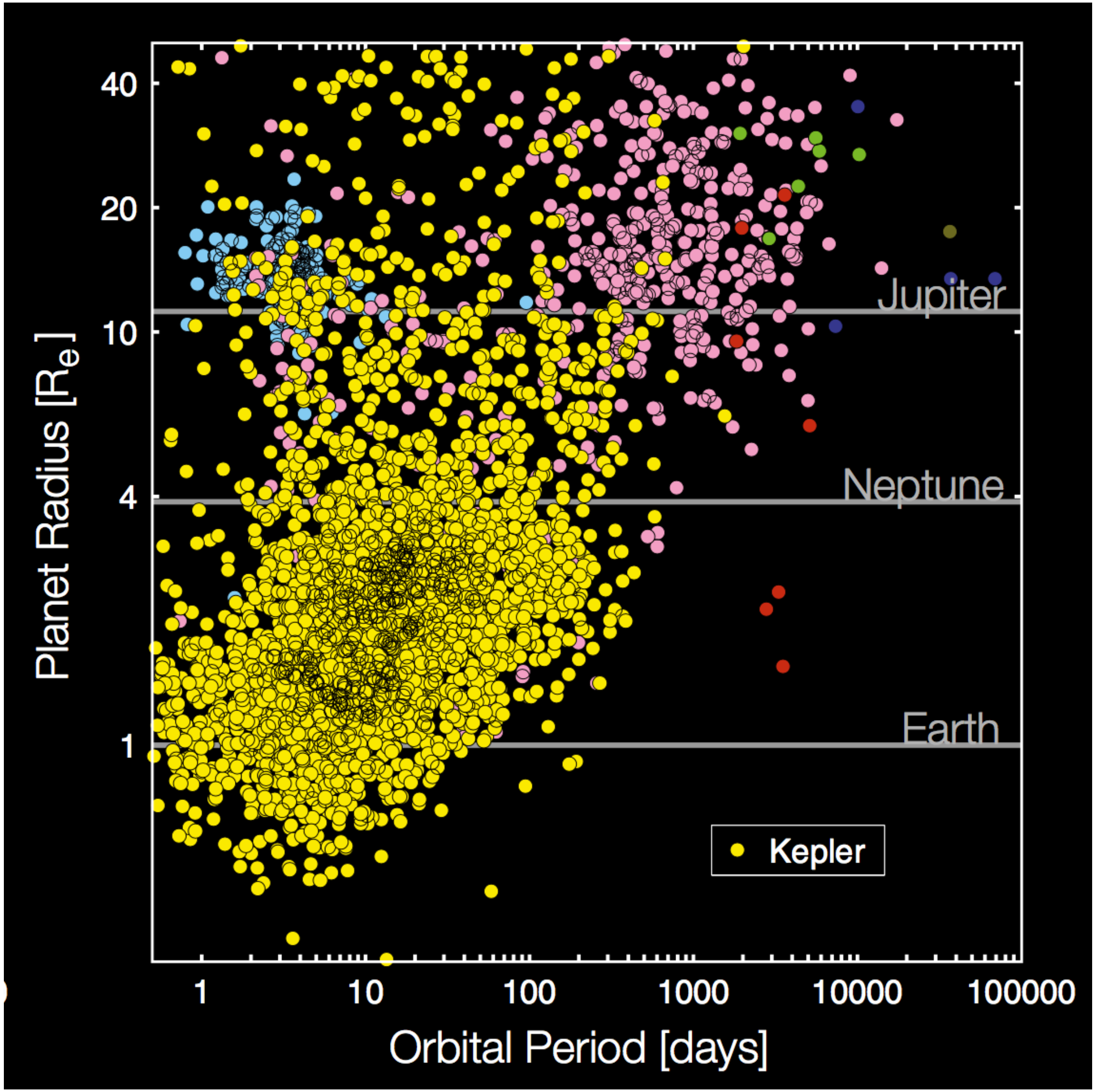


So far, Kepler has discovered 2337 confirmed planets.

The planet verification bottleneck


Planet Mass [M_e]
3000
1000
300
100
30
10
3
1
Jupiter
Neptune
Earth
Transit
Radial Velocity
Eclipse Timing Variations
Imaging
Microlensing
Pulsar Timing
1
10
100
1000
10000
100000
Orbital Period [days]

Pre-Kepler

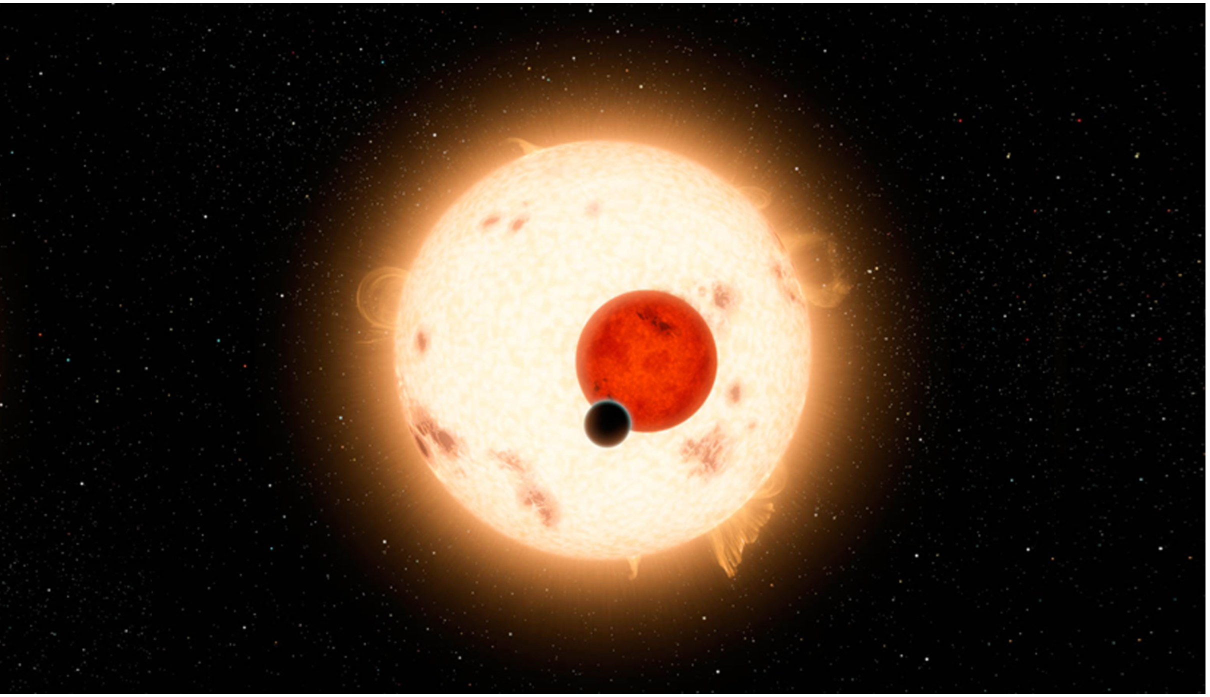


Planet Radius [Re]
40
20
10
4
1
Jupiter
Neptune
Earth
Kepler
1
10
100
1000
10000
100000
Orbital Period [days]

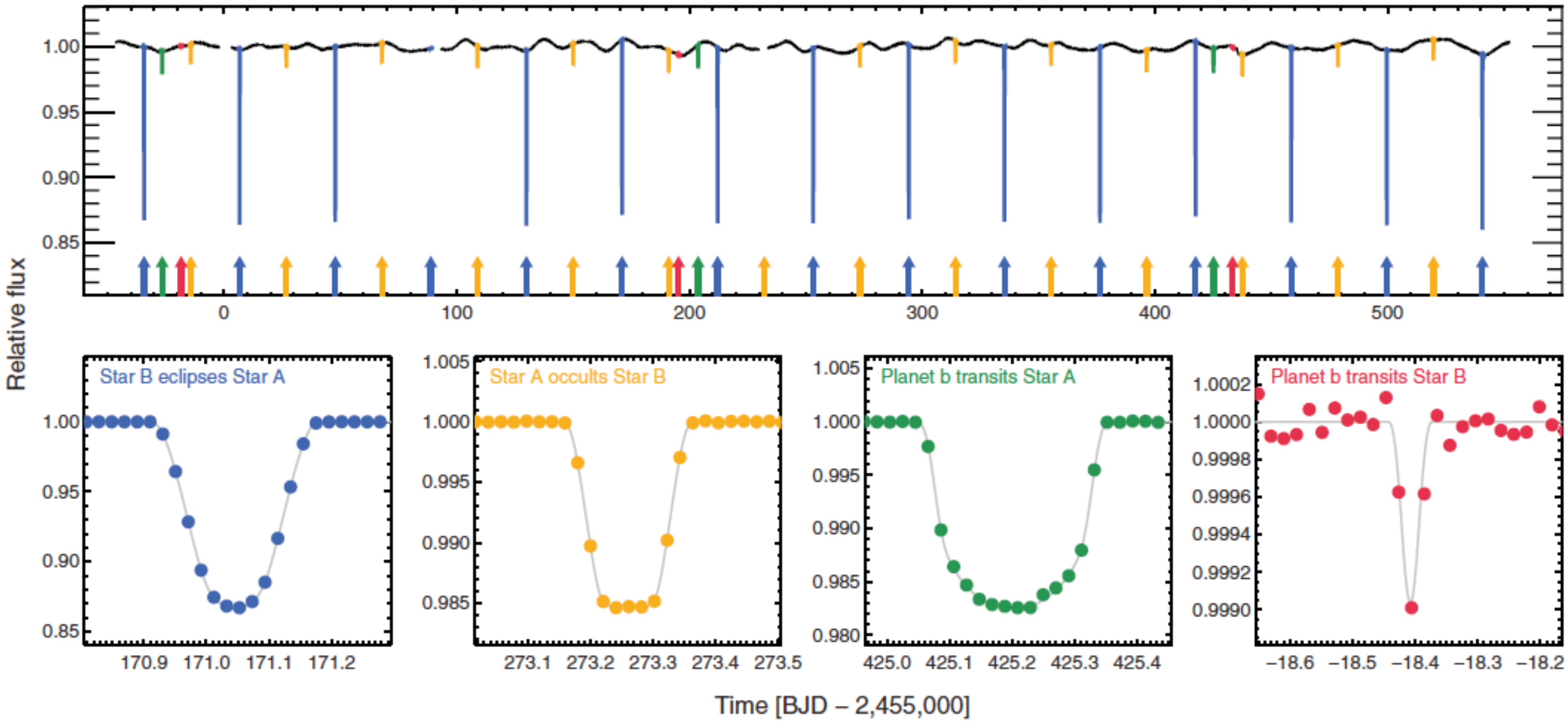
Post-Kepler

Here are some of Kepler's most exciting planets:

- In 2011, the *Kepler* team announced the first discovery of a *circumbinary* planet – a planet orbiting two stars. The two orbiting stars regularly eclipse each other; the planet also transits, each star, and Kepler data from these planetary transits allowed the size, density and mass of the planet to be extremely well determined.



Artist's impression of Kepler-16b, the "Tatooine planet"



Primary eclipse

Secondary eclipse

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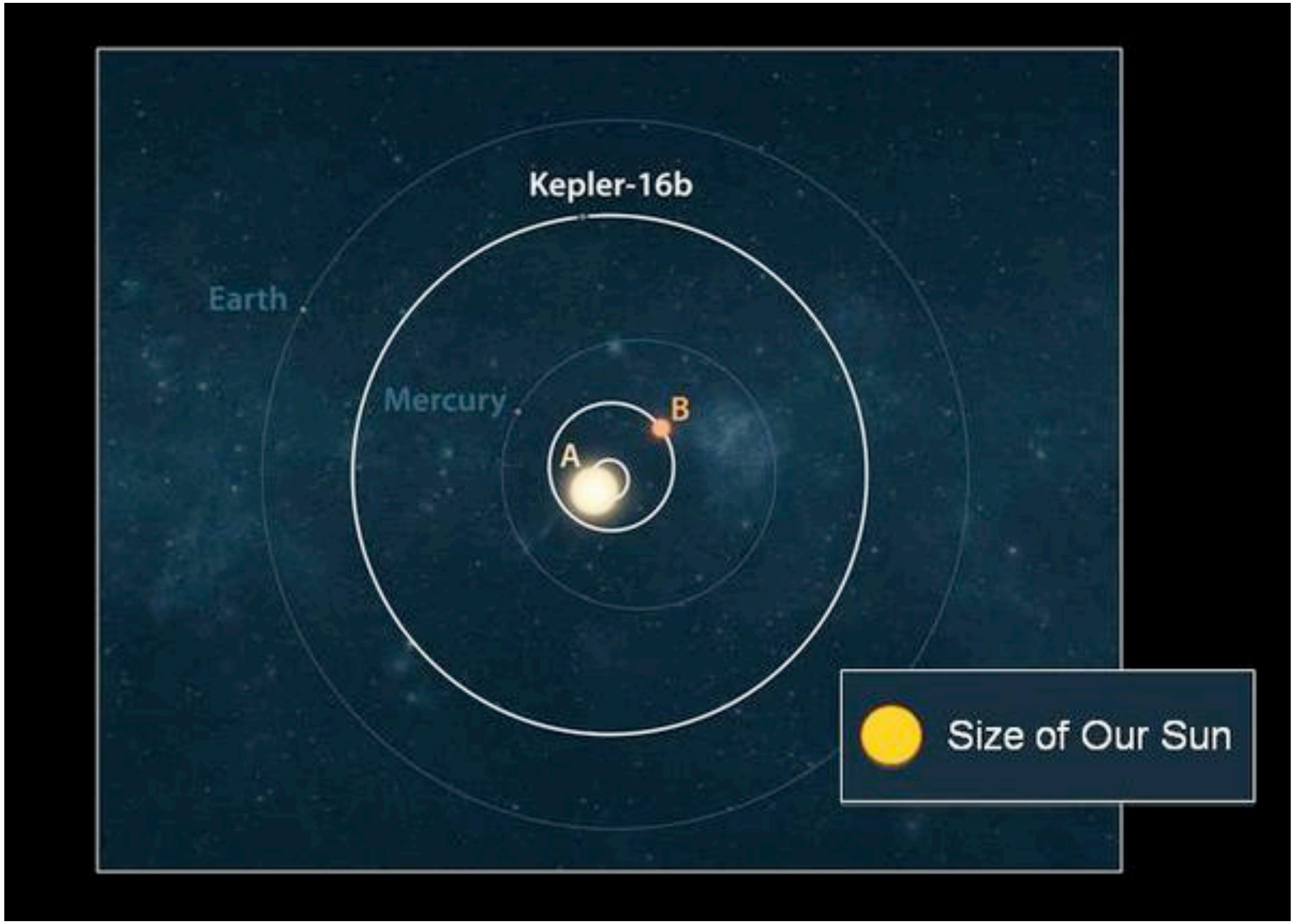
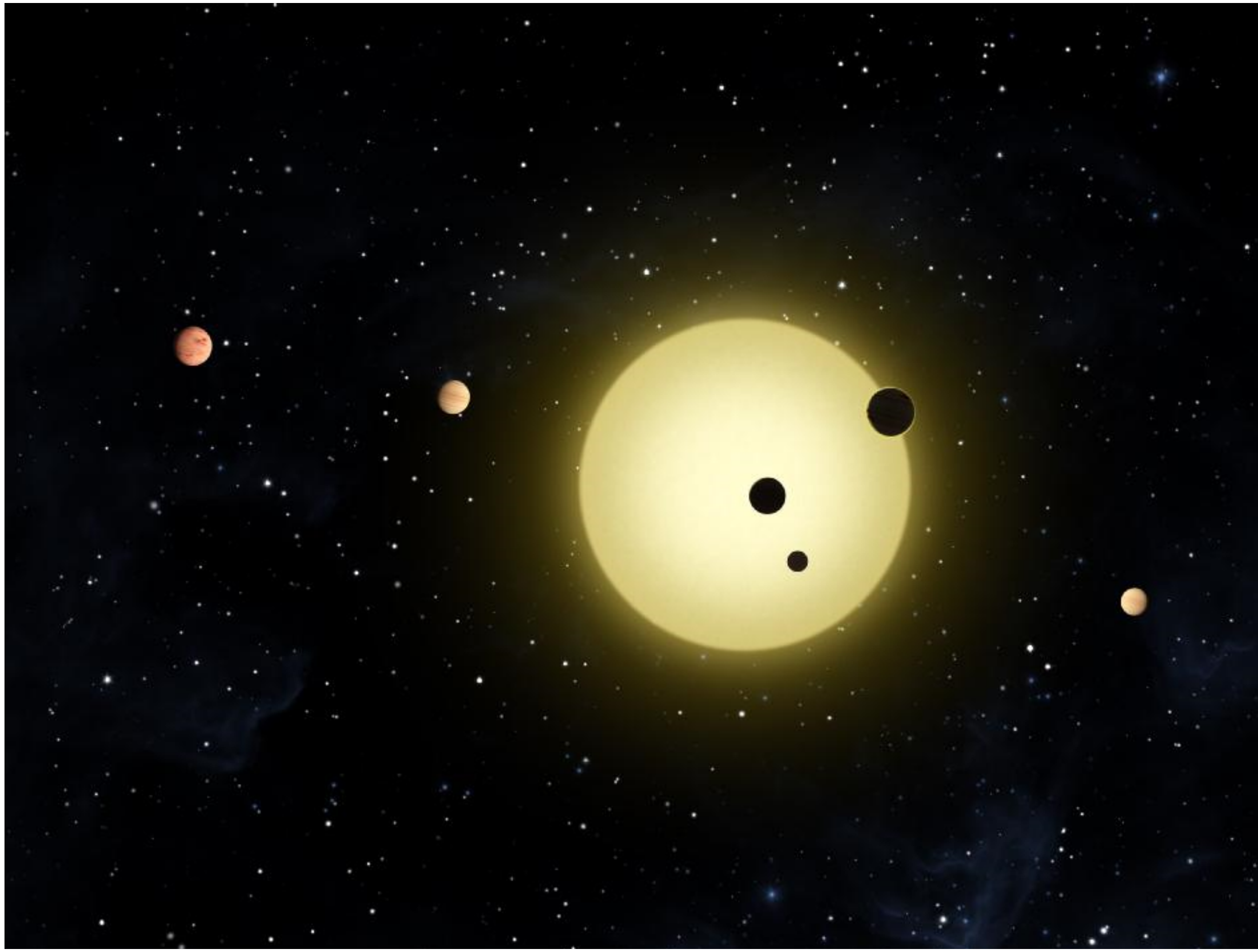
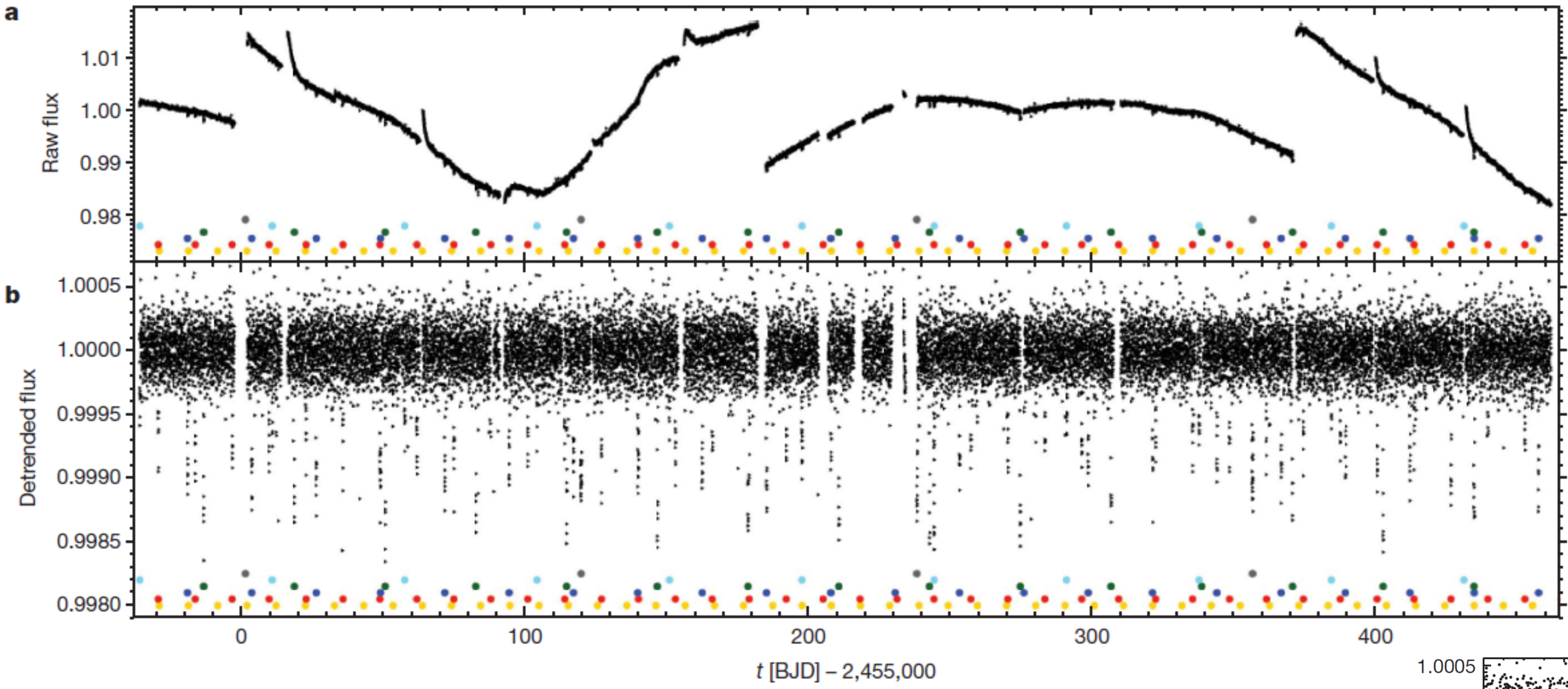
Light-curve of Kepler-16b , showing primary and secondary eclipses, as well as the transits of the planet across each star.

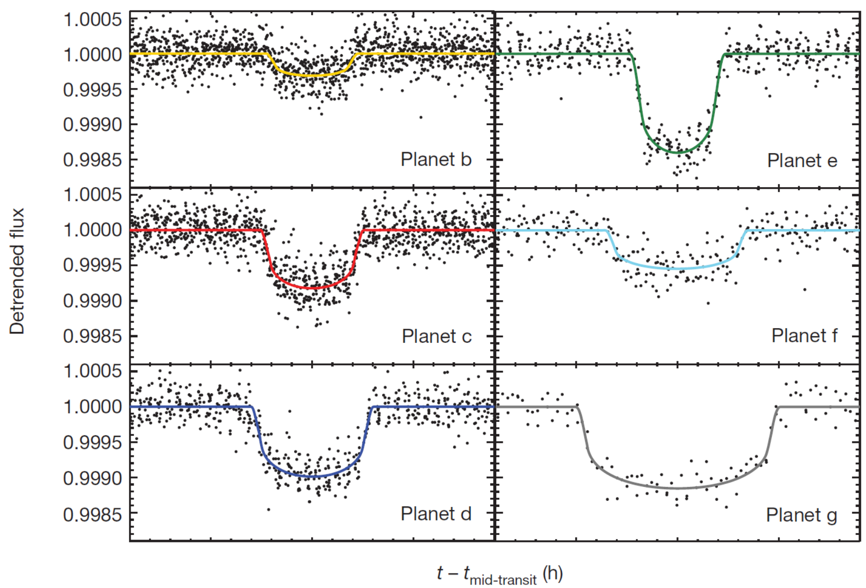


Bird's eye view of the Kepler-16b system. The planet, which is 1/3 the mass of Jupiter, orbits its star at a distance comparable to that of Venus in our own solar system, but is actually cold, as both stars are cooler than our Sun.

- The same year, the Kepler team announced the discovery of a system of *six* low-mass planets transiting Kepler-11.







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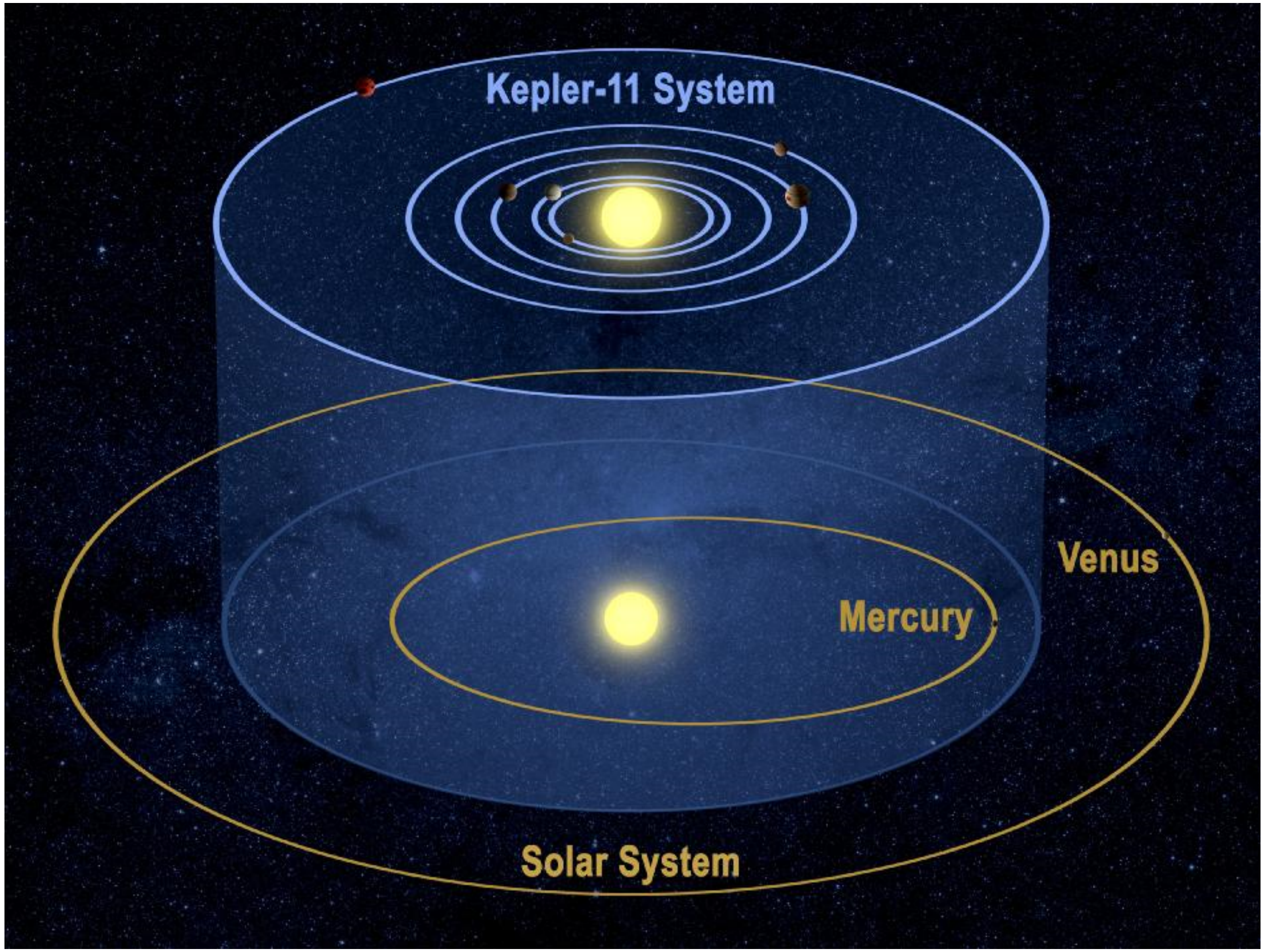
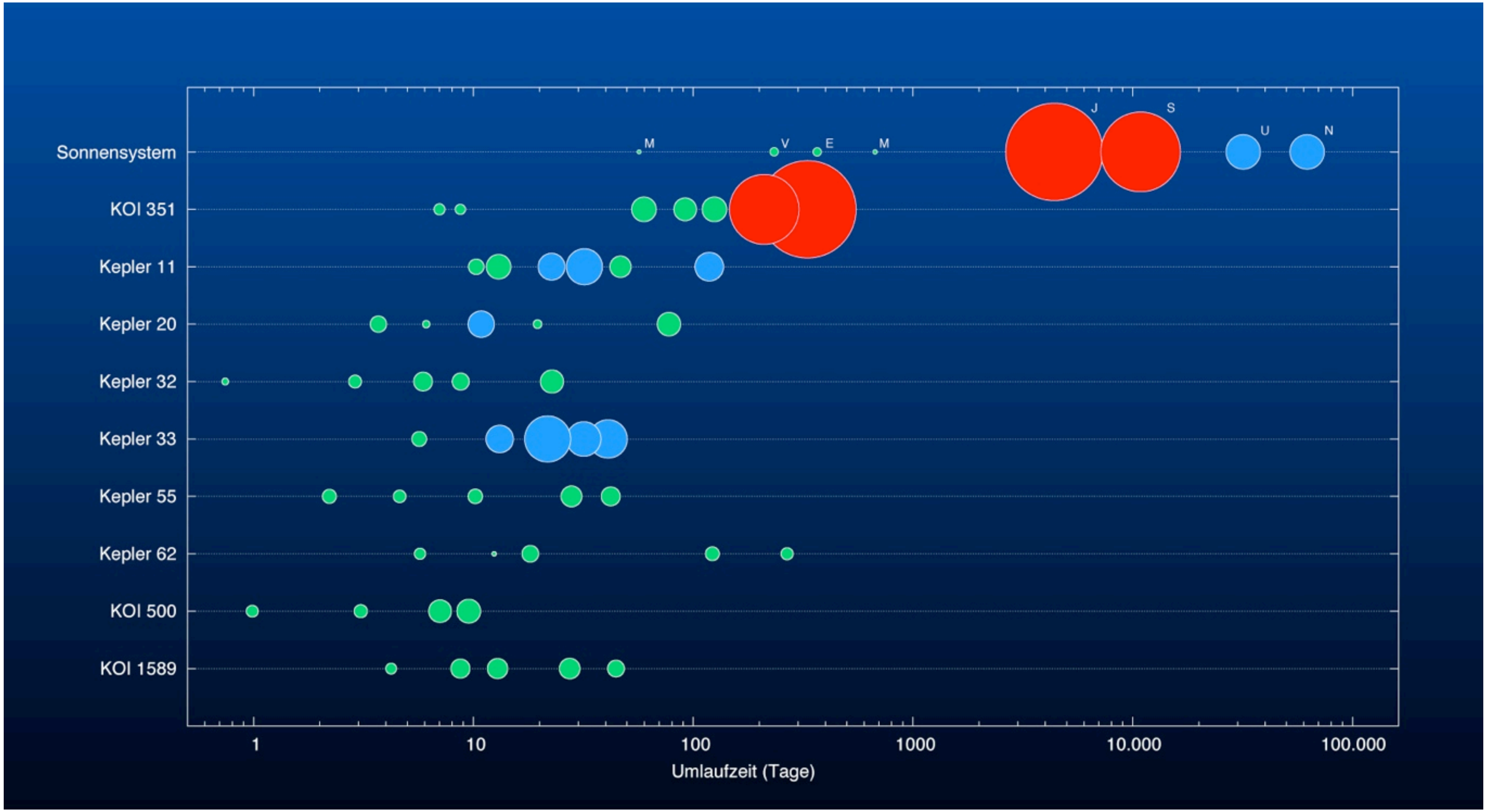
All six planets have orbits smaller than Venus, and five of the six have orbits smaller than Mercury's. The sizes are between 2 and 5 Earth radii.

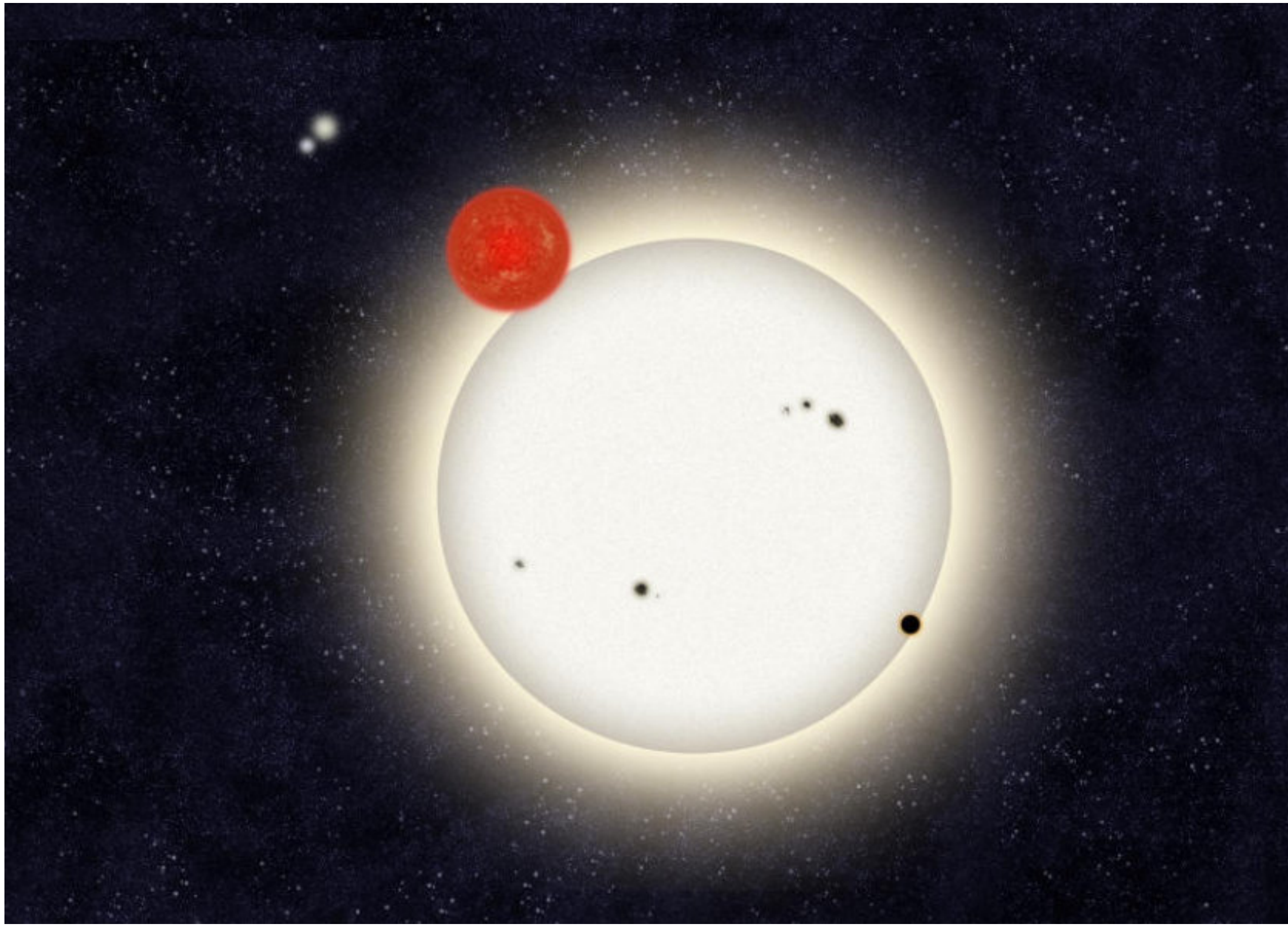


The current record number of planets is *seven*: four systems have been found with seven planets.



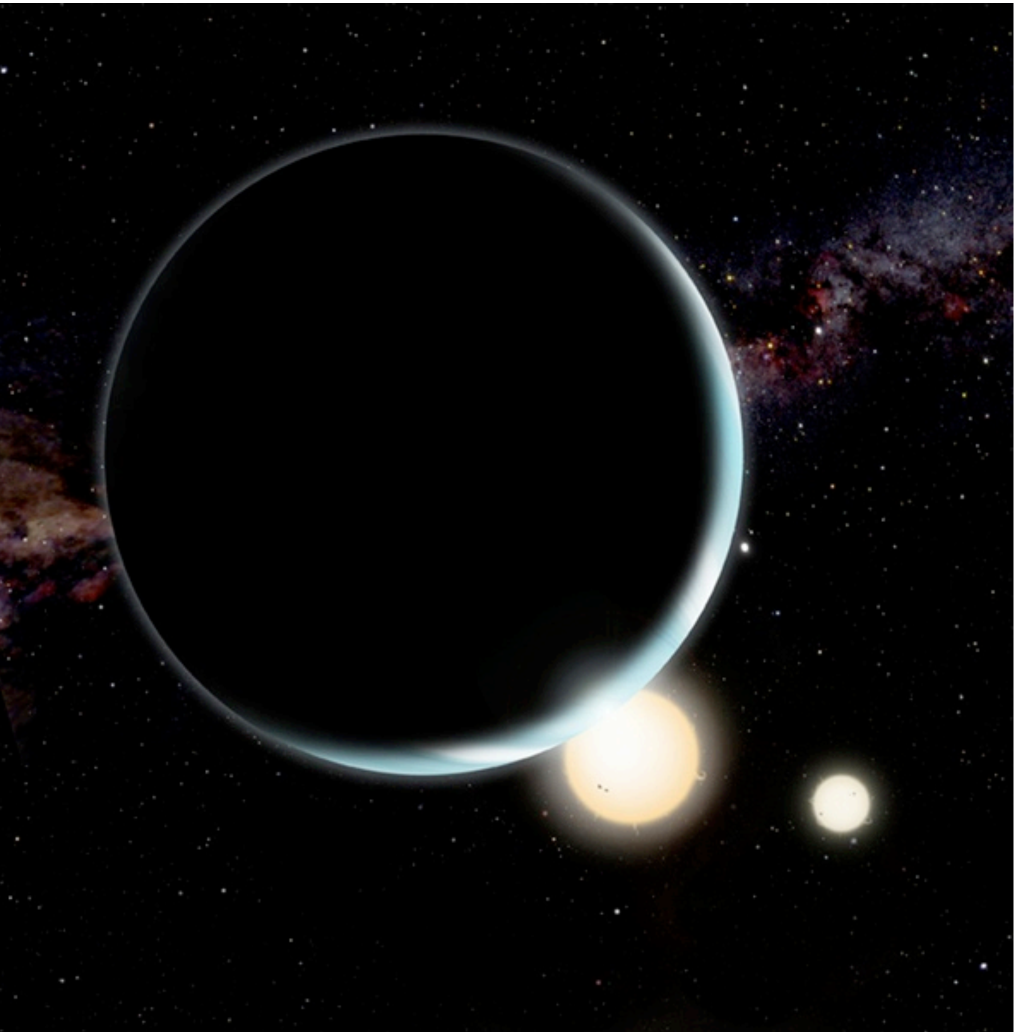
Comparison of Kepler's multiple-planet systems with the Solar System (top)

At least 20 circumbinary planets have now been discovered. There has even been a planet discovered in a *quadruple* star system: the planet orbits one pair of stars, which is in turn orbited by a distant second pair of stars.



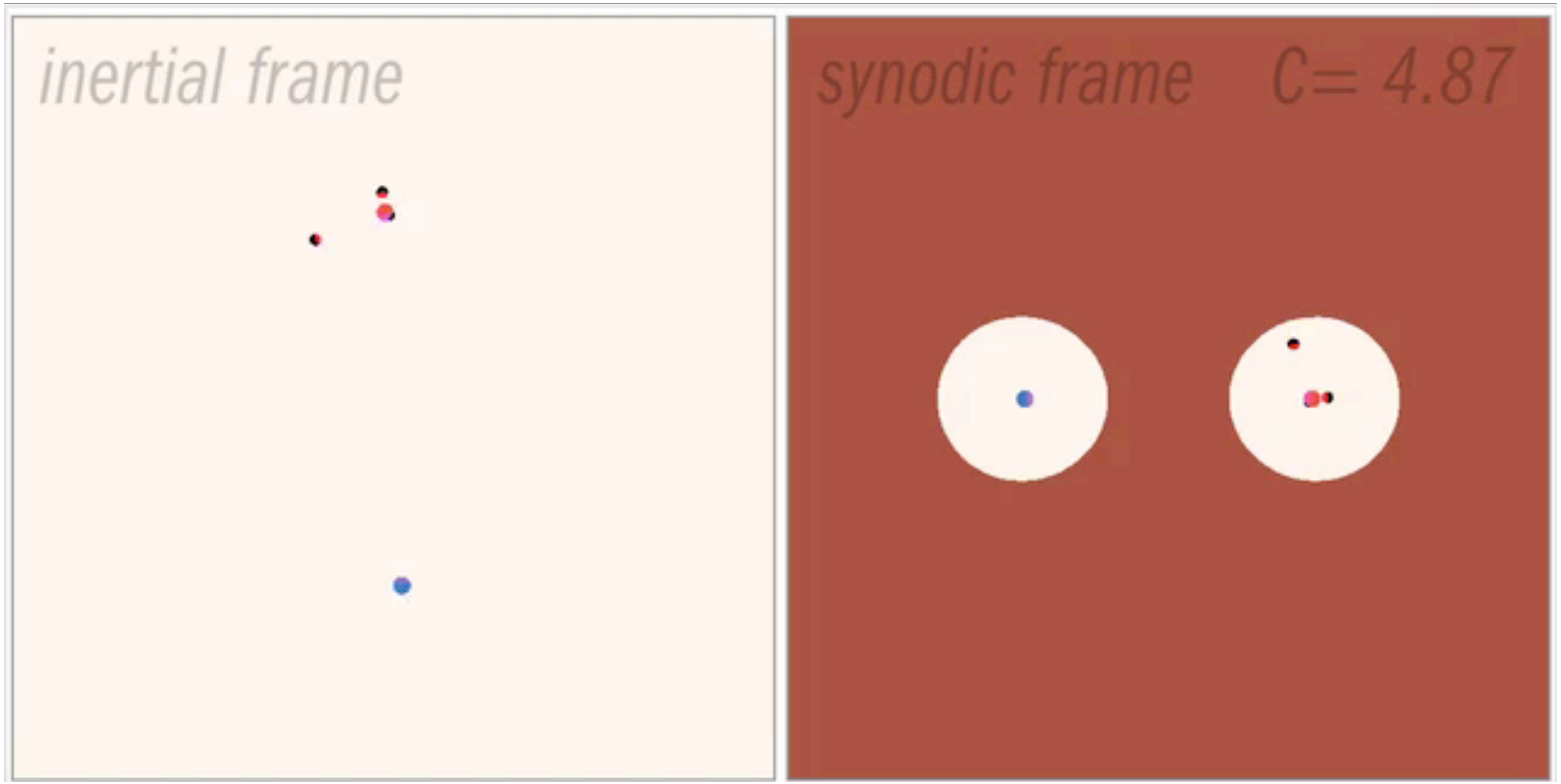
A family portrait of the PH1 planetary system: The planet is depicted in this artist's rendition transiting the larger of the two eclipsing stars it orbits. Off in the distance, well beyond the planet orbit, resides a second pair of stars bound to the planetary system.

Forming circumbinary planets is very difficult to explain: the gravity perturbations from the two stars on a circumbinary disk would have led to many destructive collisions.

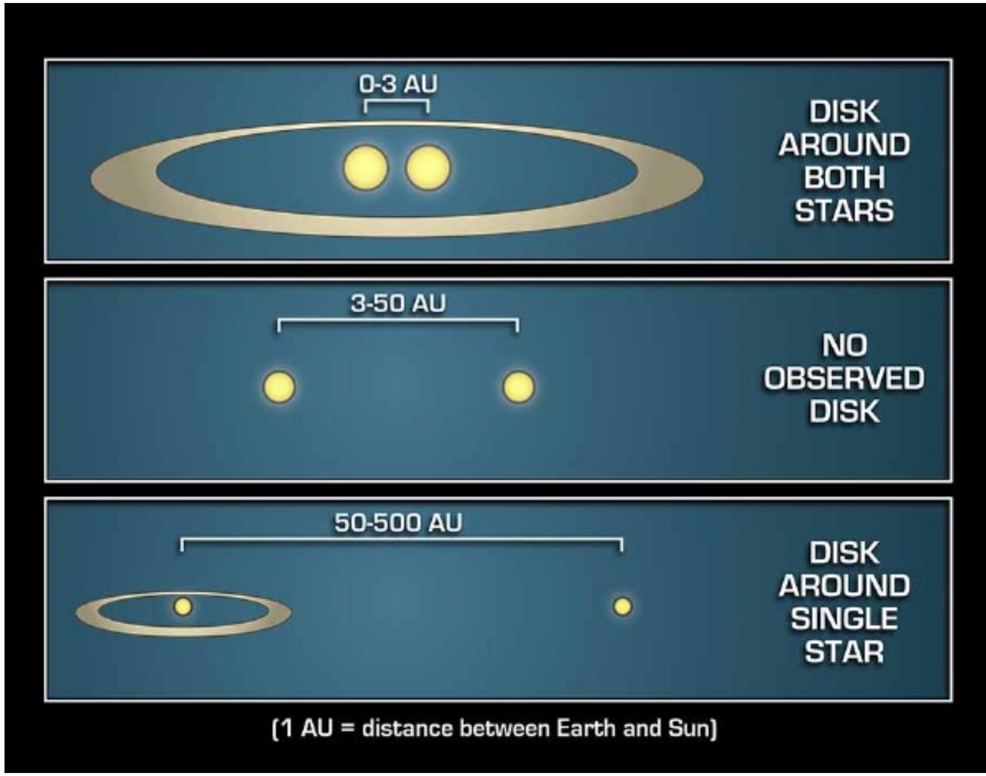


Artist's impression of Kepler-34b, a gas-giant planet that orbits a double-star system. Its two suns are both yellow G-type stars that swing around each other every 28 days. The planet circles them both in 289 days.

And planetary orbits in binaries may not be stable: planets orbiting one star in a binary can find themselves bouncing from star to star.

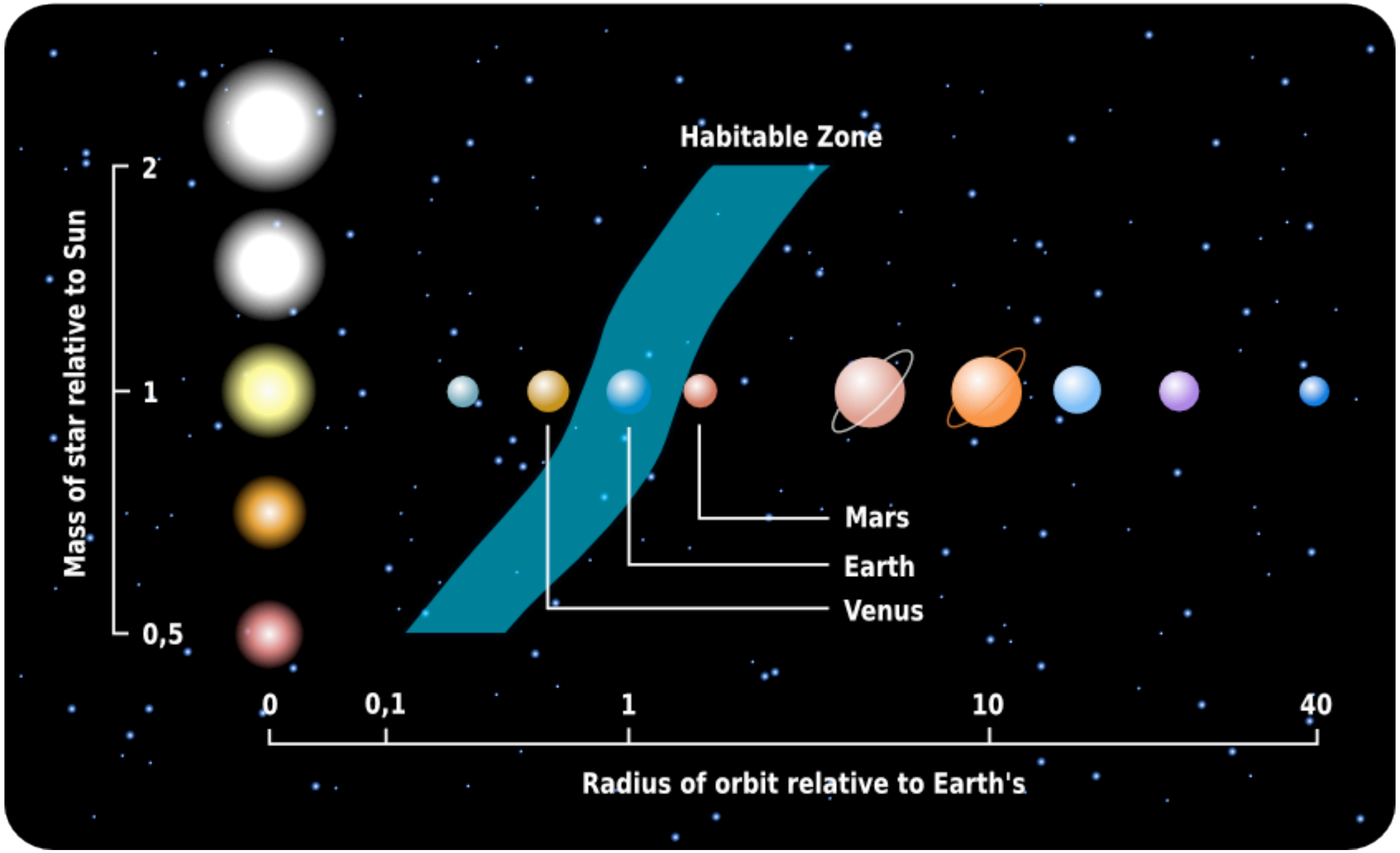


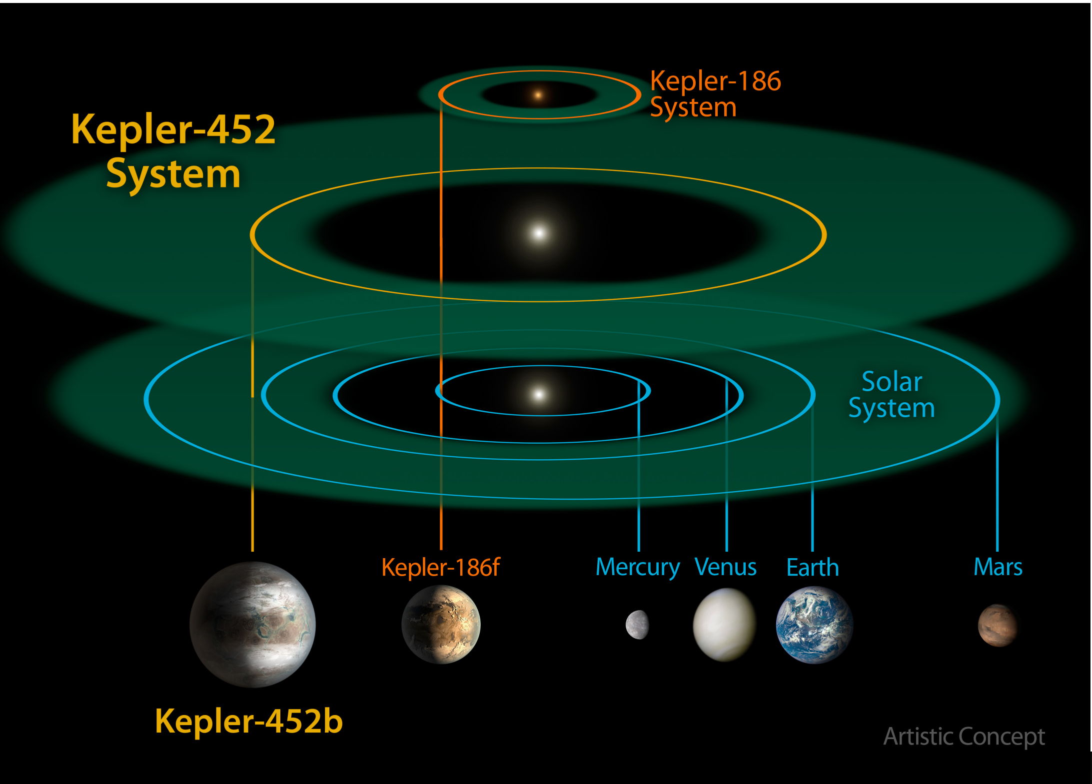
On the other hand, astronomers using the *Spitzer* infrared space telescope found that dust disks are just as likely to be found around stars in binary systems as around single stars. Around 40% of binaries showed dust disks, including extremely tight binaries. Only binaries with intermediate separations, between 3 and 50 AU, showed fewer disks.



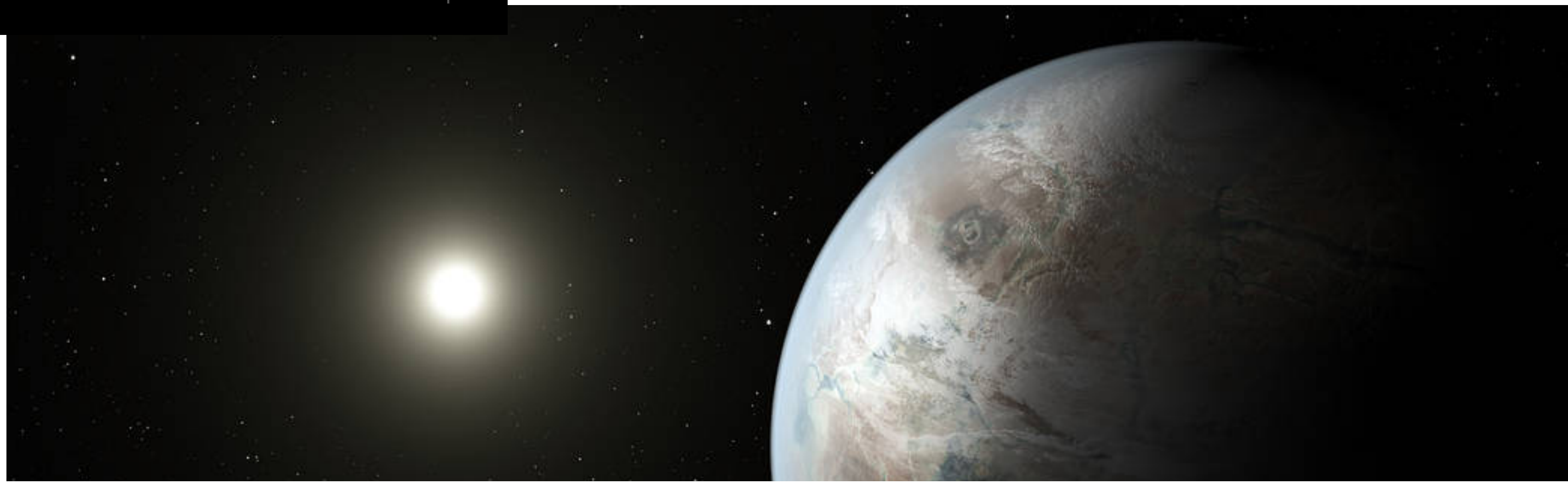
Where planets take up residence. If two stars are as far apart from each other as the sun is from Jupiter (5 AU) or Pluto (40 AU), they would be unlikely to host a family of planetary bodies.

The Holy Grail has been to find a planet located in the habitable zone, where it should be possible for Earth-like conditions (particularly liquid water) to prevail.

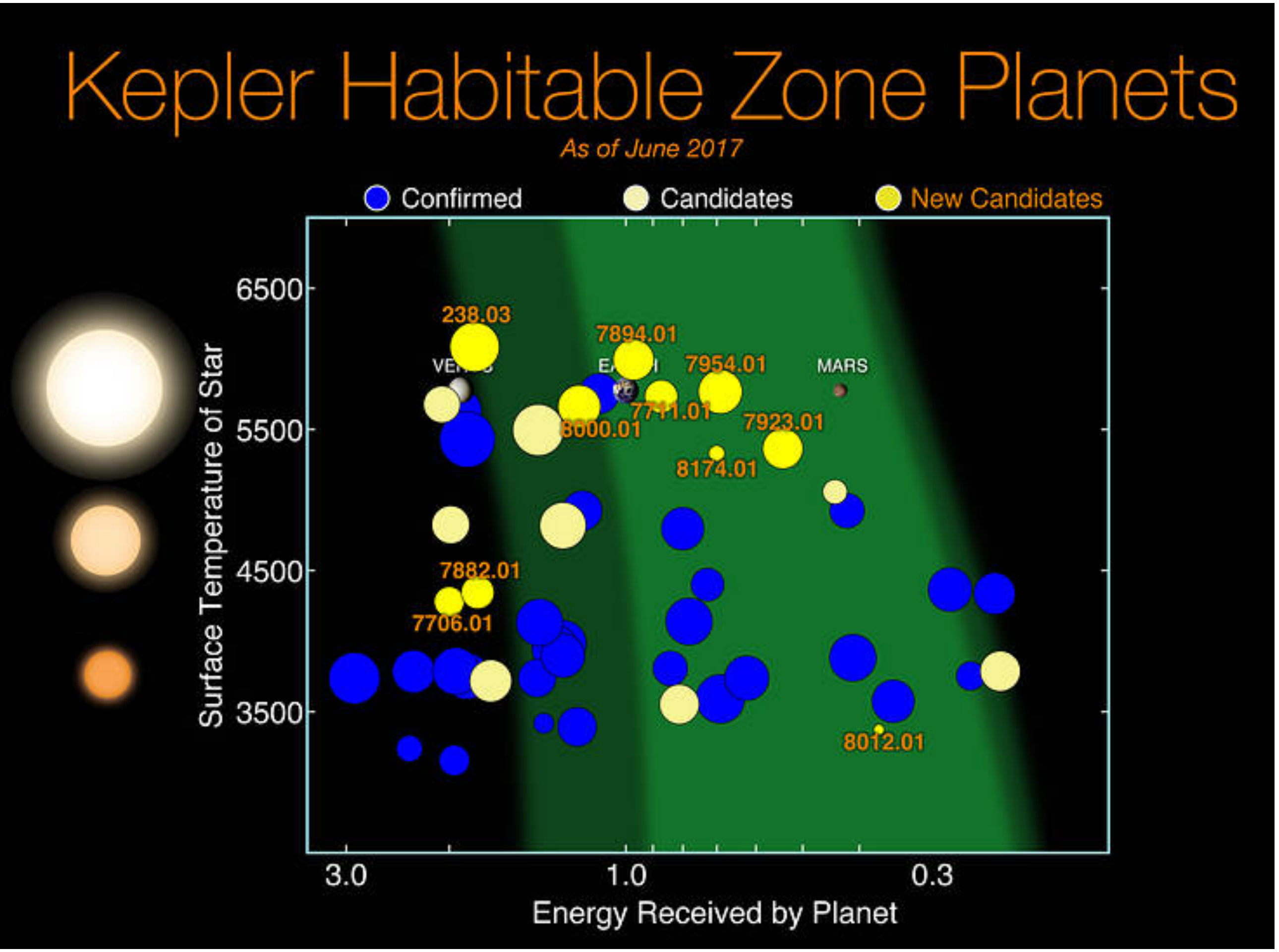




In July 2015 they announced the discovery of the first Earth-sized planet in the habitable zone of a star like ours. Kepler-452b is a planet 60 percent larger than Earth, in a 385-day orbit around a G2-star very like our Sun.



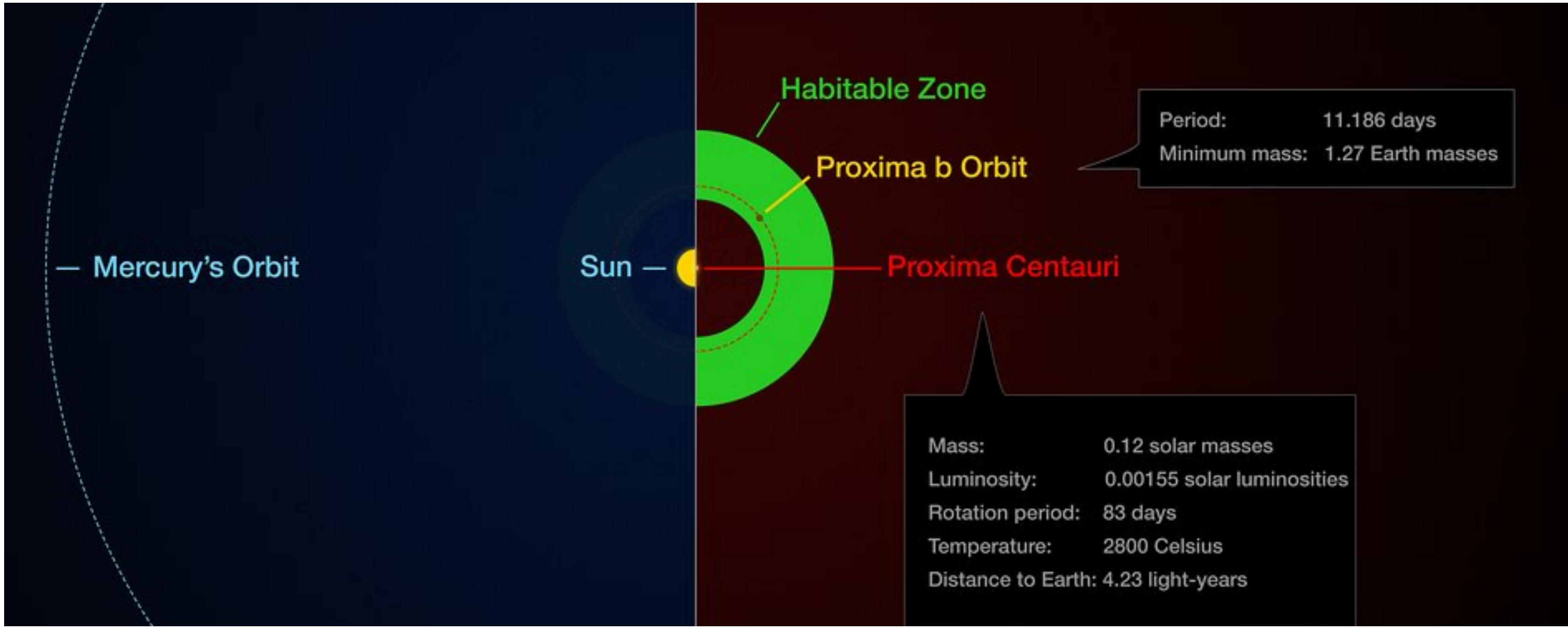
Kepler has now found several dozen confirmed exoplanets less than twice Earth-size in the habitable zone.



The dark green area represents an optimistic estimate for the habitable zone, while the brighter green area represents a more conservative estimate for the habitable zone. The sizes of the colored disks indicate the sizes of the exoplanets relative to one another and to the image of Earth, Venus and Mars, placed on this diagram for reference.

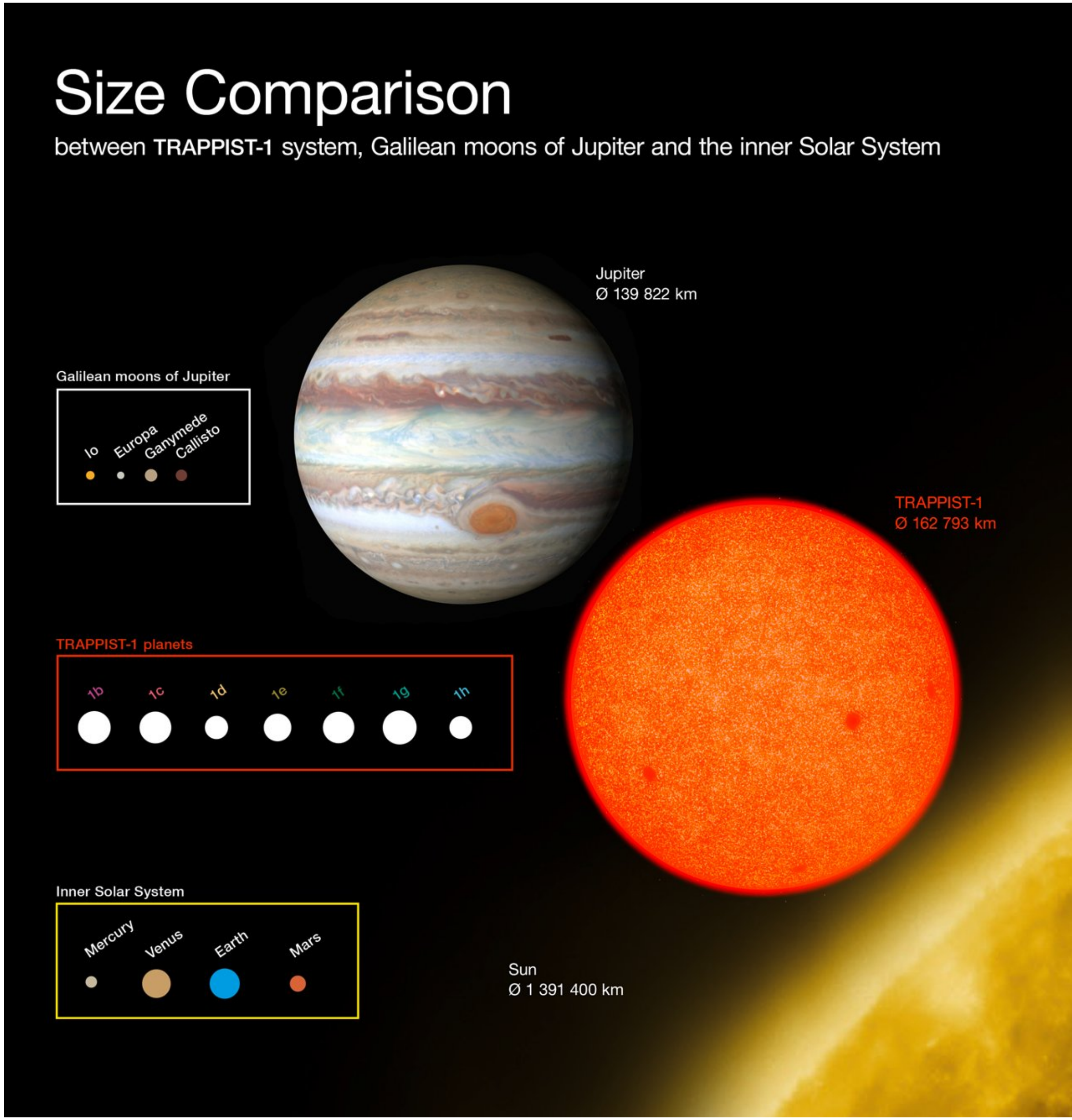
In 2016, ESO astronomers announced the discovery of an Earth-mass world in orbit around Proxima Centauri in the habitable zone.

Proxima Centauri is a red dwarf star, much smaller and fainter than our Sun. Such stars are known to produce strong flares, which would be problematic for the formation of life.

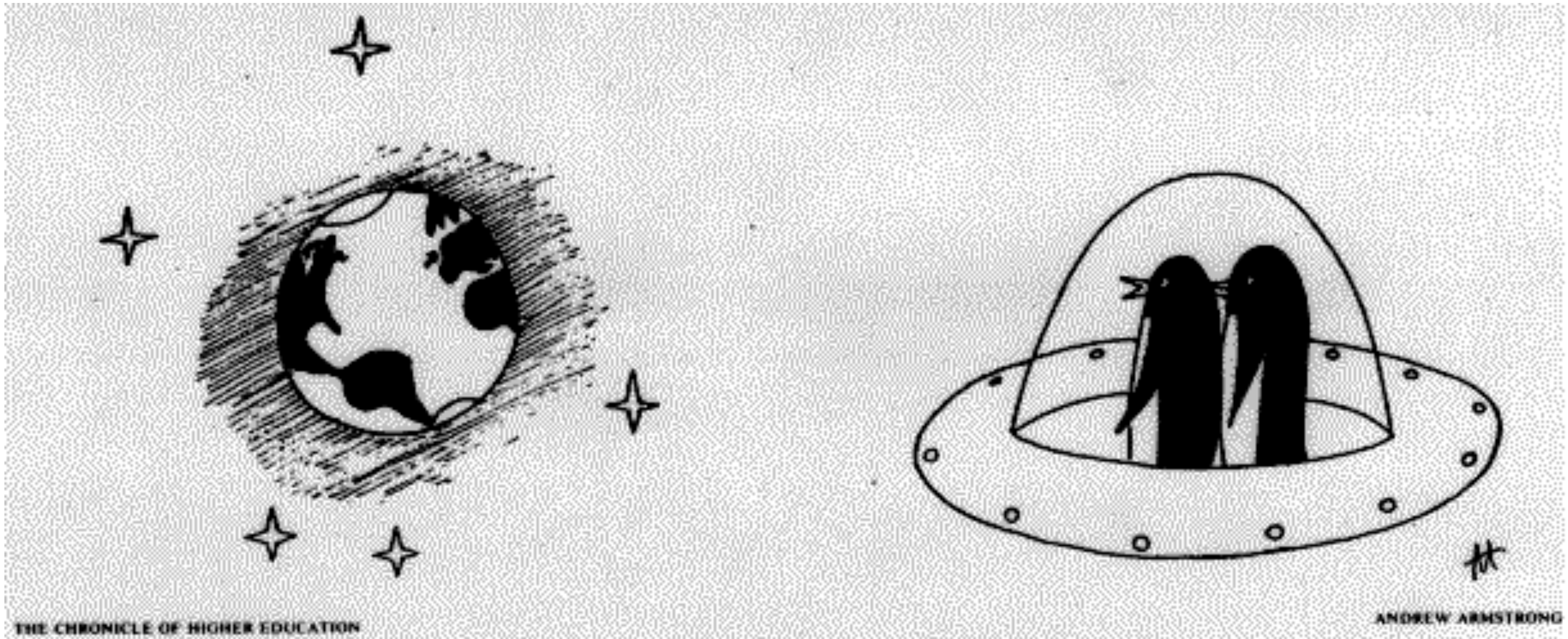


In 2017, astronomers from ESO and NASA announced the discovery of a system of seven planets around an ultra-cool dwarf star. Three of the seven planets lie in the habitable zone of the star, known as TRAPPIST-1.

All seven of the TRAPPIST-1 planets are closer to their host star than Mercury is to our sun. The planets are also very close to each other. A person standing on one of the planets' surface could gaze up and see geological features or clouds of neighboring worlds, which would sometimes appear larger than the moon in Earth's sky.



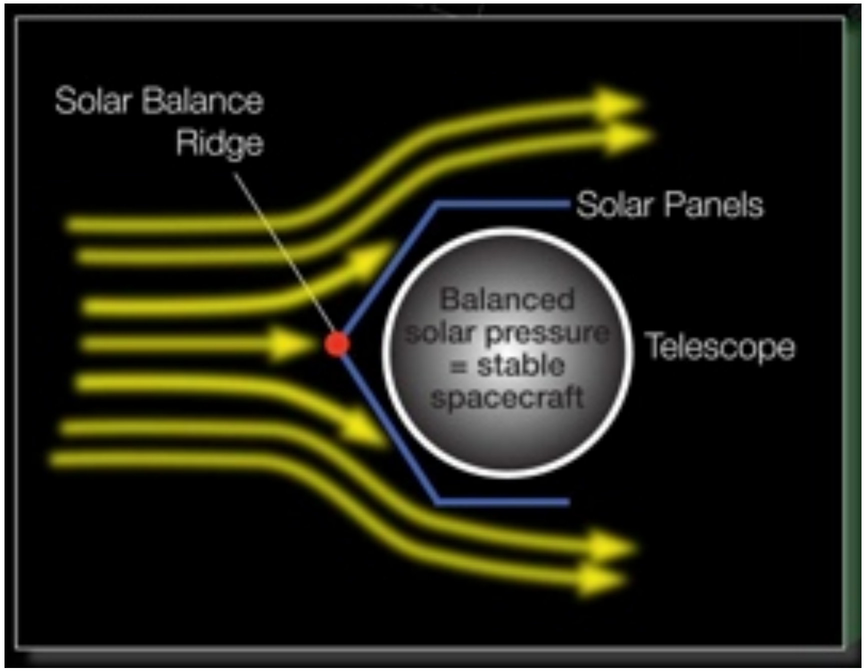

PLANET HOP FROM
TRAPPIST-1e
BHZ
VOTED BEST "HAB ZONE" VACATION WITHIN 12 PARSECS OF EARTH



"I see only a little snow at the poles. Obviously, this planet can't support intelligent life."

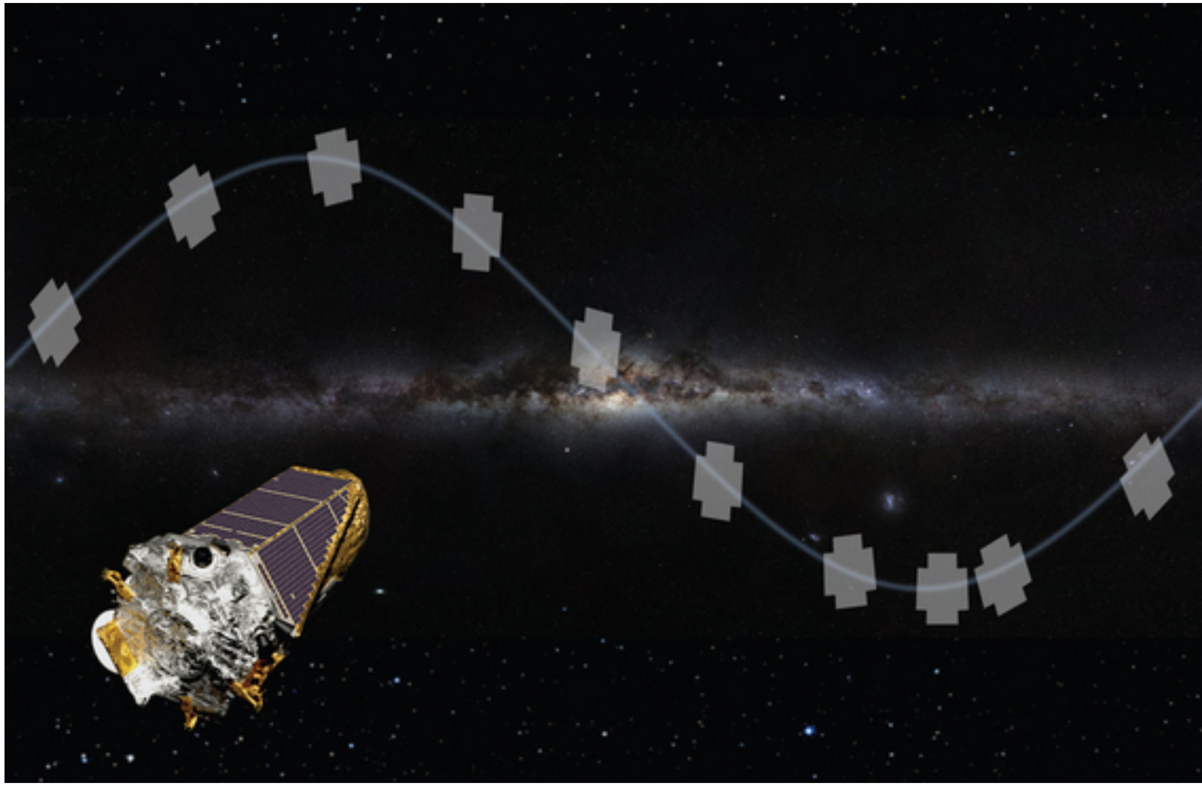
In May 2013, the second of Kepler's four reaction wheels failed. Without the ability to maintain its orientation, the spacecraft was no longer able to point precisely enough, thus terminating the main mission.

In May 2014, an extension mission called K2 was approved. This uses the solar wind to help stabilise the spacecraft, recovering pointing stabiity.



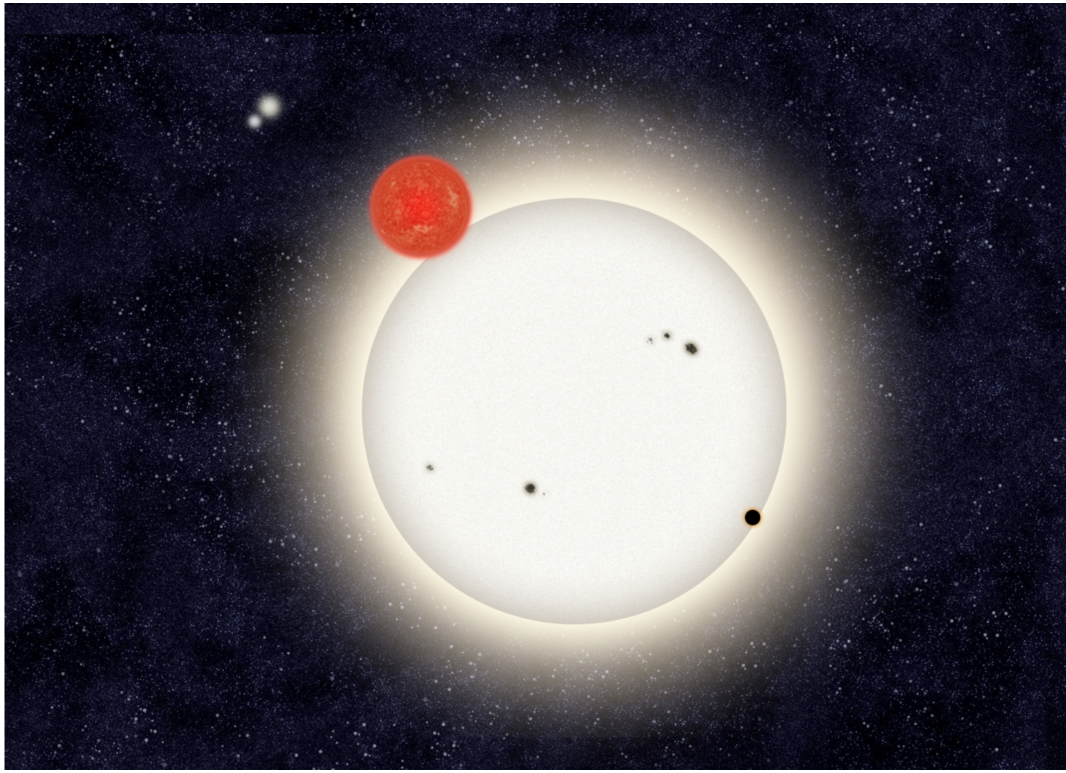
Kepler will stare at target fields in the ecliptic for about 75 days, before the spacecraft has to be rotated again.

This means completely different fields will be observed each time. *Kepler* is currently observing its 16th field, C5.



There is a "**Citizen Science**" project associated with Kepler, where members of the public identify transit events in the light curves to identify planets that the computer algorithms might miss. The first person to flag a potential transit gets credit for the discovery, and is offered authorship on the paper.

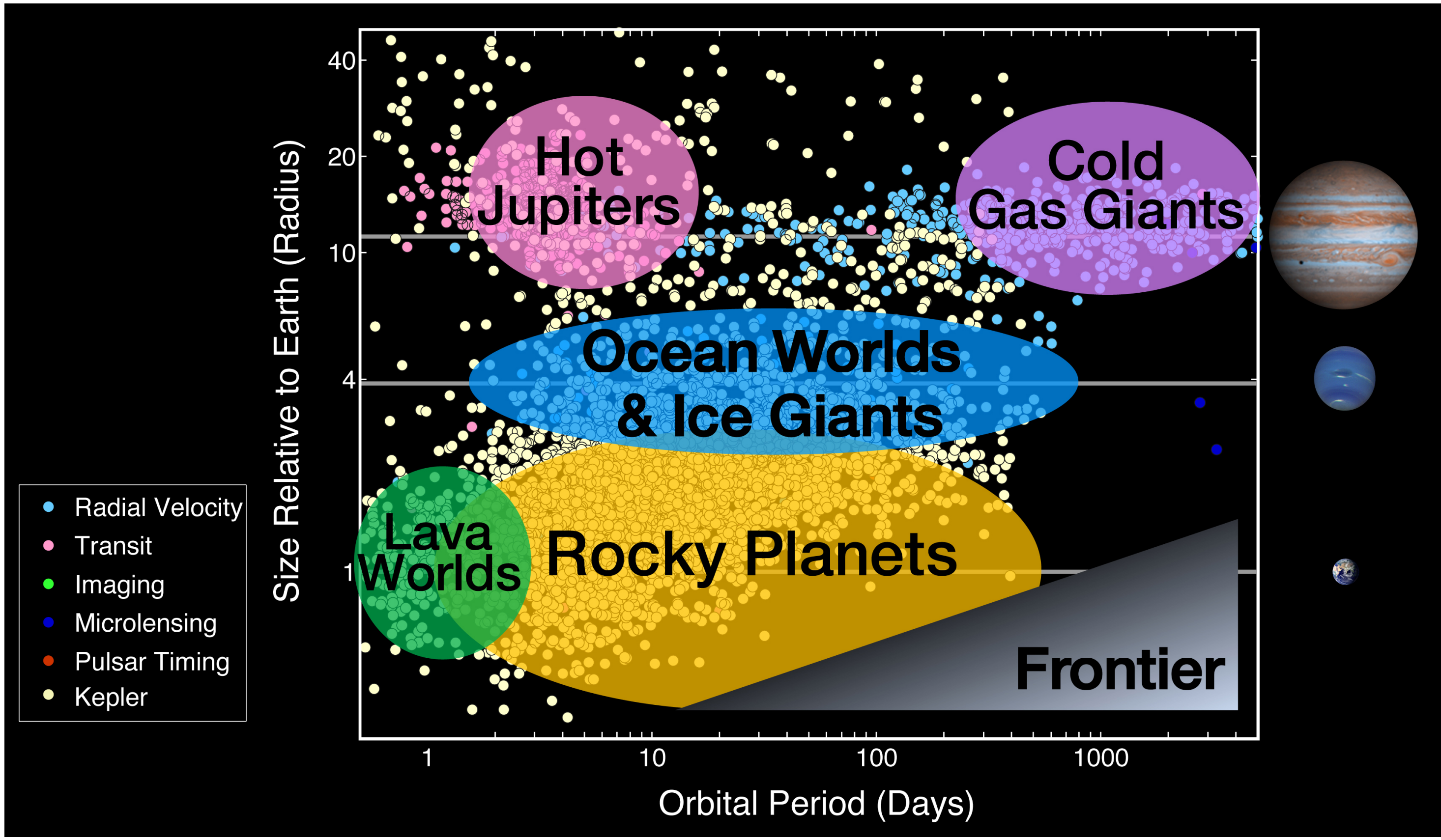
The PH-1 planetary system with four stars was first identified by citizen scientists in the PlanetHunters project.



A family portrait of the PH-1 planetary system: The newly discovered planet is depicted in this artist's rendition transiting the larger of the two eclipsing stars it orbits. Off in the distance, well beyond the planet orbit, resides a second pair of stars bound to the planetary system.

The exoplanet population

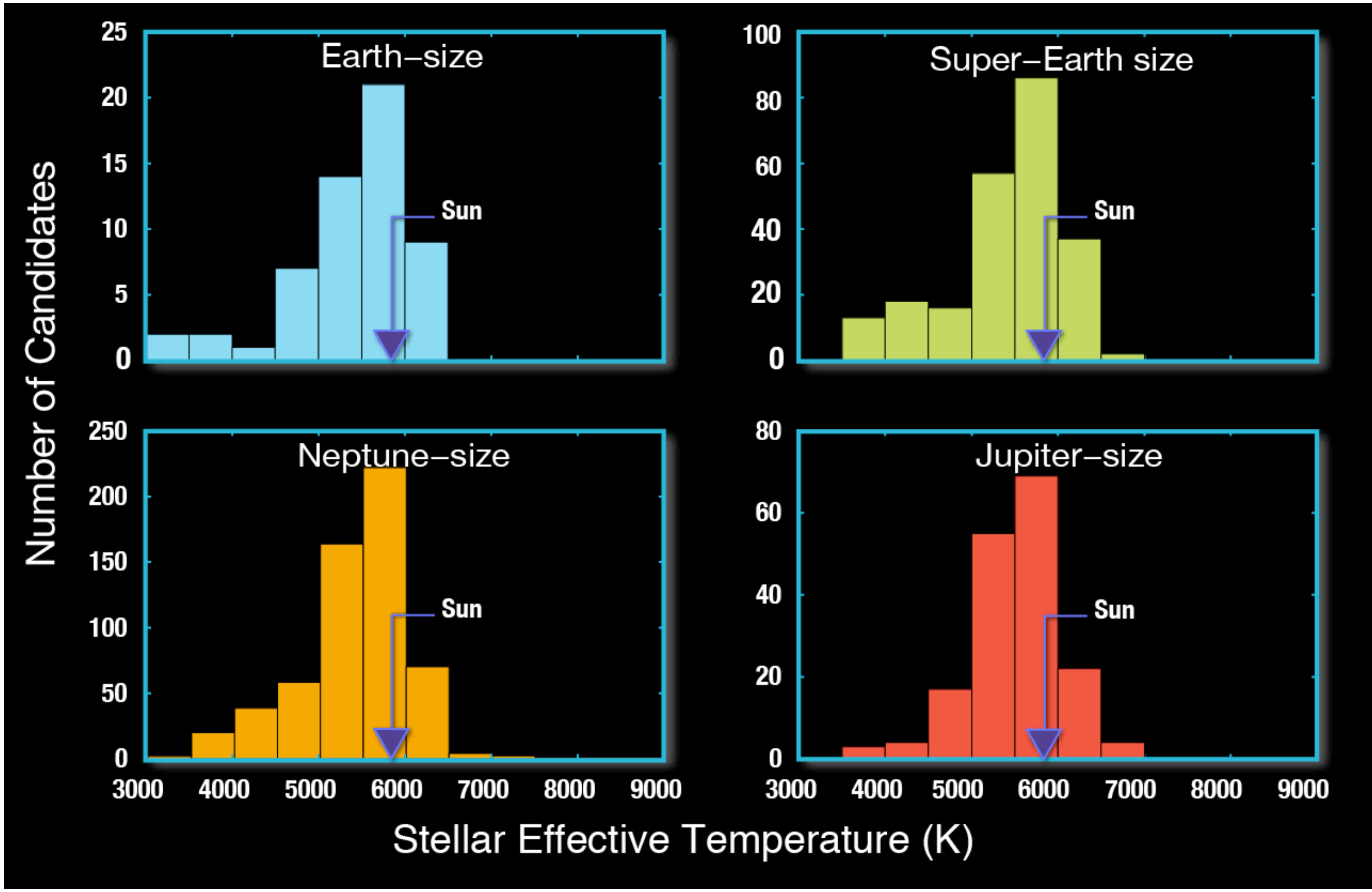
As of December 2017, we know of 3564 confirmed planets, with 590 multi-planet systems.



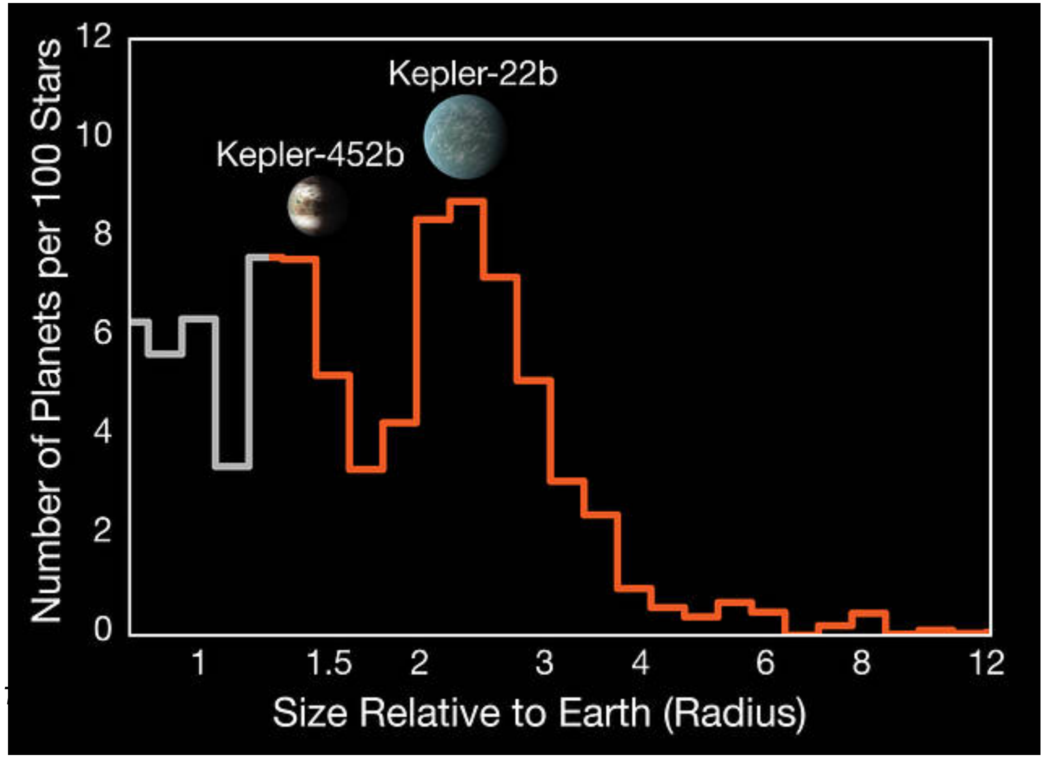
Here are some (preliminary) statistics on what has been found so far.

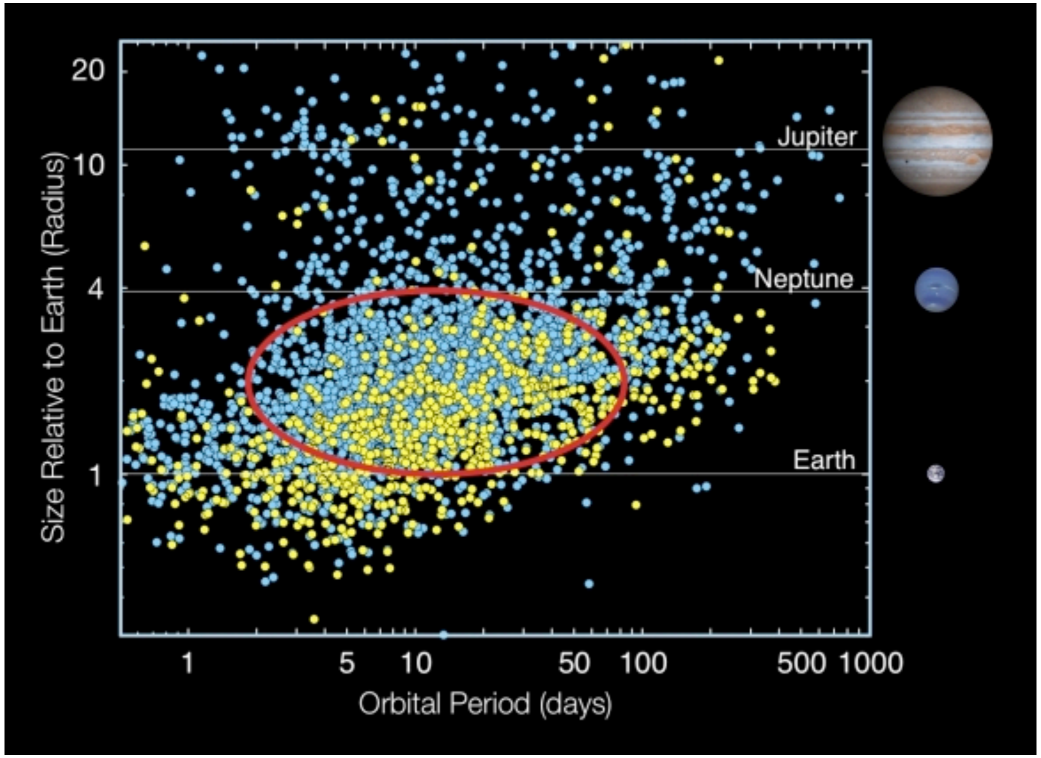
- about half of Sun-like stars have at least one planet with an orbital period of 100 days or less
- systems with multiple transiting planets are common (17% of host stars, 34% of planets)
- such systems are less likely to include a transiting giant planet
- either systems are likely to be highly co-planar, or typical systems have many planets

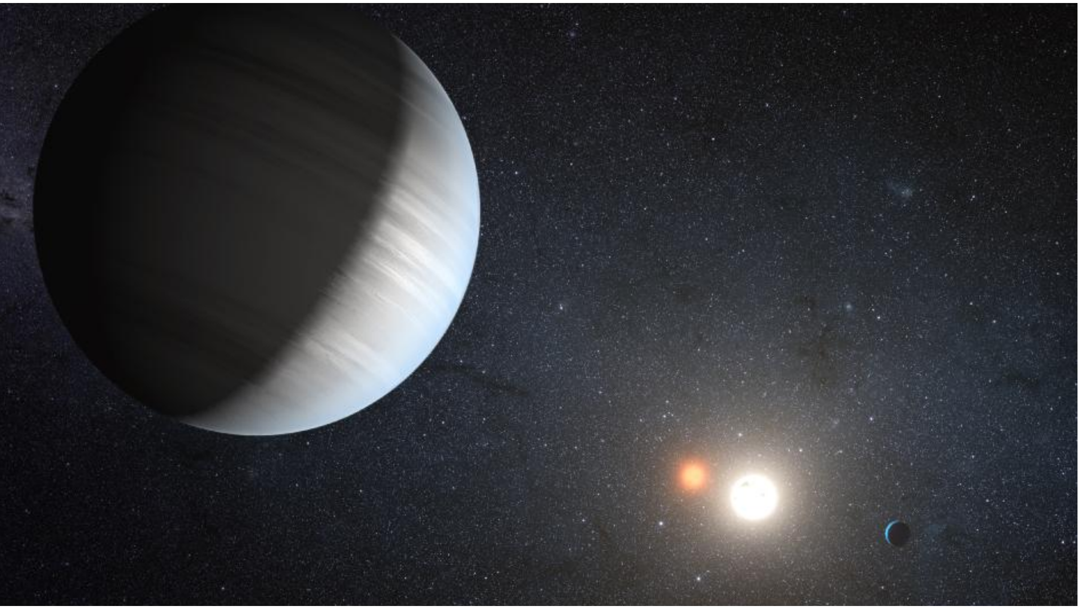
• Most of the planets orbit stars like our Sun

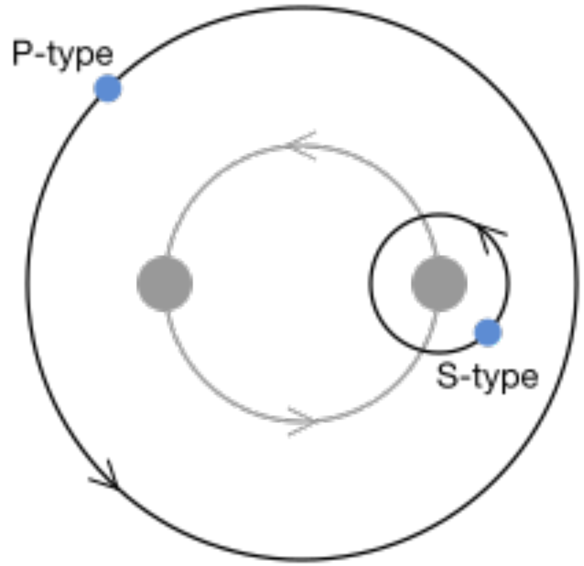


- The most common size for planets is 2–3 times the size of Earth. More than three-quarters of the planet candidates discovered by Kepler have sizes ranging from that of Earth to that of Neptune, which is nearly four times as big as Earth. Such planets dominate the galactic census but are not represented in our own solar system.



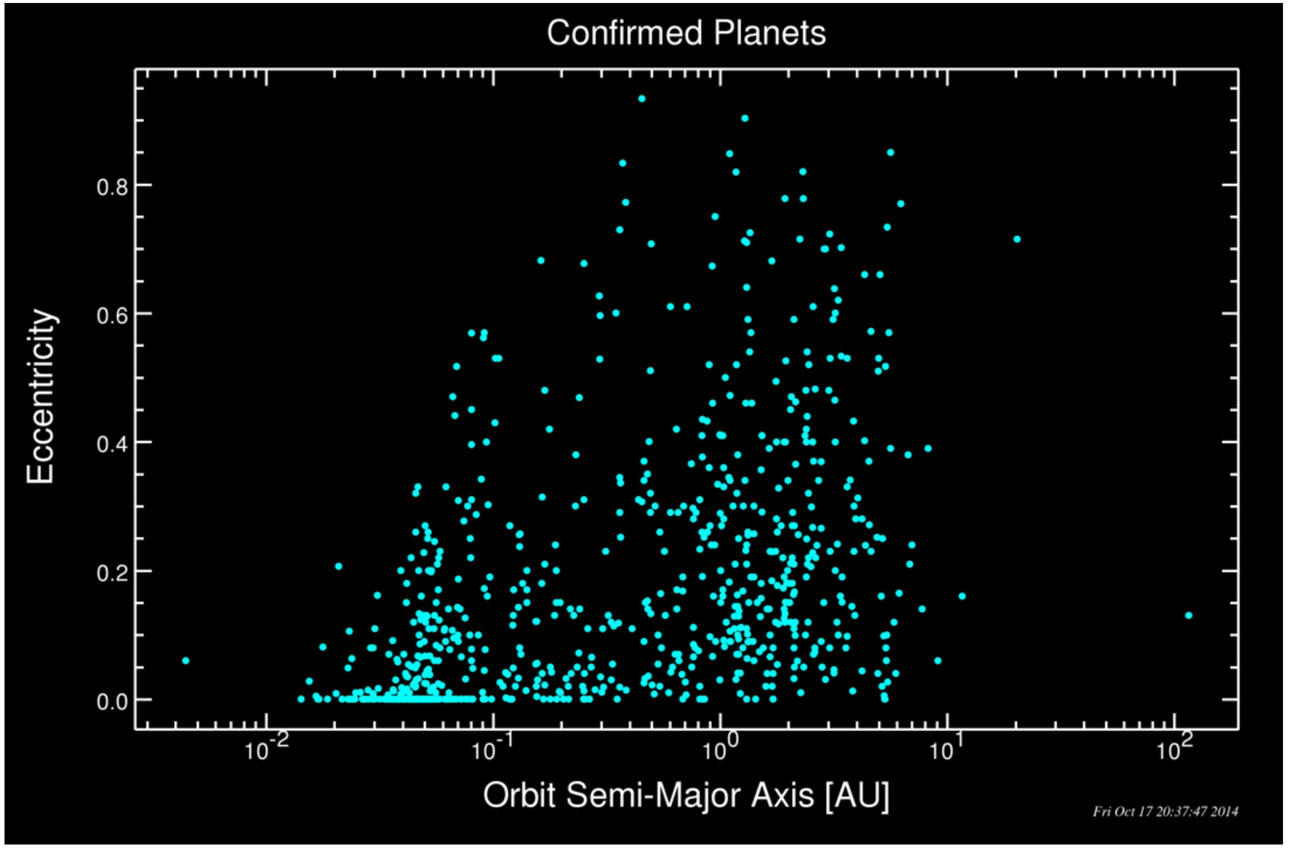






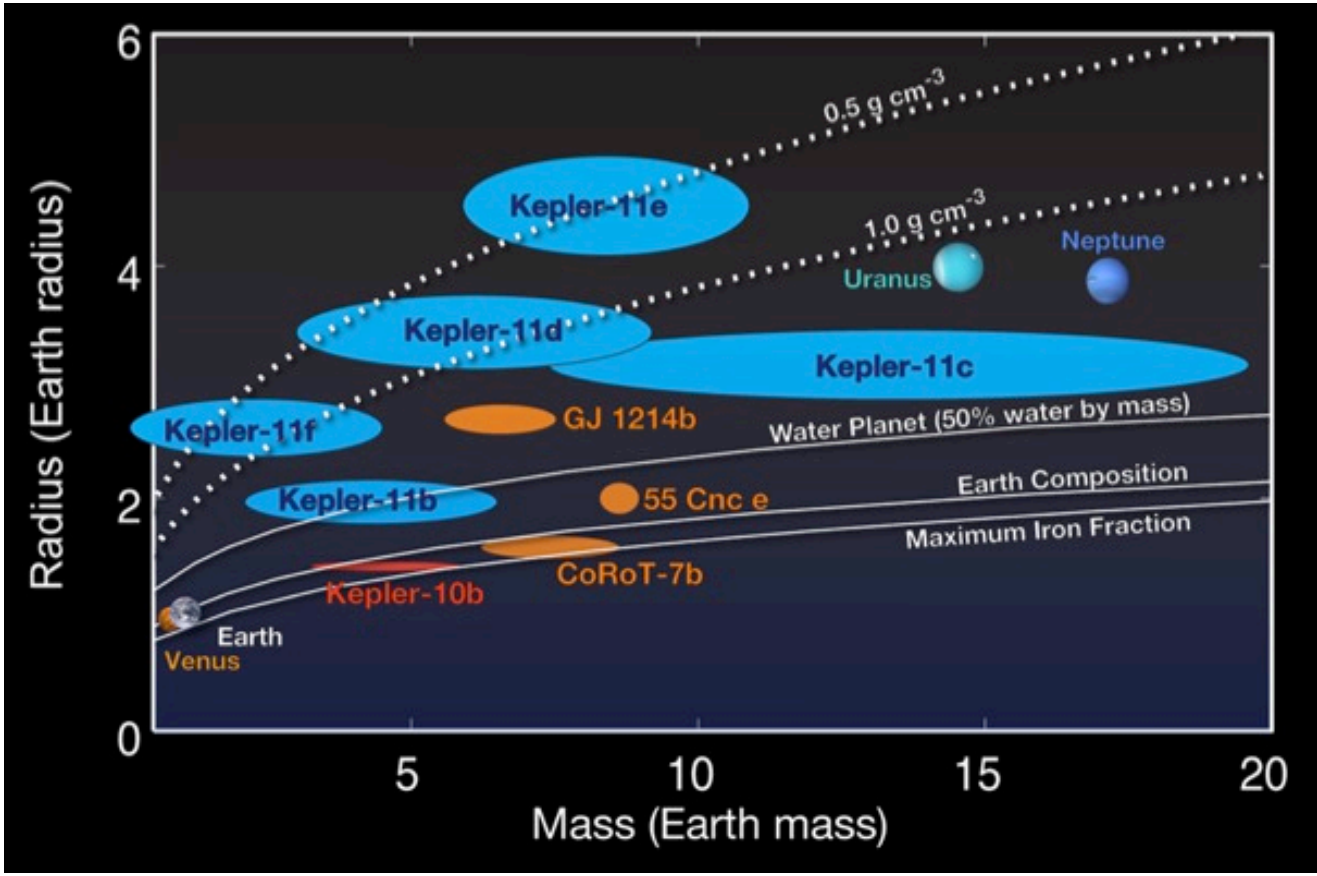
- As many as half of exoplanet host stars have a companion star; most planets orbit just one star (S-type), but some orbit both (P-type: *circumbinary planets*)

Most of the planets have eccentric orbits: the mean eccentricity is about 0.20 (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.

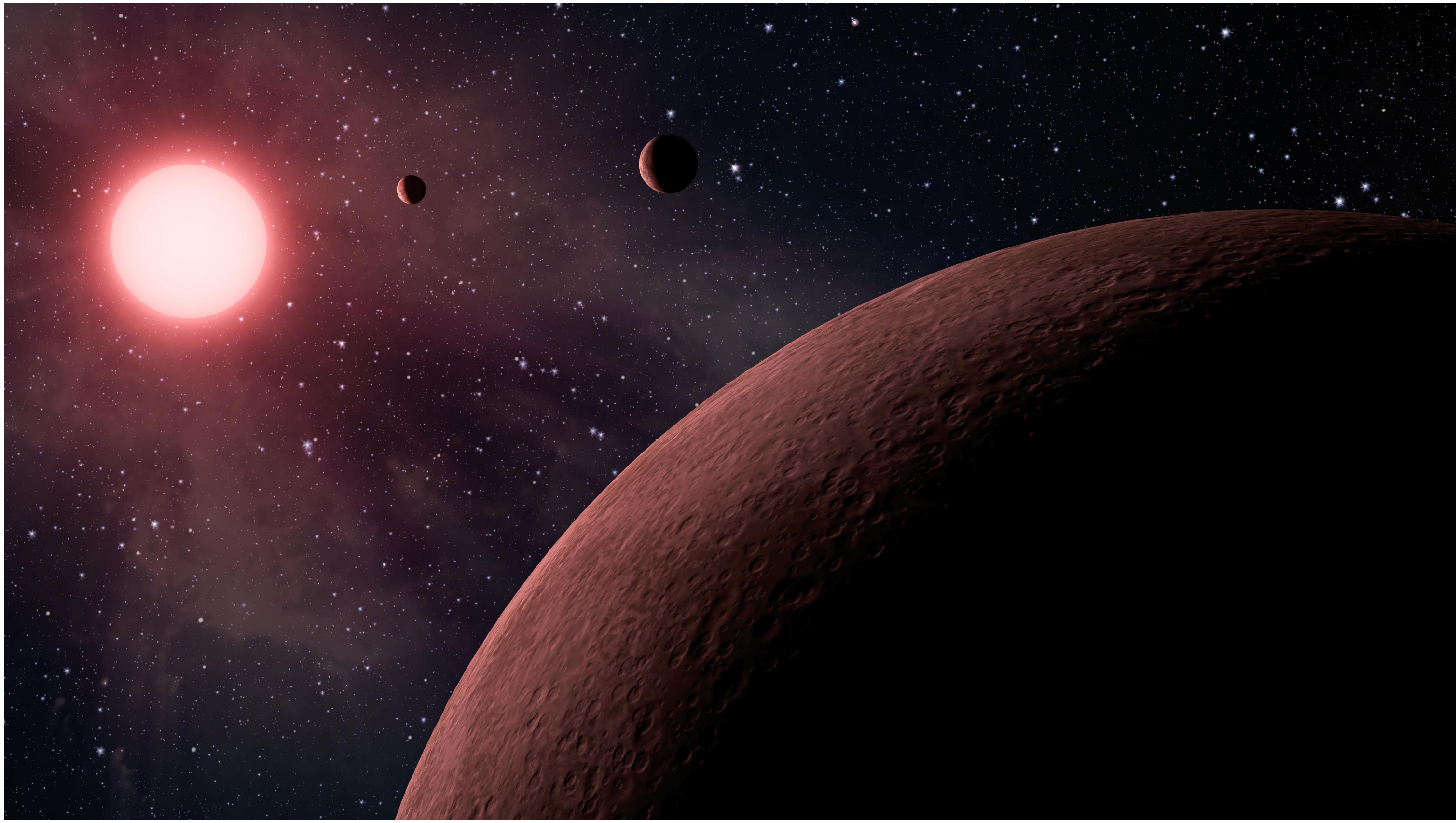


- If you can measure both the planet's *size* (from transits) and the planet's *mass* (from radial velocities), we can estimate the planet's density.

There do seem to be exoplanets of different compositions.



- So-called *tightly-packed multi-planet systems* are common: systems with 4–6 planets orbiting much closer to their star than Mercury's orbit around the Sun.



Artist's impression of Kepler-80, with five planets orbiting very close to their star.

Kepler found about 5000 likely planets from observations of ~190,000 stars for several years. So about 2.4% of stars surveyed had planets.

However, the true fraction of stars with planets is *much* greater than this, because only a small fraction of planets will show transits when viewed from a single direction.

Our best estimate is that 50% to 100% of stars have planets, and many or most of these are multi-planet systems

What does it mean?

The core-accretion theory for the formation of our Solar System that we discussed last week explained all the major features: why the planets orbit the Sun in nearly circular orbit in the same direction and in the same plane, why the inner planets are small and rocky and the outer planets huge and gaseous.

Since the theory was so beautiful, we expected that any system of planets would look pretty much the same.

Instead, as we have seen, we found planets the size of Jupiter in tiny orbits, planets in highly elliptical orbits or in orbits that don't go around their star's equator. And the most common type of planet is a "super-Earth", a type of planet that doesn't even exist in our Solar System.

Basically, *none* of the systems we've discovered look much like the Solar System at all.

Here are some of the major problems in explaining exoplanet systems, with possible solutions.

See Ann Finkbeiner, "Astronomy: Planets in chaos", Nature 511, 22 (2014)

How do you form “hot Jupiters”?

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

– too hot

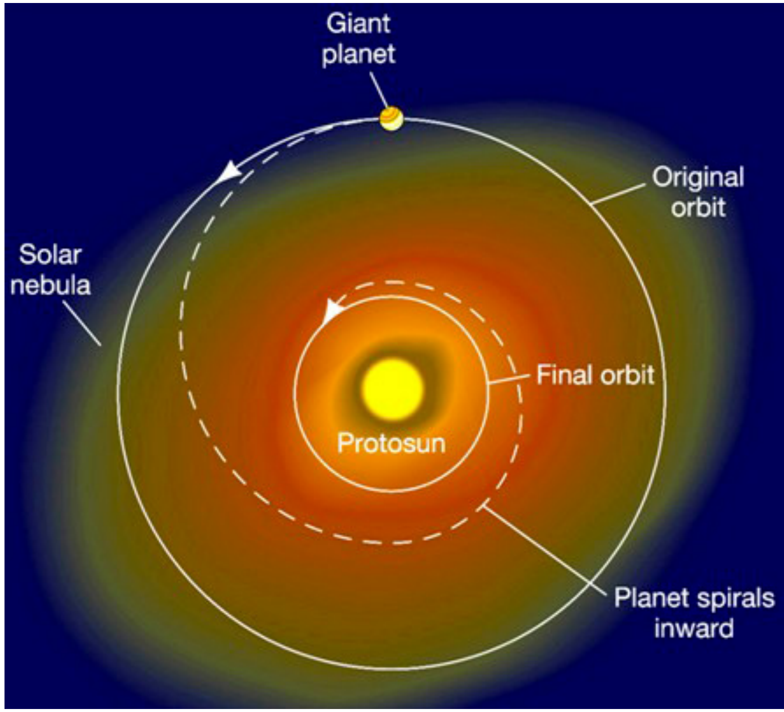
– too little material

– too little gas to form envelope

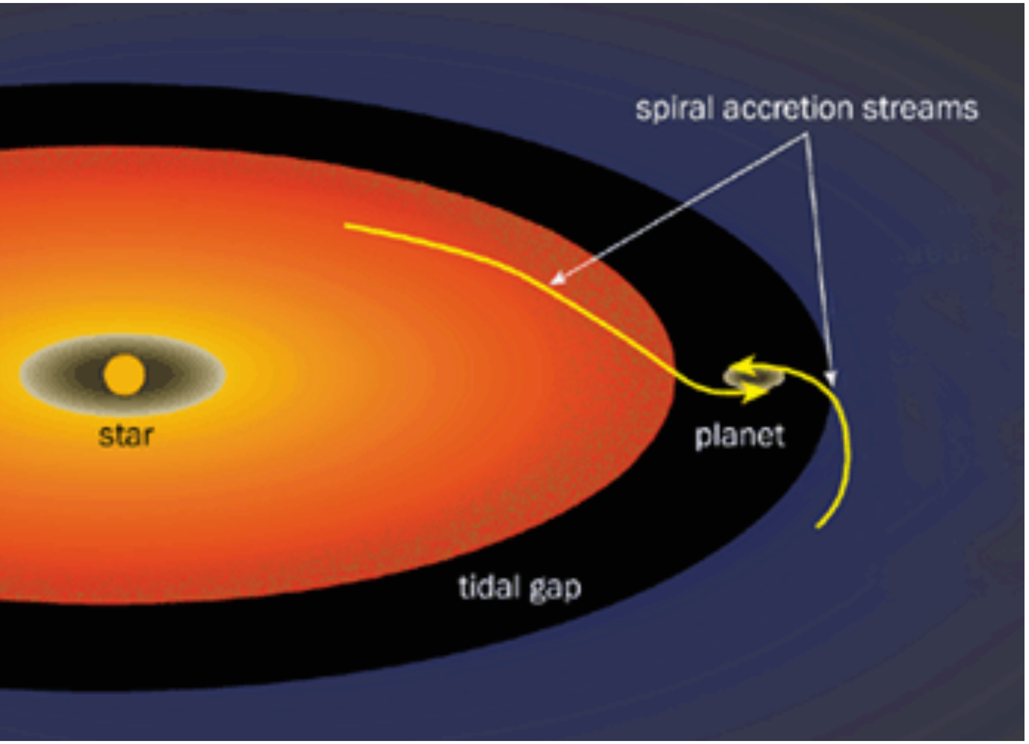
To explain this, we require *planetary migration*.

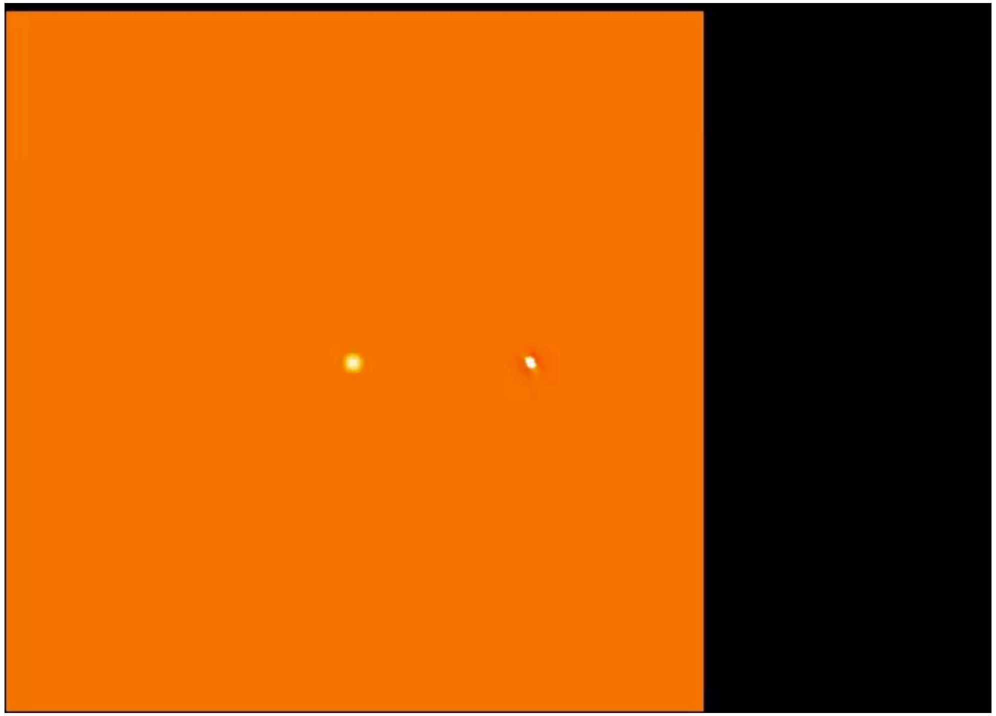
You remember that the giant planets accreted gas directly from the disk. We discussed how they had to complete their accretion before the proto-Sun blew the gas away. What we didn't stress was that there must have been a period when the giant proto-planets were embedded in the disk.

What effect does this have?



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

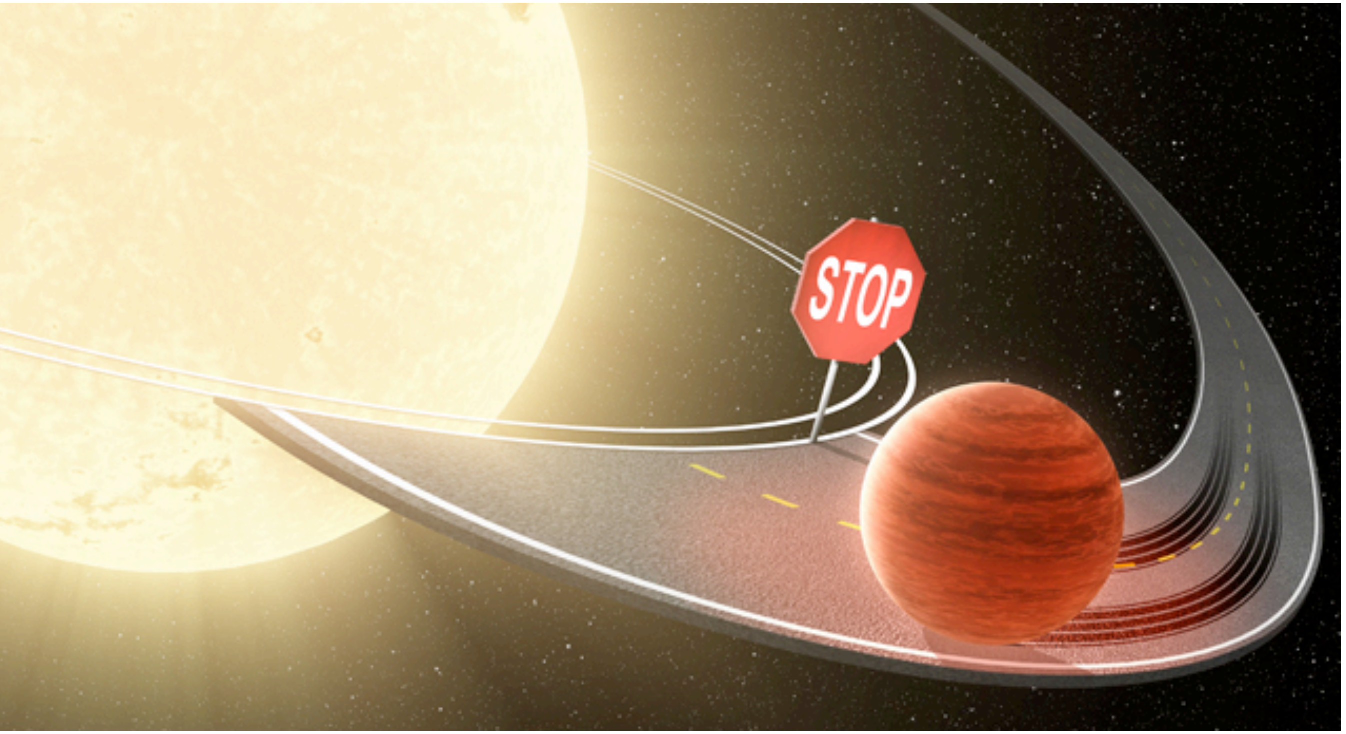




Simulation of a proto-planet growing from 10 Earth masses to 1.5 Jupiter masses

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...

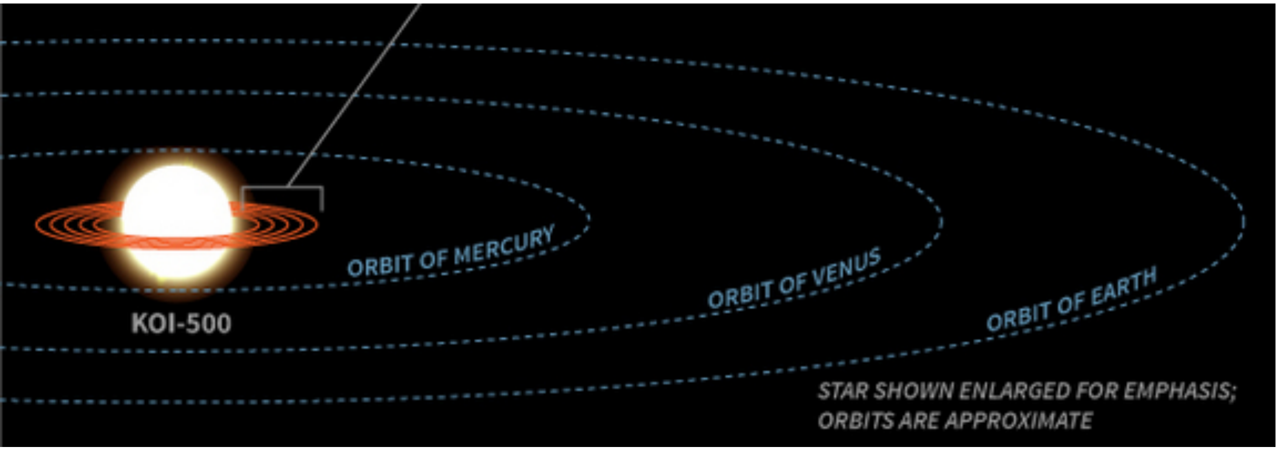


Recent research suggests that perhaps stars do not in fact consume planets very often, and that tidal forces halt the migration before the planet plunges into the star. If this is true, then we should see that the hot Jupiters of more massive stars would orbit farther out, on average, than those around less massive stars. This is in fact what is observed.

Why are some planets packed so tightly together?

Many multi-planet systems show orbital resonances. These resonances may be important when planets are tightly packed. Planets that orbit too closely to one another can become unstable and eventually either collide or be unceremoniously ejected from the system.

Kepler-80 has five closely-spaced planets, the outer four of which are in resonance. Planets in systems like this probably formed further out, and migrated inwards together.



What happens to other planets in the system when planets migrate?

The fact that hot Jupiters are seldom accompanied by additional planets close to their host star suggests that when a giant planet migrates through the disk, it probably cleans out the inner solar system on its way through.

In some cases, however, it appears there can be terrestrial planets further away from the star. Perhaps assembly of the terrestrial planets continues after the migration: the planetesimals are stirred up by the migrating giant, not necessarily destroyed.

How do you form "super-Earths"?

These are much harder to account for. Not only do you have to grow rocky planets larger than any in our Solar system, but you have to grow lots of them.

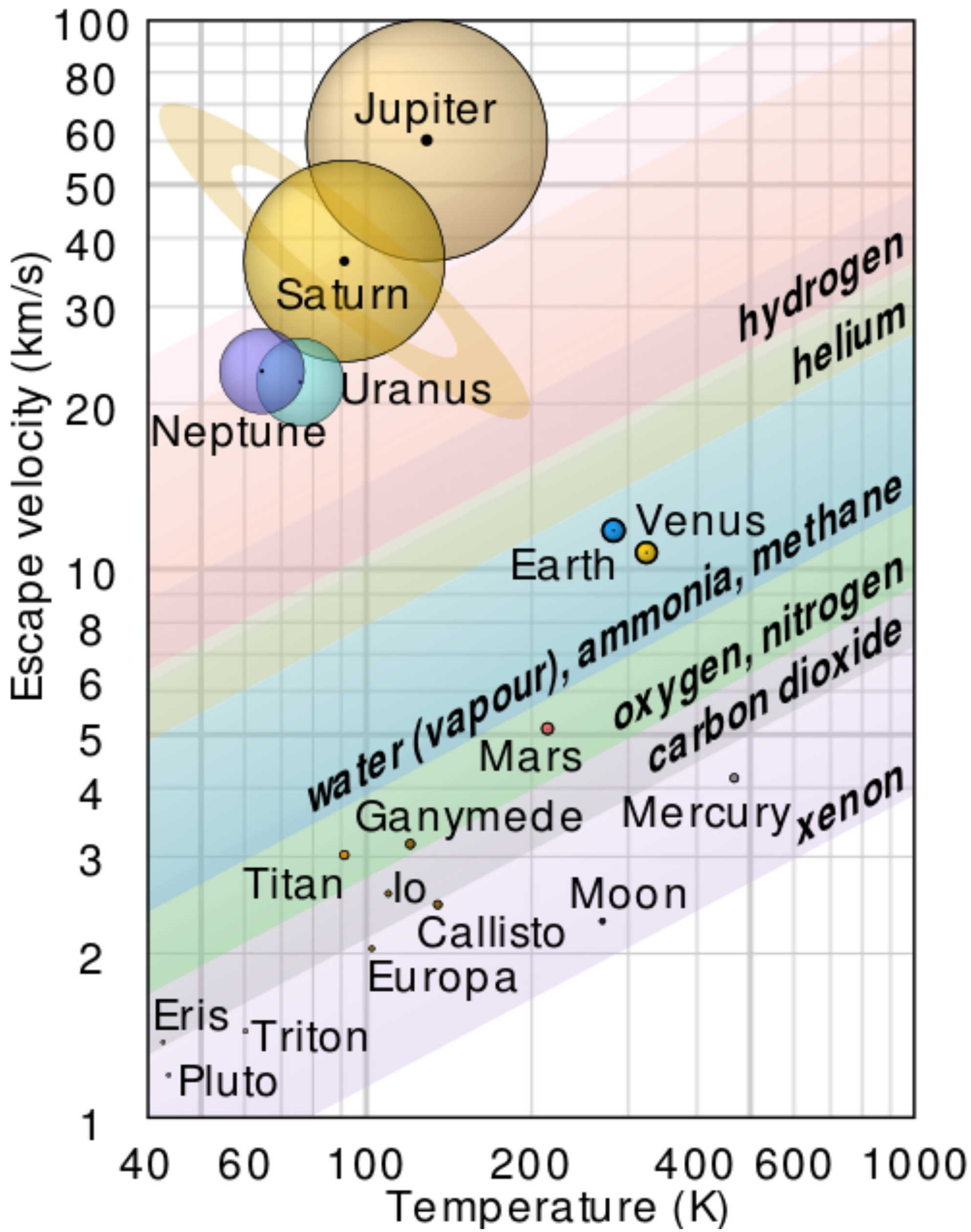
Did they form in more massive disks? or form further out and migrate in?

Of course, perhaps there is more than one sort of super-Earth: the very closest in might be the stripped cores of migrating planets that got too close and lost their gas.

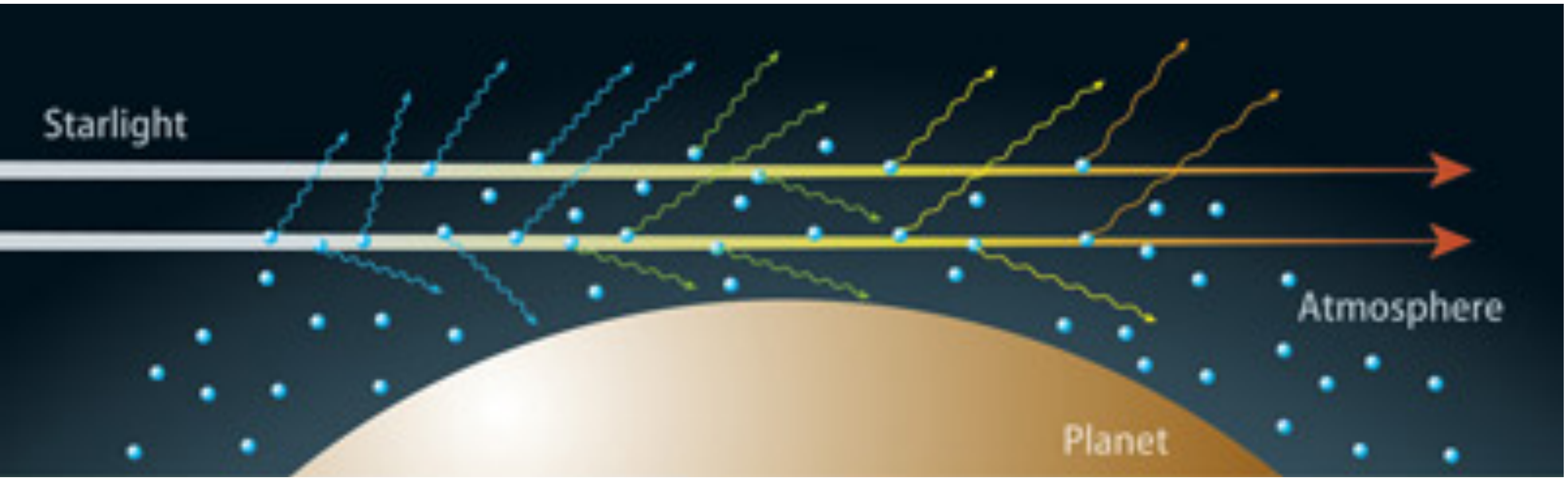
Exoplanet atmospheres

Of course, what we would like to know is whether any of these planets have atmospheres, and whether those atmospheres are likely to be able to sustain life.

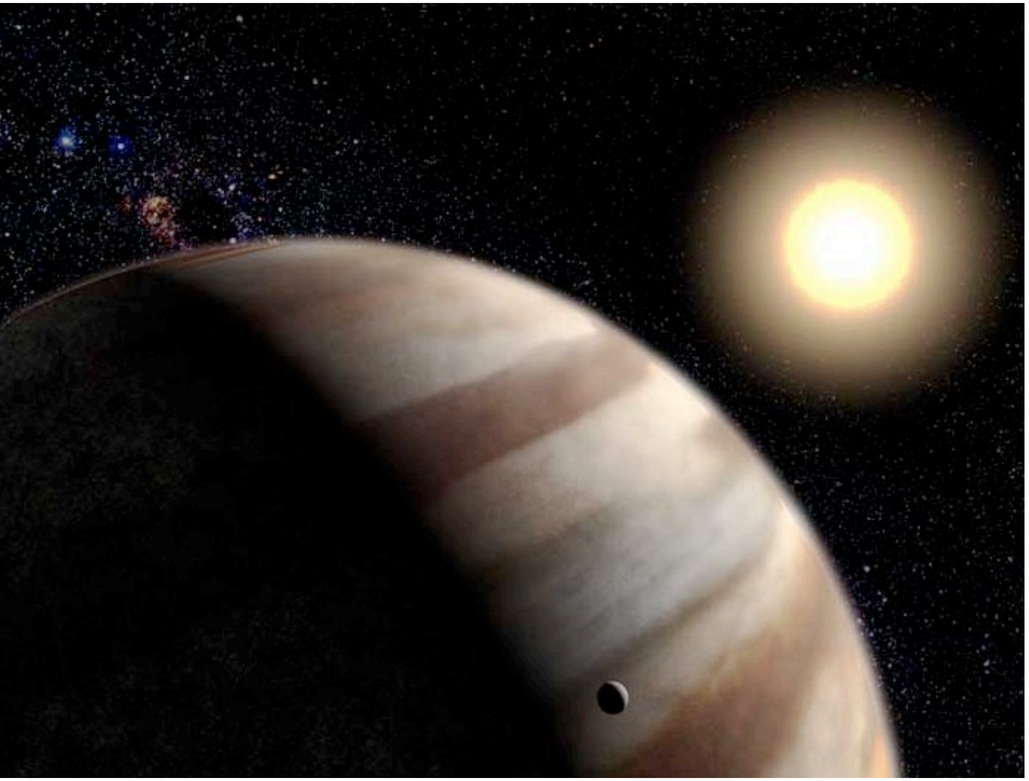
Whether a planet can have an atmosphere depends on its temperature and its surface gravity, as well as what gases the atmosphere is made of.

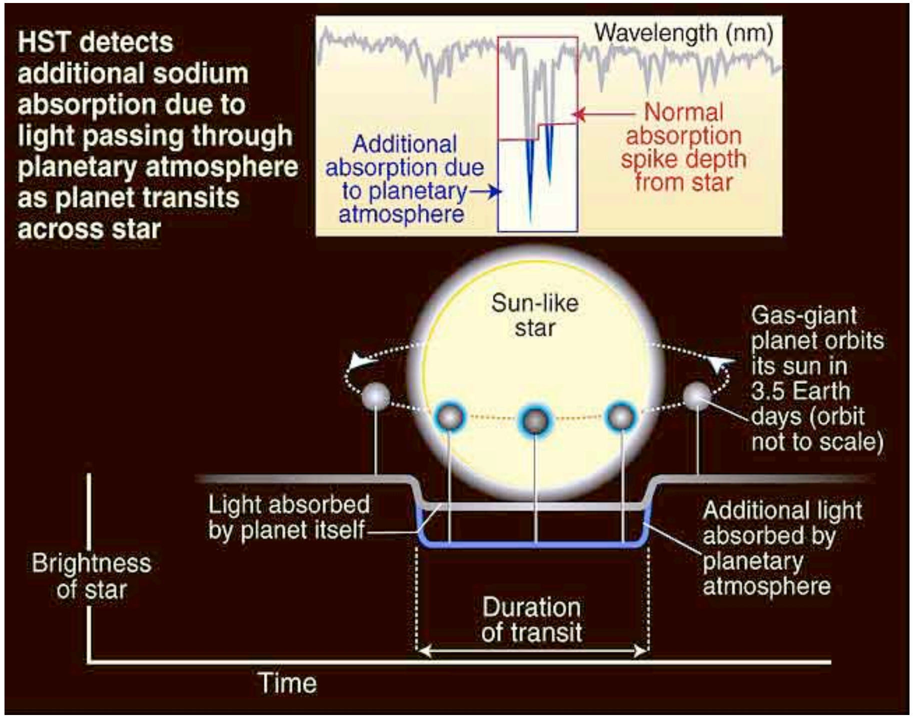


As we measure the sizes and masses of more and more exoplanets, the next step is to be able to detect their atmosphere. This can be done by detecting the star's light passing through the planet's atmosphere as it transits in front of its star.

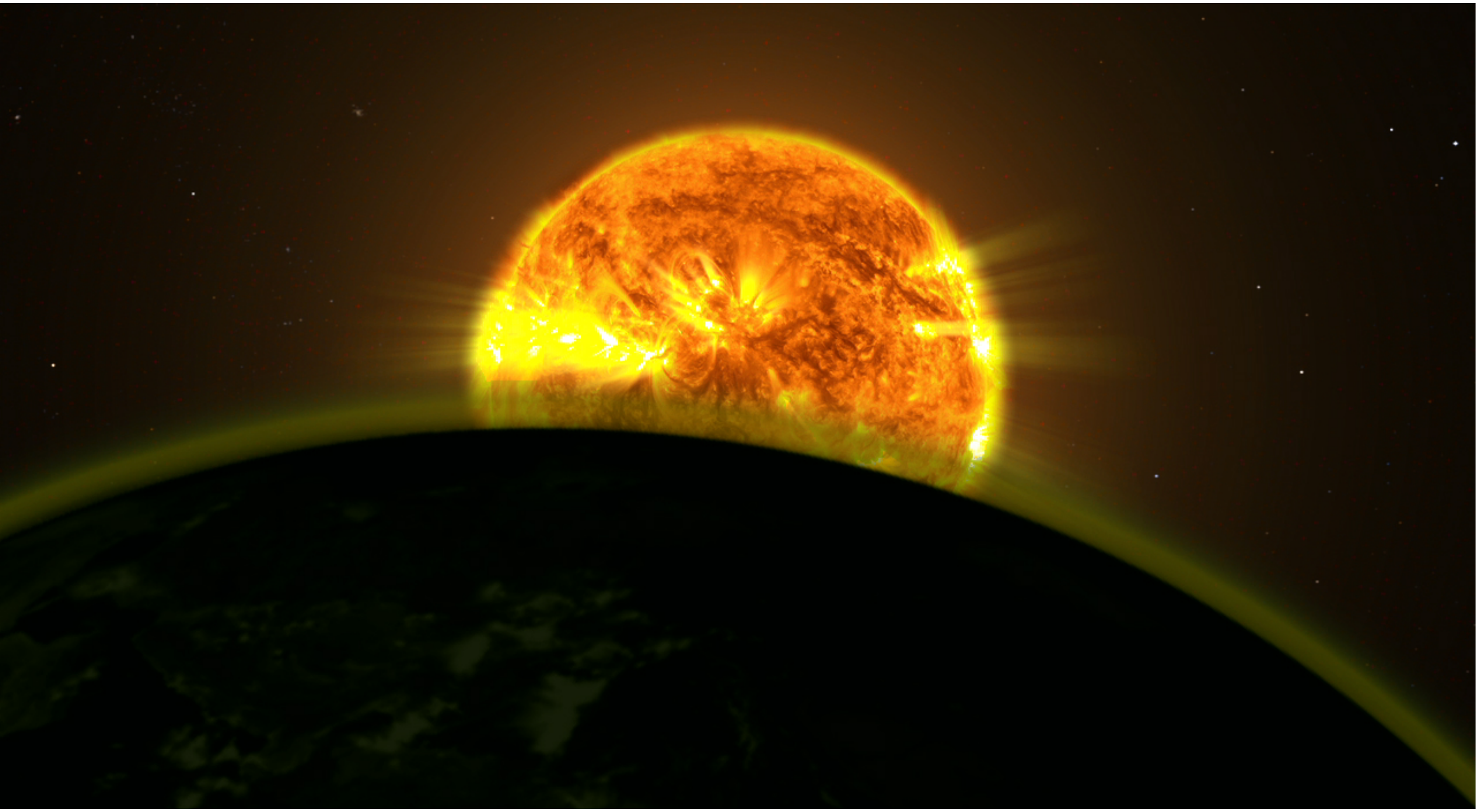


In 2001, Hubble detected an atmosphere around an extrasolar planet for the first time, detecting sodium in the atmosphere of HD 209458b, a “hot Jupiter” orbiting its star in just 3.5 days.



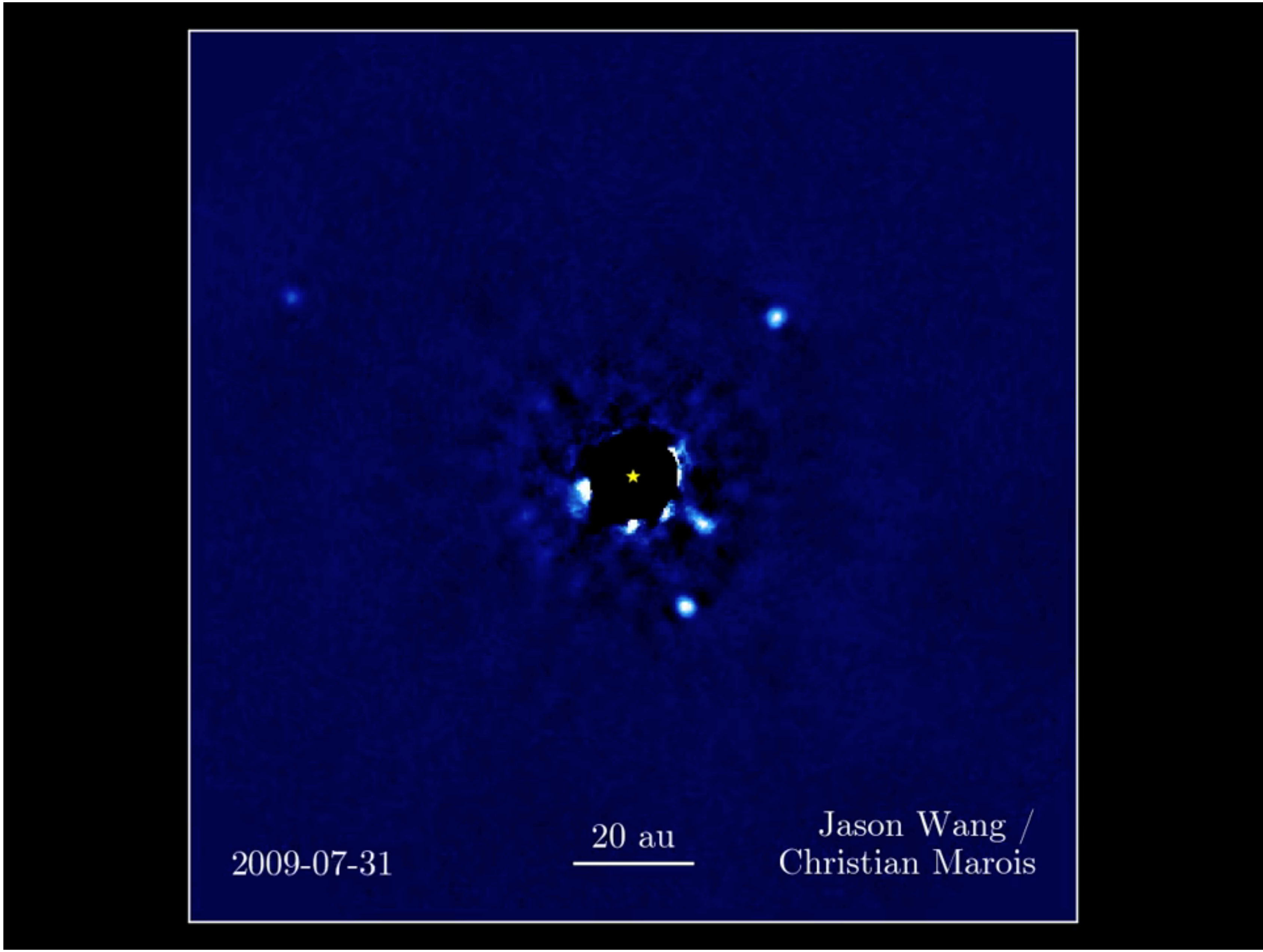


Since then, atmospheres have been detected around several exoplanets, mostly other "hot Jupiters". Many substances have been detected, including water, carbon dioxide, methane, and hydrogen.



In 2017, researchers announced the first detection of an atmosphere around an Earth-sized planet. They found evidence for a thick layer of water or methane around the "super-Earth" GJ 1132b, which is 1.4-times the size of our planet and lies 39 light years away.

Unfortunately, the surface temperature of GJ 1132b is about 370° C.

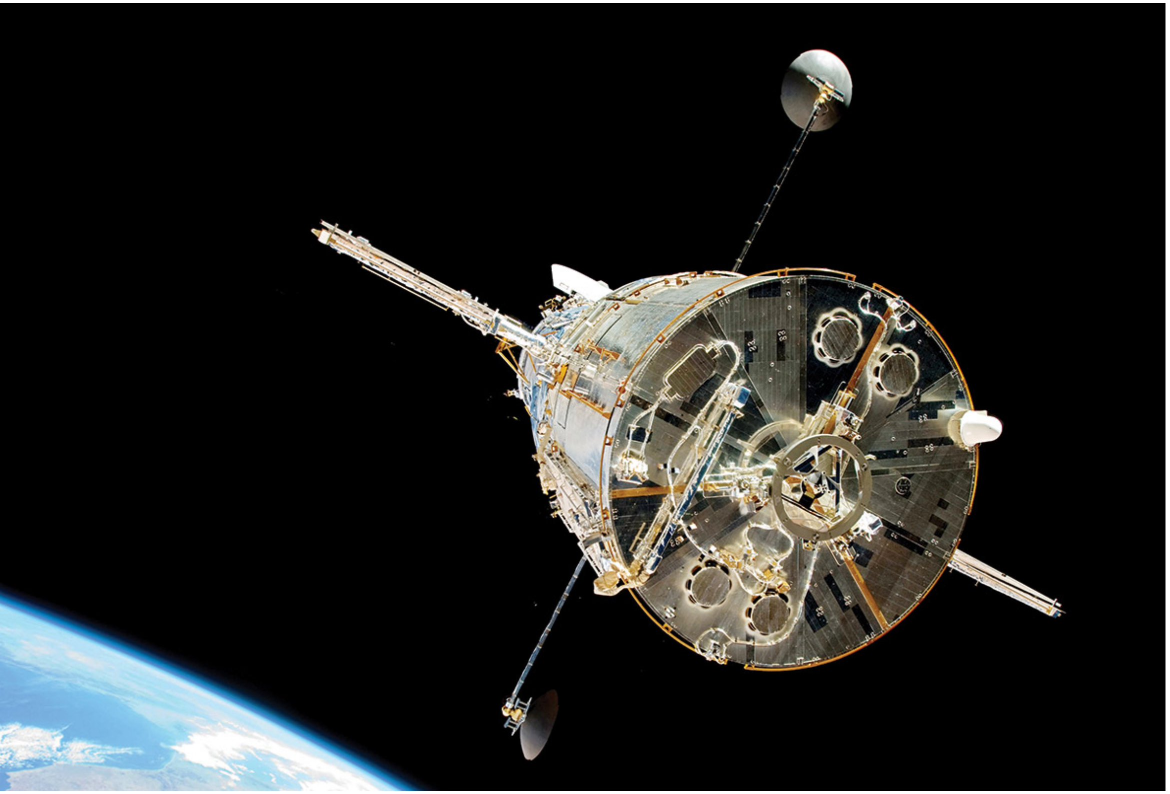


Direct images of four planets around the star HR 8799. All are Jupiter mass, and the nearest is at a similar distance to Neptune.

NASA has two upcoming missions to find terrestrial planets that might host life.

The *Transiting Exoplanet Survey Satellite* (TESS) mission is due for launch in March 2018. It will spend two years surveying the whole sky for exoplanets.

The successor to *Hubble*, the *James Webb Space Telescope,* is due to be launched in 2018. JWST is an infrared telescope, and should be able to detect biosignatures in planetary atmospheres.



So the next few years should provide lots more exciting news about extra-solar planets, what they are like and how they form.

Some of the remaining questions about our own Solar System might be answered, such as: why is the Solar System so different? Why doesn't it contain any super-Earths? Why are there no planets inside Mercury's orbit? Why do we have a balance of large and small planets, when most other systems seem to choose one or the other but not both?

One thing is clear: *diversity* seems to be the rule. There are lots more surprises ahead of us...

“There are infinite worlds both like and unlike this world of ours.”

– Epicurus (341–270 B.C.)

“There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy.”

– Hamlet, Act 1, Scene V

Upcoming dates

2018 March: Launch of *Transiting Exoplanet Survey Satellite* (TESS)

2018 August: NASA's *OSIRIS-REx* spacecraft will arrive at the asteroid Bennu, returning to Earth in September 2023 with a sample in 2023

2018 October: *BepiColombo* – Launch of ESA and ISAS orbiter and lander missions to Mercury

2019 January 1: *New Horizons* – Flies by Kuiper Belt Object 2014 MU69

2019 March: Launch of *James Webb Space Telescope* (JWST)

4,000,000: Pioneer 11 – flyby of star Lambda Aquila

see http://nssdc.gsfc.nasa.gov/planetary/upcoming.html

To infinity and beyond!

- Read "Astronomy Picture of the Day" for all the best astronomy images and news http://http://apod.nasa.gov/apod/

- Read an astronomy blog, like "Bad Astronomy" http://www.slate.com/blogs/bad_astronomy.html or "Snapshots from Space" http://www.planetary.org/blogs/emily-lakdawalla/

- Join a local astronomical club: see listing at the Astronomical Society of Australia page http://www.astronomy.org.au/ngn/engine.php?SID=1000022&AID=100136

Sign up for the "Sydney Ideas" lectures

http://sydney.edu.au/sydney_ideas/

which have lectures about a vast range of topics, including astronomy.

Particularly watch out for the "Professor Walter Stibbs Lectures", a public lecture on astronomy each year in about April.

– 2017: David Reitze, "LIGO, Gravitational Waves, and the Final Ballet of a Pair of Black Holes"

– 2016: Natalie Batalha, "A planet for Goldilocks"

– 2015: Andrea Ghez, "The monster at the heart of our Galaxy"

And, of course, attend more Continuing Education courses! Future courses include

An Introduction to Astronomy

from the solar system to distant galaxies

Lives of the Stars

A more detailed look at how stars live and die

plus occasional other courses, such as

Quarks to the Cosmos

Great discoveries in modern astronomy and physics


That’s all, folks!

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, barely a decade and a half later! What we really need is good book including all the Kepler results.

- 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. He's got a newer book out, called "The Crowded Universe: The search for living planets" (Basic Books, 2009), but it's all too much about Alan Boss and not enough about exoplanets, for my taste.

- 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 slightly more up-to-date, and has a good description of what people are now thinking about how to make these planets. It's starting to look out of date too, after Kepler.

- The article by Ann Finkbeiner, "**Planets in chaos**" is an excellent summary of the current state of affairs in our (lack of) understanding of planet formation: http://www.nature.com/news/astronomy-planets-in-chaos-1.15480

- Web-sites can at least stay up-to-date, even if they're less readable. A couple of good ones:
    - exoplanets.org has a complete up-to-date list of all exoplanets, plus some terrific tools for plotting the data.
    - The **Nasa Exoplanet Archive** at http://exoplanetarchive.ipac.caltech.edu has lots of similar features
    - NASA now has a site called "PlanetQuest: Exoplanet exploration" at http://planetquest.jpl.nasa.gov/, which has a host of useful information, including a page to search the catalogue of exoplanets in various ways
    - space.com has a list of "The Strangest Alien Planets" at http://www.space.com/159-strangest-alien-planets.html
- The *Kepler* website is at kepler.nasa.gov: they have loads of good pictures and animations, as well as a live counter telling you how many planets they've found!
- The Citizen Science project **Planet Hunters** is at http://www.planethunters.org; you can help identify transits and find new planet candidates. The site is part of the zooniverse project, which has many participatory projects, from identifying galaxies, to exploring features on the Moon.
- Check out http://www.nytimes.com/interactive/science/space/keplers-tally-of-planets.html
- NASA maintains an "Upcoming Planetary Launches and Events" page at http://nssdc.gsfc.nasa.gov/planetary/upcoming.html

Sources for images used:

- Light house and firefly: from PlanetQuest "Search for another Earth" powerpoint presentation http://planetquest.jpl.nasa.gov/gallery/frequentImages.cfm
- Astrometric displacement due to Jupiter: Planet Quest: Science - Finding planets http://planetquest.jpl.nasa.gov/science/finding_planets.cfm
- 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
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- 51 Pegasi figures: from Niel Brandt, Astro 1, http://www.astro.psu.edu/users/niel/astro1/slideshows/class44/slides-44.html
- Artist's impression of 51 Peg b: from "20 Intriguing Exoplanets" https://www.nasa.gov/feature/jpl/20-intriguing-exoplanets
- 47 Ursa Majoris: artist's impression by John Whatmough, from Astronomy Picture of the Day 1997 October 5, http://apod.nasa.gov/apod/ap971005.html; 70 Virginis, image by Walter Myers, http://www.arcadiastreet.com/cgvistas/exo_020.htm
- Orbit geometry: from "The Search for and Discovery of Extra-Solar Planets" by Richard Larson, http://www.astro.washington.edu/larson/Astro150b/Lectures/ExtraSolarPlanets/xsp.html
- Transit graph: from Kepler animations http://kepler.nasa.gov/multimedia/animations/?ImageID=38
- Venus transit: photo by David Cortner, from Astronomy Picture of the Day 2004 June 23, http://apod.nasa.gov/apod/ap040623.html
- Quadruple Saturn moon transit: from https://www.nasa.gov/mission_pages/hubble/science/hst_img_20090317.html
- Transit light curve: from "Planets orbiting around other stars" by Michael Richmond, http://spiff.rit.edu/classes/phys230/lectures/planets/planets.html
- All Kepler images are from http://kepler.nasa.gov
- HAT-P-7b light curve: from Borucki et al, 2009, "Kepler's Optical Phase Curve of the Exoplanet HAT-P-7b", http://adsabs.harvard.edu/abs/2009Sci...325..709B; animation from http://kepler.nasa.gov/multimedia/animations/
- Kepler results: from powerpoint presentation by Bill Borucki http://kepler.nasa.gov/news/nasakeplernews/index.cfm?FuseAction=ShowNews&NewsID=98
- Kepler 34-b: from http://www.cfa.harvard.edu/news/2012-02
- Kepler-453: from "Discovery of Tenth Tatooine-like Circumbinary Planet" http://www.ifa.hawaii.edu/info/press-releases/Kepler453b/
- Kepler's discoveries: from "Exploring Exoplanet Populations with NASA's Kepler Mission" by Natalie M. Batalha, https://arxiv.org/abs/1409.1904
- Planet in quadruple star system: from https://www.sciencedaily.com/releases/2012/10/121015150031.htm
- Exoplanets bouncing in a 250AU binary: from http://www.nickolas1.com/
- Debris disks from Spitzer: from http://www.spitzer.caltech.edu/images/2664-ssc2007-05a-Where-Planets-Take-up-Residence
- Habitable zone: from Wikipedia http://en.wikipedia.org/wiki/Exoplanets
- Kepler 452b: from https://www.nasa.gov/press-release/nasa-kepler-mission-discovers-bigger-older-cousin-to-earth
- Kepler habitable zone planets: from https://www.nasa.gov/image-feature/ames/kepler/kepler-habitable-zone-planets
- Proxima Centauri planet: from http://www.eso.org/public/news/eso1629/?lang
- TRAPPIST-1 planets: from https://www.eso.org/public/australia/news/eso1706/ and https://www.nasa.gov/press-release/nasa-telescope-reveals-largest-batch-of-earth-size-habitable-zone-planets-around
- Intelligent life: from Niel Brandt http://www.astro.psu.edu/users/niel/astro1/slideshows/class44/slides-44.html

- Kepler K2 mission: from http://keplerscience.arc.nasa.gov/K2/MissionConcept.shtml and
  http://kepler.nasa.gov/news/nasakeplernews/index.cfm?FuseAction=ShowNews&NewsID=341
- Exoplanet populations: from https://www.nasa.gov/image-feature/ames/kepler/exoplanet-populations
- Circumbinary planet: from http://www.bis-space.com/2012/08/29/6722/circumbinary-planets-discovered
- S-type and P-type orbits: from https://en.wikipedia.org/wiki/Habitability_of_binary_star_systems
- Exoplanet densities: from https://online.science.psu.edu/astro140_fawd001/node/11791
- Tightly packed solar system: from http://www.planetary.org/blogs/guest-blogs/2016/1031-dynamics-of-exoplanet-systems.html
- Planetary migration: from http://www.astronomycast.com/2013/05/ep-301-planetary-migration/
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