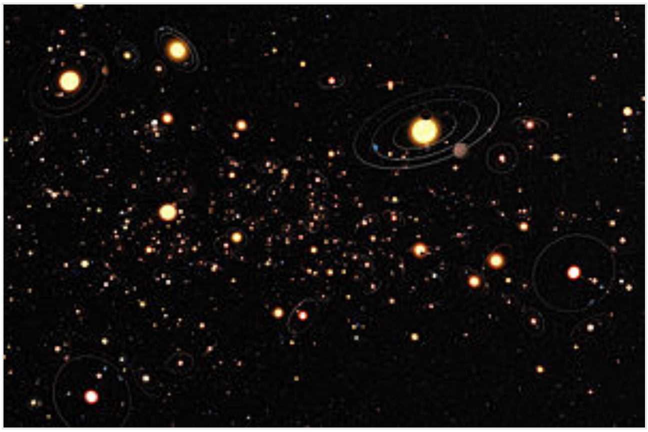
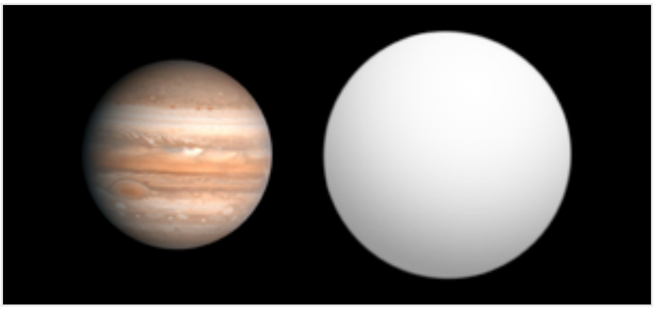
Exoplanet



An **exoplanet** or **extrasolar planet** is a planet that orbits a star other than the Sun, a stellar remnant, or a brown dwarf. Nearly 2000 exoplanets have been discovered (1930 planets in 1221 planetary systems including 484 multiple planetary systems as of 8 June 2015).[2] There are also rogue planets, which do not orbit any star and which tend to be considered separately, especially if they are gas giants, in which case they are often counted, like WISE 0855−0714, as sub-brown dwarfs.[3]

The *Kepler space telescope* has also detected a few thousand[4][5] candidate planets,[6][7] of which about 11% may be false positives.[8] There is at least one planet on average per star.[9] Around 1 in 5 Sun-like stars[a] have an "Earth-sized"[b] planet in the habitable zone,[c] with the nearest expected to be within 12 light-years distance from Earth.[10][11] Assuming 200 billion stars in the Milky Way,[d] that would be 11 billion potentially habitable Earth-sized planets in the Milky Way, rising to 40 billion if red dwarfs are included.[12] The rogue planets in the Milky Way possibly number in the trillions.[13]



Size comparison of Jupiter and the exoplanet TrES-3b. TrES-3b has an orbital period of only 31 days and is classified as a Hot Jupiter for being large and close to its star, making it one of the easiest planets to detect by the transit method.

The nearest known exoplanet, if confirmed, would be Alpha Centauri Bb, but there is some doubt about its existence. As of March 2014, the least massive planet known is PSR B1257+12 A, which is about twice the mass of the Moon. The most massive planet listed on the NASA Exoplanet Archive is DENIS-P J082303.1-491201 b,[14][15] about 29 times the mass of Jupiter, although according to most definitions of a planet, it is too massive to be a planet and may be a brown dwarf instead. There are planets that are so near to their star that they take only a few hours to orbit and there are others so far away that they take thousands of years to orbit. Some are so far out that it is difficult to tell if they are gravitationally bound to the star. Almost all of the planets detected so far are within the Milky Way, but there have also been a few possible detections of extragalactic planets.

The discovery of exoplanets has intensified interest in the search for extraterrestrial life, particularly for those that orbit in the host star's habitable zone where it is possible for liquid water (and therefore life) to exist on the surface. The study of planetary habitability also considers a wide range of other factors in determining the suitability of a planet for hosting life.[16]

Definition

IAU

The official definition of "planet" used by the International Astronomical Union (IAU) only covers the Solar System and thus does not apply to exoplanets.[17][18] As of April 2011, the only defining statement issued by the IAU that pertains to exoplanets is a working definition issued in 2001 and modified in 2003.[19] That definition contains the following criteria:

- Objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 Jupiter masses for objects of solar metallicity) that orbit stars or stellar remnants are "planets" (no matter how they formed). The minimum mass/size required for an extrasolar object to be considered a planet should be the same as that used in the Solar System.
- Substellar objects with true masses above the limiting mass for thermonuclear fusion of deuterium are "brown dwarfs", no matter how they formed or where they are located.
- Free-floating objects in young star clusters with masses below the limiting mass for thermonuclear fusion of deuterium are not "planets", but are "sub-brown dwarfs" (or whatever name is most appropriate).

Alternatives

However, the IAU's working definition is not universally accepted. One alternate suggestion is that planets should be distinguished from brown dwarfs on the basis of formation. It is widely believed that giant planets form through core accretion, and that process may sometimes produce planets with masses above the deuterium fusion threshold;[20][21][22] massive planets of that sort may have already been observed.[23] Brown dwarfs form like stars from the direct collapse of clouds of gas and this formation mechanism also produces objects that are below the 13 M_{Jup} limit and can be as low as 1 M_{Jup}.[24] Objects in this mass range that orbit their stars with wide separations of hundreds or thousands of AU and have large star/object mass ratios likely formed as brown dwarfs; their atmospheres would likely have a composition more similar to their host star than accretion-formed planets which would contain increased abundances of heavier elements. Most directly imaged planets as of April 2014 are massive and have wide orbits so probably represent the low-mass end of brown dwarf formation.[25]

Also, the 13-Jupiter-mass cutoff does not have precise physical significance. Deuterium fusion can occur in some objects with a mass below that cutoff.[22] The amount of deuterium fused depends to some extent on the composition of the object.[26] The Extrasolar Planets Encyclopaedia includes objects up to 25 Jupiter masses, saying, "The fact that there is no special feature around 13 M_{Jup} in the observed mass spectrum reinforces the choice to forget this mass limit".[27] The Exoplanet Data Explorer includes objects up to 24 Jupiter masses with the advisory: "The 13 Jupiter-mass distinction by the IAU Working Group is physically unmotivated for planets with rocky cores, and observationally problematic due to the sin i ambiguity."[28] The NASA Exoplanet Archive includes objects with a mass (or minimum mass) equal to or less than 30 Jupiter masses.[29] Another criterion for separating planets and brown dwarfs, rather than deuterium burning, formation process or location, is whether the core pressure is dominated by coulomb pressure or electron degeneracy pressure.[24][30]

History of detection

For centuries philosophers and scientists supposed that extrasolar planets existed, but there was no way of detecting them or of knowing their frequency or how similar they might be to the planets of the Solar System. Various detection claims made in the nineteenth century were rejected by astronomers. The first confirmed detection came in 1992, with the discovery of several terrestrial-mass planets orbiting the pulsar PSR B1257+12.[31] The first confirmation of an exoplanet orbiting a main-sequence star was made in 1995, when a giant planet was found in a four-day orbit around the nearby star 51 Pegasi. Some exoplanets have been imaged directly by telescopes, but the vast majority have been detected through indirect methods such as the transit method and the radial-velocity method.

Early speculations

> " This space we declare to be infinite... In it are an infinity of worlds of the same kind as our own. "
>
> —Giordano Bruno (1584)[32]

In the sixteenth century the Italian philosopher Giordano Bruno, an early supporter of the Copernican theory that Earth and other planets orbit the Sun (heliocentrism), put forward the view that the fixed stars are similar to the Sun and are likewise accompanied by planets.

In the eighteenth century the same possibility was mentioned by Isaac Newton in the "General Scholium" that concludes his *Principia*. Making a comparison to the Sun's planets, he wrote "And if the fixed stars are the centers of similar systems, they will all be constructed according to a similar design and subject to the dominion of *One*."[33]

In 1952, more than 40 years before the first hot Jupiter was discovered, Otto Struve wrote that there is no compelling reason why planets could not be much closer to their parent star than is the case in the Solar System, and proposed that Doppler spectroscopy and the transit method could detect super-Jupiters in short orbits.[34]

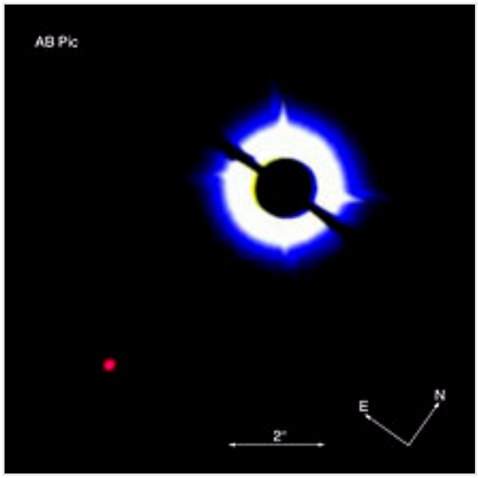
Discredited claims

Claims of exoplanet detections have been made since the nineteenth century. Some of the earliest involve the binary star 70 Ophiuchi. In 1855 Capt. W. S. Jacob at the East India Company's Madras Observatory reported that orbital anomalies made it "highly probable" that there was a "planetary body" in this system.[35] In the 1890s, Thomas

J. J. See of the University of Chicago and the United States Naval Observatory stated that the orbital anomalies proved the existence of a dark body in the 70 Ophiuchi system with a 36-year period around one of the stars.[36] However, Forest Ray Moulton published a paper proving that a three-body system with those orbital parameters would be highly unstable.[37] During the 1950s and 1960s, Peter van de Kamp of Swarthmore College made another prominent series of detection claims, this time for planets orbiting Barnard's Star.[38] Astronomers now generally regard all the early reports of detection as erroneous.[39]

In 1991 Andrew Lyne, M. Bailes and S. L. Shemar claimed to have discovered a pulsar planet in orbit around PSR 1829-10, using pulsar timing variations.[40] The claim briefly received intense attention, but Lyne and his team soon retracted it.[41]

Confirmed discoveries



Coronagraphic image of AB Pictoris showing a companion (bottom left), which is either a brown dwarf or a massive planet. The data was obtained on 16 March 2003 with NACO on the VLT, using a 1.4 arcsec occulting mask on top of AB Pictoris.

The first published discovery to receive subsequent confirmation was made in 1988 by the Canadian astronomers Bruce Campbell, G. A. H. Walker, and Stephenson Yang of the University of Victoria and the University of British Columbia.[42] Although they were cautious about claiming a planetary detection, their radial-velocity observations suggested that a planet orbits the star Gamma Cephei. Partly because the observations were at the very limits of instrumental capabilities at the time, astronomers remained skeptical for several years about this and other similar observations. It was thought some of the apparent planets might instead have been brown dwarfs, objects intermediate in mass between planets and stars. In 1990 additional observations were published that supported the existence of the planet orbiting Gamma Cephei,[43] but subsequent work in 1992 again raised serious doubts.[44] Finally, in 2003, improved techniques allowed the planet's existence to be confirmed.[45]

On 9 January 1992, radio astronomers Aleksander Wolszczan and Dale Frail announced the discovery of two planets orbiting the pulsar PSR 1257+12.[31] This discovery was confirmed, and is generally considered to be the first definitive detection of exoplanets. Follow-up observations solidified these results, and confirmation of a third planet in 1994 revived the topic in the popular press.[46] These pulsar planets are believed to have formed from the unusual remnants of the supernova that produced the pulsar, in a second round of planet formation, or else to be the remaining rocky cores of gas giants that somehow survived the supernova and then decayed into their current orbits.

On 6 October 1995, Michel Mayor and Didier Queloz of the University of Geneva announced the first definitive detection of an exoplanet orbiting a main-sequence star, namely the nearby G-type star 51 Pegasi.[47] This discovery, made at the Observatoire de Haute-Provence, ushered in the modern era of exoplanetary discovery. Technological advances, most notably in high-resolution spectroscopy, led to the rapid detection of many new exoplanets: astronomers could detect exoplanets indirectly by measuring their gravitational influence on the motion of their host stars. More extrasolar planets were later detected by observing the variation in a star's apparent luminosity as an orbiting planet passed in front of it.

Initially, most known exoplanets were massive planets that orbited very close to their parent stars. Astronomers were surprised by these "hot Jupiters", because theories of planetary formation had indicated that giant planets should only form at large distances from stars. But eventually more planets of other sorts were found, and it is now clear that hot Jupiters are a minority of exoplanets. In 1999, Upsilon Andromedae became the first main-sequence star known to have multiple planets.[48] Others were found subsequently.

As of 8 June 2015, a total of 1930 confirmed exoplanets are listed in the Extrasolar Planets Encyclopaedia, including a few that were confirmations of controversial claims from the late 1980s.[2] That count includes 1221 planetary systems, of which 484 are multiple planetary systems. Kepler-16 contains the first discovered planet that orbits around a binary main-sequence star system.[49]

On 26 February 2014, NASA announced the discovery of 715 newly verified exoplanets around 305 stars by the Kepler Space Telescope. These exoplanets were checked using a statistical technique called "verification by multiplicity".[50][51][52] Prior to these results, most confirmed planets were gas giants comparable in size to Jupiter or larger as they are more easily detected, but the Kepler planets are mostly between the size of Neptune and the size of Earth.[50]

On 6 January 2015, NASA announced the 1000th confirmed exoplanet discovered by the Kepler Space Telescope. Three of the newly confirmed exoplanets were found to orbit within habitable zones of their host stars: two of the three, Kepler-438b and Kepler-442b, are near-Earth-size and likely rocky; the third, Kepler-440b, is a super-Earth. Similar confirmed small exoplanets in habitable zones found earlier by *Kepler* include: Kepler-62e, Kepler-62f, Kepler-186f, Kepler296e and Kepler-296f.[53]

Candidate discoveries

17 October 2012 brought news of an unverified planet, Alpha Centauri Bb, orbiting Alpha Centauri B, which is one of three stars in a triple star system nearest to Earth's Sun.[54] Alpha Centauri Bb is an Earth-size planet, but not in the habitable zone within which liquid water can exist.[55]

As of March 2014, NASA's Kepler mission had identified more than 2,900 planetary candidates, several of them being nearly Earth-sized and located in the habitable zone, some around Sun-like stars.[4][5][56]

Detection methods

Main article: Methods of detecting extrasolar planets

Direct imaging

Main article: Direct imaging

Planets are extremely faint compared to their parent stars. At visible wavelengths, they usually have less than a millionth of their host star's brightness. It is difficult to detect such a faint light source, and furthermore the parent star causes a glare that tends to wash it out. It is necessary to block the light from the parent star in order to reduce the glare while leaving the light from the planet detectable; doing so is a major technical challenge.[57]

All exoplanets that have been directly imaged are both large (more massive than Jupiter) and widely separated from their parent star. Most of them are also very hot, so that they emit intense infrared radiation; the images have then been made at infrared where the planet is brighter than it is at visible wavelengths. During the gas-accretion phase of giant-planet formation the star–planet contrast may be even better in H alpha than it is in infrared—an H alpha survey is currently underway.[58]

The first direct detection of the visible light spectrum reflected from an exoplanet was reported 22 April 2015. Astronomers studied reflected light from exoplanet 51 Pegasi b—which is the first exoplanet that was discovered orbiting a main-sequence star, the Sun-like (G5V) 51 Pegasi. The direct detection was made using the High Accuracy Radial velocity Planet Searcher (HARPS) instrument at the European Southern Observatory's La Silla Observatory in Chile.[59][60]

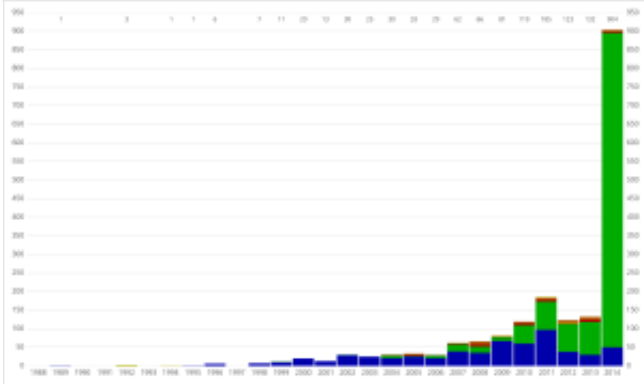
Specially designed direct-imaging instruments such as Gemini Planet Imager, VLT-SPHERE, and SCExAO will image dozens of gas giants, however the vast majority of known extrasolar planets have only been detected through indirect methods. The following are the indirect methods that have proven useful:

Indirect methods

- Transit method

  If a planet crosses (or transits) in front of its parent star's disk, then the observed brightness of the star drops by a small amount. The amount by which the star dims depends on its size and on the size of the planet, among other factors. This method suffers from a substantial rate of false positives and confirmation from another method is usually considered necessary. The transit method reveals the radius of a planet, and it has the benefit that it sometimes allows a planet's atmosphere to be investigated through spectroscopy. Because the transit method requires that part of the planet's orbit intersect a line-of-sight between the host star and Earth, the probability that an exoplanet in a randomly oriented orbit will be observed to transit the star is somewhat small. The Kepler telescope uses this method.

- Radial velocity or Doppler method



Number of extrasolar planet discoveries per year through September 2014, with colors indicating method of detection:

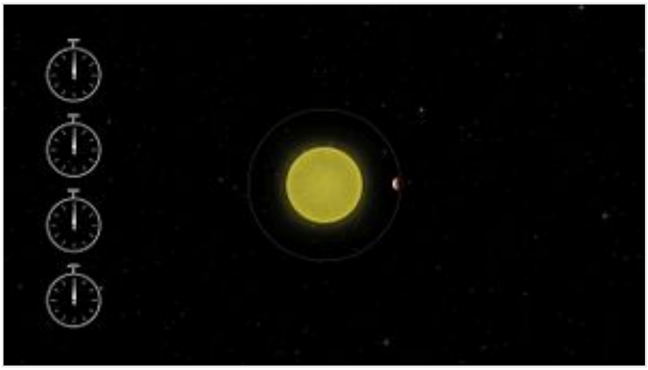
As a planet orbits a star, the star also moves in its own small orbit around the system's center of mass. Variations in the star's radial velocity—that is, the speed with which it moves towards or away from Earth—can be detected from displacements in the star's spectral lines due to the Doppler effect. Extremely small radial-velocity variations can be observed, of 1 m/s or even somewhat less.[61] This method has the advantage of being applicable to stars with a wide range of characteristics. One of its disadvantages is that it cannot determine a planet's true mass, but can only set a lower limit on that mass. However, if the radial velocity of the planet itself can be distinguished from the radial velocity of the star, then the true mass can be determined.[62]

- Transit timing variation (TTV)

When multiple planets are present, each one slightly perturbs the others' orbits. Small variations in the times of transit for one planet can thus indicate the presence of another planet, which itself may or may not transit. For example, variations in the transits of the planet Kepler-19b suggest the existence of a second planet in the system, the non-transiting Kepler-19c.[63][64] If multiple transiting planets exist in one system, then this method can be used to confirm their existence.[65] In another form of the method, timing the eclipses in an eclipsing binary star can reveal an outer planet that orbits both stars; as of August 2013, a few planets have been found in that way with numerous planets confirmed with this method.

- Transit duration variation (TDV)

When a planet orbits multiple stars or if the planet has moons, its transit time can significantly vary per transit. Although no new planets or moons have been discovered with this method, it is used to successfully confirm many transiting circumbinary planets.[66]



Play media

Animation showing difference between planet transit timing of 1-planet and 2-planet systems

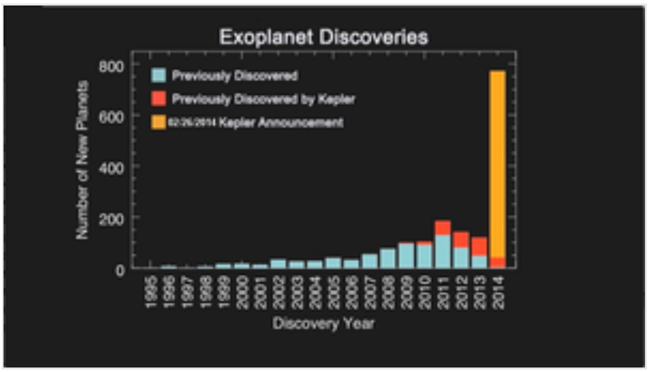
- Gravitational microlensing

  Microlensing occurs when the gravitational field of a star acts like a lens, magnifying the light of a distant background star. Planets orbiting the lensing star can cause detectable anomalies in the magnification as it varies over time. Unlike most other methods which have detection bias towards planets with small (or for resolved imaging, large) orbits, microlensing method is most sensitive to detecting planets around 1–10 AU away from Sun-like stars.

- Astrometry

  Astrometry consists of precisely measuring a star's position in the sky and observing the changes in that position over time. The motion of a star due to the gravitational influence of a planet may be observable. Because the motion is so small, however, this method has not yet been very productive. It has produced only a few disputed detections, though it has been successfully used to investigate the properties of planets found in other ways.

- Pulsar timing

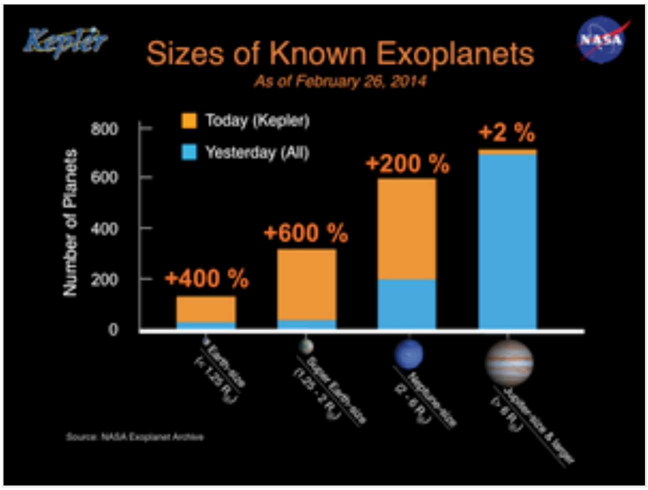


Histogram of Exoplanet Discoveries—gold bar displays new planets "verified by multiplicity" (26 February 2014).

  A pulsar (the small, ultradense remnant of a star that has exploded as a supernova) emits radio waves extremely regularly as it rotates. If planets orbit the pulsar, they will cause slight anomalies in the timing of its observed radio pulses. The first confirmed discovery of an extrasolar planet was made using this method. But as of 2011, it has not been very productive; five planets have been detected in this way, around three different pulsars.

- Variable star timing (pulsation frequency)

  Like pulsars, there are some other types of stars which exhibit periodic activity. Deviations from the periodicity can sometimes be caused by a planet orbiting it. As of 2013, a few planets have been discovered with this method. [67]



Histogram of exoplanets by size—the gold bars represent Kepler's latest newly verified exoplanets (26 February 2014).

- Reflection/emission modulations

  When a planet orbits very close to the star, it catches a considerable amount of starlight. As the planet orbits around the star, the amount of light changes due to planets having phases from Earth's viewpoint or planet glowing more from one side than the other due to temperature differences.[68]

- Relativistic beaming

  Relativistic beaming measures the observed flux from the star due to its motion. The brightness of the star changes as the planet moves closer or further away from its host star.[69]

- Ellipsoidal variations

  Massive planets close to their host stars can slightly deform the shape of the star. This causes the brightness of the star to slightly deviate depending how it is rotated relative to Earth.[70]

- Polarimetry

  With polarimetry method, a polarized light reflected off the planet is separated from unpolarized light emitted from the star. No new planets have been discovered with this method although a few already discovered planets have been detected with this method.[71][72]

- Circumstellar disks

  Disks of space dust surround many stars, believed to originate from collisions among asteroids and comets. The dust can be detected because it absorbs starlight and re-emits it as infrared radiation. Features in the disks may suggest the presence of planets, though this is not considered a definitive detection method.

Nomenclature

Proper names

Most exoplanets have catalog names which are explained in the following sections, but in 2014 the IAU launched a process for giving proper names to exoplanets.[73][74] The process involves public nomination and voting for the new names, and the IAU plans to announce the new names in August 2015.[75] The decision to give the planets new names followed the private company Uwingu's exoplanet naming contest, which the IAU harshly criticized.[75] Previously a few planets had received unofficial names: notably Osiris (HD 209458 b), Bellerophon (51 Pegasi b), and Methuselah (PSR B1620-26 b).

Multiple-star standard

The convention for naming exoplanets is an extension of the one used by the Washington Multiplicity Catalog (WMC) for multiple-star systems, and adopted by the International Astronomical Union.[76] The brightest member of a star system receives the letter "A". Distinct components not contained within "A" are labeled "B", "C", etc. Subcomponents are designated by one or more suffixes with the primary label, starting with lowercase letters for the 2nd hierarchical level and then numbers for the 3rd.[77] For example, if there is a triple star system in which two stars orbit each other closely with a third star in a more distant orbit, the two closely orbiting stars would be named Aa and Ab, whereas the distant star would named B. For historical reasons, this standard is not always followed: for example Alpha Centauri A, B and C are *not* labelled Alpha Centauri Aa, Ab and B.

Extrasolar planet standard

Following an extension of the above standard, an exoplanet's name is normally formed by taking the name of its parent star and adding a lowercase letter. The first planet discovered in a system is given the designation "b" and later planets are given subsequent letters. If several planets in the same system are discovered at the same time, the closest one to the star gets the next letter, followed by the other planets in order of orbital size.

For instance, in the 55 Cancri system the first planet – 55 Cancri b – was discovered in 1996; two additional farther planets were simultaneously discovered in 2002 with the nearest to the star being named 55 Cancri c and the other 55 Cancri d; a fourth planet was claimed (its existence was later disputed) in 2004 and named 55 Cancri e despite lying closer to the star than 55 Cancri b; and the most recently discovered planet, in 2007, was named 55 Cancri f despite lying between 55 Cancri c and 55 Cancri d.[78] As of April 2012 the highest letter in use is "j", for the unconfirmed planet HD 10180 j, and with "h" being the highest letter for a confirmed planet, belonging to the same host star).[2]

If a planet orbits one member of a binary star system, then an uppercase letter for the star will be followed by a lowercase letter for the planet. Examples are 16 Cygni Bb[79] and HD 178911 Bb.[80] Planets orbiting the primary or "A" star should have 'Ab' after the name of the system, as in HD 41004 Ab.[81] However, the "A" is sometimes omitted; for example the first planet discovered around the primary star of the Tau Boötis binary system is usually called simply Tau Boötis b.[82] The star designation is necessary when more than one star in the system has its own planetary system such as in case of WASP-94 A and WASP-94 B.[83]

If the parent star is a single star, then it may still be regarded as having an "A" designation, though the "A" is not normally written. The first exoplanet found to be orbiting such a star could then be regarded as a secondary subcomponent that should be given the suffix "Ab". For example, 51 Peg Aa is the host star in the system 51 Peg; and the first exoplanet is then 51 Peg Ab. Because most exoplanets are in single-star systems, the implicit "A" designation was simply dropped, leaving the exoplanet name with the lower-case letter only: 51 Peg b.

A few exoplanets have been given names that do not conform to the above standard. For example, the planets that orbit the pulsar PSR 1257 are often referred to with capital rather than lowercase letters. Also, the underlying name of the star system itself can follow several different systems. In fact, some stars (such as Kepler-11) have only received their names due to their inclusion in planet-search programs, previously only being referred to by their celestial coordinates.

Circumbinary planets and 2010 proposal

Hessman et al. state that the implicit system for exoplanet names utterly failed with the discovery of circumbinary planets.[76] They note that the discoverers of the two planets around HW Virginis tried to circumvent the naming problem by calling them "HW Vir 3" and "HW Vir 4", i.e. the latter is the 4th object – stellar or planetary – discovered in the system. They also note that the discoverers of the two planets around NN Serpentis were confronted with multiple suggestions from various official sources and finally chose to use the designations "NN Ser c" and "NN Ser d".

The proposal of Hessman et al. starts with the following two rules:

> **Rule 1**. The formal name of an exoplanet is obtained by appending the appropriate suffixes to the formal name of the host star or stellar system. The upper hierarchy is defined by upper-case letters, followed by lower-case letters, followed by numbers, etc. The naming order within a hierarchical level is for the order of discovery only. (This rule corresponds to the present provisional WMC naming convention.)
> **Rule 2**. Whenever the leading capital letter designation is missing, this is interpreted as being an informal form with an implicit "A" unless otherwise explicitly stated. (This rule corresponds to the present exoplanet community usage for planets around single stars.)

They note that under these two proposed rules all of the present names for 99% of the planets around single stars are preserved as informal forms of the IAU sanctioned provisional standard. They would rename Tau Boötis b formally as Tau Boötis Ab, retaining the prior form as an informal usage (using Rule 2, above).

To deal with the difficulties relating to circumbinary planets, the proposal contains two further rules:

> **Rule 3.** As an alternative to the nomenclature standard in Rule 1, a hierarchical relationship can be expressed by concatenating the names of the higher order system and placing them in parentheses, after which the suffix for a lower order system is added.
> **Rule 4**. When in doubt (i.e. if a different name has not been clearly set in the literature), the hierarchy expressed by the nomenclature should correspond to dynamically distinct (sub)systems in order of their dynamical relevance. The choice of hierarchical levels should be made to emphasize dynamical relationships, if known.

They submit that the new form using parentheses is the best for known circumbinary planets and has the desirable effect of giving these planets identical sublevel hierarchical labels and stellar component names that conform to the usage for binary stars. They say that it requires the complete renaming of only two exoplanetary systems: The planets around HW Virginis would be renamed HW Vir (AB) b & (AB) c, whereas those around NN Serpentis would be renamed NN Ser (AB) b & (AB) c. In addition the previously known single circumbinary planets around PSR B1620-26 and DP Leonis) can almost retain their names (PSR B1620-26 b and DP Leonis b) as unofficial informal forms of the "(AB)b" designation where the "(AB)" is left out.

The discoverers of the circumbinary planet around Kepler-16 followed the naming scheme proposed by Hessman et al. when naming the body Kepler-16 (AB)-b, or simply Kepler-16b when there is no ambiguity.[49]

Other naming systems

Another nomenclature, often seen in science fiction, uses Roman numerals in the order of planets' positions from the star. (This was inspired by an old system for naming moons of the outer planets, such as "Jupiter IV" for Callisto.) But such a system is impractical for scientific use, because new planets may be found closer to the star, changing all numerals.

Formation and evolution

Planets form within a few tens of millions of years of their star forming,[84][85][86] and there are stars that are forming today and other stars that are ten billion years old, so unlike the planets of the Solar System, which can only be observed as they are today, studying exoplanets allows the observation of exoplanets at different stages of evolution. When planets form they have hydrogen envelopes that cool and contract over time and, depending on the mass of the planet, some or all of the hydrogen is eventually lost to space. This means that even terrestrial planets can start off with large radii.[87][88][89] An example is Kepler-51b which has only about twice the mass of Earth but is almost the size of Saturn which is a hundred times the mass of Earth. Kepler-51b is quite young at a few hundred million years old.[90][91][92][93][94][95][96]

Planet-hosting stars

Main article: Planetary system § Planet-hosting stars

There is at least one planet on average per star.[9] Around 1 in 5 Sun-like stars[a] have an "Earth-sized"[b] planet in the habitable zone [11]

Most known exoplanets orbit stars roughly similar to the Sun, that is, main-sequence stars of spectral categories F, G, or K. Lower-mass stars (red dwarfs, of spectral category M) are less likely to have planets massive enough to detect by the radial-velocity method.[97][98] Although several tens of planets around red dwarfs have been discovered by the Kepler spacecraft which uses the transit method which can detect smaller planets.

Stars with a higher metallicity than the Sun are more likely to have planets, especially giant planets, than stars with lower metallicity.[99]

Some planets orbit one member of a binary star system,[100] and several circumbinary planets have been discovered which orbit around both members of binary star. A few planets in triple star systems are known[101] and one in the quadruple system Kepler 64.

Orbital parameters

Most known extrasolar planet candidates have been discovered using indirect methods and therefore only some of their physical and orbital parameters can be determined. For example, out of the six independent parameters that define an orbit, the radial-velocity method can determine four: semi-major axis, eccentricity, longitude of periastron, and time of periastron. Two parameters remain unknown: inclination and longitude of the ascending node.

Distance from star, semi-major axis and orbital period

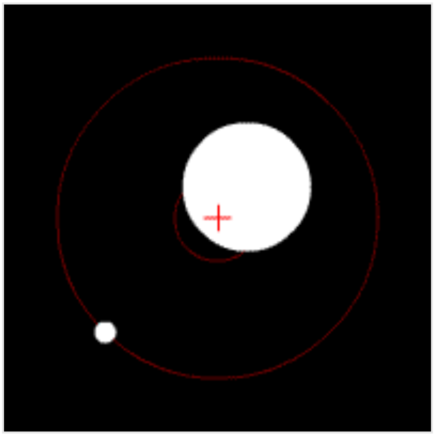
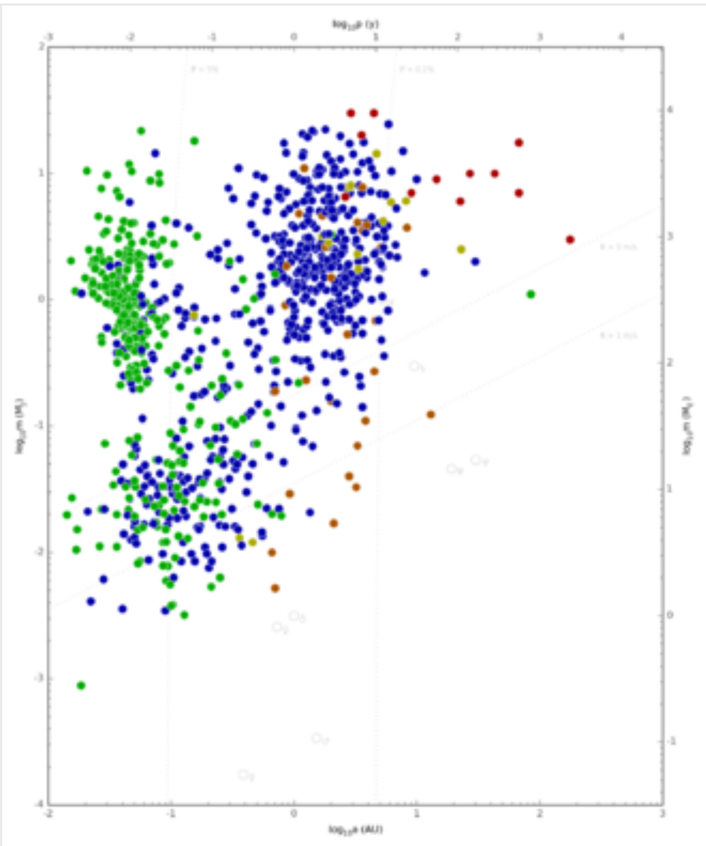


Diagram showing how a planet and a star orbit their common center of mass (red cross).



Scatterplot showing masses and orbital radii (and period) of all extrasolar planets discovered through September 2014, with colors indicating method of detection: For reference, Solar System planets are marked as gray circles. The horizontal axis plots the log of the semi-major axis, and the vertical axis plots the log of the mass.

There are exoplanets that are much closer to their parent star than any planet in the Solar System is to the Sun, and there are also exoplanets that are much further from their star. Mercury, the closest planet to the Sun at 0.4 AU, takes 88 days for an orbit, but the smallest known orbits of exoplanets have orbital periods of only a few hours, e.g. Kepler-70b. The Kepler-11 system has five of its planets in smaller orbits than Mercury's. Neptune is 30 AU from the Sun and takes 165 years to orbit it, but there are exoplanets that are thousands of AU from their star and take tens of thousands of years to orbit, e.g. GU Piscium b.[102]

The orbit of a planet is not centered on the star but on their common center of mass (see diagram on right). For circular orbits, the semi-major axis is the distance between the planet and the center of mass of the system. For elliptical orbits, the planet–star distance varies over the course of the orbit, in which case the semi-major axis is the average of the largest and smallest distances between the planet and the center of mass of the system. If the sizes of the star and planet are relatively small compared to the size of the orbit and the orbit is nearly circular and the center of mass is not too far from the star's center, such as in the Earth–Sun system, then the distance from any point on the star to any point on the planet is approximately the same as the semi-major axis. However, when a star's radius expands when it turns into a red giant, then the distance between the planet and the star's surface can become close to zero, or even less than zero if the planet has been engulfed by the expanding red giant, whereas the center of mass from which the semi-major axis is measured will still be near the center of the red giant.

Orbital period is the time taken to complete one orbit. For any given star, the shorter the semi-major axis of a planet, the shorter the orbital period. Also comparing planets around different stars but with the same semi-major axis, the more massive the star, the shorter the orbital period.

Over the lifetime of a star, the semi-major axes of its planets changes. This planetary migration happens especially during the formation of the planetary system when planets interact with the protoplanetary disk and each other until a relatively stable position is reached, and later in the red-giant and asymptotic-giant-branch phases when the star expands and engulfs the nearest planets that can cause them to move inwards, and when the red giant loses mass as the outer layers dissipate causing planets to move outwards as a result of the red giant's reduced gravitational field.

The radial-velocity and transit methods are most sensitive to planets with small orbits. The earliest discoveries such as 51 Peg b were gas giants with orbits of a few days.[97] These "hot Jupiters" likely formed further out and migrated inwards. The Kepler spacecraft has found planets with even shorter orbits of only a few hours, which places them within the star's upper atmosphere or corona, and these planets are Earth-sized or smaller and are probably the left-over solid cores of giant planets that have evaporated due to being so close to the star,[103] or even being engulfed by the star in its red-giant phase in the case of Kepler-70b. As well as evaporation, other reasons why larger planets are unlikely to survive orbits only a few hours long include orbital decay caused by tidal force, tidal-inflation instability, and Roche-lobe overflow.[104] The Roche limit implies that small planets with orbits of a few hours are likely made mostly of iron.[104]

The direct imaging method is most sensitive to planets with large orbits, and has discovered some planets that have planet–star separations of hundreds of AU. However, protoplanetary disks are usually only around 100 AU in radius, and core accretion models predict giant planet formation to be within 10 AU, where the planets can coalesce quickly enough before the disk evaporates. Very-long-period giant planets may have been rogue planets that were captured,[105] or formed close-in and gravitationally scattered outwards, or the planet and star could be a mass-imbalanced wide binary system with the planet being the primary object of its own separate protoplanetary disk. Gravitational instability models might produce planets at multi-hundred AU separations but this would require unusually large disks.[106][107] For planets with very wide orbits up to several hundred thousand AU it may be difficult to observationally determine whether the planet is gravitationally bound to the star.

Most planets that have been discovered are within a couple of AU from their host star because the most used methods (radial-velocity and transit) require observation of several orbits to confirm that the planet exists and there has only been enough time since these methods were first used to cover small separations. Some planets with larger orbits have been discovered by direct imaging but there is a middle range of distances, roughly equivalent to the Solar System's gas giant region, which is largely unexplored. Direct imaging equipment for exploring that region is being installed on the world's largest telescopes and should begin operation in 2014. e.g. Gemini Planet Imager and VLT-SPHERE. The microlensing method has detected a few planets in the 1–10 AU range.[108] It appears plausible that in most exoplanetary systems, there are one or two giant planets with orbits comparable in size to those of Jupiter and Saturn in the Solar System. Giant planets with substantially larger orbits are now known to be rare, at least around Sun-like stars.[109]

The distance of the habitable zone from a star depends on the type of star and this distance changes during the star's lifetime as the size and temperature of the star changes.

- The Fate of Scattered Planets, Benjamin C. Bromley, Scott J. Kenyon, 10 October 2014
- Planetary Populations in the Mass-Period Diagram: A Statistical Treatment of Exoplanet Formation and the Role of Planet Traps, Yasuhiro Hasegawa, Ralph E. Pudritz, 8 October 2013

Eccentricity

The eccentricity of an orbit is a measure of how elliptical (elongated) it is. All the planets of the Solar System except for Mercury have near-circular orbits ($e<0.1$).[110] Most exoplanets with orbital periods of 20 days or less have near-circular orbits, i.e. very low eccentricity. That is believed to be due to tidal circularization: reduction of eccentricity over time due to gravitational interaction between two bodies. The mostly sub-Neptune-sized planets found by the Kepler spacecraft with short orbital periods have very circular orbits.[50] By contrast, the giant planets with longer orbital periods discovered by radial-velocity methods have quite eccentric orbits. (As of July 2010, 55% of such exoplanets have eccentricities greater than 0.2, whereas 17% have eccentricities greater than 0.5.[2]) Moderate to high eccentricities ($e>0.2$) of giant planets are *not* an observational selection effect, because a planet can be detected about equally well regardless of the eccentricity of its orbit. The prevalence of elliptical orbits for giant planets is a major puzzle, because current theories of planetary formation strongly suggest planets should form with circular (that is, non-eccentric) orbits.[39]

However, for weak Doppler signals near the limits of the current detection ability the eccentricity becomes poorly constrained and biased towards higher values. It is suggested that some of the high eccentricities reported for low-mass exoplanets may be overestimates, because simulations show that many observations are also consistent with two planets on circular orbits. Reported observations of single planets in moderately eccentric orbits have about a 15% chance of being a pair of planets.[111] This misinterpretation is especially likely if the two planets orbit with a 2:1 resonance. With the exoplanet sample known in 2009, a group of astronomers has concluded that "(1) around 35% of the published eccentric one-planet solutions are statistically indistinguishable from planetary systems in 2:1 orbital resonance, (2) another 40% cannot be statistically distinguished from a circular orbital solution" and "(3) planets with masses comparable to Earth could be hidden in known orbital solutions of eccentric super-Earths and Neptune mass planets".[112]

Radial velocity surveys found exoplanet orbits beyond 0.1 AU to be eccentric, particularly for large planets. Kepler spacecraft transit data is consistent with the RV surveys and also revealed that smaller planets tend to have less eccentric orbits.[113]

Inclination vs. spin–orbit angle

Orbital inclination is the angle between a planet's orbital plane and another plane of reference. For exoplanets the inclination is usually stated with respect to an observer on Earth: the angle used is that between the normal to the planet's orbital plane and the line of sight from Earth to the star. Therefore most planets observed by the transit method are close to 90 degrees.[114] Because the word 'inclination' is used in exoplanet studies for this line-of-sight inclination then the angle between the planet's orbit and the star's rotation must use a different word and is termed the spin–orbit angle or spin–orbit alignment. In most cases the orientation of the star's rotational axis is unknown. The Kepler spacecraft has found a few hundred multi-planet systems and in most of these systems the planets all orbit in nearly the same plane, much like the Solar System.[50] However, a combination of astrometric and radial-velocity measurements has shown that some planetary systems contain planets whose orbital planes are significantly tilted relative to each other.[115] More than half of hot Jupiters have orbital planes substantially misaligned with their parent star's rotation. A substantial fraction of hot-Jupiters even have retrograde orbits, meaning that they orbit in the opposite direction from the star's rotation.[116] Rather than a planet's orbit having been disturbed, it may be that the star itself flipped early in their system's formation due to interactions between the star's magnetic field and the planet-forming disc.[117]

Periastron precession

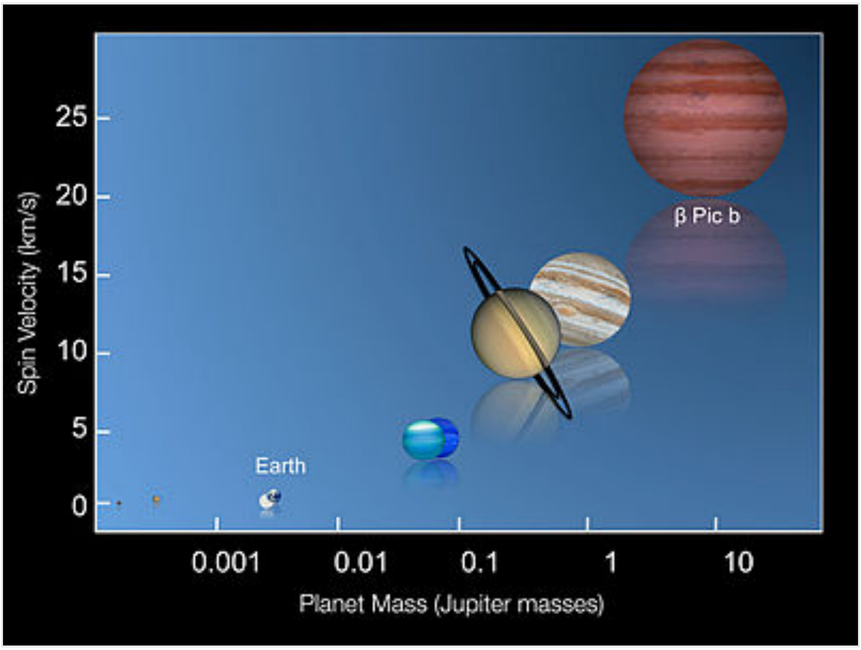
Periastron precession is the rotation of a planet's orbit within the orbital plane, i.e. the axes of the ellipse change direction. Various factors cause the precession. In the Solar System perturbations from other planets are the main cause, but for close-in exoplanets the largest factor can be tidal forces between the star and planet. For close-in exoplanets, the general relativistic contribution to the precession is also significant and can be orders of magnitude larger than the same effect for Mercury. Some exoplanets have significantly eccentric orbits, which makes it easier to detect the precession. The effect of general relativity can be detectable in timescales of roughly 10 years or less.[118]

Nodal precession

Nodal precession is rotation of a planet's orbital plane. This differs from periastron precession, which is rotation of a planet's orbit within that plane. Nodal precession is more easily seen as distinct from periastron precession when the orbital plane is inclined to the star's rotation, the extreme case being a polar orbit.

WASP-33 is a fast-rotating star that hosts a hot Jupiter in an almost polar orbit. The quadrupole mass moment and the proper angular momentum of the star are 1900 and 400 times, respectively, larger than those of the Sun. This causes significant classical and relativistic deviations from Kepler's laws. In particular, the fast rotation causes large nodal precession because of the star's oblateness and the Lense–Thirring effect.[119]

Rotation and axial tilt



Plot of equatorial spin velocity vs. mass for planets comparing Beta Pictoris b to the Solar System planets. (ESO/I. Snellen (Leiden University)

In April 2014 the first measurement of a planet's rotation period was announced: the length of day for the super-Jupiter gas giant Beta Pictoris b is 8 hours (based on the assumption that the axial tilt of the planet is small.)[120][121][122] With an equatorial rotational velocity of 25 km per second, this is faster than for the giant planets of the Solar System, in line with the expectation that the more massive a giant planet, the faster it spins. Beta Pictoris b's distance from its star is 9AU. At such distances the rotation of Jovian planets is not slowed by tidal effects.[123] Beta Pictoris b is still warm and young and over the next hundreds of millions of years, it will cool down and shrink to about the size of Jupiter, and if its angular momentum is preserved then as it shrinks the length of its day will decrease to about 3 hours and its equatorial rotation velocity will speed up to about 40 km per second.[121] The images of Beta Pictoris b do not have high enough resolution to directly see details but doppler spectroscopy techniques were used to show that different parts of the planet were moving at different speeds and in opposite directions from which it was inferred that the planet is rotating.[120] With the next generation of large ground-based telescopes it will be possible to use doppler imaging techniques to make a global map of the planet, like the recent mapping of the brown dwarf Luhman 16B.[124][125]

Origin of spin and tilt of terrestrial planets

Giant impacts have a large effect on the spin of terrestrial planets. The last few giant impacts during planetary formation tend to be the main determiner of a terrestrial planet's rotation rate. On average the spin angular velocity will be about 70% of the velocity that would cause the planet to break up and fly apart; the natural outcome of planetary embryo impacts at speeds slightly larger than escape velocity. In later stages terrestrial planet spin is also affected by impacts with planetesimals. During the giant impact stage, the thickness of a protoplanetary disk is far larger than the size of planetary embryos so collisions are equally likely to come from any direction in three-dimensions. This results in the axial tilt of accreted planets ranging from 0 to 180 degrees with any direction as likely as any other with both prograde and retrograde spins equally probable. Therefore, prograde spin with a small axial tilt, common for the Solar System's terrestrial planets except Venus, is not common in general for terrestrial planets built by giant impacts. The initial axial tilt of a planet determined by giant impacts can be substantially changed by stellar tides if the planet is close to its star and by satellite tides if the planet has a large satellite.[126]

Tidal effects

For most planets the rotation period and axial tilt (also called obliquity) are not known, but a large number of planets have been detected with very short orbits (where tidal effects are greater) and will probably have reached an equilibrium rotation that can be predicted.

Tidal effects are the result of forces acting on a body differing from one part of the body to another.[123] For example the gravitational effect of a star varies with distance from one side of a planet to another. Also heat from a star creates a temperature gradient between the day and nightsides which is another source of tides. For example, on Earth, air pressure variations on the ground are affected more by temperature differences than gravitational ones.

Tides modify the rotation and orbit of planets until an equilibrium is reached. Whenever the rotation rate is slowed, there is an increase of the orbit semi-major axis due to the conservation of angular momentum. Most of the large moons in the Solar System, including the Moon, are tidally locked to their host planet; the same side of the moon is always facing the planet. This means the moons' rotation periods are synchronous with their orbital period. However, when an orbit is eccentric, as is the case with many exoplanets' orbits of their host stars, there are equilibrium states such as spin–orbit resonances that are far more likely than synchronous rotation. A spin–orbit resonance is when the rotation period and the orbital period are in an integer ratio – this is called a commensurability. Non-resonant equilibriums such as the retrograde rotation of Venus can also occur when both gravitational and thermal atmospheric tides are both significant.

A synchronous tidal lock isn't necessarily particularly slow – there are planets with orbits that take only a few hours.

Gravitational tides tend to reduce the axial tilt to zero but over a longer time-scale than the rotation rate reaches equilibrium. However, the presence of multiple planets in a system can cause axial tilt to be captured in a resonance called a Cassini state. There are small oscillations around this state and in the case of Mars these axial tilt variations are chaotic.

Hot Jupiters' close proximity to their host star means that their spin–orbit evolution is mostly due to the star's gravity and not the other effects. Hot Jupiters rotation rate is not thought to be captured into spin–orbit resonance due to way fluid-body reacts to tides, and therefore slows down to synchronous rotation if it is on a circular orbit or slows to a non-synchronous rotation if on an eccentric orbit. Hot Jupiters are likely to evolve towards zero axial tilt even if they had been in a Cassini state during planetary migration when they were further from their star. Hot Jupiters' orbits will become more circular over time, however the presence of other planets in the system on eccentric orbits, even ones as small as Earth and as far away as the habitable zone, can continue to maintain the eccentricity of the Hot Jupiter so that the length of time for tidal circularization can be billions instead of millions of years.

The rotation rate of planet HD 80606 b is predicted to be about 1.9 days. HD 80606 b avoids spin–orbit resonance because it is a gas giant. The eccentricity of its orbit means that it avoids becoming tidally locked.

Physical parameters

See also: Planet § Physical characteristics

Mass

When a planet is found by the radial-velocity method, its orbital inclination *i* is unknown and can range from 0 to 90 degrees. The method is unable to determine the true mass (*M*) of the planet, but rather gives a lower limit for its mass, $M \sin i$. In a few cases an apparent exoplanet may be a more massive object such as a brown dwarf or red dwarf. However, the probability of a small value of i (say less than 30 degrees, which would give a true mass at least double the observed lower limit) is relatively low ($1-(\sqrt{3})/2 \approx 13\%$) and hence most planets will have true masses fairly close to the observed lower limit.[97]

If a planet's orbit is nearly perpendicular to the line of vision (i.e. *i* close to 90°), a planet can be detected through the transit method. The inclination will then be known, and the inclination combined with $M \sin i$ from radial-velocity will give the planet's true mass.

Also, astrometric observations and dynamical considerations in multiple-planet systems can sometimes provide an upper limit to the planet's true mass.

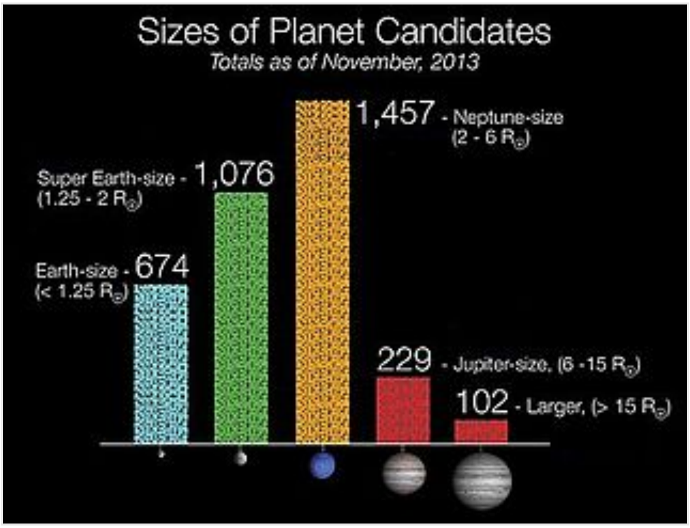
The mass of a transiting exoplanet can also be determined from the transmission spectrum of its atmosphere, as it can be used to constrain independently the atmospheric composition, temperature, pressure, and scale height.[127]

Transit-timing variation can also be used to find planets' masses.[128]

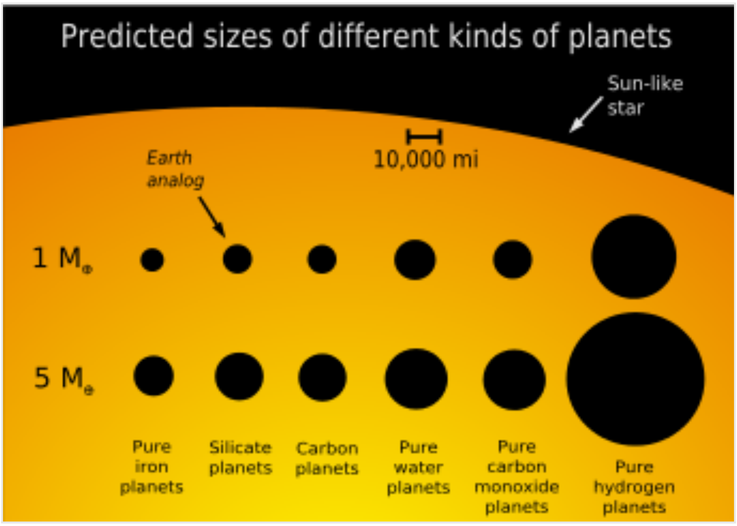
Radius, density and bulk composition

Prior to recent results from the Kepler spacecraft most confirmed planets were gas giants comparable in size to Jupiter or larger because they are most easily detected. However, the planets detected by Kepler are mostly between the size of Neptune and the size of Earth.[50]

If a planet is detectable by both the radial-velocity and the transit methods, then both its true mass and its radius can be found. The planet's density can then be calculated. Planets with low density are inferred to be composed mainly of hydrogen and helium, whereas planets of intermediate density are inferred to have water as a major constituent. A planet of high density is inferred to be rocky, like Earth and the other terrestrial planets of the Solar System.

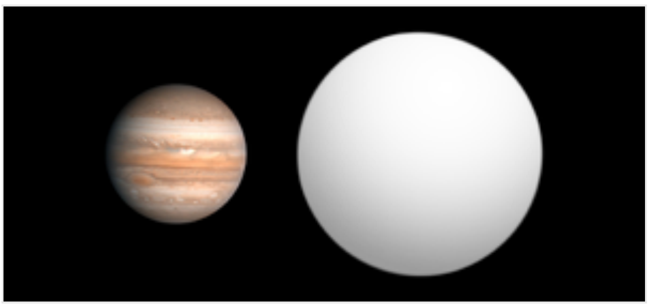


Sizes of *Kepler* Planet Candidates – based on 2,740 candidates orbiting 2,036 stars as of 4 November 2013 (NASA).



Comparison of sizes of planets with different compositions.

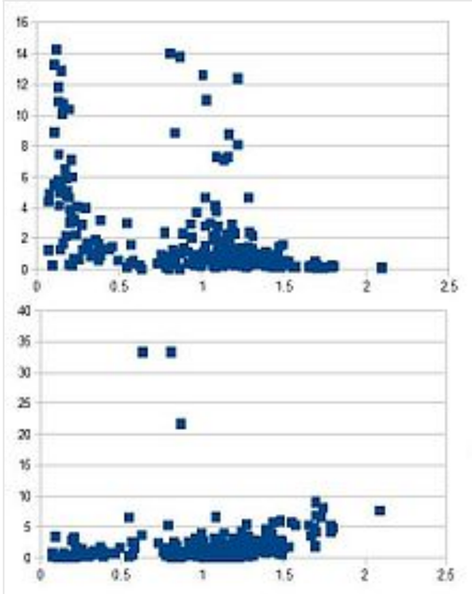
Gas giants, puffy planets, and super-Jupiters



Gaseous planets that are hot because they are close to their star or because they are still hot from their formation are expanded by the heat. For colder gas planets there is a maximum radius which is slightly larger than Jupiter which occurs when the mass reaches a few Jupiter-masses. Adding mass beyond this point causes the radius to shrink.[30][129][130]

Even when taking heating from the star into account, many transiting exoplanets are much larger than expected given their mass, meaning that they have surprisingly low density.[131] See the magnetic field section for one possible explanation.

Besides those inflated hot Jupiters there is another type of low-density planet: occurring at around 0.6 times the size of Jupiter where there are very few planets. The planets around Kepler-51[90] are far less dense (far more diffuse) than the inflated hot Jupiters as can be seen in the plots on the right where the three Kepler-51 planets stand out in the diffusity vs. radius plot. A more detailed study taking into account star spots may modify these results to produce less extreme values.[90]



Plots of exoplanet density and radius.[e] Top: Density vs. Radius. Bottom: Diffusity=1/Density vs. Radius. Units: Radius in RJup. Density in g/cm^3. Diffusity in cm^3/g. These plots show that there are a wide range of densities for planets between Earth and Neptune size, then the planets of 0.6RJup size are very low-density and there are very few of them, then the gas giants have a large range of densities.

Ice giants and super-Neptunes

Main article: Ice giant

Kepler-101b is the first super-Neptune planet. It has three times Neptune's mass but a Neptune-like composition with more than 60% heavy elements unlike hydrogen/helium-dominated gas giants.[132]

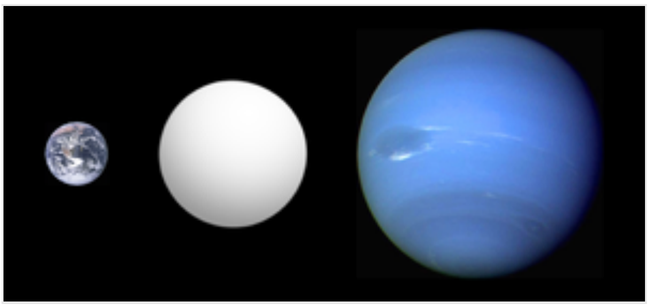
Super-Earths, mini-Neptunes, and gas dwarfs

If a planet has a radius and/or mass between that of Earth and Neptune then there is a question about whether the planet is rocky like Earth, a mixture of volatiles and gas like Neptune, a small planet with a hydrogen/helium envelope (mini-Jupiter), or of some other composition.

Some of the Kepler transiting planets with radii in the range 1–4 Earth radii have had their masses measured by radial-velocity or transit-timing methods. The calculated densities show that up to 1.5 Earth radii, these planets are rocky and that density increases with increasing radius due to gravitational compression. However, between 1.5 and 4 Earth radii the density decreases with increasing radius. This indicates that above 1.5 Earth radii planets tend to have increasing amounts of volatiles and gas. Despite this general trend there is a wide range of masses at a given radius, which could be because gas planets can have rocky cores of different masses or compositions[133] and could also be due to photoevaporation of volatiles.[134] Thermal evolutionary atmosphere models suggest a radius of 1.75 times that of Earth as a dividing line between rocky and gaseous planets.[135] Excluding close-in planets that have lost their gas envelope due to stellar irradiation, studies of the metallicity of stars suggest a dividing line of 1.7 Earth radii between rocky planets and gas dwarfs; then another dividing line at 3.9 Earth radii between gas dwarfs and gas giants. These dividing lines are statistical trends and do not necessarily apply to specific planets because there are many other factors besides metallicity that affect planet formation, including distance from star – there may be larger rocky planets formed at larger distances.[136]

The discovery of the low-density Earth-mass planet Kepler-138d shows that there is an overlapping range of *masses* in which both rocky planets and low-density planets occur.[137] Low-mass low-density planets could be ocean planets or super-Earths with a remnant hydrogen atmosphere, or hot planets with a steam atmosphere, or mini-Neptunes with a hydrogen-helium atmosphere.[138] Other possibilities for low-mass low-density planets are large atmospheres of carbon monoxide, carbon dioxide, methane, or nitrogen.[139]

Massive solid planets



In 2014, new measurements of Kepler-10c found that it is a Neptune-mass planet (17 Earth masses) with a density higher than Earth's, indicating that Kepler-10c is made mostly of rock with possibly up to 20% high-pressure water ice but without a hydrogen-dominated envelope. Because this is well above the 10-Earth-mass upper limit that is commonly used for the term 'super-Earth', the term **mega-Earth** has been coined.[140] A similarly massive and dense planet could be Kepler-131b, although its density is not as well measured as that of Kepler 10c. The next most massive known solid planets are half this mass: 55 Cancri e and Kepler-20b.[141]

Gas planets can also have large solid cores: the Saturn-mass planet HD 149026 b has only two-thirds of Saturn's radius, so it may have a rock–ice core of 60 Earth masses or more.[30]

Transit-timing variation measurements indicate that Kepler-52b, Kepler-52c and Kepler-57b have maximum-masses between 30 and 100 times the mass of Earth, although the actual masses could be much lower. With radii about 2 Earth radii in size, they might have densities larger than that of an iron planet of the same size. They orbit very close to their stars, so they could be the remnant cores (chthonian planets) of evaporated gas giants or brown dwarfs. If cores are massive enough they could remain compressed for billions of years despite losing the atmospheric mass.[142][143]

Solid planets up to thousands of Earth masses may be able to form around massive stars (B-type and O-type stars; 5–120 solar masses), where the protoplanetary disk would contain enough heavy elements. Also, these stars have high UV radiation and winds that could photoevaporate the gas in the disk, leaving just the heavy elements.[144] For comparison, Neptune's mass equals 17 Earth masses, Jupiter has 318 Earth masses, and the 13 Jupiter-mass limit used in the IAU's working definition of an exoplanet equals approximately 4000 Earth masses.[144]

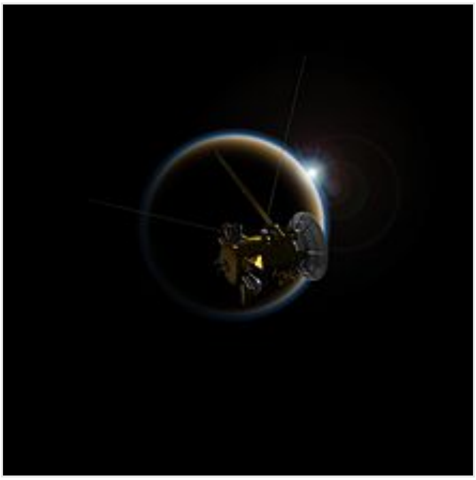
Another way of forming massive solid planets is when a white dwarf in a close binary system loses material to a companion neutron star. The white dwarf can be reduced to planetary-mass, leaving just its crystallised carbon–oxygen core. A likely example of this is PSR J1719-1438 b.

Cold planets have a maximum radius because adding more mass at that point causes the planet to compress under the weight instead of increasing the radius. The maximum radius for solid planets is smaller than the maximum radius for gas planets.[144]

Shape

When the size of a planet is described using its radius this is approximating the shape by a sphere. However, the rotation of a planet causes it to be flattened at the poles so that the equatorial radius is larger than the polar radius, making it closer to an oblate spheroid. The oblateness of transiting exoplanets will affect the transit light curves. At the limits of current technology it has been possible to show that HD 189733b is less oblate than Saturn.[145] If the planet is close to its star, then gravitational tides will elongate the planet in the direction of the star, so that the planet will be closer to a triaxial ellipsoid.[146] Because tidal deformation is along a line between the planet and the star, it is difficult to detect from transit photometry—it will have an order of magnitude less effect on the transit light curves than that caused by rotational deformation even in cases where the tidal deformation is larger than rotational deformation (such as is the case for tidally locked hot Jupiters).[145] Material rigidity of rocky planets and rocky cores of gas planets will cause further deviations from the aforementioned shapes.[145] Thermal tides caused by unevenly irradiated surfaces are another factor.[147]

Atmosphere



As of February 2014, more than fifty transiting and five directly imaged exoplanet atmospheres have been observed,[148] resulting in detection of molecular spectral features; observation of day–night temperature gradients; and constraints on vertical atmospheric structure.[149] Also, an atmosphere has been detected on the non-transiting hot Jupiter Tau Boötis b.[150][151]

Spectroscopic measurements can be used to study a transiting planet's atmospheric composition,[152] temperature, pressure, and scale height, and hence can be used to determine its mass.[127]

Stellar light is polarized by atmospheric molecules; this could be detected with a polarimeter. HD 189733 b has been studied by polarimetry.

Extrasolar planets have phases similar to the phases of the Moon. By observing the exact variation of brightness with phase, astronomers can calculate atmospheric-particle sizes.

Atmospheric composition

In 2001 sodium was detected in the atmosphere of HD 209458 b.[153]

In 2008 water, carbon monoxide, carbon dioxide[154] and methane[155] were detected in the atmosphere of HD 189733 b.

In 2013 water was detected in the atmospheres of HD 209458 b, XO-1b, WASP-12b, WASP-17b, and WASP-19b.[156][157][158]

In July 2014, NASA announced finding very dry atmospheres on three exoplanets (HD 189733b, HD 209458b, WASP-12b) orbiting Sun-like stars.[159]

In September 2014, NASA reported that HAT-P-11b is the first Neptune-sized exoplanet known to have a relatively cloud-free atmosphere and, as well, the first time molecules of any kind have been found, specifically water vapor, on such a relatively small exoplanet.[160]

The presence of oxygen may be detectable by ground-based telescopes,[161] which, if discovered, would suggest the presence of life on an exoplanet.

Atmospheric circulation

The atmospheric circulation of planets that rotate more slowly or have a thicker atmosphere allows more heat to flow to the poles which reduces the temperature differences between the poles and the equator.[162]

Clouds

In October 2013, the detection of clouds in the atmosphere of Kepler-7b was announced,[163][164] and, in December 2013, also in the atmospheres of GJ 436 b and GJ 1214 b.[165][166][167][168]

Precipitation

Precipitation in the form of liquid (rain) or solid (snow) varies in composition depending on atmospheric temperature, pressure, composition, and altitude. Hot atmospheres could have iron rain,[169] molten-glass rain,[170] and rain made from rocky minerals such as enstatite, corundum, spinel, and wollastonite.[171] Deep in the atmospheres of gas giants it could rain diamonds[172] and helium containing dissolved neon.[173]

Abiotic oxygen

The processes of life result in a mixture of chemicals that are not in chemical equilibrium but there are also abiotic disequilibrium processes that need to be considered. The most robust atmospheric biosignature is often considered to be molecular oxygen O_2 and its photochemical byproduct ozone O_3. The photolysis of water H_2O by UV rays followed by hydrodynamic escape of hydrogen can lead to a build-up of oxygen in planets close to their star undergoing runaway greenhouse effect. For planets in the habitable zone it was believed that water photolysis would be strongly limited by cold-trapping of water vapour in the lower atmosphere. However, the extent of H_2O cold-trapping depends strongly on the amount of non-condensible gases in the atmosphere such as nitrogen N_2 and argon. In the absence of such gases the likelihood of build-up of oxygen also depends in complex ways on the planet's accretion history, internal chemistry, atmospheric dynamics and orbital state. Therefore, oxygen on its own cannot be considered a robust biosignature.[174] The ratio of nitrogen and argon to oxygen could be detected by studying thermal phase curves[175] or by transit transmission spectroscopy measurement of the spectral Rayleigh scattering slope in a clear-sky (i.e. aerosol-free) atmosphere.[176]

Surface

Surface composition

Surface features can be distinguished from atmospheric features by comparing emission and reflection spectroscopy with transmission spectroscopy. Mid-infrared spectroscopy of exoplanets may detect rocky surfaces, and near-infrared may identify magma oceans or high-temperature lavas, hydrated silicate surfaces and water ice, giving an unambiguous method to distinguish between rocky and gaseous exoplanets.[177]

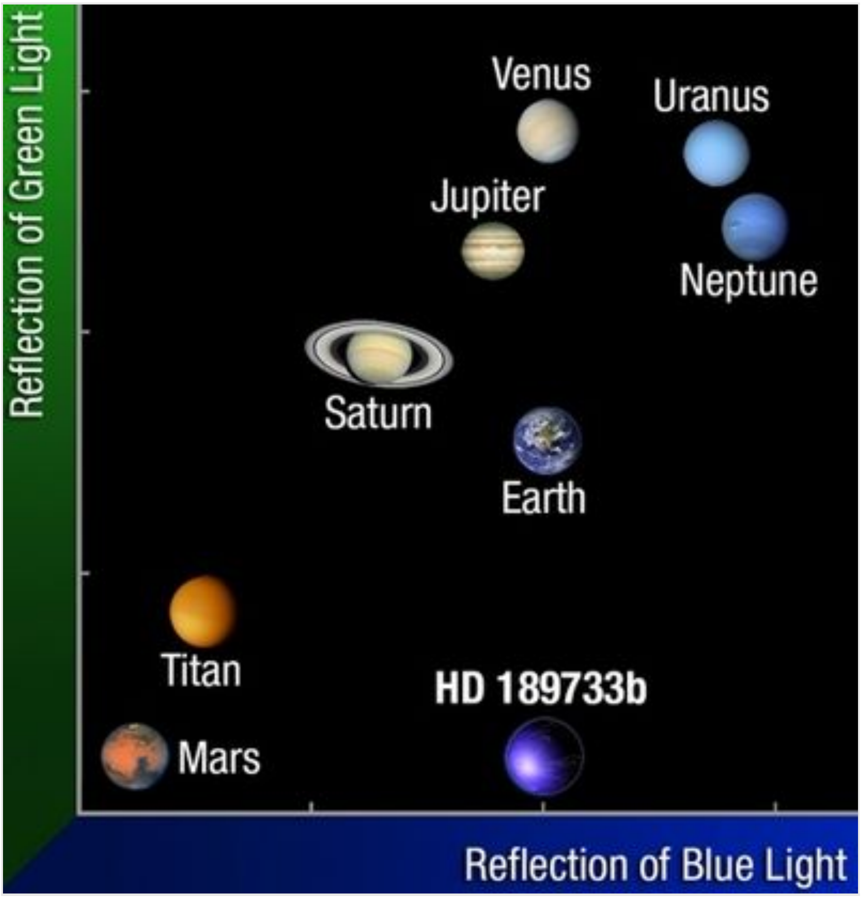
Surface temperature

One can estimate the temperature of an exoplanet based on the intensity of the light it receives from its parent star. For example, the planet OGLE-2005-BLG-390Lb is estimated to have a surface temperature of roughly −220 °C (50 K). However, such estimates may be substantially in error because they depend on the planet's usually unknown albedo, and because factors such as the greenhouse effect may introduce unknown complications. A few planets have had their temperature measured by observing the variation in infrared radiation as the planet moves around in its orbit and is eclipsed by its parent star. For example, the planet HD 189733b has been found to have an average temperature of 1205±9 K (932±9 °C) on its dayside and 973±33 K (700±33 °C) on its nightside.[178]

General features

Color and brightness

See also: Sudarsky's gas giant classification



This color–color diagram compares the colors of planets in the Solar System to exoplanet HD 189733b. The exoplanet's deep blue color is produced by silicate droplets, which scatter blue light in its atmosphere.

In 2013 the color of an exoplanet was found for the first time. The best-fit albedo measurements of HD 189733b suggest that it is deep dark blue.[179][180]

The apparent brightness (apparent magnitude) of a planet depends on how far away the observer is, how reflective the planet is (albedo), and how much light the planet receives from its star, which depends on how far the planet is from the star and how bright the star is. So, a planet with a low albedo that is close to its star can appear brighter than a planet with high albedo that is far from the star.[181]

The darkest known planet in terms of geometric albedo is TrES-2b, a hot Jupiter that reflects less than 1% of the light from its star, making it less reflective than coal or black acrylic paint. Hot Jupiters are expected to be quite dark due to sodium and potassium in their atmospheres but it is not known why TrES-2b is so dark—it could be due to an unknown chemical.[182][183][184]

For gas giants, geometric albedo generally decreases with increasing metallicity or atmospheric temperature unless there are clouds to modify this effect. Increased cloud-column depth increases the albedo at optical wavelengths, but decreases it at some infrared wavelengths. Optical albedo increases with age, because older planets have higher cloud-column depths. Optical albedo decreases with increasing mass, because higher-mass giant planets have higher surface gravities, which produces lower cloud-column depths. Also, elliptical orbits can cause major fluctuations in atmospheric composition, which can have a significant effect.[185]

There is more thermal emission than reflection at some near-infrared wavelengths for massive and/or young gas giants. So, although optical brightness is fully phase-dependent, this is not always the case in the near infrared.[185]

Temperatures of gas giants reduce over time and with distance from their star. Lowering the temperature increases optical albedo even without clouds. At a sufficiently low temperature, water clouds form, which further increase optical albedo. At even lower temperatures ammonia clouds form, resulting in the highest albedos at most optical and near-infrared wavelengths.[185]

Magnetic field

Interaction between a close-in planet's magnetic field and a star can produce spots on the star in a similar way to how the Galilean moons produce aurorae on Jupiter.[186] Auroral radio emissions could be detected with radio telescopes such as LOFAR.[187][188] The radio emissions could enable determination of the rotation rate of a planet which is difficult to detect otherwise.[189]

Earth's magnetic field results from its flowing liquid metallic core, but in super-Earths the mass can produce high pressures with large viscosities and high melting temperatures which could prevent the interiors from separating into different layers and so result in undifferentiated coreless mantles. Magnesium oxide, which is rocky on Earth, can be a liquid metal at the pressures and temperatures found in super-Earths and could generate a magnetic field in the mantles of super-Earths.[190]

Hot Jupiters have been observed to have a larger radius than expected. This could be caused by the interaction between the stellar wind and the planet's magnetosphere creating an electric current through the planet that heats it up causing it to expand. The more magnetically active a star is the greater the stellar wind and the larger the electric current leading to more heating and expansion of the planet. This theory matches the observation that stellar activity is correlated with inflated planetary radii.[191]

Plate tectonics

On Earth-sized planets, plate tectonics is more likely if there are oceans of water; however, in 2007 two independent teams of researchers came to opposing conclusions about the likelihood of plate tectonics on larger super-earths[192][193] with one team saying that plate tectonics would be episodic or stagnant[194] and the other team saying that plate tectonics is very likely on super-earths even if the planet is dry.[195]

If super-earths have more than 80 times as much water as Earth then they become ocean planets with all land completely submerged. However, if there is less water than this limit, then the deep water cycle will move enough water between the oceans and mantle to allow continents to exist.[196][197]

Rings

The star 1SWASP J140747.93-394542.6 is orbited by an object that is circled by a ring system much larger than Saturn's rings. However, the mass of the object is not known; it could be a brown dwarf or low-mass star instead of a planet.[198][199]

The brightness of optical images of Fomalhaut b could be due to starlight reflecting off a circumplanetary ring system with a radius between 20 to 40 times that of Jupiter's radius, about the size of the orbits of the Galilean moons.[200]

The rings of the Solar System's gas giants are aligned with their planet's equator. However, for exoplanets that orbit close to their star, tidal forces from the star would lead to the outermost rings of a planet being aligned with the planet's orbital plane around the star. A planet's innermost rings would still be aligned with the planet's equator so that if the planet has a tilted rotational axis, then the different alignments between the inner and outer rings would create a warped ring system.[201]

Moons

In December 2013 a candidate exomoon of a rogue planet was announced.[202] No exomoons have been confirmed so far.

Comet-like tails

KIC 12557548 b is a small rocky planet, very close to it star, that is evaporating and leaving a trailing tail of cloud and dust like a comet.[203] The dust could be ash erupting from volcanos and escaping due to the small planet's low surface-gravity, or it could be from metals that are vaporized by the high temperatures of being so close to the star with the metal vapor then condensing into dust.[204]

Habitability

Habitable zone

The habitable zone around a star is the region where the temperature is just right to allow liquid water to exist on a planet; that is, not too close to the star for the water to evaporate and not too far away from the star for the water to freeze. The heat produced by stars varies depending on the size and age of the star so that the habitable zone can be at different distances. Also, the atmospheric conditions on the planet influence the planet's ability to retain heat so that the location of the habitable zone is also specific to each type of planet: desert planets (also known as dry planets), with very little water, will have less water vapor in the atmosphere than Earth and so have a reduced greenhouse effect, meaning that a desert planet could maintain oases of water closer to its star than Earth is to the Sun. The lack of water also means there is less ice to reflect heat into space, so the outer edge of desert-planet habitable zones is further out.[205][206] Rocky planets with a thick hydrogen atmosphere could maintain surface water much further out than the Earth–Sun distance.[207]

Planetary rotation rate is one of the major factors determining the circulation of the atmosphere and hence the pattern of clouds: slowly rotating planets create thick clouds that reflect more and so can be habitable much closer to their star. Earth with its current atmosphere would be habitable in Venus's orbit, if it had Venus's slow rotation, so Venus must have had a higher rotation rate in the past if it lost its water ocean as a result of going through a runaway greenhouse effect, but if Venus never had an ocean because water vapor was lost to space during its formation before it could cool to form an ocean,[208] Venus could have had its slow rotation throughout its history.[209]

Habitable zones have usually been defined in terms of surface temperature, however over half of Earth's biomass is from subsurface microbes,[210] and the temperature increases as you go deeper underground, so the subsurface can be conducive for life when the surface is frozen and if this is considered, the habitable zone extends much further from the star,[211] even rogue planets could have liquid water at sufficient depths underground.[212] In an earlier era of the universe the temperature of the cosmic microwave background would have allowed any rocky planets that existed to have liquid water on their surface regardless of their distance from a star.[213]

Jupiter-like planets might not be habitable, but they could have habitable moons.[214][215]

Ice ages and snowball states

The outer edge of the habitable zone is where planets will be completely frozen but even planets well inside the habitable zone can periodically become frozen. If orbital fluctuations or other causes produce cooling then this creates more ice but ice reflects sunlight causing even more cooling creating a feedback loop until the planet is completely or nearly completely frozen. When the surface is frozen this stops carbon dioxide weathering resulting in a build-up of carbon dioxide in the atmosphere from volcanic emissions. This creates a greenhouse effect which unfreezes the planet again. Planets with a large axial tilt[216] are less likely to enter snowball states and can retain liquid water further from their star. Large fluctuations of axial tilt can have even more of a warming effect than a fixed large tilt.[217][218] Paradoxically planets around cooler stars, such as red dwarfs, are less likely to enter snowball states because the infrared radiation emitted by cooler stars is mostly at wavelengths that are absorbed by ice which heats it up.[219][220]

Tidal heating

If a planet has an eccentric orbit then tidal heating can provide another source of energy besides stellar irradiation. This means that eccentric planets in the radiative habitable zone can be too hot for liquid water (Tidal Venus). Tides also circularize orbits over time so there could be planets in the habitable zone with circular orbits that have no water because they used to have eccentric orbits.[221] Eccentric planets further out than the radiative habitable zone would still have frozen surfaces but the tidal heating could create a subsurface ocean similar to Europa's.[222] In some planetary systems, such as in the Upsilon Andromedae system, the eccentricity of orbits is maintained or even periodically varied by perturbations from other planets in the system. Tidal heating can cause outgassing from the mantle, contributing to the formation and replenishment of an atmosphere.[223]

Potentially habitable planets

Main article: List of potentially habitable exoplanets

Confirmed planet discoveries in the habitable zone include the Kepler-22b, the first super-Earth located in the habitable zone of a Sun-like star.[224] In September 2012, the discovery of two planets orbiting the red dwarf Gliese 163[225] was announced.[226][227] One of the planets, Gliese 163 c, about 6.9 times the mass of Earth and somewhat hotter, was considered to be within the habitable zone.[226][227] In 2013, three more potentially habitable planets, Kepler-62 e, Kepler-62 f, and Kepler-69 c, orbiting Kepler-62 and Kepler-69 respectively, were discovered.[228][229] All three planets were super-Earths[228] and may be covered by oceans thousands of kilometers deep.[230]

Earth-size planets

See also: Earth analog

In November 2013 it was announced that 22±8% of Sun-like[a] stars have an Earth-sized[b] planet in the habitable[c] zone.[10][11] Assuming 200 billion stars in the Milky Way,[d] that would be 11 billion potentially habitable Earths, rising to 40 billion if red dwarfs are included.[12]

Kepler-186f is the first Earth-sized planet in a habitable zone to have been discovered, a 1.1-Earth-radius planet in the habitable zone of a red dwarf, announced in April 2014.

In February 2013, researchers calculated that up to 6% of small red dwarfs may have planets with Earth-like properties. This suggests that the closest "alien Earth" to the Solar System could be 13 light-years away. The estimated distance increases to 21 light-years when a 95 percent confidence interval is used.[231] In March 2013 a revised estimate based on a more accurate consideration of the size of the habitable zone around red dwarfs gave an occurrence rate of 50% for Earth-size planets in the habitable zone of red dwarfs.[232]

Cultural impact

On 9 May 2013, a congressional hearing by two United States House of Representatives subcommittees discussed "Exoplanet Discoveries: Have We Found Other Earths?", prompted by the discovery of exoplanet Kepler-62f, along with Kepler-62e and Kepler-62c. A related special issue of the journal *Science*, published earlier, described the discovery of the exoplanets.[233]

See also

Notes

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- NASA Exoplanet Archive
- Open Exoplanet Catalogue
- The Habitable Exoplanets Catalog (PHL/UPR Arecibo)
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