Lecture 10: Planets Orbiting Other Stars

Aims of Lecture

(1) To explain the methods that can be used to detect planets orbiting other stars

(2) To discuss the possibility of detecting evidence for life on planets around other stars

Contents of Lecture

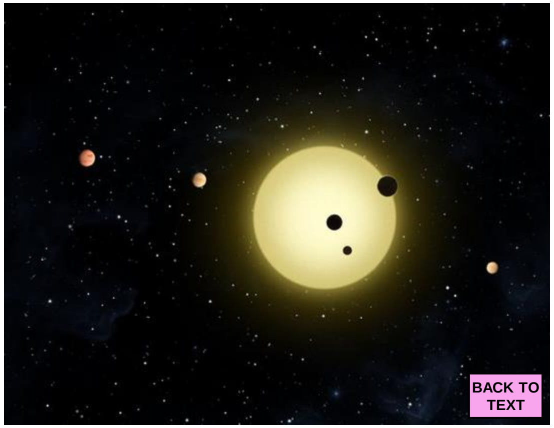


Fig. 1. Artist's drawing of an exoplanetary system (NASA)

1. Introduction

It seems likely that planets are needed to provide the stable physical conditions needed for the origin and evolution of life (although we should perhaps keep an open mind even on this point). Thus, the prospects for life in the Universe beyond the Solar System depend on whether planets are common around other stars. Detecting planets around other stars ('exoplanets') has been a 'holy grail' of astronomy for centuries. It has proved difficult to achieve, as planets are very small and faint compared to the stars about which they orbit (Fig. 1). Moreover, the stars are very far away, which makes the angular separation between star and planet very small, and hence it is difficult to separate star and planet on the sky – the planet would be 'drowned out' by the light from the star. Nevertheless, in one of the most exciting developments in modern astronomy, over 4000 extrasolar planets have been detected since the first was found in 1995.

2. Detection methods

2.1 Astrometric method

Although we tend to think that planets orbit stars, really both planet and star orbit their common centre of gravity (CoG). Because the star is much more massive than the planet, the CoG is much closer to the star (Fig. 2). Thus, as the planet executes a large circle around the CoG, the star moves around a small one. A distant observer, unable to detect the planet, could thus infer its presence by observing the motion of the star.

As an example, the motion of the Sun due to its planets, as seen in the sky of an alien astronomer located 30 light-years away, is shown in Fig. 3. The CoG of the Solar System lies only 1.2 solar radii from the centre of the Sun (i.e. 0.2 solar radii outside the Sun), and from even the nearest star (4 light-years away) this subtends an angle of ~10^{-6} of a degree. Until recently, such small angular motions were on the limit of detectability. ESA's GAIA satellite is now able to measure star positions to an accuracy of ~2×10^{-9} degrees for sufficiently bright stars (V<10), making the method practical for sufficiently short orbital periods. To-date, only about a dozen exoplanets have been detected by this method.

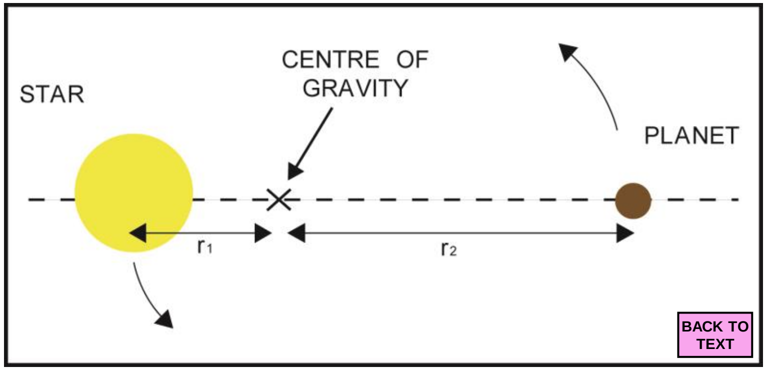


Fig.2. Diagram showing a star and a planet orbiting their common centre-of-gravity, viewed from directly above the orbital plane. The distance r_1 is much less than the distance r_2, as the star is much more massive than the planet (if M_* is the mass of the star, and M_p the mass of the planet, then $r_1/r_2 = M_p/M_*$).

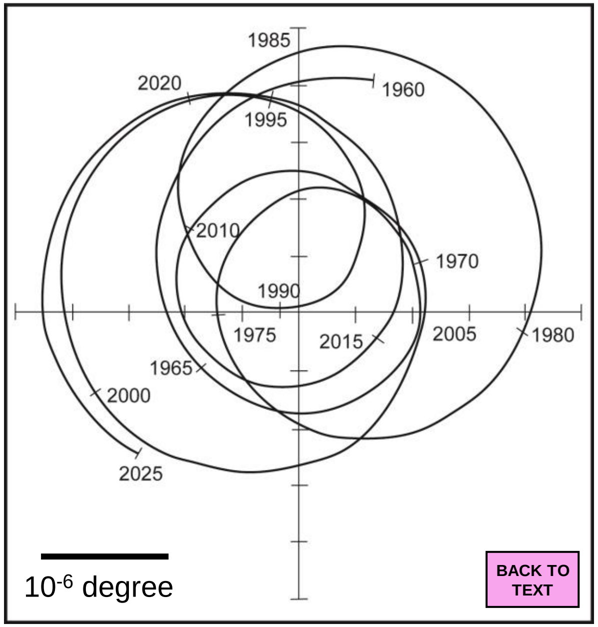


Fig. 3. The motion of the Sun over several decades, as seen from ~30 light-years.

2.2 Radial velocity method

Until recently, this was the first successful method of exo-planet detection, and has discovered over 900 extrasolar planets since 1995. To understand how it works, have another look at Fig. 2. While a star orbited by a planet will seem to move in a circle to an observer looking down on the system from ‘above’, an observer viewing the system in the plane of a planet’s orbit (i.e. in the plane of the diagram in Fig. 2) will see the star periodically moving towards and away from them. This motion can be detected spectroscopically by means of the Doppler effect, which causes the star’s light to be red-shifted when the star is moving away, and blue-shifted when the star is moving towards the observer. By continuously monitoring the star’s spectrum, an orbiting planet can be inferred through the periodic Doppler shifts – the so-called radial velocity curve (Fig. 4). The period of the radial velocity variations will be exactly equal to the orbital period of the planet, T. This is related to the orbital semi-major axis, a (essentially the separation of the star and planet for circular orbits) through Kepler’s Third Law:

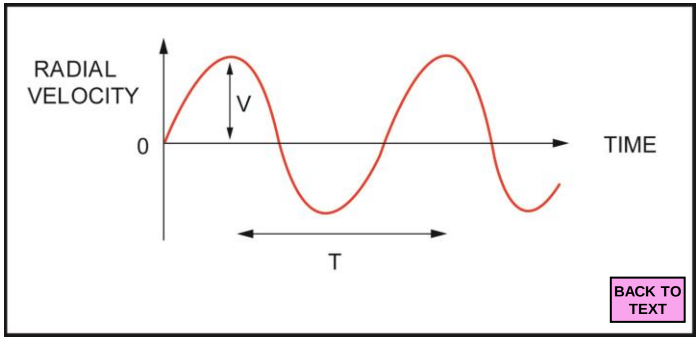


Fig.4 Periodic variation of the radial velocity of a star with a planet. By convention, red-shifts are positive and blue-shifts are negative. The period of the radial velocity curve, T, is equal to the orbital period of the unseen planet.

$$T^2 = \frac{4\pi^2}{GM_*} \times a^3$$

where G is Newton’s constant of universal gravitation, and M_* is the mass of the star. Thus, if M_* can be estimated (e.g. from the spectral type), a can be obtained from the observed radial velocity period. This is the first step in assessing an extrasolar planet’s temperature, and thus possible habitability.

As more massive planets lead to larger velocities, the amplitude of the radial velocity curve will give a measurement of the planetary mass. However, as in general we won't be observing the system exactly in its orbital plane, and we usually won't know at what angle we are observing it, the amplitude actually only gives us the product ($m_p$sin i), where m_p is the mass of the planet, and i is the (usually unknown) angle between the planet's orbital plane and the plane of our sky. The equation linking the radial velocity amplitude, V, to ($m_p$sin i) is:

$$V = \left(\frac{2\pi G}{T}\right)^{1/3} \times m_p \sin i \times M_*^{-2/3}$$

Note that we can only obtain m_p uniquely if we have an independent means of determining the angle i.

Fig. 5 shows the radial velocity variations of the Sun due to the planets of our Solar System. Jupiter pulls the Sun around with a velocity amplitude of ±13 m/s with a period of 12 years, while the next most massive planet, Saturn, superimposes a longer period (29 year) lower amplitude (±3 m/s) variations. The Earth, by contrast, pulls the Sun around by only ±0.09 m/s, with a period of one year. The detection limit of modern astronomical instruments is ~0.5 m/s. Thus, giant planets are easily detectable, but Earth-mass planets in Earth-like orbits are not undetectable around Sun-like stars using this technique. However, because the radial velocity amplitude is larger for shorter period orbits and/or lower mass stars, the technique is able to detect Earth-mass planets orbiting close to low-mass stars.

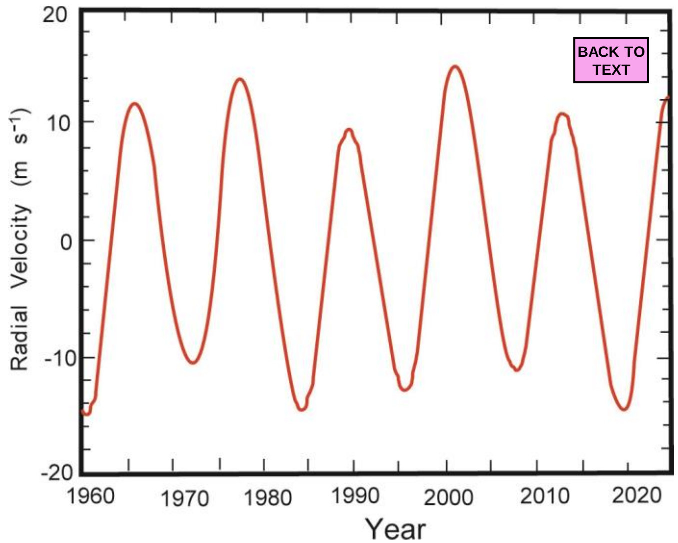
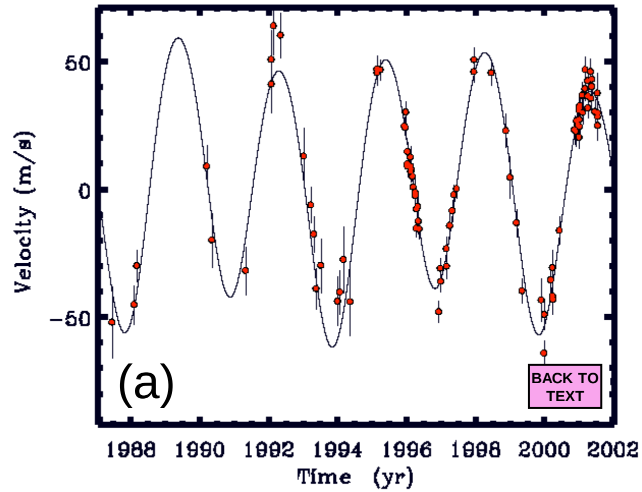


Fig. 5. The radial velocity curve of the Sun, as it would be seen by an alien astronomer. Note the modulation by Jupiter and Saturn, and the barely perceptible velocity variations due to Earth and Venus.

As an example, Fig. 6(a) shows the radial velocity curve for the star 47 Ursa Majoris, which has two planets with (m_p*sin i*) values of 2.5 and 0.8 Jupiter-masses, and orbital periods of 3.0 and 7.1 years, respectively; in our Solar System, both these planets would lie between Mars and Jupiter (Fig. 6(b)). In one of the most exciting recent exoplanet discoveries, in August 2016, the RV method detected an approximately Earth-mass planet within the habitable zone of the nearest star, Proxima Centauri (Fig. 7).



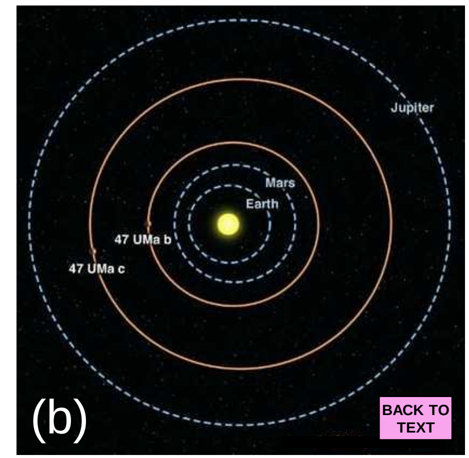
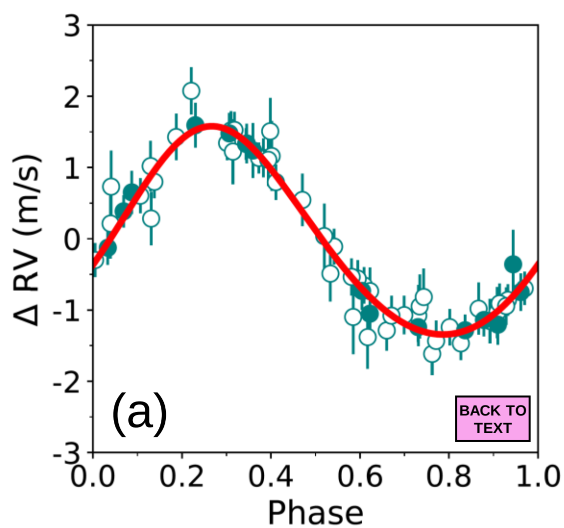


Fig. 6. **(a)** The radial velocity curve of 47 Ursa Majoris, revealing the presence of two massive planets, with orbital periods of 3.0 and 7.1 years. (California and Carnegie Planet Search; http://exoplanets.org/). **(b)** A sketch of the 47 UMa planets, relative to the planetary orbits in our own Solar System (NASA/ L. Cook).



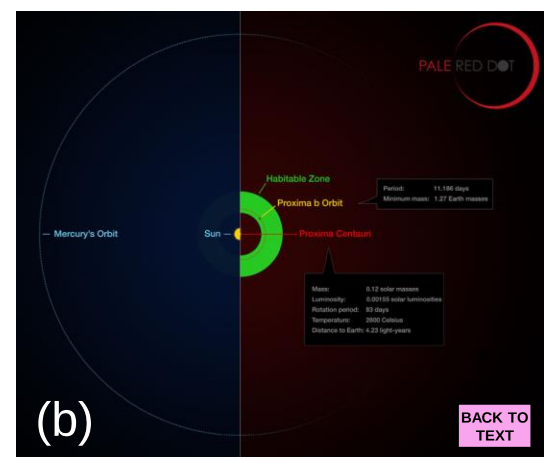


Fig. 7. (a). RV curve for Proxima Centauri. Solution corresponds to a planet with $m_p$sin i=1.17 M_E, T=11.2 days, a=0.05 AU (Suárez Mascareño et al., "Revisiting Proxima with ESPRESSO", public domain). There is also less secure evidence for a smaller ($m_p$sin i = 0.3 M_E) planet with T=5.2 days and a=0.03 AU, and a larger ($m_p$sin i = 6 M_E) with T=5.2 years and a=1.5 AU. **(b)** Comparison of Proxima Centauri system with the Solar System; green band marks estimated location of the Proxima habitable zone (Pale Red Dot/ESO).

2.3 Transit method

If we view an extrasolar planetary system exactly in the orbital plane of its planets, then periodically a planet will pass in front of the star causing it to dim slightly (Fig. 8). In 1999, a planet that was originally discovered orbiting the star HD 209458 by the radial velocity method was independently confirmed when transits were observed. The star was observed to dim by about 1.5% (Fig. 9(a)), from which the geometry of the transit was deduced (Fig. 9(b)). Since then over 3100 transiting planets have been observed (mostly with the Kepler telescope; see below). Many have been confirmed by the radial velocity method. Note that transits will always be relatively rare as the viewing angle must be just right. Transits are important, because the fact that a transit is observed means that the inclination angle $i \sim 90^\circ$ (i.e. $\sin i \sim 1$), which means that the planetary mass can be determined uniquely from the star's radial velocity.

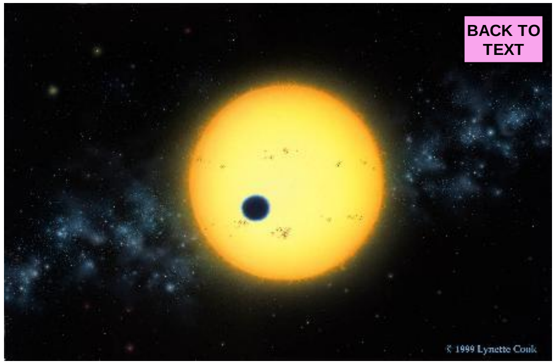


Fig. 8 A painting by Lynette Cook, showing the effect of a planet transiting across the face of its parent star (reproduced with permission; Lynette Cook/NASA).

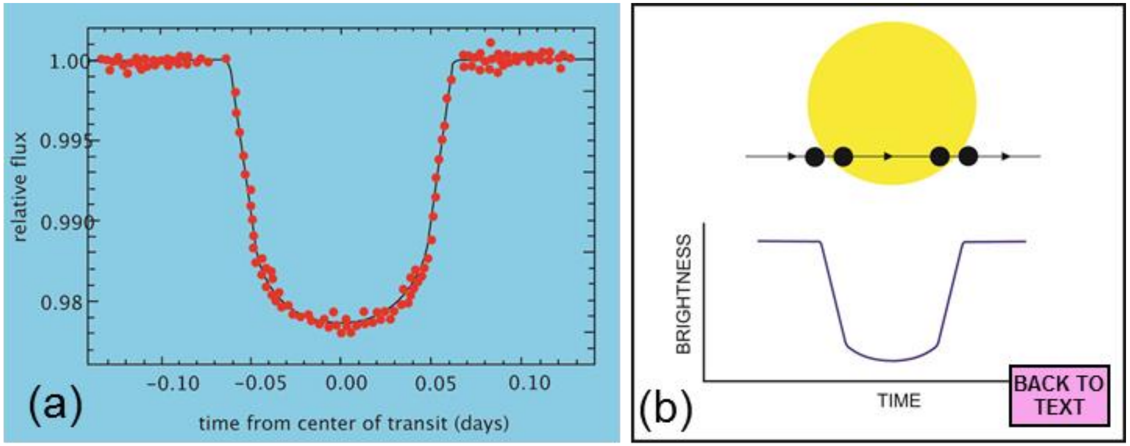


Fig. 9 (a) The observed light curve of HD 209458 as its planet passes in front. The star dims by 1.5% during each transit, which lasts for 0.12 days (i.e. 2.9 hours). The transits repeat every 3.5 days. **(b)** Diagram showing the geometry of the HD 209458 transit. The 1.5% brightness drop implies that the projected area of the planet is 1.5% of the projected area of the star.

Transits also give the size of the transiting planet, as larger planets result in more dimming. Thus, by observing a transit *and* the radial velocity of the star it is possible to deduce the planet's density, which gives a first-order estimate of its composition. In the case of the planet orbiting HD 209458, the planetary mass was determined to be 0.7 Jupiter-masses, and the density was found to be 0.35 g/cm^3, demonstrating that this planet is a gas giant. The detailed shape of the light curve tells us where on the disk of the star the transit occurred (Fig. 9(b); in this case we almost missed being able to see transits).

Information about other planets in a system can be obtained from transit data, even if these other planets do not themselves transit. For a single planet orbiting a star we would expect the transits to recur with a precise period. However, if other planets are present their gravity can perturb the orbit of the transiting planet, causing slight irregularities in the orbital period. Such discrepancies are known as transit timing variations (TTVs). As of 2020, ~20 exoplanets have been discovered by TTVs.

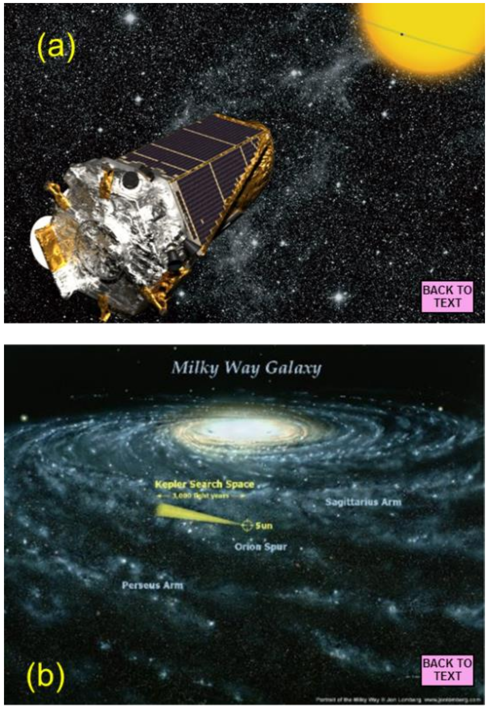


Fig. 10. (a) Artist's drawing of the *Kepler* space telescope. **(b)** Kepler field of view superimposed on an artist's drawing of the Milky Way Galaxy (NASA/Jon Lomberg).

The transit method has been employed very successfully by the Kepler space telescope during its primary mission between 2009 and 2013. Although the orbit of an extrasolar planet must be aligned with the Earth in order for us to see a transit, Kepler (Fig. 10) monitored over 150,000 stars simultaneously. If they all have planets, a few percent will have suitably aligned orbits resulting in several thousand detections. The fact that over 2000 planets were detected by Kepler (Fig. 11) indicates that planets must be common. Allowing for known limitations, the Kepler data imply that "every late-type [spectral class G-M] main sequence star has at least one planet (of any size)" (Natalia Batalha, PNAS, 111, 12647, 2014).

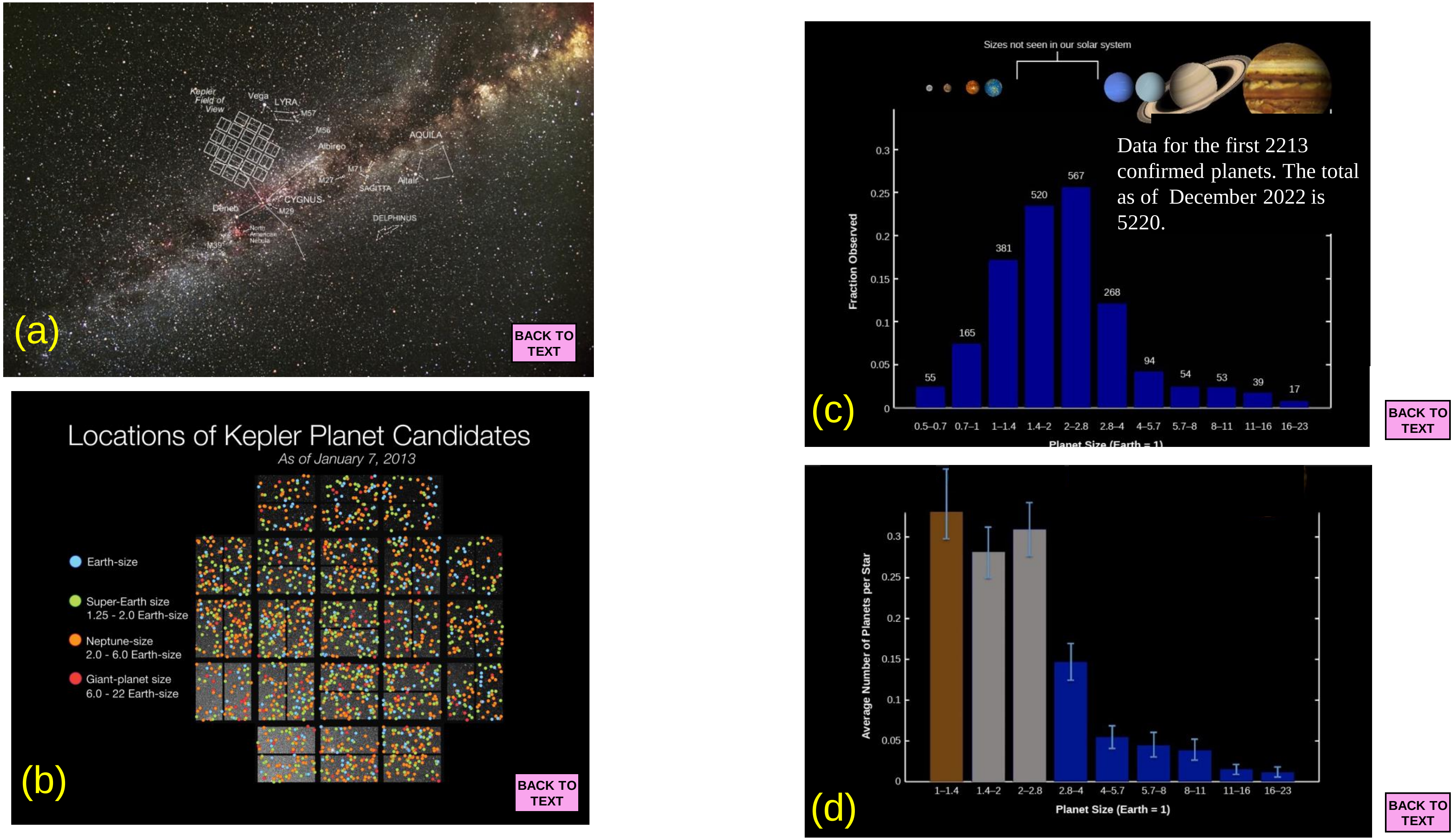


Fig. 11 (a) Kepler field of view on the sky: each square represents a CCD detector in the telescope focal plane. **(b)** Kepler results from the first 22 months data (released in January 2013; note that here ‘Earth-size’ implies radii less than 1.25 Earth radii). **(c)** Total confirmed Kepler planets (see https://exoplanets.nasa.gov/keplerscience/ for updates). **(d)** Kepler detections corrected for known selection effects; note that statistics are incomplete for small planets (<1 R_E) and long orbital periods (>500 days) and these planets are not included in this plot – allowing for smaller planets and longer periods will increase the total number of planets, implying that essentially all stars have planets and that systems of multiple planets are common. (Images: (a), (b): NASA/Kepler Project; (c), (d): OpenStax CNX/Lumen Astronomy/Creative Commons: https://courses.lumenlearning.com/astronomy/).

Kepler is now being followed by NASA's TESS (Transiting Exoplanet Survey Satellite) mission, which was launched in April 2018 and which will survey 85% of the whole sky for planets transiting stars brighter than about magnitude 12 (Fig. 12). As of October 2020, TESS has discovered over 2000 candidate exoplanets (of which 67 have been confirmed). Importantly, TESS is designed to discover small (Earth to super-Earth) potentially habitable planets orbiting relatively nearby solar-type stars. These will then be amenable to follow-up observations by more specialised instruments, such as NASA's James Webb Space Telescope (for possible direct imaging; see Section 2.5 below), and ESA's Ariel mission.

Ariel (the Atmospheric Remote-sensing Infrared Exoplanet Large-survey; Fig. 13) is due to be launched in 2028 and consists of a 1.1×0.7 m telescope capable of recording light-curves of transiting planets at a range of IR wavelengths. It is designed to determine the compositions of ~1000 transiting exoplanet atmospheres by observing small changes in the spectrum of the target star due to light passing through the planet's atmosphere when the planet is transiting (see Section 4 below).

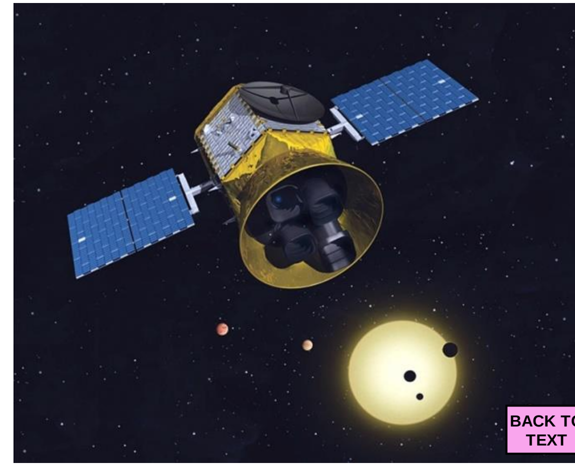


Fig. 12. Artist's impression of the Transiting Exoplanet Survey Satellite (TESS) (NASA)

Fig. 13. Artist's drawing of ESA's Ariel spacecraft, designed to characterise exoplanet atmospheres by transit spectro-scopy (ESA).

2.4 Gravitational lensing

Another technique that can potentially detect planets around other stars exploits the phenomenon of gravitational lensing. This occurs when a foreground star passes in front of a brighter background star as seen from Earth. As it does so, the gravity of the foreground star bends the light from the background star, essentially focussing it towards the Earth and causing the apparent brightness of the background star to increase (Fig. 14). The effect is called gravitational lensing, and it has now been observed many times. If the foreground star has a planet, the planet's own gravity distorts the lensing effect and results in an asymmetric light curve (Fig. 15). The method valuable because it is sensitive to detecting planets in more distant orbits (especially beyond the ‘snow line’), and orbiting stars much further from the Sun, than other exoplanet detection methods.

As of October 2020, 130 extrasolar planets have been detected by this method (in 116 separate systems). The detection statistics can be used to estimate the fraction of stars with planetary systems. The results imply that essentially all stars have planets (see, e.g., D. Suzuki et al., *Astrophysical Journal*, 833, 145, 2016), consistent with those from radial velocity and transit surveys.

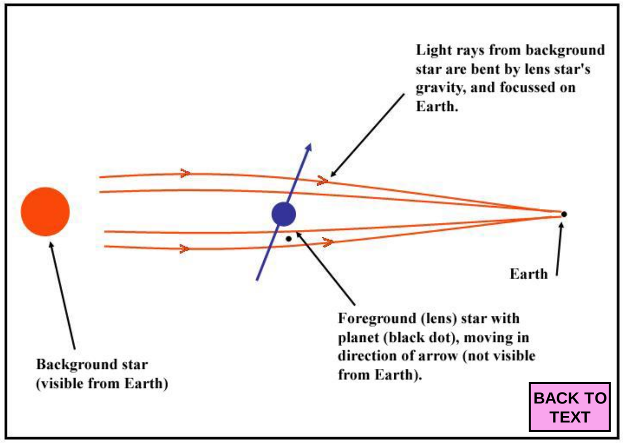


Fig. 14. Diagram showing the principle of a gravitational lens. The foreground star (here shown with a planet) focuses the light from a background star towards the Earth, causing it to momentarily brighten.

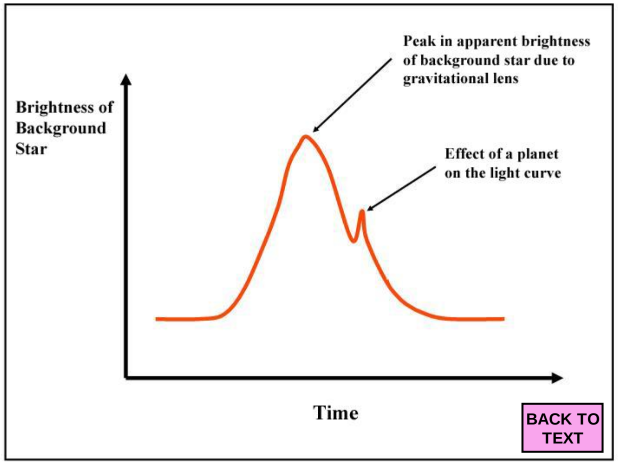


Fig. 15. The light curve of the background star as the foreground (lens) star moves in front of it. Note the effect of the planet.

2.5 Direct imaging

To-date, ~140 direct detections of possible extra-solar planets (in ~100 systems) have been reported. This is difficult owing to the brightness of the parent star and the small angular separations of the planets. It is easiest at infra-red (IR) wavelengths, and thus most sensitive to newly formed giant planets that are still emitting IR light as they cool down. Among the most reliable detections are the four probable planets orbiting the A5V star HR 8799 (distance 130 light years; Fig. 16). The four planets have estimated masses of 7, 10, 10 and 7 times that of Jupiter, at distances of 14, 24, 38 and 68 AU from the star. The system has an estimated age of only 30 Myr, and the planets are luminous at IR wavelengths as they are still contracting. Closer orbiting (and/or lower mass) planets are possible, but are not detectable owing to the glare from the central star.

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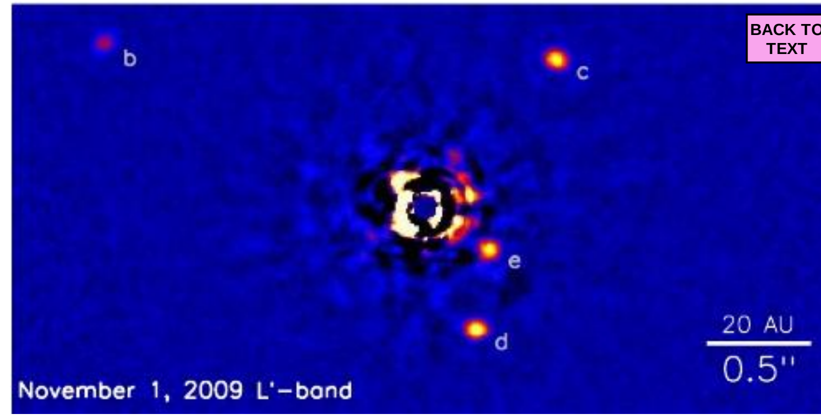


Fig. 16. A near infra-red (3.7 micron) image of the HR 8799 system obtained with the Keck II telescope on Hawaii. Flux from the star is suppressed, leaving four hot, young giant planets visible. Planetary nature is confirmed by orbital motion in an anti-clockwise direction (see Marois et al., *Nature*, 468, 1080, 2010).

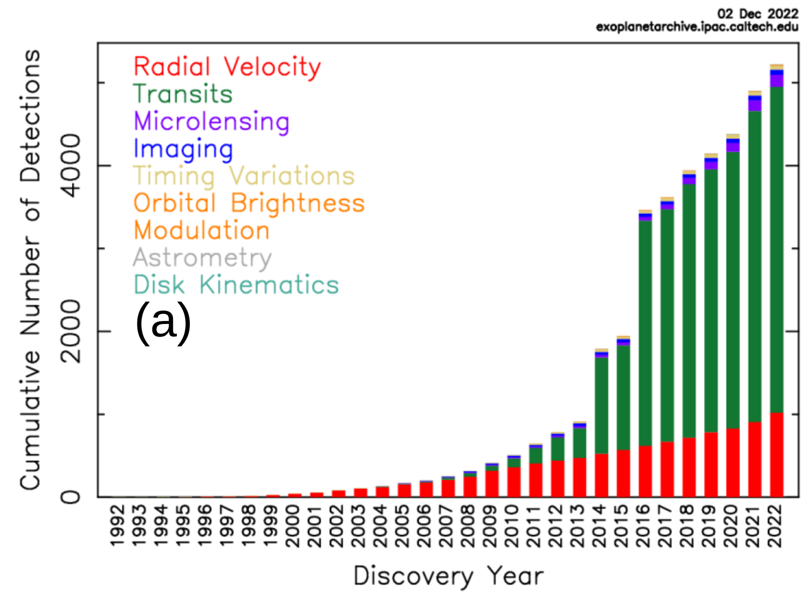
2.6 Pulsar timing

Strangely, the first detection of terrestrial-mass ‘planets’ was made by radio astronomers in 1992, who detected three objects (~0.015, 3.4 and 2.8 Earth-masses) orbiting at ~0.19, 0.36 and 0.47 AU, respectively, from a pulsar. Pulsars are spinning neutron stars, produced by the imploding core of a supernova, and it is unclear whether these ‘planets’ survived the supernova explosion, or accreted from the debris. In 1994 another pulsar planet was detected so the process is not unique. However, the radiation environment around pulsars is such that these bodies are probably of little astrobiological interest.

3. Summary of key results

In order to keep up with this fast-moving field, it is recommended that students regularly check one of the excellent on-line summaries of recent exoplanet discoveries, such as [The Extrasolar Planets Encyclopedia](#) and NASA's [Exoplanet Archive](#).

A summary of detections up to September 2019 is given in Fig. 17, which shows exoplanet discoveries by (a) detection method, (b) planetary mass, and (c) planetary radius.



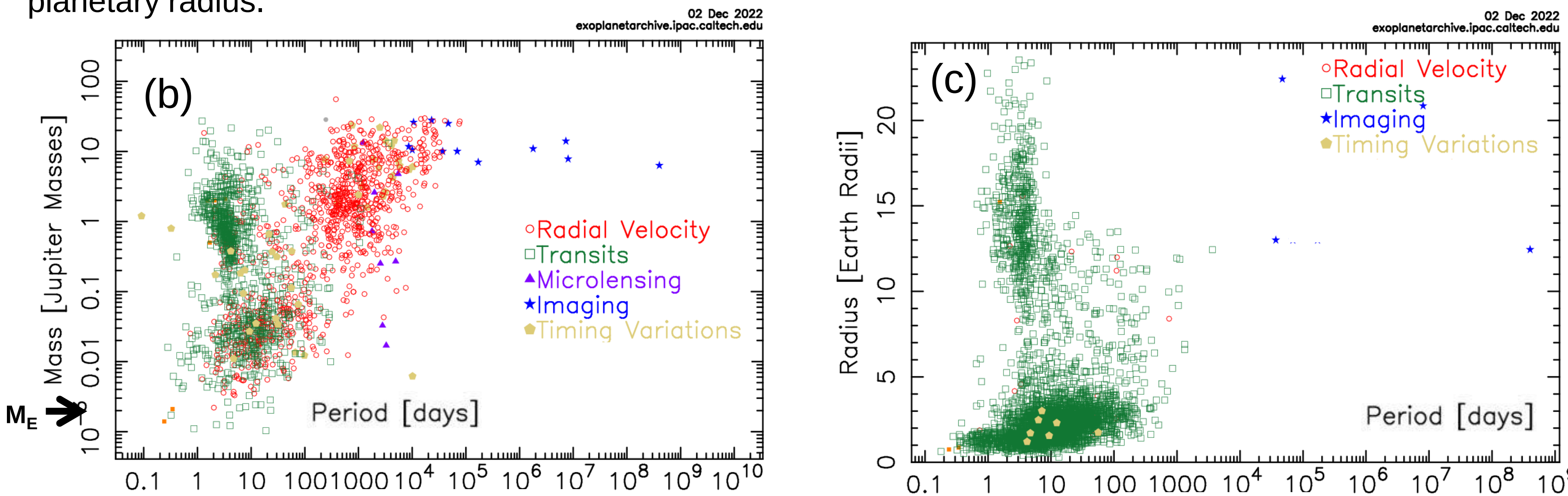


Fig. 17. Detected extrasolar planets as of December 2022. Note (i) the growing dominance of the transit method in detecting exoplanets (Fig. 17a); (ii) few really massive (>10 M_J) planets have been found, even though they will be the easiest to detect (Fig. 17b); (iii) small (i.e. Earth to super-Earth sized) planets are very common (Fig. 17c; note that these appear to be missing in Fig. 17b because most of them don't have independent mass estimates). Credit: NASA Exoplanet Archive.

Key Points:

- Most stars have planets of one kind or another. Not only is this true for approximately solar-type (i.e. spectral class FGK) stars, but it is also true of the very numerous M-dwarf stars.
- Small (Earth to super-Earth) planets in short-period orbits are common (Fig. 17c); at least 50% of these are multiple systems.
- Many exoplanets have orbits that are more eccentric than those in our Solar System (Fig. 18). For comparison, Earth's orbit has an eccentricity of 0.02; the most eccentric planetary orbit in our Solar System is that of Pluto (0.25). Planets with such high eccentricities would be prone to severe seasonal variations as they move in and out of the HZ on each orbit (Fig. 19).
- Planets are commonly found in binary systems, both in close orbits around the individual stars and, in a handful of systems in circumbinary orbits (e.g. Kepler-16; Fig. 20). . Stellar multiplicity itself is not therefore a barrier to planet formation (although zones of gravitational stability need to be considered).
- Early RV work had indicated that planets are more likely to be found around stars enriched in heavy chemical elements. However, this relationship is not so pronounced for low mass planets (Fig 21).

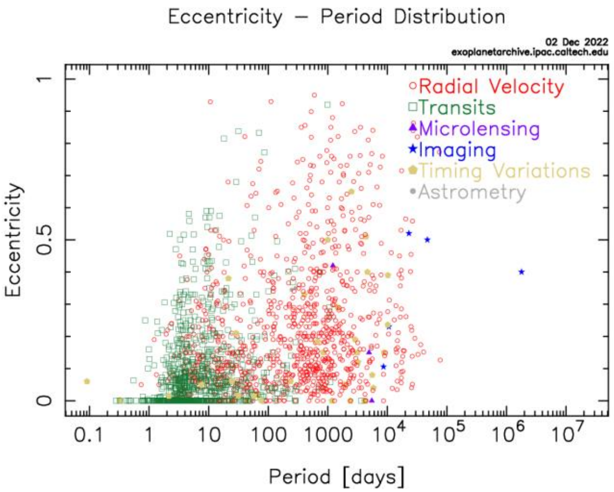


Fig. 18. The orbital eccentricity distribution of known exoplanets. Note that many have much more eccentric orbits than the planets of our Solar System (NASA Exoplanet Archive).

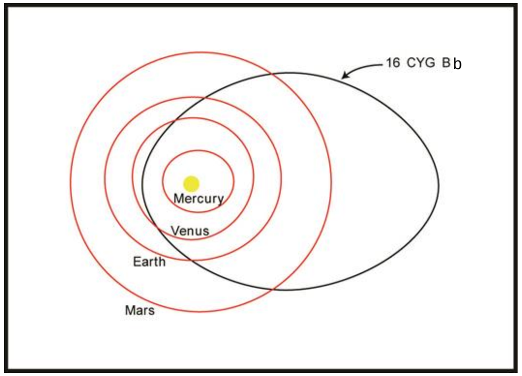


Fig. 19. The eccentric orbit (e = 0.67) of the 1.7 Jupiter-mass planet orbiting 16 Cygni B, relative to planets in our Solar System.

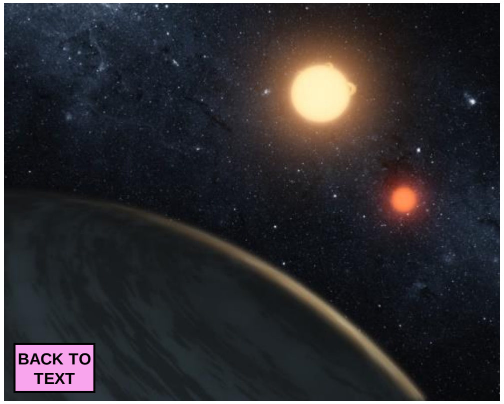


Fig. 20. Artist's concept of Kepler 16b, a Saturn-mass planet orbiting a binary star (K and M stars 0.22 AU apart) with a period of 229 days. The planet is probably just outside the habitable zone (NASA).

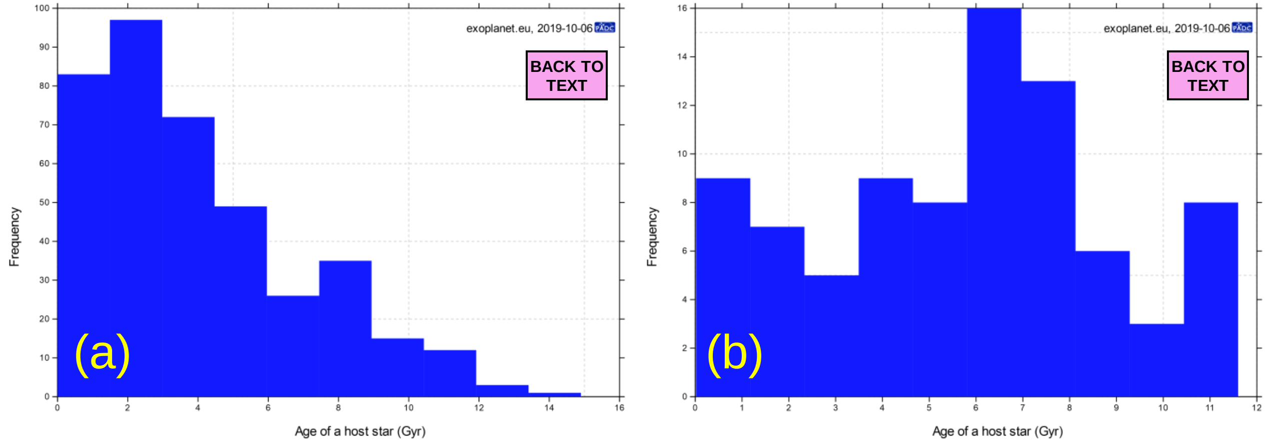


Fig. 21. (a) The number of giant planets ($R>10R_E$) shown as a function of estimated stellar age; note the pronounced fall in the number of these planets with age. **(b)** The corresponding plot for small planets ($R<2R_E$); note that the number of these planets appears almost independent of age, with a peak for stars having ages of ~7 Gyr. (http://exoplanet.eu; data as of October 2019).

The data in Fig. 21 are consistent with theories of planetary formation, where planetary embryos have to grow quickly in order to attract gas from the protoplanetary disk to make giant planets; if heavy elements are rare the process may proceed more slowly, making it difficult to build gas giants. However, while occurring more slowly, it is clear that rocky planets can still be built in metal-poor disks. A good example is provided by Kepler 444, a K0V star with five sub-Earth-sized planets, despite its estimated age of 11.2 Gyr and a heavy element abundance only 28% of the solar value. Theoretical estimates (e.g. Zackrisson et al., *ApJ*, 833, 214, 2016) imply that the *average* age of small rocky planets in the Galaxy is about 7 Gyr (i.e. 2.5 billion years older than the Solar System), consistent with the age distribution shown in Fig. 21(b). This suggests that rocky planets orbiting old stars, and that have therefore had a long time for biological evolution to occur, are likely to be common. On the other hand, recall that other factors, e.g. accumulation of key elements and/or high-energy galactic activity (Lecture 2), may have militated against their early habitability.

4. Searching for life

Already ~100 planets are known to lie within or close to the circumstellar habitable zone (CHZ), but bear in mind the caveats that need to be placed on that concept (Lecture 2). Fig. 22 shows known exoplanets plotted in terms of the energy they receive from the Sun together with a common definition of the CHZ. Based on these statistics, it appears that ~3% of planetary systems may have planets within the CHZ. However, the observational data are known to be incomplete, especially for small planets at Earth-Mars orbital distances. Allowing for this incompleteness results in estimates of ~ 20% of solar-type stars having planets in the CHZ, and a larger fraction (possibly as much as 50%) for M-dwarf stars (see, e.g., Natalie Batalha, *PNAS, 111, 12647, 2014*). Indeed, it is now known that many M-dwarf stars are orbited by several Earth and super-Earth-sized planets, with more than one planet within the likely CHZ. A good example is the TRAPPIST-1 system, which has three such planets within the CHZ (Fig. 23). These statistics imply that there are billions of potentially habitable planets in the Galaxy (even ignoring habitable planets and moons that lie outside the usual definition of the CHZ).

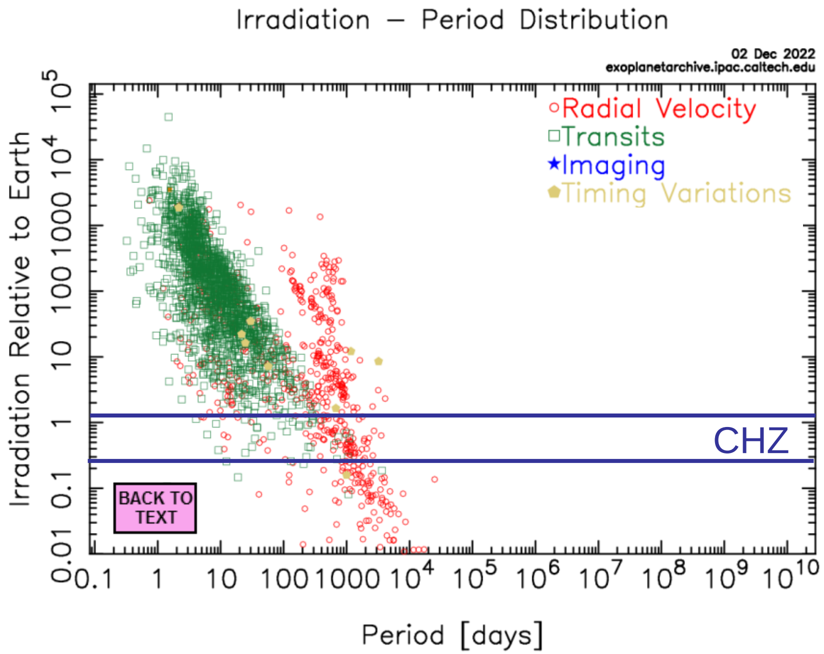


Fig. 22. Known exoplanets (as of December 2022) plotted in terms of the energy they receive from the Sun, together with a common definition of the CHZ: i.e., illumination between 0.25 and 1.23 times that received by the Earth and an Earth-like albedo (corresponding to planetary equilibrium temperatures between 180 and 270 K; see Selsis et al., *Astronomy and Astrophysics*, 476, 1373, 2007). Of course, we don't know if any of these planets are actually habitable because in most cases we don't know anything about their atmospheric or surface conditions (recall that the Moon receives the same quantity of energy from the Sun as the Earth). Data from the NASA Exoplanet Archive (NASA).

Most of these stars, especially the Kepler targets, are too far away for detailed follow-up studies, but the statistics imply that nearby habitable planets will also be common (recall Proxima Centauri!), for which follow-up spectroscopic observations may be possible. Many such objects are expected to be discovered by the TESS satellite (Fig. 12).

Once potentially habitable planets are discovered, detailed follow-up studies will be required. A start is being made using existing space telescopes such as the Hubble Space Telescope (HST) and the IR telescope Spitzer. For example, in 2019 Angelos Tsiaras and colleagues from UCL used the HST to detect water vapour in the atmosphere of the $8M_E$ super-Earth planet K2-18b (here K-2 refers to the extended Kepler mission). Instruments such as NASA's James Webb Space Telescope (JWST; Fig. 24) and ESA's *Ariel* mission (Fig. 13, above) will extend such observations and improve our knowledge of atmospheric compositions for planets orbiting nearby stars.

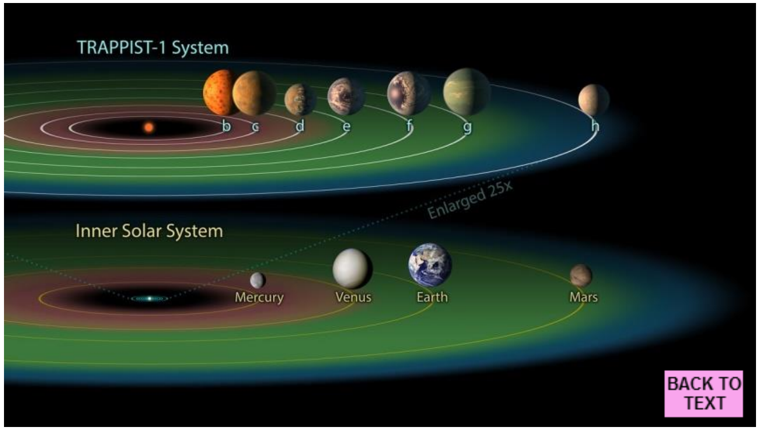


Fig. 23. The TRAPPIST (TRAnsiting Planets and PlanetesImals Small Telescope)-1 planetary system compared to the Solar System and their respective CHZs. TRAPPIST-1 is a red dwarf (M8) star 12 pc (39 light-years). It is orbited by 7 Earth to super-Earth-sized planets, of which three are plausibly within the CHZ. TRAPPIST-1 has an estimated age of 7.6±2.2 Gyr, but owing to its low luminosity a probable total lifetime of 12,000 Gyr (i.e. 12 *trillion* years!). Image: NASA/STScI.

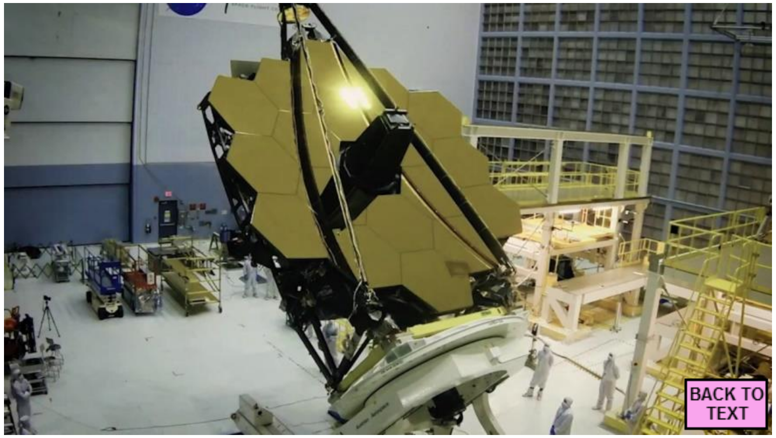


Fig. 24. The 6.5m diameter primary mirror of JWST under construction. The telescope is due for launch in 2021 and, among other projects, will be used to study the atmospheric compositions of nearby exoplanets (NASA).

To fully characterise exoplanet atmospheres, and to search for molecular biosignatures within them, even larger space telescopes are likely to be needed in the future. One idea for such a telescope is *Darwin* mission concept once proposed to the European Space Agency but never selected (Fig. 25). This would consist of a cluster of about six 1.5 meter diameter telescopes, flying about 100 meters apart. The infra-red (IR) light from the component telescopes would be combined in an 'interferometer' in such a way that the cluster will have the same angular resolution as would a single dish 100 meters in diameter. Similar instruments, are under study in the US (e.g. the Terrestrial Planet Finder, TPF), but technical and financial hurdles mean that such instruments are probably decades from realisation.

The principal aims of the *Darwin* proposal were:

(a) To detect Earth-mass planets around stars up to about 30 light-years away; and

(b) To obtain IR spectra of the atmospheres of any planets detected in order to search for signs of life.

To illustrate the potential of IR spectroscopy in this respect, Fig. 26 shows spectra of the three terrestrial planets in our Solar System with atmospheres. All three planets have CO_2 in their atmospheres, and in consequence all have a strong absorption feature due to this molecule at a wavelength of approximately 15 μm.

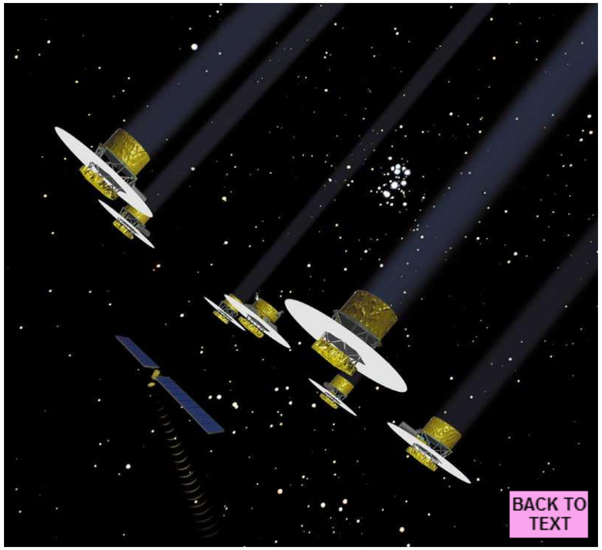


Fig. 25. Artist's drawing of ESA's proposed Darwin mission: a flotilla of several 1.5-meter space telescopes (ESA).

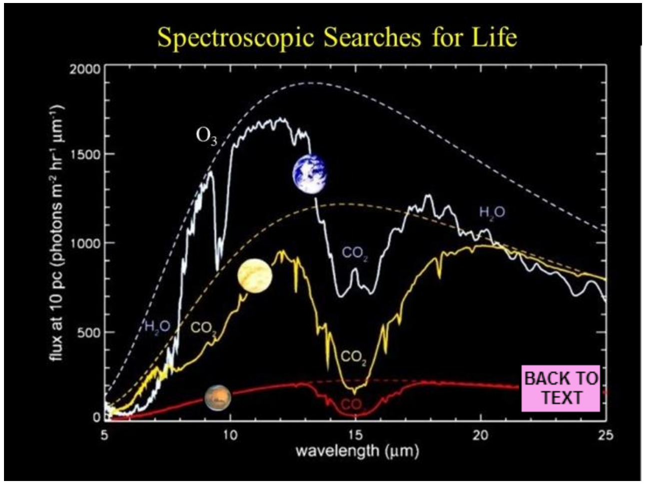


Fig. 26. IR spectra of three terrestrial planets with atmospheres; see text for details. Image modified from ESA *Darwin* proposal/F. Selsis/G. Tinetti/ESA.

However, the Earth has additional absorption features due to the presence of water vapour and ozone (O_3). Water vapour in the atmosphere implies that a reservoir of liquid water exists at the surface, while ozone (which is produced from normal molecular oxygen, O_2, by solar ultra-violet light) implies the presence of oxygen. On Earth, atmospheric oxygen has been produced by photosynthesis. The hope is that future large space telescopes will obtain similar spectra from planets of other stars. Fig. 27 shows sketches of the kinds of spectra that would be obtained from various different types of planet, in order of increasing evidence for biological activity.

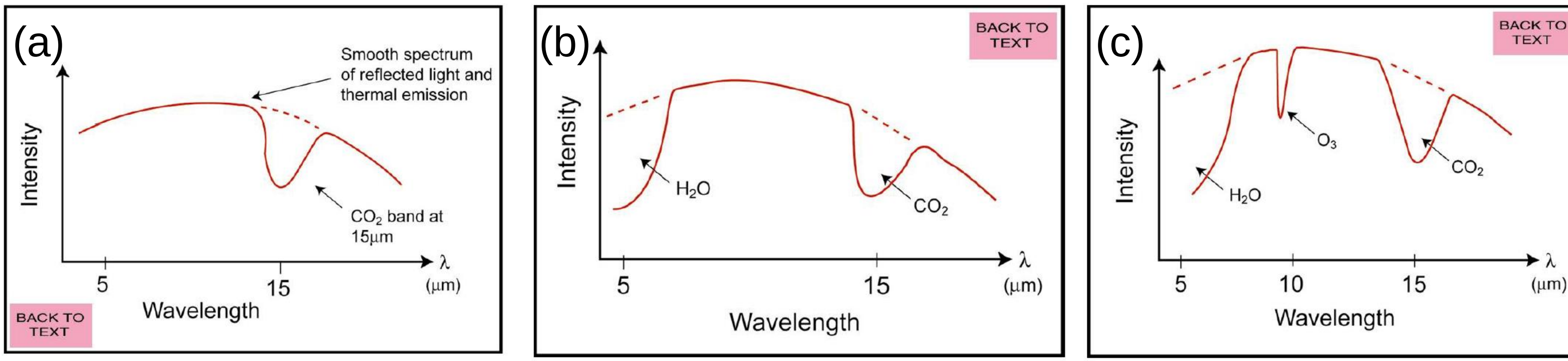


Fig. 27. Sketches of the kinds of spectra that a Darwin-type instrument might obtain for different types of extrasolar planet. **(a)** A planet like Mars or Venus, with a CO_2-rich atmosphere. There is nothing to suggest that life is present (although it could be: sub-surface chemolithotrophic organisms, for example, would not be detectable by this method). **(b)** A planet such as the Earth (and Mars) were billions of years ago. The presence of water vapour in the atmosphere implies the existence of liquid water at the surface. Such a planet would appear to be habitable, but this doesn't mean that life is necessarily present. **(c)** A planet like the Earth is today. The presence of ozone (O_3) implies the presence of atmospheric molecular oxygen (O_2), which on the Earth at any rate is produced and maintained by biological photosynthesis. Such a spectrum would be a very strong indication, although not quite a proof, that the planet has an indigenous biosphere.

5. Interstellar panspermia?

At first sight, the vast distances between the stars appear to rule out any possibility of life travelling between them. For example, at a speed of 10 km/s, appropriate for objects naturally ejected from planetary systems, it would take ~10^5 years to travel a typical interstellar distance of ~1 parsec. The survivability of (dormant) microbes for such durations is unknown, but these timescales are actually less than those discussed in Lecture 9 for the time taken by meteorites to travel between planets in our own Solar System.

There are at least four possibilities for interstellar panspermia that might be considered:

(a) Most stars form in clusters (Fig. 28), so if life formed early on a planet of one member of such a cluster, and was somehow ejected from it, the distance for it to travel to companion stars would be less than typical interstellar distances. Indeed, stars may approach each other to within a few hundred AU every few tens of Myr, facilitating the transfer of material between them.

(b) When solar-type stars become red giants and planetary nebulae (Fig. 29), dust grains from once inhabited planets might be ejected into the interstellar medium, ultimately to be collected by other planetary systems.

Fig. 28. The Pleiades open cluster (~130 pc away and ~100 Myr old) contains hundreds of stars within a radius of a few parsecs. The average separations of stars in such clusters varies, but might typically be <0.2 pc, much less than the ~2 pc in the Galactic disk (NASA).

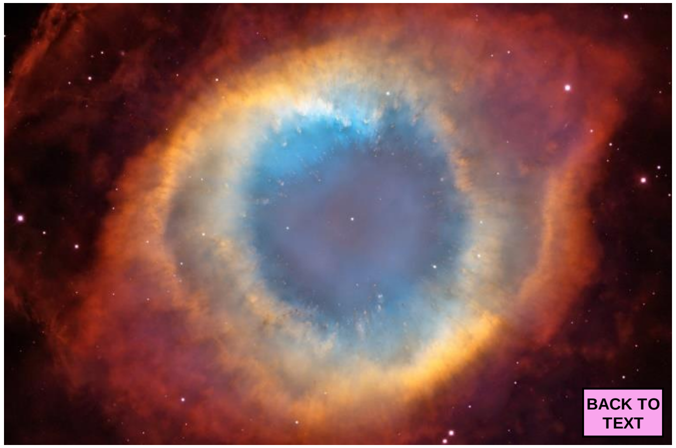


Fig. 29. Red giant stars and planetary nebulae (like the Helix nebula pictured) may distribute material from once inhabited planetary systems into interstellar space (NASA).

(c) The discovery of the interstellar asteroid ‘Oumuamua (Fig. 30) has raised awareness that such bodies ejected from one planetary system often pass through other planetary systems. For example, ~10^4 such objects are thought to be passing through the Solar System at any given time, and over the history of the Solar System tens of millions may have been captured into bound orbits around the Sun through gravitational interactions with the planets. Moreover, one such object might be expected to collide with the Earth every 10-100 Myr (see Ginsburg et al., ‘Galactic Panspermia’, *Astrophysical Journal Letters, Vol. 868, L12, 2018*). Note that capture of interstellar objects has a higher probability for multiple star systems, like alpha Centauri, than for single stars like the Sun, owing to the possibility of multiple gravitational interactions.

(d) As first pointed out by Francis Crick in his 1981 book *Life Itself*, technological civilisations such as our own would be able to build quite simple spacecraft to protect micro-organisms and direct them towards nearby planetary systems (Fig. 31). This concept has become known as *directed panspermia*. Whether or not it has ever been attempted will depend on how common technological civilisations have been in Galactic history (see Lecture 11).

All these ideas are very speculative, but they indicate that the possibility of interstellar panspermia should not be completely ruled out.

Fig. 30. Artist’s concept of the ‘Oumuamua interstellar asteroid discovered passing through the Solar System in 2017 (NASA/ESO).

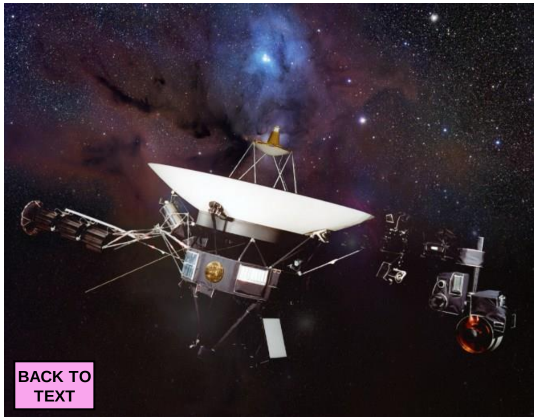


Fig. 31. The Voyager space probes are currently leaving the Solar System with speeds of ~16 km/s, which would take ~80,000 years to travel to the nearest star (if pointed in the right direction). They are not designed to carry micro-organisms, but even with our current technology it would be possible to design similar vehicles that *could* do so if we wished to engage in directed panspermia (NASA).