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REVIEWS

Light and shadow from distant worlds

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Exoplanets are distant worlds that orbit stars other than our Sun. More than 370 such planets are known, and a growing fraction of them are discovered because they transit their star as seen from Earth. The special transit geometry enables us to measure masses and radii for dozens of planets, and we have identified gases in the atmospheres of several giant ones. Within the next decade, we expect to find and study a 'habitable' rocky planet transiting a cool red dwarf star close to our Sun. Eventually, we will be able to image the light from an Earth-like world orbiting a nearby solar-type star.

The first exoplanet found to orbit a solar-type star (51 Peg) was a startling discovery[1]. This gas-giant planet of half a Jupiter mass orbits its star at a distance six times closer than the radius of Mercury's orbit in our own Solar System. The exoplanet, 51 Peg b, was discovered by measuring the line-of-sight (radial) velocity of the star as it orbited the centre-of-mass of the system. The magnitude of this velocity reflex yields—via conservation of momentum—the planet mass times the sine of the orbital inclination. Given an astronomical estimate of the stellar mass, the semi-major axis of the planet's orbit follows from Kepler's law. At an orbital distance of 0.05 astronomical units (1 AU is the Earth–Sun distance), 51 Peg b should be heated by stellar irradiation to a temperature in excess of 1,000 K. The astonishing close orbits and incredibly high planetary temperatures for the so-called hot Jupiters shattered the Solar System paradigm of planet formation and was the first surprising discovery of many in exoplanetary science.

The most exciting goal in exoplanetary science is to find and characterize a rocky habitable planet like our Earth. Although we have not yet found a planet that matches Earth in terms of habitability, we have measured light from exoplanets—especially the hot Jupiters—and we are beginning to characterize the properties of their atmospheres. This review concentrates on the bulk properties (masses, radii) and atmospheric compositions of exoplanets, with an eye towards the eventual characterization of a rocky, habitable world.

The best summary of exoplanets is their distribution of mass versus the semi-major axis of their orbit (Fig. 1). Most significantly, exoplanets span all ranges of mass and semi-major axis available to current detection techniques. This is a consequence of both the stochastic nature of planet formation, and of planet migration through the protoplanetary disk. Regions of Fig. 1 are blank because of selection effects and technological limitations. Fewer planets detected by radial velocity are found at large orbital distances (>5 AU) in Fig. 1 because most of these planets have not yet completed a sufficient portion of their >12-year orbits for the detection to be finalized. Also, the sensitivity of the radial velocity surveys is currently limited by stellar activity to about 1 m s^{-1} in velocity amplitude. This precludes the detection of Earth-twins at 1 AU, but allows the detection of rocky planets as small as several Earth masses orbiting close to their host stars. These so-called super-Earths are loosely defined to be rocky or icy planets between 1 and 10 Earth masses, and can have radii twice that of our Earth, or more. Current research aims to detect and characterize a habitable super-Earth orbiting a nearby low-mass star within the next decade. Over a longer term, the detection and characterization of exoplanets that are very similar to our Earth may be possible, using advanced imaging techniques.

Direct detection and characterization of exoplanets

In spite of the astounding success of the radial velocity technique[2], this method only measures the wobble of the star and does not detect planets directly. In other words, the radial velocity technique does not measure light from the planets. To characterize the nature of the planet's atmosphere, we must invoke techniques that isolate the light emitted from, or reflected by, the planet. An extension of traditional astronomical techniques to observe a planet spatially resolved from the star is high-contrast imaging, as being developed for a Terrestrial Planet Finder mission[3,4]. Recent advances in ground-based imaging[5,6] have led to the discovery of giant planets orbiting dozens to hundreds of astronomical units from young massive stars—shown in the upper

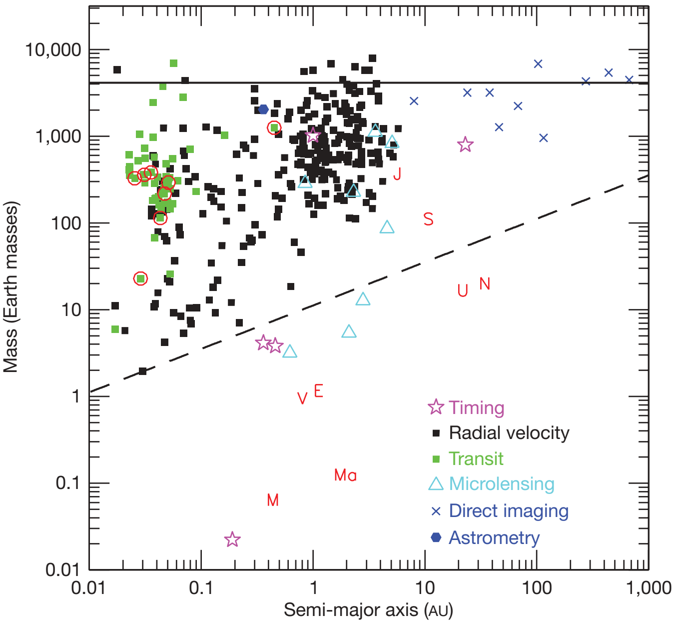

Figure 1 | Distribution of known exoplanets in mass and orbital semi-major axis. Planets detected by different techniques are shown using different symbols. The symbols circled in red are those planets with an analysis of their atmosphere, published as of September 2009. The solid horizontal line is the nominal upper mass limit above which an object is not considered to be a planet. The dashed line represents a radial velocity reflex of 1 m s^{-1} for a solar-type star, and planets orbiting solar-mass stars producing smaller velocity signals are generally not detectable using the radial velocity technique. Red letters indicate Solar System planets: M, Mercury; V, Venus; E, Earth; Ma, Mars; J, Jupiter; S, Saturn; U, Uranus; N, Neptune.

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right of Fig. 1. The masses of planets at such large distances cannot be measured using radial velocities, so they are estimated by comparison of the planet brightness to cooling curves for young planets[7], or by their gravitational effect on disk structure[8].

A major challenge in imaging exoplanets is that the ratio of their brightness to that of their star is very low (from 10^{-3} to 10^{-10}, depending on planet and stellar types, and wavelength). Extension of large-separation, giant planet imaging to Earth-like planets must bridge several orders of magnitude in planet–star brightness and a factor of 10 or more in planet–star orbital separation (Fig. 1), and will require space-borne measurements. Although dramatic progress has been made in the laboratory[3], a Terrestrial Planet Finder mission is a decade or more in the future. Meanwhile, significant progress is being made in direct detection and characterization of exoplanets using the transit technique.

Shadows of distant worlds

The nearness of the hot Jupiters to their stars means that they have a significant probability (typically about 0.1) of transiting their star as seen from Earth. During the transit, our Earth falls within the shadow of the exoplanet, and the light we receive from the parent star is diminished by a small amount. The occurrence of a transit—when the planet passes in front of its star as seen from Earth—is a great advantage to physical characterization of the planet[9], as illustrated in Fig. 2. High precision photometry during transit can be used to measure the blocking of stellar light versus time, and this so-called transit light curve is sufficient to determine the radii of both the planet and star, if the stellar mass can be estimated (for example, by using stellar models and the star's colours). Moreover, the planetary and stellar radii are proportional to the cube-root of the stellar mass, and are thus minimally sensitive to errors in the adopted stellar mass value. Nearly every transiting planet host star has also been measured by radial velocity, so both the planet's radius and mass are known.

The first transiting exoplanet[10,11] revealed a mystery that has so far defied explanation. The observed mass–radius diagram for transiting giant planets (Fig. 3) shows that several hot Jupiters have radii significantly greater than predicted[12]. Although a reduced size of the heavy element core in a giant planet allows a larger radius, this is not enough to explain the inflated radii of some giant planets, as shown in Fig. 3. Some process must be at work that generates energy in the interiors of these planets, inflating their radii, and possibly perturbing other aspects of their interior structure, in ways that we do not understand. One possibility that is currently the subject of debate is remnant heat from cosmically recent tidal circularization of their orbits[13]. Timing the eclipse of the planet (see below) shows that the orbits are often very close to circular[14,15], suggesting that the tidal evolution of the orbital shape is complete, but that may not preclude remnant internal energy from tidal dissipation. Another possibility (among many) is that convective transport of energy from the planetary interior may be less efficient[16] than calculated in simple homogenous models, owing to inhomogeneities in mean molecular weight.

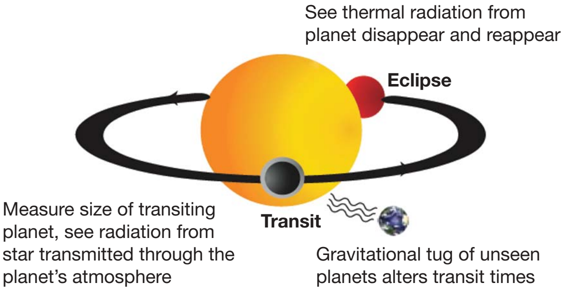

Figure 2 | Geometry and science yield from transiting planets. During transit, the fraction of stellar light blocked by the planet (shown black), together with the detailed shape of the transit curve, yields the radius of both the star and the planet. Stellar light transmitted through the annulus of the atmosphere (grey ring around black planet) reveals atomic and molecular absorption features from the planet's atmosphere. During eclipse, the disappearance of the planet (shown red) allows the stellar light to be measured in isolation, and subtracted from the total light of the system to yield the light from the planet, and its spectrum. Note also that the presence of unseen planets can in principle be inferred from variations in transit times (and also eclipse times). Representative Earth at bottom right indicates possible unseen planets that could perturb transit times.

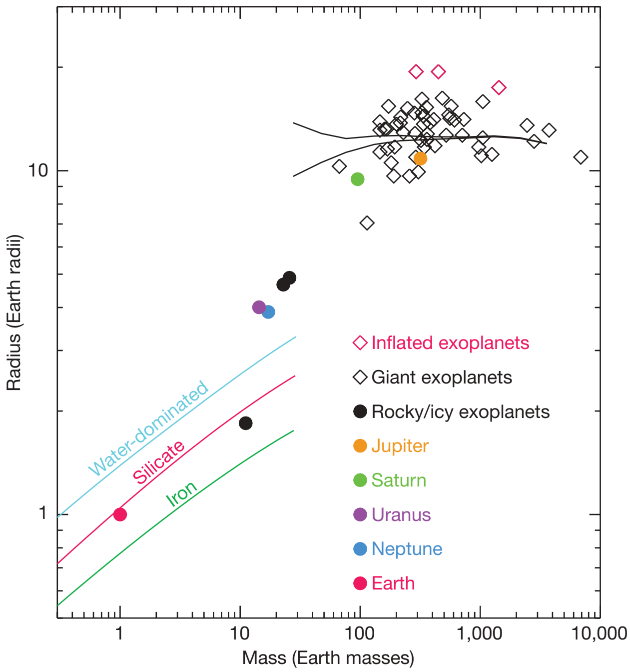

Figure 3 | Mass–radius diagram for transiting planets. Black diamonds are giant exoplanets. Three inflated giant exoplanets are indicated as red diamonds; from left to right they are: TrES-4, WASP-12 and OGLE-TR-L9. The lower black line is a theoretical mass–radius relation[74] for 1-Gyr-old giant planets orbiting at 0.045 AU from a solar-type star, and having a 10-Earth-mass core of heavy elements, plus a hydrogen–helium envelope. The upper black line is the same, but with zero core mass. The rocky/icy exoplanets (black filled circles) are the two exo-Neptunes (GJ 436b and HAT-12), and the super-Earth CoRoT-7b[22]. The coloured lines are theoretical mass–radius relations[66] for super-Earths lacking a hydrogen–helium envelope, but having a solid composition that is either water-dominated, silicates, or iron. Note the positions of Solar System planets, including Earth.

Detection of transits of HD 209458b galvanized the astronomical community to find more transiting planets, and currently more than 45 planets are known to transit stars brighter than thirteenth visual magnitude. Most of these transits were discovered by photometric surveys, and the discovery rate has exploded in the past few years[17–19] as the transit technique matured and groups learned to cull their candidates and eliminate false-positives. Transit surveys have now discovered two planets comparable to Neptune in size[20,21], and one super-Earth only 70% larger in radius than our own Earth[22]. The recent launch of NASA's Kepler mission[23] will greatly increase the number of rocky and/or icy transiting planets known. Most exciting is that Kepler is designed to tell us the frequency of true Earth analogues—by detecting Earth-sized planets orbiting in the habitable zones of Sun-like stars.

Light from distant worlds

Planets that transit their star will also pass behind the star (for planets on circular orbits). This eclipse of the planet by the star will occur approximately half an orbital period after transit (Fig. 2). Radiation from the planet can be measured from the modulation of the combined planet and starlight, because the planet's light is blocked out during eclipse and then later reappears. Such eclipse measurements can be made with existing or planned facilities, because observatories optimized for general astronomy turn out to be suitable for transiting planet observations (for example, the Hubble Space Telescope and Spitzer Space Telescope). Hot Jupiters are expected to have temperatures between 1,000 and 2,000 K, so their atmospheres emit infrared radiation and the emitted flux peaks in the relatively near infrared wavelength region (1–5 μm). Successful detection of infrared light from exoplanets was first accomplished via eclipses observed using the Spitzer Space Telescope[14,24]. Spitzer has observed eclipses for more than two dozen exoplanets, and one of the best-observed[25–27] examples (HD 189733b) is shown in Fig. 4. Many additional in-depth analyses are becoming available at a rapid pace[15,28–31]. The Spitzer results, in combination with other key observations, have clarified several aspects of hot Jupiter atmospheres (but have also raised new questions) in three key areas as follows:

Hot Jupiters are both hot and dark. Hot Jupiters are blasted with radiation from the host star. The hot Jupiters should therefore be kinetically hot, heated externally by the stellar irradiance. Indeed, early hot Jupiter model atmospheres already predicted temperatures exceeding 1,000 K (refs 32, 33). The first and most basic conclusion from the Spitzer detections was the confirmation of this prediction[34]. The fact that the planets emit generously in the infrared implies that they efficiently absorb visible light from their stars. Searches for the reflected component of their energy budget have indicated that the planets must be very dark in visible light, with geometric albedos less than about 0.2 (refs 35, 36) and probably much lower. Purely gaseous atmospheres lacking reflective clouds can be very dark[33,37,38] but HD209458b also requires a high-altitude absorbing layer (see below) to account for its atmospheric temperature structure.

Water vapour in emergent spectra of hot Jupiters. A planetary atmosphere with elemental composition close to solar and heated upwards of 1,000 K is expected to be dominated by the molecules H_2, H_2O, and, depending on the temperature and metallicity, CO and/or methane (CH_4). Of these molecules, H_2O is by far the most spectroscopically active gas. Water vapour is therefore expected to be the most significant spectral feature in a hot Jupiter atmosphere. Some initial indications from Spitzer spectroscopy that water absorption was absent[39,40] were superseded by additional work that clearly showed water absorption[41–43]. Although models correctly predicted that the spectra of hot Jupiters are shaped by water absorption, the variation in temperature structure from one planet to another is not fully understood.

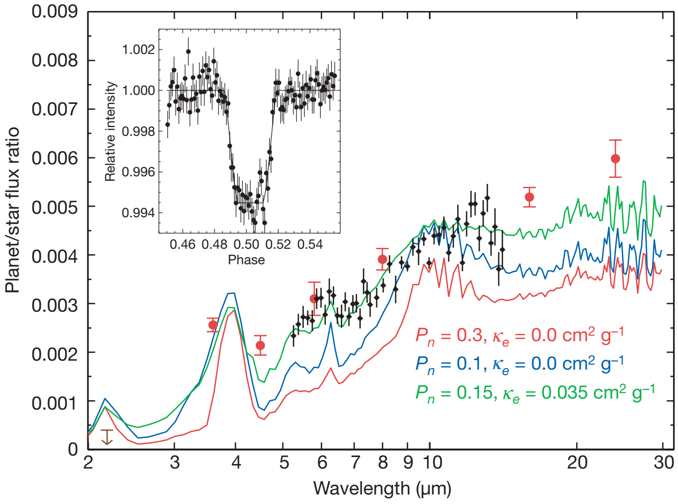

Figure 4 | Spitzer observations of the giant exoplanet HD 189733b. Observations of the planet are plotted as planet flux divided by stellar flux (stellar flux is reliably known). The red points with error bars (s.e.m.) are the results from eclipse depths measured[26] using photometry; the black points with error bars (s.e.m.) are from spectroscopy during eclipse[41]. The models (for example, ref. 75) have different amounts of assumed heat redistribution by winds (P_n parameter) and different opacities (κ_e) for a high-altitude absorbing layer. An example[25] of Spitzer eclipse photometry at 16-μm wavelength is shown in the inset. (Eclipses like that shown in the inset, but at multiple wavelengths, are used via photometry and spectroscopy to define the points that are compared to the models.) Main figure reproduced from ref. 41 with permission.

Other atoms and molecules identified in hot Jupiter atmospheres are atomic hydrogen[44], atomic sodium[45], methane[42] and carbon dioxide[43]. Atomic hydrogen is slowly escaping from HD 209458b, possibly forming a comet-like coma around the planet[44].

Day–night temperatures and thermal inversions. Hot Jupiters are fascinating fluid dynamics laboratories because they probably have a permanent dayside and a permanent nightside. Close-in giant planets are theorized to have their rotation synchronized with their orbital motion by tidal forces. Under this tidal-locking condition, the planet will keep one hemisphere perpetually pointed towards the star, with the opposite hemisphere perpetually in darkness. In the absence of atmospheric circulation, the star-facing hemisphere would be strongly heated, and the opposite hemisphere would be cold. There is evidence that such planets exist[46,47]. In contrast, other hot Jupiter exoplanets show relatively little temperature variation from the dayside to the nightside[27,47,48], and one particularly relevant Spitzer measurement is illustrated in Fig. 5. It seems likely that at least some hot Jupiters transport energy horizontally via zonal winds having speeds comparable to the speed of sound[49].

Figure 5 shows the Spitzer observations[27] of HD 189733b, where the strong winds have advected the hottest region to the east of the sub-stellar point. Giant planets in our Solar System also have strong zonal winds, appearing in multiple bands at different latitudes.

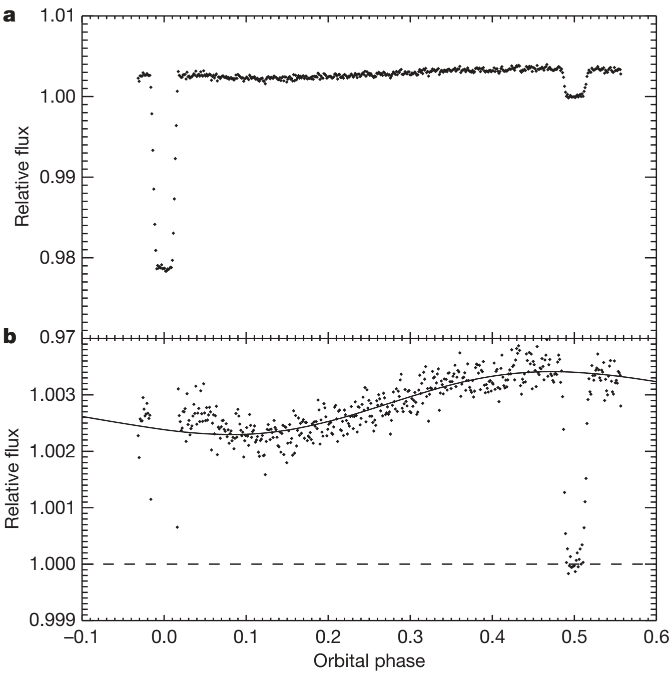

Figure 5 | Spitzer 'around the orbit' observations of the transiting exoplanet HD 189733b. **a**, The transit (at left) and the eclipse (at right) of the planet. **b**, Expanded intensity scale for the same observations as **a**, showing the variation of flux with orbital phase. Following transit of a planet having a tidally locked rotation, the planet's dayside will increasingly contribute to the combined light, resulting in greater flux. Note that the flux increase (dayside versus nightside) is only a fraction of the eclipse depth (dayside versus planet in eclipse), hence the flux difference between dayside and nightside is only a fraction of the planet's total infrared emission at this wavelength (8 μm). Note also that the peak flux from the planet occurs before eclipse, and that implies that the hottest region of the planet has been advected eastward by the strong zonal circulation. Figure reproduced from ref. 27 with permission.

Consideration of the relatively slow rotation rate of hot Jupiters (probably equal to their orbital period of a few days) leads us to believe that their zonal winds will occur predominately in one or two major jets that are quite extended in latitude and longitude[50]. The relatively large spatial scale of hot Jupiter winds—and the corresponding temperature field—should be a boon to their observational characterization. Planets with temperature fluctuations only on small scales will have little to no variation in the amount of their hemisphere-averaged flux as a function of orbital phase.

Many Solar System planets have thermal inversions high in their atmospheres (that is, the temperature is increasing with height above the surface). These so-called stratospheres are due to absorption of ultraviolet solar radiation by CH_4-induced hazes or O_3. Thermal inversions in hot Jupiter atmospheres were not widely predicted, because of the expected absence of CH_4, hydrocarbon hazes, and O_3. But Spitzer data show that the upper atmospheres of several planets do have thermal inversions[15,29–31], probably fuelled by absorption of stellar irradiance in a high-altitude absorbing layer. Possibilities for a high-altitude absorber include gaseous titanium dioxide and vanadium dioxide[51,52], as well as possibilities involving photochemical hazes[53]. Under a simple irradiation-driven scenario, the stronger the stellar irradiance, the more likely that an inversion would occur[51,52]. In addition, under such a scenario, planets with strong thermal inversions are also expected to show strong day–night temperature gradients. Hot Jupiters are probably more complex than this simple division allows; HD 189733b and XO-1b have virtually identical levels of irradiation and yet XO-1b has an inversion[30] while HD 189733b does not[26]. So it is possible that not-yet-understood chemistry may be a more dominant factor than stellar irradiance.

The growing diversity of exoplanets

The diversity of planet types available for study is expanding rapidly—planets with astonishing orbital and physical characteristics are announced with increasing frequency. Several close-in giant exoplanets have quite eccentric orbits, the eccentricity reaching to $e = 0.93$ in the case of HD 80606b. The stellar irradiance level received by a planet in an eccentric orbit can vary strongly with time. For example, HD 80606b receives a blast of radiation near periastron equal to 10,000 times the flux that our Earth receives from the Sun, and the planet is rapidly heated in response[54]. The blast at periastron lasts about two Earth-days, a small time frame compared to the 111-day orbit. We can learn much about the physics of the planet's atmosphere—and even its interior—by studying the atmosphere's response to such strongly varying stellar irradiance.

Much of the current excitement lies in the discovery and characterization of exoplanets different from the hot Jupiters that have been the main focus for the past decade. Core-dominated planets have interiors composed largely of iron, rock, or icy materials, which are fundamentally different to the predominant hydrogen/helium composition of hot Jupiters and other giant exoplanets. We anticipate a large sample of transiting core-dominated planets with measured masses and radii that will shed light on the nature and formation of rocky planets like our Earth. Masses and radii give average densities; together these can constrain the composition of planet interiors.

We are also beginning to study planets on more distant orbits, with correspondingly cooler atmospheres, and that are orbiting different kinds of stars (for example, stars of much lower and much greater mass than the Sun). One of the most fascinating recent exoplanet discoveries is the finding that some hot Jupiters appear to have retrograde orbits—the planets are revolving around the star in a different direction from that in which the star is rotating[55]. This is especially interesting, because planets form out of the protoplanetary gas and dust disk that is believed to rotate in the same direction as the star. These 'backward-orbiting planets' may have experienced a violent close encounter with another planet in the same system. Alternatively, the backward planet's orbit could have been gradually 'flipped' during planet migration by a more distant planet in the system[56,57].

New observing windows and techniques

Spitzer infrared observations have been the dominant source of characterization data for exoplanets to date, but new observational windows and techniques are being developed. Visible light thermal emission is predicted to be of significance for the hottest planets[58]. Eclipses of CoRoT planets[59] have been detected using visible light, and the Kepler team recently reported a spectacular measurement[60] of the eclipse of HAT-P-7b. Additional detections are expected from Kepler, and possibly from EPOXI[61]. Visible wavelength observations combined with infrared data help us to understand the relative contribution of thermal emission and reflected light, and will enable constraints on the planetary albedo. New ground-based photometric detections[62,63] of hot Jupiter eclipses are opening up a new wavelength range (2–5 μm). Combined with Warm Spitzer (that is, the non-cryogenic phase of the mission) observations and models, the new ground-based observations could enable constraints on the abundances of spectroscopically active gases and the presence and reflectivity of clouds or hazes that may exist in the atmospheres of these hot giant planets, thereby shedding light on hot Jupiter atmospheric chemistry.

In addition to photometry of exoplanets, the advent of new space-borne instrumentation like the Cosmic Origins Spectrograph[64] on the Hubble Space Telescope opens the possibility of spectroscopic detection of molecular features in the ultraviolet to visible spectral range. Even ground-based spectroscopy of exoplanets may become possible, as astronomers improve the observing and signal-processing techniques needed to isolate the faint exoplanet light[65].

The era of super-Earths begins now

The most exciting of all questions is whether exoplanets host life, so the long-term focus of our interest is on rocky planets in the habitable zones of their stars, where the planet's average temperature permits liquid water. Our own Earth is currently the only site where we know that life exists, and that makes analogues of our Earth the best candidates for hosting life. Unfortunately, an Earth analogue—a twin of our Earth, orbiting in the habitable zone of a solar-type star—will be a difficult world to find and characterize. An Earth analogue lies below the limiting sensitivity of the radial velocity surveys (Fig. 1). The Kepler mission will determine the frequency of occurrence of Earth analogues, and will find many transiting examples (unless they are intrinsically rare). But Kepler surveys stars to relatively faint magnitudes over a limited angular region of the sky, and Earth analogues have a low probability of transiting (about 0.005). Hence the nearest example to be found by Kepler will be distant from us. Eclipse observations (as in Fig. 4) will probably involve too few photons to be useful when applied to an Earth analogue found by Kepler. Eventually, sensitive space-borne astrometric measurements may be able to find Earth analogues orbiting the nearest solar-type stars, and space-borne high-contrast imaging may be able to characterize them. But it will take many years for these missions to be developed and launched, so in the interim we look to other types of habitable planets.

In the search for cosmic life, we naturally turn to super-Earths because their greater mass and larger radii make them easier to find and characterize than Earth analogues. Super-Earths are theorized to vary in composition from solid iron planets, through silicate-dominated planets like our Earth, to water-worlds having bulk compositions that are primarily ice- or water-dominated[66]. The radial velocity surveys have announced about a dozen planets in the mass range of super-Earths, and the K-dwarf star HD 40307 is known to host three of them[67]. One estimate based on the microlensing results[68] is that about one-third of lower main sequence stars host a Neptune-mass or super-Earth-mass planet—this is consistent with a similar estimate based on radial velocity observations[67]. Although the microlensing and radial velocity surveys have given us the tantalizing result that super-Earths are common, especially orbiting lower main sequence stars, these techniques cannot be used to characterize the planets themselves.

Fortunately, transit surveys and transit follow-up observations can both find and characterize nearby super-Earths as they push the domain of their detections down in mass from gas-giants to rocky planets (Fig. 1). The stars nearest to our Sun are predominately low-mass M-dwarf stars. The habitable zone of an M-dwarf is typically ten times closer to the star than is the habitable zone around our Sun, because of the much lower luminosity of M-dwarfs compared to the Sun. Owing to the smaller planet–star separation, planets in the habitable zone of M-dwarfs have a greater probability of transiting than do planets in the habitable zone of solar-type stars. The current frontier in exoplanet science is the push to find and characterize a habitable super-Earth orbiting a nearby M-dwarf star. One reason for this focus is that we can find and characterize such worlds using facilities that are already operable, or in development for flight. Beyond characterizing individual objects, astronomers harbour huge hopes that a large sample of transiting super-Earths with measured masses, radii, semi-major axes, and possibly atmospheric measurements will provide insights on planet formation, migration, interior composition, and evolution.

The next decade

Astronomers have a clear vision of how to discover and characterize super-Earths in the next decade, so as to study the special ones that transit in habitable zones of M-dwarf stars. The ground-based MEarth project[69] is conducting a survey of the nearest 2,000 M-dwarfs to find transiting super-Earths. However, there are more than 10,000 M-dwarfs in the solar neighbourhood (within 35 pc), and a survey of that many stars to the requisite photometric precision will have to be space-based. One such survey that is feasible within the next few years is the proposed Transiting Exoplanet Survey Satellite (TESS) mission. TESS is designed to find a nearby transiting habitable super-Earth, and the best cases found by TESS could be characterized[70] using the James Webb Space Telescope (JWST).

JWST, to be launched in 2014, will be able to characterize the handful of habitable-zone transiting super-Earths we expect to find. It will be able to measure the temperature of such a planet using infrared photometry when the planet is eclipsed[70]. This telescope will also be able to identify the major gases in the planets's atmosphere by observing their absorption during transit, but it will probably not be able to find biosignatures as those are too subtle. The magnitude of the absorption seen during transit (Fig. 2) depends not only on the abundance of the specific molecule being sought, but also on the molecular weight of the atmosphere[71]. Low-molecular-weight atmospheres, for example those that contain significant remnant hydrogen, will have greater pressure scale heights than do high-molecular-weight atmospheres. Greater scale heights increase the area of the absorbing annulus during transit, and provide greater absorption in the transit spectrum[71]. Currently, we do not know the nature of super-Earth atmospheres—that is, whether they are invariably thin (like Earth), and of high molecular weight, or whether they are sometimes much thicker (like Venus) and contain significant hydrogen, either as a remnant from the primordial atmosphere or from outgassing. Hence the fundamental source of uncertainty in this field is the cosmic uncertainty in the nature of the atmospheres on rocky super-Earth worlds.

Super-Earths orbiting in the habitable zones of their host M-stars hold our near-term interest because they are the most accessible planets that have potential to support life. But these planets could be quite different from our own Earth. For example, at small planet–star separations they will be tidally locked, with their sun fixed in their sky at all times, that is, no day–night cycle. Close to their star, the planets may be blasted by ultraviolet radiation from flares that are common on M-dwarf stars, and this would significantly affect[72] the conditions for life on these worlds.

Decades beyond 2020

The astronomical community is developing technology for new space missions to find and characterize true Earth analogues in future decades. One concept[73] calls for a flagship successor to the Hubble Space Telescope: this telescope would operate at ultraviolet–visible wavelengths, and be equipped with an external occulter. It would act part-time as a planet finder, and (while the occulter was moving to another target) part-time as a general observatory. An exciting alternative is to launch an external occulter[4] to be used in conjunction with the JWST, enabling a Terrestrial Planet Finder to happen within one decade. Whatever concept becomes reality, light from a truly Earth-like world is within the grasp of our instruments in the foreseeable future.

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