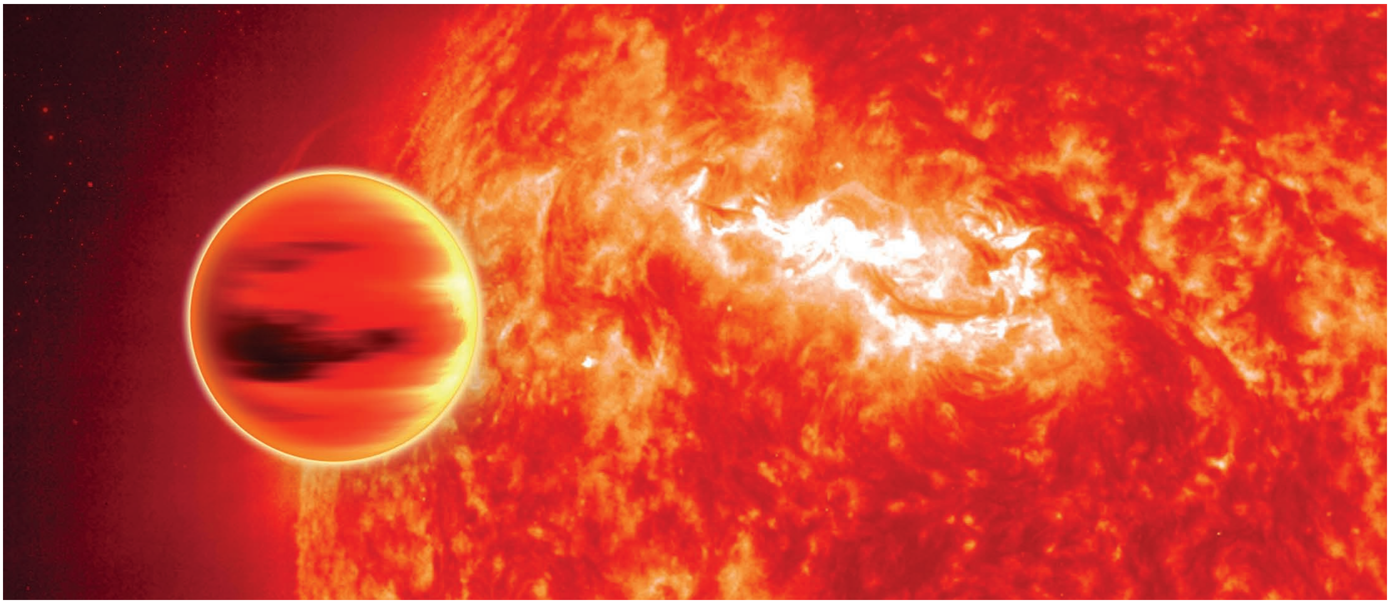
Q&A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ASTRONOMY

Extrasolar planets

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Hundreds of planets are known to orbit stars other than the Sun, and unprecedented observations of their atmospheres and structures are being made. It's an invaluable opening for understanding the planets' diverse natures, the formation of our Solar System, and the possibility of habitable planets beyond our home.

How many planets outside our Solar System have we found so far?

The number is going up week by week, but at the moment there are about 270 confirmed extrasolar planets — exoplanets, as they're known in the jargon. Not bad, considering the first one was discovered just 13 years ago, and they're not that easy to spot.

What makes exoplanets difficult to find?

They are, by definition, far away and orbiting close to a star that is far bigger and brighter than them. Light contrast ratios of 10^{10} (at visible wavelengths) to 10^7 (in the infrared) between a star and planet make direct detection by imaging extremely hard. Exploiting mass ratios, which are generally in the region of 10^3–10^5, is slightly less daunting. Indeed, the most popular way of spotting an exoplanet is through a star's 'wobble', which is caused by the gravitational pull of an orbiting planet. This is measured through the Doppler effect — a shift in wavelength — in the spectrum of visible light from the star. It's a tiny effect, proportional to the mass ratio. Measuring it requires patience, because the wobble must be followed for at least one complete orbit of the planet. A wobble can also be detected directly by carefully observing the position of the star with respect to other stars (a technique known as astrometry), but this is technically even more demanding.

What other ways are there of finding exoplanets, besides the Doppler effect?

Gravitational lensing is another common method, and also exploits the star–planet mass ratio. For this, a source of light is needed, usually another star, behind the star being investigated. As we look at it, the light from the background star will be bent by the gravity of the intervening star. If the intervening star has an attendant planet, this will alter the lensing effect in a noticeable way.

And what about the transiting method?

Transiting is perhaps the most fruitful method of observation, because of the information we can glean about the planet. It exploits the least daunting inequality between star and planet — the factor 10 to 100 difference in size. As it passes across the disk of its parent star, a planet will dim the star's light by a fraction $(R_p/R_s)^2$, where R_p and R_s are the respective radii of the planet and star. For a planet the size of Jupiter and a star the size of the Sun, this dimming effect would be roughly 1%, which is easily detectable even with amateur equipment. The catch is that a transit requires the planet's orbit to be almost exactly edge-on as we look at the star, which is extremely unlikely. Tens of thousands of stars must be monitored with patience to detect periodic dimming in just a handful.

What can these crude remote-sensing techniques tell us about exoplanets?

A surprising amount. The Doppler technique gives the size, period and eccentricity (deviation from a perfect circle) of the planet's orbit, as well as a quantity $M_p\sin(i)$ that contains both the planet's mass M_p and the inclination, i, of its orbit to our line of sight. The transit technique contributes the planet's radius and a direct value for i. Combining these two parameters can thus provide the actual value of M_p, and also — a big prize, this, because it tells us something about what the planet is made of — the planet's mean density, calculated from

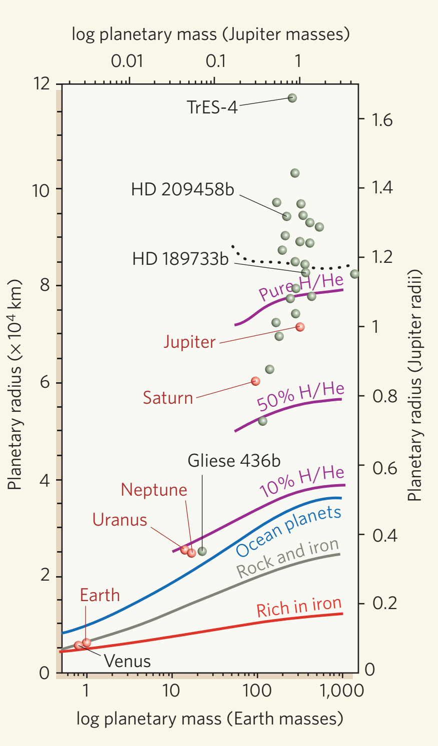

Figure 1 | The gamut of transiting exoplanets. The composition of a planet will determine its average density and where it will lie on a plot of radius against mass. Here, various planets within (red circles) and beyond (grey circles) the Solar System are compared with models of different interior composition: from an interior made of rock and iron alone (Venus and Earth approximate to this state) to a gaseous composition of just hydrogen and helium (of which Jupiter is the closest example in our Solar System). Owing to difficulties in spotting such small bodies, few exoplanets at the small, dense end of the scale have so far been found. Many giant planets have been detected that have very low densities above the upper range of pure hydrogen–helium planets (dotted line) — the exoplanet TrES-4 is the most extreme example — and these are a serious challenge to theory.

the radius and the mass. More than 20 transiting planets are already known, and the radius and mass of several have been determined to better than 4% and 8% accuracy, respectively. But there's a sting in the tail of this simple, surprisingly accurate method — most of the planets found so far are much less dense than our theories predict (Fig. 1).

Why are less-dense planets a problem for theoretical models?

Most exoplanets known so far are Jupiter-like 'gas giants', with masses between 0.5 and 3 times that of Jupiter (150–1,000 Earth masses). But they have an unexpectedly wide range of sizes, with radii between 0.8 and 1.7 times Jupiter's. Jupiter is thought to have a small core of heavy elements, surrounded by envelopes of hydrogen with some helium intermingled. Explaining an exoplanet with a similar mass to Jupiter but a smaller size (higher mean density) is easy — it probably has a larger core, with more heavy elements in general. But for exoplanets that are less dense, there comes a point when even a planet made just of hydrogen isn't enough to explain its low density.

How can we get around this difficulty?

A possible explanation is additional heating, either because of some persistent heat source or a seriously delayed cooling of the planet. One obvious source of heat is the parent star itself: the exoplanets in Figure 1 are mainly 'hot Jupiters' that orbit extremely close to their stars. But then it's unclear why some planets would absorb much of that heat and others would not. The same problem — accounting for the entire range of observed planetary sizes — also bedevils other proposed solutions.

What more can remote sensing tell us about a planet, besides basic features such as its size and density?

This is where transiting exoplanets come into their own. Their well-constrained basic parameters and natural 'on–off switch' allow their weak signal to be calibrated accurately. That means we can perform basic spectroscopy: atomic sodium and hydrogen have already been detected in exoplanets' upper atmospheres. Unprecedented spectroscopy and thermal mapping of the atmosphere of the transiting hot Jupiter HD 189733 b has been possible at the point where it is seen 'side-on', just as it disappears behind its star. Here, the infrared light flux from the planet can be discerned at a level just 10^{-4} that of the star's flux. NASA's infrared Spitzer space telescope has proved perfect for this task.

What have we learnt about the atmosphere of HD 189733 b?

First, we have a measure of the temperature difference between the day and night side, which is about 230 °C. In such an extremely close orbit — HD 189733 b circulates around its star at just 3% of the Earth–Sun distance — a planet's rotation and orbital revolution become synchronized, with one side permanently facing the star. (In the same way, the Moon always presents the same side to Earth.) During transit, we thus see the night side, and the heat flux we see coming from this side indicates that the planet's atmosphere must transport heat very efficiently from the day side. The hottest and coldest regions are not, as would be expected, seen at the longitudes facing exactly towards and away from the star, respectively, but are slightly offset from these longitudes, indicating a very dynamic, windy atmosphere.

Is there evidence for water on any exoplanet?

It would be surprising not to find some water in the atmospheres of hot Jupiters: water is very common in the low-temperature environments where planets form and evolve, owing to the large cosmic abundance of both hydrogen and oxygen. Absence of water might indicate thermal and radiative loss, as seems to have been the case with our small and hot planetary neighbour Venus. Hot Jupiters should be massive enough to stave off complete loss, but then again we know little about the extreme conditions in their upper atmospheres. By measuring the 'depth' (the loss or gain in intensity) of eclipse or transit in different infrared wavelength bands, Spitzer can crudely sample the molecular lines not only of water, but also of other gases of interest, such as carbon dioxide and methane. Water has already been seen on three hot Jupiters — TrES-1, HD 209458 b and HD 189733 b.

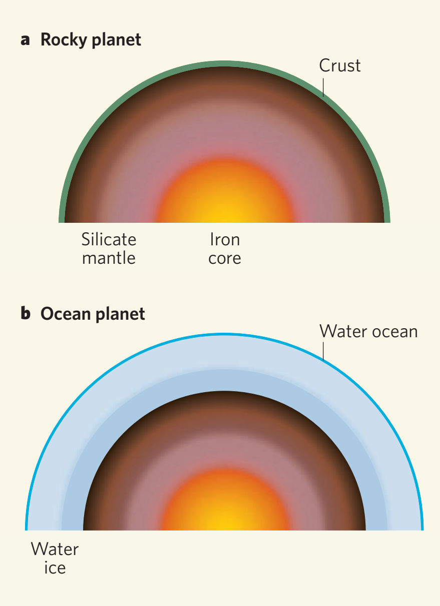

Figure 2 | Journey to the centre of a super-Earth. Super-Earth planets, with masses between two and ten times that of Earth, come in at least two varieties: **a**, rocky; **b**, ocean. Both types originate in a well-mixed structure of solids (silicates) and volatiles (such as water and ammonia), with trace amounts of hydrogen and noble gases. The structure differentiates very quickly and in a strictly predictable way: iron and siderophile elements (high-density transition metals that like to bond with iron) precipitate into a core, and excess water, ammonia and so on precipitate above a silicate mantle. If water is present in significant quantities, most of it will be under pressures in excess of 10 gigapascals, and thus in a solid state — ice — despite the high temperatures. An ocean planet will be larger than a rocky one owing to the lower density of water, and the size of a planet of a given mass will depend on the proportion of core, mantle and water. Models show that an uncertainty of less than 5% in radius and less than 10% in mass are needed to distinguish ocean from rocky planets.

We seem to know of many larger, Jupiter-sized planets — what about Earth-like planets?

First off, the rich diversity of giant exoplanets came as a surprise to astronomers — we expected to find a greater variety of 'terrestrial' planets. But to date we know of only a handful. None of them is transiting, so we don't know their mean densities or even their exact masses. And 'terrestrial' is perhaps a misnomer: the masses of such planets discovered so far are between 5 and 10 times Earth's mass (M_{E}). Such 'super-Earths' do not feature in our Solar System, but are seemingly common elsewhere. The limit of 10 M_{E} is theoretically inspired: when planets form in a typical protoplanetary disk of gas and dust, 10 M_{E} is roughly the critical mass above which hydrogen can be accreted and retained by the growing planet, turning it into a Neptune-like giant. Given the diversity of models for predicting the composition of the planet interiors at 10 M_{E}, we need a large sample of planets and their mean densities to check this.

Why do astronomers expect a great diversity among smaller planets?

Because smaller, solid planets can have more varied material compositions. Depending on how its material compresses, cools and mixes, and what it weighs, a planet's interior can come to be dominated by an iron or iron-alloy core, a silicate mantle, (mostly water) ice, or a hydrogen–helium envelope. A rare fifth type of interior material is a carbon-rich mantle. In general, we expect two distinct families: 'ocean planets', with water making up more than 10% of their mass; and rocky, Earth-like planets (water makes up only about 0.05% of Earth by mass) that may still have oceans (Fig. 2).

So should we expect other solar systems just as diverse as our own?

Yes indeed — there's no reason to think that our Solar System is special in any way; and equally, we are beginning to realize that there is a great diversity of planetary types not represented in our own backyard (Fig. 3). Since early 2007, for example, we have spotted at least three planets orbiting the star Gliese 581. Two of them are super-Earths, but they do not transit, so we know only their minimum possible mass through the term $M_{\mathrm{p}}\sin(i)$ — 5 and 8 M_{E} — and their orbital distances, which are 7% and 25% of the distance from Earth to the Sun, respectively. Because Gliese 581 is small, cool and faint (it is 75 times less luminous than our Sun), the tiny orbits of these planets mean that their surface temperatures might range from that of Venus (around 460 °C) down to that of Mars (a mean temperature of −55 °C). One of the planets, Gliese 581 d, might have a temperature similar to that of Earth's polar regions.

Could any of these planets be habitable?

Probably not: the inner, 5-M_{E} super-Earth is probably too hot, and the outer one is probably too cold, although still potentially habitable. But because they do not transit, we have no constraints on their bulk composition — except that the existence of a third, Neptune-mass planet implies the presence of gravitational forces that caused them to migrate from an initial location farther out in the protoplanetary disk. The two super-Earths are thus probably ocean planets, as they must have formed outside the disk's snow line, where water freezes and accretes easily; some of this surface water would have liquefied when the planets were pushed closer in.

	Mass (Earth masses)	Distance from star (AU)	Density (Earth densities)	Mean surface temperature (K)	Notable features
Venus	0.8	0.7	0.95	735	Sweltering CO_2 atmosphere
Earth	1	1	1	287	Life
Gliese 581 c	> 5	0.07	> 0.7	> 400	Hot super-Earth
Gliese 581 d	> 8	0.25	> 0.8	< 280	Cool super-Earth — habitable?
Neptune	17	30	0.30	72	Vivid blue colour — cold
Gliese 436 b	23	0.03	0.32	712	Neptune-like, but orbiting close around a red dwarf
HD 209458 b	219	0.05	0.07	1,600	Hydrogen, sodium and possibly water vapour
TrES-4	267	0.05	0.04	2,100	Largest known planet in size — but would float on water
Jupiter	318	5.2	0.24	165	The 'Great Red Spot' — a violent, centuries-old storm
HD 189733 b	366	0.03	0.18	1,200	Efficient heat transfer in a turbulent atmosphere
XO-3 b	~4,400	0.05	0.4–2.0	Unknown	Most massive planet known — a planet, or a failed star?

Figure 3 | A world of worlds. Our own Solar System is home to an amazing variety of planets (examples in red), from the small, rocky sisters Earth and Venus to the gas giants Neptune and, largest of all, Jupiter. But that is nothing compared with the diversity that is emerging among exoplanets, as this selection of particularly notable examples shows. Limitations on current observational capabilities favour the discovery of exoplanets that are particularly large (and are therefore gas giants), and those orbiting very close to their stars. 1 astronomical unit, AU, is the Earth–Sun distance; data for exoplanets can by their nature be highly uncertain.

What will be the next stage of exoplanet discovery?

It will be to match recent observational breakthroughs with breakthroughs in our understanding. For that, we need a large enough sample to encompass the full diversity of planets out there — meaning many more hundreds, if not thousands. That will be achieved quickly in the coming years with results from dedicated space missions such as the French-led COROT (for 'COnvection, ROtation and planetary Transits'), which was launched in December 2006, and NASA's Kepler, scheduled to launch in early 2009. In the meantime, with advances in remote-sensing techniques, exoplanet science is already shifting from mere discovery to exploration. As planet hunters hone their tools to discover smaller and smaller planets, more surprises should be in store.

When will we find another Earth?

The goal of characterizing Earth-like planets — even true analogues of Earth — is very exciting, and is feasible before 2020. By that time, spectroscopy at very low resolutions could allow us to see signatures of familiar global planetary cycles (the carbonate–silicate cycle, which stabilizes Earth's climate over long timescales, for example), and perhaps let us take the first steps in the search for markers of biological entities. The essential precondition is that we know something of the make-up of the planet in question — that is, its mass and radius. Kepler is designed to find Earth-sized planets by 2014 using transits. Following this up with spectroscopy will sort out the planets' true nature.

And would another Earth necessarily be habitable?

The first terrestrial planets that we will be able to study in detail will be super-Earths that transit small stars. We are likely to learn a lot of geophysics from them, and, who knows, they might turn out to have excellent habitable potential as well. But ultimately, we'll have to anchor our theoretical models to the only true reference — Earth. Exploring planets down to Earth's size remains a priority of enormous resonance, both scientific and emotional. ■

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