commentary

Strange news from other stars

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The dawn of exoplanet discovery has unearthed a rich tapestry of planets different from anything encountered in the Solar System. Geoscientists can and should be in the vanguard of investigating what is out there in the Universe.

The frontispiece chosen for Gerard Kuiper's 1949 book *The Atmospheres of the Earth and Planets*[1] was an aerial photograph of the Earth from a sounding rocket, labelled "The Earth as a Planet." The book recognized the commonality in physics governing the Earth and other planets of the Solar System. With its publication, the subject of comparative planetology was born.

Before the 1950s, astrophysics, planetary science and the Earth sciences — including study of Earth's atmosphere and ocean — had proceeded along largely separate tracks. All these fields were, however, pursuing closely related phenomena[2]. When these disciplines broke out of their individual cages, goaded in part by the emergence of space exploration, it unleashed a creative storm that led to seminal work on a number of crossover problems between disciplines.

For example, it became clear that the reduced luminosity of the early Sun would imply, all other things being equal, that the Earth should have spent billions of years as a frozen snowball, which it manifestly did not; work on resolving this 'faint young Sun' problem shed a great deal of light on the climate of the ancient Earth. On the hot side of climates, the concept of a runaway greenhouse effect, where incoming solar radiation to a planet with an ocean can no longer be balanced by radiation of heat to space, was developed and then applied to Venus, suggesting a way our neighbour planet's water could have been lost. The enigma of an evidently warm and wet early Mars, despite its current cold and dry state, was discovered. Inquiry into the range of distances from a planet's star within which a liquid water ocean can exist, given a suitable atmosphere, led to the concept of habitable zones. Missions to the bodies of the Solar System have continued to yield spectacular discoveries. With so much learned from just eight planets and a stray Kuiper Belt object, think what could be done if only we had more planets to play with.

Well, now we do — in fact, a whole lot more. A mere seventeen years after the first confirmed planet outside the Solar System, there are now more than 600 confirmed exoplanets in the catalogue[3]. And over 2,300 additional objects of interest from the Kepler space telescope mission are very probably going to be added to the store[4]. The era of exoplanet exploration opens up vast opportunities for Earth scientists of all stripes.

What we know about these new additions to the planetary family comes from two main techniques used for finding exoplanets. Radial velocity surveys detect the wobble in a star's motion caused by an orbiting planet, and transit surveys detect the slight dimming in starlight when a planet passes between a star and the observer. To be able to observe a transit, a planetary system needs to be lined up just right. But there are a lot of stars with planets out there, so the method still yields a rich bounty of planets. From either transit or radial velocity observations, we learn at least the orbits of the exoplanets (that is, the length of year) and distance from the host star. Together with the star's luminosity, these parameters provide a basis for estimating the planet's climate. The radial velocity method yields the eccentricity of the orbit, as well as the planet's minimum mass, or even its actual mass if the planet is known to be transiting.

Furthermore, the transit method yields the planet's size and — for stars with multiple planets — estimates of mass and eccentricity through analysis of subtle variations in the timing of transits. In those cases where a planet's mass and radius are both known, we've hit the jackpot: mass and radius together determine the density and hence constrain what the planet might be made of. In some cases, the spectrum of starlight blocked by a transiting planet, or of planetary emission blocked by the star when the planet passes behind it, provides information about the composition of the planet's atmosphere.

There has been a focus on the search for Earth twins. However, it turns out that there are a lot of interesting bodies out there that challenge conventional concepts. For example, there are three types of gas giants that call into question current understanding of planet formation, composition and evolution: 'Hot Jupiters', 'Black Jupiters' and 'Puffy Jupiters' (see Box 1).

Fans of small rocky planets are not left out either. Super Earths are planets with a mass larger than Earth's but too small to accrete enough hydrogen to turn into a gas giant. They range from rocky specimens with a permanent molten magma ocean to planets with carbon-rich cores that may be made of diamond, and onwards to an unanticipated class of Super Earths of such low density that they must be largely or entirely composed of light volatile materials such as water, hydrogen or carbon dioxide.

There are even bodies with super-hot atmospheres, where it may snow rubies and sapphires[7]. These extrasolar planetary set-ups challenge the conventional boundaries of what we consider to be a mineral, or even an atmosphere. Nevertheless, the underlying thermodynamic principles are precisely the same. Atmospheric scientists will learn to think of rock as just another kind of ice.

Exoplanets provide the opportunity to observe processes that are key to planetary evolution, but no longer active in the Solar System. Understanding how atmospheres are blown off planets through hydrodynamics is, for example, very important: a suitable atmosphere is a great asset for habitability. Dim red M stars are the most common kind of star in the Universe. They are long lived, host many planets and would be excellent candidates for habitability — were it not for the threat that their planets are subject to an extreme level of ultraviolet radiation that would be expected to blast away their atmospheres.

If very hot planets can retain hydrogen, it bodes well for the possible expansion of the habitable zone through use of hydrogen as a greenhouse gas. Cooler planets should be able to retain hydrogen more easily[8]. The signature of escaping hydrogen can be seen in the Lyman-alpha ultraviolet lines of stars. This signature has been observed for a number of Hot Jupiters, where it is

Box 1 | Exoplanetary diversity

Exoplanet exploration has revealed a great diversity of planets radically different from anything encountered in the Solar System. Figure B1 displays these new types of planets in the context of their size and climate regime, with a few Solar System bodies for comparison.

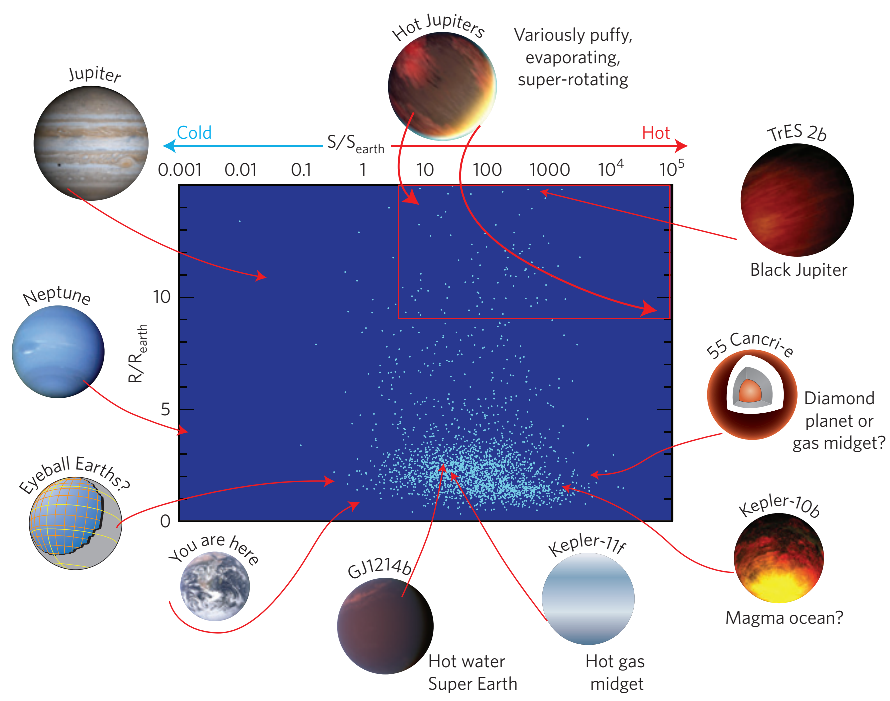

Figure B1 | The radius of the planet, relative to Earth's, is shown on the vertical axis. The horizontal axis gives the amount of energy incident on the planet from its host star, relative to that incident on Earth from the Sun. A planet with $S/S_{earth} = 1$ would have the same climate as Earth if it had the same mass and the same kind of atmosphere. The small blue dots are planet candidates identified by the Kepler space telescope. The relative lack of cold planets is due to difficulty of detection, as cold planets generally orbit their stars at great distances, and also have long-period orbits that require several years of observation to detect.

Gas giants

Hot Jupiters. These are hydrogen-rich gas giants in orbits so close to their stars that there would not be enough hydrogen available to form them *in situ*. Their very existence shakes up theories of planetary migration.

Black Jupiters. TrES 2b is an as-yet unexplained Black Jupiter, a gas giant that is darker than coal. The kind of atmospheric chemistry that could account for this effect at present remains a mystery.

Puffy Jupiters. These hot gas giants are larger than they ought to be, based on conventional ideas about interior temperatures. An unknown mechanism to deliver heat to deep interiors of gas giants is required to explain their existence.

Super Earths

Kepler-10b. With a radius 1.4 times that of our own Earth and a density high enough to make it rocky, Kepler-10b is in an orbit so close to its star that it is probably tide-locked, always presenting the same side inwards. Kepler-10b's dayside would be hot enough to maintain a permanent molten magma ocean. If so, the magma ocean would outgas a rock-vapour atmosphere that, cooling as it flowed towards the nightside, would rain or snow out various minerals to the surface. If some of that atmosphere escapes to space, future observations of the starlight blocked by the escaping plume could provide information about the composition of the planet.

GJ1214b. This exoplanet is similar in size to Kepler-10b, but its density is extremely low. GJ1214b is probably composed entirely of a light volatile such as water[5]. GJ1214b orbits a dim red M star — the coolest class of stars — but so closely that it receives 16 times as much energy from its star as the Earth does from the Sun. During the star's youth, GJ1214b should have been blasted by massive fluxes of atmosphere-busting extreme ultraviolet radiation. How a large volatile inventory could have been retained under those conditions is an open question.

Kepler-11f. This is another low-density Super Earth in a hot orbit. A hydrogen envelope remains possible for this planet.

55 Cancri-e. Even more bizarre is 55 Cancri-e, whose star can be seen with the naked eye in the Cancer constellation. It is dense enough to require a rocky core, but light enough to require a volatile envelope. Yet it is in such a close orbit that it would have a magma ocean similarly to Kepler-10b. Alternatively, 55 Cancri-e could be a carbon-rich solid planet without much volatile envelope[6]. What kind of atmosphere such a planet would outgas — and what this atmosphere would look like as (and if) it escapes into space — is a puzzle. The interior structure would, in any event, be novel: it would be composed largely of diamond.

Eyeball Earths

This is a hypothetical climate state expected for tide-locked ocean worlds in the outer portions of the habitable zone about M stars. Most of the ocean is frozen over, but a pool of open water is maintained on the day side of the planet.

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expected, but not for 55 Cancri-e, where it would be equally expected if the planet has a hydrogen-rich envelope[9]. Planets can have magma oceans such as those that prevailed on the very early Earth, albeit with a different cause. Other processes from the Solar System's distant past, including the runaway greenhouse and globally glaciated snowball states, have not yet been seen on exoplanets. But with so many planets out there, it is surely only a matter of time before we are able catch them in action.

Most of the grand challenge questions that geoscientists have pondered for decades need to be re-thought and generalized to deal with exoplanets. In this enterprise, the cornucopia of exoplanets has something for everybody. For geodynamicists, there is the question of whether plate tectonics occurs on rocky Super Earths[10,11], with implications for atmospheric composition through its effect of recycling carbonate carbon back into the atmosphere. Fluid dynamicists will be interested to see how atmospheric super-rotation — an atmosphere that rotates faster than the underlying planet — plays out on a grander scale. According to theory, Hot Jupiters should super-rotate[12], and super-rotation on exoplanets has already been observed through its effect on the time-course of infrared emission[13]. Climate scientists may widen their horizons, too, when considering habitable-zone planets around dim red M stars that are likely to be tide-locked, always presenting the same face to their star. Already, the weak temperature gradient theory — worked out for the Earth's tropics — has turned out to be the key to understanding when horizontal heat transports are strong enough to keep the atmospheres of tide-locked planets from snowing out on the nightside[14].

In contrast to the rather boring, nearly circular orbits that prevail in the Solar System, high eccentricities are common among exoplanets. We are therefore confronted with a real need to understand the climates of planets that may receive a hundred times as much illumination during the brief periods of close approach as they do during their long, dark winters. And given that planets orbiting reddish M stars appear to be common, we need to come to an understanding of how the greenhouse effect differs when a high proportion of the incoming sunlight is near-infrared and thus subject to absorption by greenhouse gases.

Earth scientists are well placed to mine this rich lode of new problems. They simply need to shed Earth-centric preconceptions, and learn to extract general physical principles of planetary climate from the lessons learned from their work on Earth[15]. As new observing platforms such as the Giant Magellan telescope and the James Webb Space telescope come online, the present flood of planetary data is poised to become a veritable torrent. It's going to be a wild ride down the rapids. Geoscientists should hold on to their hats and jump right on board — the more, the merrier. ❐

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