Alien Earths: What Makes Us Special?
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The discovery of 51 Pegasi b, the first exoplanet around a normal star, in 1995 started a revolution in astronomy. With more than 6000 confirmed planets now known, and thousands more likely to be revealed when data from the *Gaia* satellite is released later this year, it seems like a good time to consider what we can learn from a sky that is now known to be as full of alien worlds as any science fiction writer could want. Together, these discoveries are starting to give us a brand new story of how planets form and evolve, and in the process some of the oldest ideas in astronomy are being challenged.

For centuries, when astronomers had only our own Solar System to study, things were simple. The eighteenth-century astronomer lecturing to a somewhat attentive crowd in Joseph Wright's great painting, *A Philosopher Lecturing on the Orrery*[1], has to hand an exquisite model of an exquisitely order Solar System. Here, the planets travel on nearly circular orbits around a single star at the centre, arrayed in a thin plane. Planets come in two types, neatly separated from each other: small, rocky worlds close to the Sun, and larger, gas giants further out. One of the rocky worlds, of course, lies at just the right distance from its star, and has the right kind of atmosphere, to provide the kind of conditions that make (at least our sort) of life possible.

Our model of planet formation was built to explain these facts. As a star forms, so left over material forms into a protoplanetary disk surrounding them. Within the disk, dust grains clump together, growing into larger bodies. Once big enough, they can hoover up gas from the disk, too. This process happens in the outer disk, where the influence of the new star's heat is less, and so we get rocky worlds close in and gaseous ones further out. Once formed, the planets continue on their orbits for as long as the star survives, providing a nice stable environment for any world in the habitable zone.

Given this picture, it has been natural to frame our discovery of new worlds as a search for places like Earth, to seek planets in an attempt to understand how common life is in the cosmos. Though this is useful shorthand, it obscures the sheer diversity and oddness of many of the systems we now know about.

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[1] Currently on display in the National Gallery.

Take 51 Pegasi b itself. It is the size of Jupiter, but orbiting its star in just four days. Indeed, this is why it was found – the radial velocity technique used, which measures the slow back and forth movement of the host star induced by a planet's gravity, is most sensitive to massive planets on short orbits. This makes it the first of a new class of planet. In this lecture, I will use 51 Peg and other recent discoveries to show just how unusual our Solar System may turn out to be.

1. 51 Peg b[2]

The radial velocity technique with which this planet was discovered gives us a mass – about half that of Jupiter – and the period. With an orbital semi-major axis just under 8 million kilometers (0.05 AU), 51 Peg b sits much closer to its star than Mercury is to the Sun. It must be a weird world, with a temperature likely around 1000 degrees Centigrade, and puffed up, with a superheated atmosphere. The tidal effect of its star will keep it tidally locked, with one face permanently facing the star, creating conditions which must lead to violent winds within its atmosphere. A similar world, Wasp-17b, seems to have clouds made up of quartz crystals.

The existence of hot Jupiters alone tells us that planet formation is a dynamic process. While it still seems plausible that large planets must form in the outer regions of a proto-planetary disk, where gas is plentiful, they must then migrate inwards. Questions about when such migration happens, what can stop it, and why it seems not to have happened in our Solar System are now open questions.

2. PSR B1257+12 b

One has to be careful to say that 51 Peg b was the first planet found around a normal star. Three years before this discovery, variations in timing in the pulses received from a nearby pulsar, PST B1257+12, indicated the presence of a planet around this supernova remnant. The precision of pulsar timing means that this is the least massive planet known, with a mass of just two percent of the Earth's.

The nature of the handful of pulsar planets that have been found is unclear. Are they survivors of more conventional solar systems which existed before their star went supernova, producing the pulsar? Or are we seeing the products of a totally alien form of planet formation, with new worlds being assembled from the debris left after the explosion that ends the central star's life? Whatever is happening, it hard to imagine a world more different from the Earth.

3. Gilese 581c, a 'super-Earth'

Despite these early discoveries, neither pulsar planets nor hot Jupiters turn out to be especially common. (The task of extrapolating from what we have found already to what exists in the cosmos is a tricky one, given the many biases in any survey method). Nonetheless, the most common type of planet appears to be something we simply don't have in the Solar System, with a mass intermediate between rocky planets like Earth and small gas giants like Uranus and Neptune.

In keeping with our main theme, these 'super-Earths' or 'mini-Neptunes' are diverse. Defined by their mass, they have a variety of orbits, atmospheres, compositions and temperatures. Gilese 581c, for example, is 6 times the mass of Earth, and orbits its faint stellar host with a period of 13 days. Though it seems to lie in the star's habitable zone, the region in which an Earth-sized planet with an Earth-like atmosphere has conditions suitable for life, it could be made of rock, iron, or diamond, or be primarily hydrogen or helium.

Nonetheless, if planet formation tends to produce larger planets than our own, maybe it isn't guaranteed that the Milky Way is full of rocky planets; understanding when super-Earths leave room for smaller worlds is now essential in taking our census of the planetary population of the galaxy.

4. HR 5183 b – the whiplash planet.

Of the rules we thought were well established in the Solar System, we have left at least the fact that planets lie on nearly circular orbits. While most do, there are exceptions, and none more odd than HR 5183, a three-Jupiter-mass planet which has a particularly eccentric orbit, swinging from what in our Solar System would be within the orbit of Jupiter to beyond that of Neptune. Such eccentric orbits were once believed to be the result of perturbations by neighbouring stars, but no such companion has yet been identified.

A moment's thought shows that the presence of such a world must surely disrupt any closer-in companions, scattering them widely: the existence of such eccentric worlds thus has an influence on broader questions of planetary system architecture. Other systems, like that around KOI-134, challenge the idea that planetary systems always form in a plane: its two resonant worlds have a mutual inclination of 15 degrees, and defy easy explanation.

Other orbital excitements include a growing number of circumbinaries, with planets orbiting not one but two stars, including PH1b, a planet in a four star system discovered by citizen scientists via the Planethunters.org project[2].

5. TOI-561 b : The lava world

Even Earth-sized planets aren't necessarily Earth-like. Perhaps the strangest of our new discoveries are lava worlds like TOI 561 b. This scorching world is about 1.4 times the size of the Earth – small enough that it should be rocky, not gaseous – but it orbits its Sun-like star in less than 11 hours. Such worlds are believed to be molten, but TOI-561 b has a lower density than one would expect, a result explained by the recent discovery with JWST of a thick atmosphere on this unusual planet.

This discovery neatly explains TOI 561 b's measured properties, but the big question is how it manages to have an atmosphere. Exposed to the star's harsh radiation, it

[2] Should you feel like trying to find your own planet, Planet Hunters still needs volunteers.

should have boiled away a long time ago. (Indeed, one explanation for the formation of these lava worlds is that they are the cores of what were once hot Jupiters, denuded of their atmosphere).

6. Rogue Planets

The oddest planets of all are the rogue planets, free-floating bodies condemned to wander forever between the stars, having been expelled from their natal solar systems. There may be as many of two such wanderers for each star in the Milky Way, making it at least a theoretical possibility that the most common form of planet may not even be part of a solar system at all.

These discoveries and many more reveal a diversity of worlds that constantly surprises, and which reveals how myopic a search for clones of our Solar System really is. Instead of finding our mirror image amongst the stars, we see a planetary equivalent of the old Star Trek motto – Infinite Diversity in Infinite Combinations. Studying these worlds will help us write the new physics of planet formation. We have already started to understand the rules which shape each system, and learn which features are controlled by physics and which by chance or the chaos that now appears an inescapable feature of the process by which planets form.

I started with a 18th century view of an ordered solar system. As we discover new wonders, we would do well to remember Joseph Addison, who wrote in 'On the pleasures of the imagination' in 1712 that contemplating planets means that 'we are filled with a pleasing astonishment, to see so many worlds, hanging one above another, and sliding round their axels in such an amazing pomp and solemnity…our imagination finds its capacity filled with so immense a prospect, and puts itself upon the stretch to comprehend it'.

References

The definitive list of Exoplanets is maintained by the NASA Exoplanet Archive at https://exoplanetarchive.ipac.caltech.edu. Their weekly updates give a good sense of how fast things are moving.

A good recent summary of the field – from which this lecture takes its title – is *Alien Earths* by Lisa Kaltenegger (Allen Lane, 2024). I also recommend *The Little Book of Exoplanets,* by Josh Winn (Princeton University Press, 2023), and *The Planet Factory: Exoplanets and the search for a second Earth* by Elizabeth Tasker (Bloomsbury Sigma, 2019). A more technical view is available in the *Exoplanet Handbook* (Michael Perryman, 2nd ed. 2018, CUP).

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