Hi this is Steve Nerlich from Cheap Astronomy www.cheapastro.com and this is *What are exoplanets made of?*

Part 1: The 1.7 and 3.9 earth Radii rule.

As of August 2016, the current count of confirmed exoplanets is up around 3,400 in 2,617 systems – with 590 of those systems confirmed to be multiplanet systems. And the latest thinking is that if you want to understand what exoplanets are made of you need to appreciate the physical limits of planet-hood, which are defined by the boundaries of 1.7 and 3.9 Earth radii.

Consider that the make-up of an exoplanet is largely determined by the elemental make up of its protoplanetary disk. While most material in the Universe is hydrogen and helium – these are both tenuous gases. In order to generate enough gravity to hang on to them, you need a lot of mass to start with. So, if you're Earth, or anything up to 1.7 times the radius of Earth – you've got no hope of hanging onto more than a few traces of elemental hydrogen and helium. Indeed, any exoplanet that's less than 1.7 Earth radii has to be primarily composed of non-volatiles – that is, things that don't evaporate or blow away easily – to have any chance of gravitationally holding together. A non-volatile exoplanet might be made of rock – which for our Solar System is a primarily silicon/oxygen based mineral matrix, but as we'll hear, small sub-1.7 Earth radii exoplanets could be made of a whole range of other non-volatile materials.

For exoplanets in the next size range up – that is, 1.7 to 3.9 Earth radii – you find what we call gas dwarfs. The composition of these is still *primarily* a mix of non-volatiles, but in this larger size range these planets do have enough mass to start hanging onto a hydrogen and helium atmosphere. And above 3.9 Earth radii – there's no point talking about atmospheres anymore. Exoplanets in this size range are primarily-composed of hydrogen and helium. So, above 3.9 Earth radii you enter the realm of the gas giants.

Now, finding any exoplanets below 1.7 Earth radii or even below 3.9 Earth radii is firstly dependent on the composition of the gas cloud that collapses down to form each stellar system. A gas cloud composed of solely hydrogen and helium can collapse down to become a stellar system, but it will only have gas giant planets – and they'll all be larger than 3.9 Earth radii. But, if a gas cloud that collapses down to form a stellar system has a higher metallicity, that is more elements than just hydrogen and helium then you'll start seeing gas dwarves above 1.7 Earth radii and you'll also start seeing sub-1.7 Earth radii planets – like, for example, the Earth.

So, that's the size story out of the way, but what are exoplanets made of? Since 99% of the mass of most stellar systems will be concentrated in their stars, you can accurately determine the elemental composition of any visible star system by analysing its star's light with spectroscopy. So, when you detect high metallicity in a stellar system, you'll know there's a good chance of Earths, super-Earths and also mini-Earths – but, in a low metallicity stellar system, it's just going to be gas giants all the way.

So, across all the exoplanets we've seen so far, there's plenty of gas giants, but we've also seen super-Earths. Super-Earths are defined by their radius – anything bigger than 1.7 Earth radii you start calling them gas dwarves and for anything above 2 Earth radii, they start being compared them to Neptune rather than Earth. For super-Earths, it's all about radii, because there's not a lot of point in trying to define super-Earths by their mass – as their mass is very dependent upon their composition and their density. But as a general rule once you get up towards1.7 radii limit, these exoplanets masses may be up to 5 times that of Earth, because more mass equals more gravity, which compresses more mass into the same volume – in other words, those super-Earths have a much higher density than Earth does.

Part 2: OK, so tell us about some actual exoplanets now.

Here on the real Earth, we live in a stellar system that formed about 5 billion years ago, in a Universe that formed about 14 billion years ago. So, around our relatively late-coming, high metallicity star we have small rocky asteroids near the star and small dirty snowballs and plutoids further out past its frost line. We don't have super Earth's or gas dwarves, but we do have Earth-like planets – namely Earth and also Venus and we have the mini-Earth's Mercury and Mars. We also have gas giants – Jupiter and Saturn, and Uranus and Neptune, which are sometimes called ice-giants, but are really just smaller colder gas giants which are actually just around the 3.9 Earth radii boundary.

But that's just our how our particular high metallicity system works. A high metallicity star system is a like box of chocolates - you never know what you're going to get. But here are a few of the options…

Ice Planets: In this context, ice is a generic term to encompass any otherwise volatile compound that has solidified by virtue of being outside the frost-line of its local star. So, an ice planet might be composed of water ice, carbon dioxide ice or methane ice – or a mix of all three. A good example is OGLE-2005-BLG-390Lb, which is a super-Earth of 1.65 Earth radii. Being one of the first ice planets found, NASA gave it the unofficial name of Hoth, but although it's just a bit bigger than Earth, it has about 5 times Earth's mass – so, it's unlikely its denizens are going about on Ton-Tons, which would collapse under their own weight – let alone that of their riders.

Chthonian planets: These types of exoplanets may form from a high metallicity gas giant like Jupiter, which is thought to have a rocky core around which hydrogen and helium have accumulated. If such a gas giant experiences orbital decay and slowly spirals in towards its star, it first becomes a hot Jupiter, but as its gas envelope is stripped away by the stellar wind, it may briefly become a *Helium planet* – since the lighter hydrogen is the first gas to be blown off – and after that it becomes a *Chthonian planet*, when all the gases have been blown away and only its rocky core is left behind. A Chthonian planet might be Earth or super-Earth sized and if it keeps getting closer to its star it might also become a *Lava planet* – a bit like Jupiter's innermost moon Io – except, it would be a planet. One likely *Chthonian planet* example is COROT 7b – which is about 500 light years away.

But of course, those are exoplanets in particular temperature extremes, in stellar Goldilocks zones you might find *Ocean planets*. Given the abundance of hydrogen and oxygen in the Universe there are vast amounts of H_2O out there. Although the Earth has a lot of surface water – that water only accounts for about 0.05% of the Earth's mass. Using mass, size and density estimates of exoplanets we think we've identified exoplanets where water makes up at least 10% of their mass. It's thought these planets would be completely covered by a continuous ocean that might be hundreds of kilometres deep. An example is Gliese 1214 b, where we even been able to detect clouds in its atmosphere, that atmosphere being mostly composed of hydrogen and helium, since it is on that cusp between super-Earth and gas dwarf.

Also, in stellar Goldilocks zones, you might find *Carbon planets*. In our stellar system we tend to think that rocky planets will be made of rock – that is something with a silicon/oxygen matrix, where the most abundant element in that matrix is actually the oxygen. But spectroscopy tells us that lots of high metallicity stellar systems are oxygen-poor and carbon-rich. So although exoplanets in these exosystems might be of a similar size and mass to Earth, their fundamental mineral matrix will be carbon-based. These planets will probably still have iron nickel cores, because once a planet is massive enough and molten enough to start gravitationally-differentiating, the heavy elements will always sink to the core. But the crust of these planets – rather than being silicon oxides, may be silicon carbides, or perhaps titanium carbides. And their low relative oxygen content means there won't be much water (H_2O) or carbon dioxide (CO_2). So these will be very different planets from anything that we're familiar with. One possible example is 55 Cancri e, which is about 40 light years away – and which is a super-Earth of about 2 Earth radii and hence also a gas dwarf. It was the first exoplanet to have had its atmosphere directly analysed – which, being a gas dwarf was predominantly hydrogen and helium.

There may also be *Iron planets*, which like Mercury, will be close in to their star, since as dust clouds starts collapsing – heavier elements will tend to accumulate more quickly towards the centre of mass of the collapsing cloud. Kepler 10-b, allegedly the first Earth-like exoplanet to be discovered, back in 2011, might be such an iron planet. With a radius of 1.4 Earths and a mass of 3 Earths, it orbits its star in less than a day, is tidally-locked and it's starlit face has a surface temperature hot enough to melt iron – so, it's pretty much a lava planet at least on one side – and so not a particularly likely candidate for supporting life, nor a particularly Earth-like planet.

There are also *Rogue planets* (without a star) which may number in the billions although all we've seen so far are big gas giants, small ones would be very hard to find. Some of these bigger gas giants are now called sub-brown dwarfs – kind of a failed, failed star. You need 13 Jupiter masses to get a deuterium-burning brown dwarf – which we might call a successful failed star and you need 75 Jupiter masses to achieve hydrogen fusion, which is what a proper star does.

Current rogue planet theory is that you won't find any rogue planets that are of less than 3 Jupiter masses, unless they have been ejected from the stellar system in which they formed. It's apparently impossible for a small gas cloud to collapse down into a single body that's less than 3 Jupiter masses – since bringing things close together tends to heat them up and that heat pushes them apart again. The only way you can form a planet of less than 3 Jupiter masses is within a stellar system because within a gravitationally-constrained and rotating stellar disk, materials get concentrated and things can be forced together that otherwise wouldn't allow themselves to be forced together.

Finally, there are also *Extra-galactic planets*. While no-one really doubts there are planets in other galaxies, we are yet to develop the technology to detect them. However, there have been a couple of solid attempts to establish at least circumstantial evidence for their existence.

And that's our cheap, round-the-visible-Universe tour of exoplanets.

Thanks for listening. This is Steve Nerlich from Cheap Astronomy, www.cheapastro.com. Cheap Astronomy offers an educational website with enough gravity to keep you hanging on. No ads, no profit, just good science. Bye.