Is the Earth Unique? What the different rocky bodies in our solar system can tell us about planet formation

Helen Ashcroft

One of the major projects undertaken by astronomers at the moment is the search for Earth-like bodies orbiting stars other than the sun, and to see whether life could form and be supported elsewhere across the universe. For a planet to support life as we know it, it has to exist in the 'habitable zone' around a star, where liquid water can exist. Advances in astronomy mean that more and more planets orbiting stars other than our Sun have been identified, some of which are similar in size to our Earth. However, in order to understand how or where life forms we need to understand how planets formed, and whether life on Earth is unique, unusual or fortuitous.

There are two chief questions to answer – what are planets made of, and what processes have occurred? To answer these questions we have to go back to the birth of our solar system. 4.567 Billion years ago a nebula (gas and dust cloud) collapsed due to gravitational instability forming our solar system. A spinning disk of gas and dust formed with the sun in the centre. The gas and dust particles started to clump together, gradually growing into larger rocky bodies. These planetisimals collided into each other, either smashing each other apart or accreting together, until eventually the planets formed and evolved to the way they are today. We can observe this accretionary process occurring in different stages around other stars across the galaxy.

The composition across the solar system was thought to be fairly homogenous to start with (roughly the same composition of the sun minus the amount of hydrogen and helium), however the elements that were able to condense into solid phases at any point depended on the distance from the sun, as there was a decreasing temperature gradient across the disk. Therefore rocky refractory elements and metal elements, like Calcium, Aluminium, Silicon and Iron condensed close to the sun to form the terrestrial planets (like Earth), and more volatile elements C, O etc. condensed further out forming the gas giants. The inner rocky planets and the outer gas giants are actually separated by two things – the snow line and the asteroid belt. The snow line is the distance away from the sun where it is cold enough for water to condense as ice. The asteroid belt is a region between Mars and Jupiter where hundreds of 10- to 100-km sized planetary bodies (asteroids) exist in the same orbit. Asteroids are the parent bodies to the samples of rock, which fall to the Earth's surface known as meteorites. They range in size from dust particles to 100s of kg blocks. The asteroid belt represents a region in our solar system where the accretion process stopped prematurely. As the gas giant Jupiter grew, it swept up its surrounding gas and dust, including that of the asteroid belt. Therefore the asteroid belt preserves a snapshot into the processes and conditions of the early solar system and allows us to observe the building blocks of the larger planets.

During the accretion of the terrestrial planets, some planetisimals gained enough energy to melt allowing differentiation into different layers: an iron-nickel metal core, a rocky mantle and crust. This energy either came from short-lived radioactive nuclides for the smaller rocky bodies, like ^{60}Fe or ^{26}Al, or for the larger terrestrial planets from gravitational potential energy released during differentiation. These layers all have different chemical and physical properties and are separated by discrete boundaries. Each of these layers is represented in the meteorite record – we have metallic samples that were the cores of asteroids, and the igneous rocks of the mantles and crusts of other planets and asteroids. Differentiated meteorites can give us information on melting processes and timescales of larger planetary formation.

The other main types of meteorites are the undifferentiated ones; these are sample planetary bodies that have not undergone complete melting. These samples provide a lot of information the chemical composition of the solar system, and one type of undifferentiated meteorites – the CI Chondrites are observed to have the same elemental ratios of our Sun (minus the hydrogen and helium). As the mass of the sun is 99% of the mass of the solar system, we therefore have an estimate of the composition of the solar system, and a starting point for the formation of planets.

We can directly sample the Earth's crust, and we also have samples from the Martian and Lunar surfaces, from the rovers, which have landed there. There are also a few meteorite samples, which have travelled to Earth from these heavenly bodies. It is interesting to note that the composition of all of these basaltic crusts is incredibly similar, although there are minor variations in Ti, Al and Fe content. The differences between martian, lunar and terrestrial crust compositions are thought to be due to the differences in the temperatures and pressures of formation. For example, the Earth is larger than Mars and therefore higher pressures can be reached in the interior.

Although we have a few samples from the upper mantle of the Earth, we cannot directly sample most of the mantle or the Earth's core at all. The composition of the core is estimated from the density, which suggests that it is predominantly iron and nickel with up to 10 % of another element. Although meteorites can provide information about the cores of asteroids, most meteorites cannot be traced back to their parent asteroid, and therefore cannot be placed into a geological context. In fact, only one suite of meteorites can be linked to their parent body – the HED (Howardite – Eucrite-Diogenite meteorites) which originate from the asteroid 4 Vesta. These meteorites are similar to the basaltic extrusive and cumulate rocks seen on Earth, Mars, and the moon. Vesta is the second largest asteroid in our solar system, residing in the asteroid belt with the dimensions ~ 270 x 270 x 220 km and has been one of the foci of the latest NASA *DAWN* mission where a satellite orbited it for one year between 2011-2012. From spectrographic studies of the asteroids in the asteroid belt, Vesta is thought to be the only remaining intact (more or less!) protoplanet with a crust, mantle and core. Therefore it is the perfect natural laboratory for investigating the processes of planetary formation and evolution.

After core formation the silicate portion of a rocky planet is thought to evolve in a magma ocean, where as the planet cools after initial early melting, different minerals start to crystallise and settle. The crystals that form are a function of pressure, temperature and composition. In the larger planets, global magma oceans are thought to form but in the smaller rocky bodies like 4 Vesta, not enough heat might have been present to completely melt the planetisimals and so heterogeneous amounts of partial melting may have occurred.

One interesting feature about Mars, the moon and Vesta are that none of these bodies have a significant atmosphere, and are all depleted in the volatile elements (e.g. N, C, H) compared to CI Chondrites – or their suggested bulk composition. These volatiles would have been present in these planets during the early stages of the planetary accretion, but would degas out of the planets through volcanism. Therefore it is believed that Venus, Earth and Mars would have started with a similar atmosphere in terms of composition and density. The Earth has managed to retain its atmosphere, through gravity however Mars, which is much smaller, could not hold on to its atmosphere. Venus is the same size as the Earth and so has managed to retain its own atmosphere, however as it is slightly closer to the sun, the initial water would have vaporized from the surface, concentrating the greenhouse gases, which in turn caused a runaway greenhouse gas effect.

From this understanding of planetary formation we can see that the process of terrestrial planetary formation is a fairly standard recipe– accretion of the planetary disk material occurs to build a number of rocky planets, the exact size and composition of which is dependent on nature of the final collisions between different protoplanets. All planetary bodies start with volatiles, however on most bodies they are degassed to space through volcanism, and when gravity is low an atmosphere cannot be retained. This would suggest that Earth is unlikely to be completely unique – lucky perhaps, in terms of its position in the 'Goldilocks' Zone, and its size.