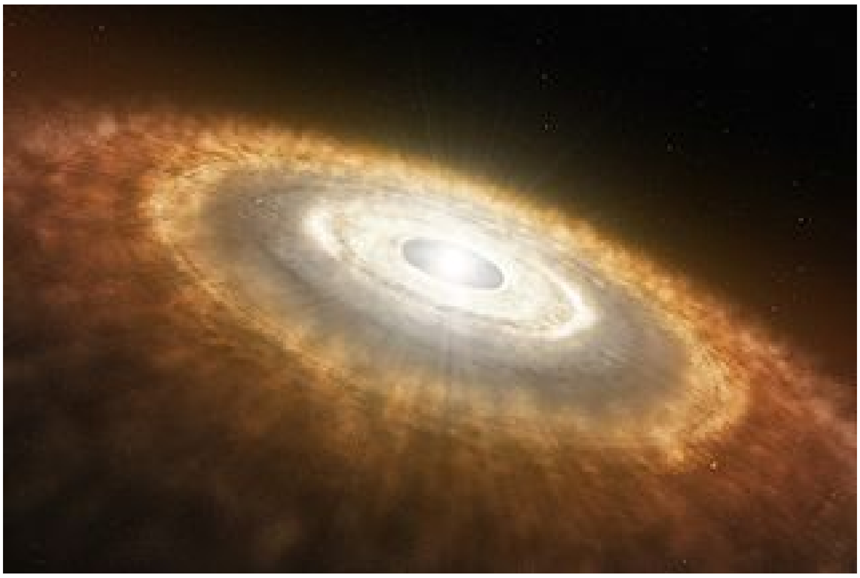
Planetary science

New ideas on evolution of the Solar System (*April 2016*)

The Kepler Space Telescope launched in 2009 was designed to detect and measure planetary bodies orbiting other stars. It was hoped that it would help slake the growing thirst for signs of alien but Earth-like worlds, extraterrestrial life and communications from other sentient beings. Results from the Kepler mission have, however, fostered a growing awareness that all is not well with the simple, Laplacian formation of planetary systems. For a start not one of the thousands of exoplanets revealed by Kepler is in a planetary system resembling the Solar System, let along sharing crucial attributes with the Earth. Giant planets occur around only a tenth of the stars observed, and even fewer in stable, near-circular orbits. Although it is early days in the quest for Earth- and Solar System look-alikes, some unexpected contrasts with the Solar System are emerging. For instance, many of the systems have far more mass in close orbit around their star, including gas giants with orbital periods of only a few days and giant rocky planets. Such configurations defy the accepted model for the Solar System where an outward increase in the proportion of volatiles and ices was thought to be the universal rule. Could these 'hot Jupiters' have formed further out and then somehow been dragged into scorching proximity to their star? Answers to this and other questions have been sought from computer simulations of the evolution of nebulas. Inevitably, the software has been applied to that of the Solar System, and the results are, quite literally, turning ideas about its early development inside out (Batygin, K., Laughlin, G. & Morbidelli, A., 2016. Born of chaos. *Scientific American*, v. 314(May 2016), p. 28-37; DOI: 10.1038/scientificamerican0516-28).



An artist's impression of a protoplanetary disk

It seems that at some stage in its growth from the protoplanetary disk the gravitational influence of a planet creates mass perturbations in the remainder of the disk. These feed back to the planet itself, to others and different parts of the disk to create complex and continuously evolving motions; individual planets may migrate inwards, outwards or escape their star's influence altogether in a chaotic, unpredictable dance. Ultimately, some balance emerges, although that may involve the star engulfing entire worlds and other bodies ending up in interstellar space. It may also end up with worlds dominated by 'refractory' materials – i.e. rocky planets like Earth – orbiting further from their star than those composed of 'volatiles'. In the case of the early Solar System the modelling revealed Jupiter and Saturn drifting inwards and dragging planetesimals, dust, ice and gas with them to create a gap in the protoplanetary disk. Within about half a million years the two giant planets became locked in their present orbital resonance, which changed the distribution of angular momentum between them and reversed their motion to outward. The clearing of mass neatly explains the asteroid belt and Mars's otherwise inexplicably small size.

One of the characteristics emerging from Kepler's discoveries is that 'super Earths' orbit close to their star in other systems. Had they existed in the early Solar System the inward drive of Jupiter and Saturn and their 'bow wave' of smaller bodies would have had consequences. Swarms of matter from the 'bow wave' captured and dissipated angular momentum from the super Earths and dissipated it within a few hundred thousand years, thereby pushing them into death spirals to be consumed by the Sun. This explains what by comparison with Kepler data is a mass deficit in the Inner Solar System. The rocky planets – Mercury, Venus, Earth and Mars – accreted from the leftovers, perhaps over longer periods than previously thought.

Intense bombardment of the Moon and the Earth took place during the first half billion years after they had formed, rising to a crescendo in its later stages. Formation of the *mare* basins brought it to a sudden close at 3.8 Ga, which coincides with the earliest evidence for life on Earth. Lunar evidence indicates that this Late Heavy Bombardment spanned 4.1 to 3.8 Ga. Previously explained by a variety of unsatisfying hypotheses it forms part of the new grand modelling of jostling among the giant planets. Once Jupiter and Saturn together with Uranus and Neptune had stabilised, temporarily, they accumulated lesser orbital perturbations from an outlying disk of evolving dust and planetesimals throughout the Hadean Eon. Ultimately, around 4.1 Ga, the giant planets shifted out of resonance, pushing Jupiter slightly inwards to its current orbit and thrusting the other 3 further outwards. Incidentally, this may have flung another giant planet out of solar orbit to the void. Over about 300 million years they restabilised their orbits through gravitational interaction with the Kuiper belt but at the expense of destabilising the icy bodies within it. Some fled inwards as a barrage of impactors, possibly to deliver much of the water in Earth's oceans. By 3.8 Ga the giants had settled into their modern orbital set-up; hopefully for the last time.

Exotic geology on far-off Pluto (*April 2016*)

About 9 months ago NASA's *New Horizons* spacecraft flew past the binary dwarf planets Pluto and Charon more than 9 years after launch. Everyone knew they would be frigid little worlds but the great risk was that they might turn out to be geologically boring. The relief when the first images finally arrived – *New Horizons'* telecoms are pretty slow – was obvious on the faces at mission control. Even non-Trekkies, such as me, will be thrilled by the first in-depth, illustrated account (Moore, J.M. and 41 others 2016. The geology of Pluto and Charon through the eyes of New Horizons. *Science*, v. **351**, p. 1284-1293), part of a five-article summary of early findings; the other 4 are on-line and scheduled for full publication later (summaries in *Science*, 2016, v. **351**, p. 1280-1284). A gallery of images can be seen here and an abbreviated summary of the series here.

Pluto imaged in approximately natural colour by New Horizons. (Credit: NASA)

They are astonishing places, even at a resolution of only about 1 km (270 m for some parts), and only one fully illuminated hemisphere was imaged for each because of the short duration of the fly-by. Pluto is by no means locked in stasis, for one of its largest features, *Sputnik Planum*, is so lightly cratered that is must be barely 10 Ma old at most. It is a pale, heart-shaped terrane dominated by smooth plains, which have a tiled or cellular appearance, with flanking mountains up to 9 km high that appear to be a broken-up chaos. Much of it is made of frozen nitrogen, carbon monoxide and methane. The dominant nitrogen ice has low strength which accounts for the large area of very low relief. The highly angular mountains are water ice that is buoyant and stronger relative to the others making up *Sputnik Planum*. Across the plain are areas of pitting and blades that seem to have formed by ice sublimation (solid to gas phase transitions) much like terrestrial snow or ice fields that have begun to degrade, and there are even signs of glacier-like flow.

4 Ga old cratered, upland terranes surrounding *Sputnik Planum* display grooved, 'washboard' and a variety of other surface textures reminiscent of dissection. The may have formed by long-term lateral flow (advection) of nitrogen ice and perhaps some melting. It is in this rugged part of Pluto that colour variation is spectacular, with yellows, blues and reds, probably due to deposition of hydrocarbon 'frosts' condensed from the atmosphere. That Pluto is still thermally active is shown by a few broad domes with central depressions that

suggest volcanism, albeit with a magma made of ices. Areas of aligned ridges and troughs provide signs of tectonics, possibly extensional in nature.

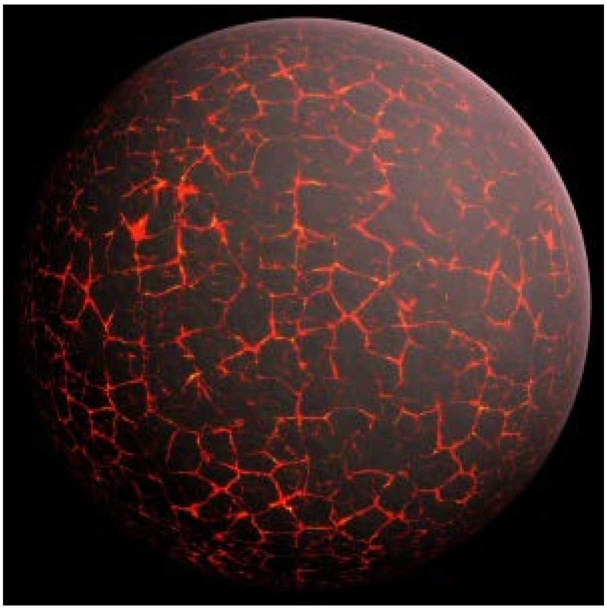
Charon imaged in approximately natural colour by New Horizons. (Credit: NASA)

Charon shows little sign of remaining active and capable of remoulding its surface. The hemisphere that has been imaged is spectacularly bisected by a 200 km wide belt of roughly parallel escarpments, ridges and troughs with a relief of about 10 km. Superimposed by large craters the extensional system probably dates back to the early history of the outer Solar System. Dominated by water ice it seems that Charon's surface may have lost any more volatile ices by sublimation and loss to space. This suggests that superficial differences between two small worlds of similar density may be explained by Charon's lower mass and gravitational field, resulting in the loss of its most volatile components that partly veneer the surface of Pluto.

Being hugely distant from any other sizeable body it is likely that the energy used to form cryovolcanic eruptions and deform the surface of both dwarf planets is due to internal radioactivity. Their similar mean density around 1.9 implies rocky cores that could host the required unstable isotopes. Being the only Kuiper Belt objects that have been closely examined naturally suggests that the rest of the myriad bodies that clutter it are similar. There are currently as many as 9 other sizable bodies suspected of eccentrically orbiting the Sun in the Kuiper Belt, including one that may be ten times more massive than Earth – a candidate for a ninth planet to replace Pluto, which was removed from that status following redefinition in 2006 of what constitutes a *bona fide* planet.

Tungsten isotopes provide a 'vestige of a beginning' (*May 2016*)

Apart from ancient detrital zircons no dated materials from the Earth's crust come anywhere near the age when our home world formed, which incidentally was derived by indirect means. Hutton's famous saying towards the close of the 18th century, '*The result, therefore, of our present enquiry is, that we find no vestige of a beginning, – no prospect of an end'* seems irrefutable. Hardly surprising, you might think, considering the frantic pace of events that have reworked the geological record for four billion years and convincing evidence that not long after accretion the Moon-forming collision may have melted most of the early Earth's mantle. But there is a way of peering beyond even that definitive catastrophe. The metal tungsten alloys very nicely with iron and makes it harder, stronger and more temperature resistant. Most of the Earth's original complement of tungsten probably ended up in the core; it is a siderophile element. But traces can be detected in virtually any rock and, of course, in W-rich ore bodies. Its interest to modern-day geochemists lies in its naturally occurring isotopes, particularly ^{182}W, a proportion of which forms by decay of a radioactive isotope of hafnium (^{182}Hf). Or rather it did, for ^{182}Hf has a half-life of about 9 million years. Only a vanishingly small amount from a nearby supernova that may have triggered formation of the solar system remains undecayed.



Artistic impression of the early Earth before Moon formation. (Source: Creative Commons)

A sign of the former presence of ^{182}Hf in the early Earth comes from higher amounts of its daughter isotope ^{182}W in some Archaean rocks (3.96 Ga) than in younger rocks. That excess is probably from undecayed ^{182}Hf in asteroidal masses that bombarded the Earth between 4.1 and 3.8 Ga. Now it turns out that some much younger flood basalts from the Ontong Java Plateau on the floor of the West Pacific Ocean (~120 Ma) and from Baffin Island in northern Canada (~60 Ma) also contain anomalously high $^{182}W/^{184}W$ ratios (Rizo, H. *et al*. 2016. Preservation of Earth-forming events in the tungsten isotopic composition of modern flood basalts. *Science*, v. **352**, p. 809-812; DOI: 10.1126/science.aad8563. **see also**: Dahl, T.W. 2016. Identifying remnants of early Earth. *Science*, v. **352**, p. 768-769; DOI: 10.1126/science.aaf2482). A different explanation is required for these occurrences. The flood basalts must have melted from chemically anomalous mantle, which originally contained undecayed ^{182}Hf. The researchers have worked out that this heterogeneity may stem from a silicate-rich planetesimal that had formed in the first 50 Ma of the solar system's history, and was accreted to the Earth before the Moon-forming event – lunar rocks formed after ^{182}Hf became extinct. That catastrophe and the succeeding 4.51 Ga of mantle convection failed to mix the ancient anomaly with the rest of the Earth.

Oceans of magma, Moon formation and Earth's 'Year Zero' (*August 2016*)

That the Moon formed and Earth's geochemistry was reset by our planet's collision with another, now vanished world, has become pretty much part of the geoscientific canon. It was but one of some unimaginably catastrophic events that possibly characterised the early Solar System (see *New ideas on evolution of the Solar System* above) and those around other stars. Since the mantle geochemistry of the Earth's precursor was fundamentally transformed to that which underpinned all later geological events, notwithstanding the formation of the protoEarth about 4.57 Ga ago, I now think of the Moon-forming event as our homeworld's 'Year Zero'. It was the 'beginning' of which James Hutton reckoned there was 'no vestige'. Any modern geochemist might comment, 'Well, there must be some kind of signature!', but what that might be and when it happened are elusive, to say the least. One way of looking for answers is, as with so many thorny issues these days, to make a mathematical model. James Connelly and Martin Bizzarro of the University of Copenhagen, Denmark, have designed one based on the fact that one of the volatile elements that must have been partially 'blown off' by such a collision is lead and, of course, that is an element with several isotopes that are daughters of long-term decay of radioactive uranium and thorium (Connelly, J.N. & Bizzarro, M. 2016. Lead isotope evidence for a young formation age of the Earth–Moon system. *Earth and Planetary Science Letters*, v. **452**, p. 36-43. DOI: 10.1016/j.epsl.2016.07.010).

Artist's impression of the impact of a roughly Mars-size planet with the proto-Earth to form an incandescent cloud, from part of which the Moon formed. A NASA animation of lunar history can be viewed here.

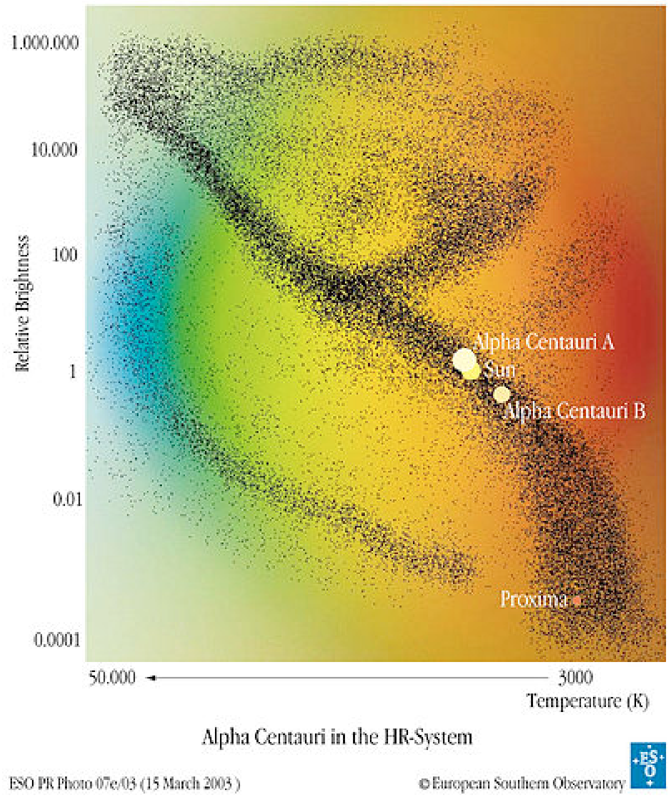
Loss of volatile daughter isotopes of Pb produced by the decay schemes of highly refractory isotopes of U and Th would have reset the U-Pb and Th-Pb isotopic systems and therefore the radiogenic 'clocks' that depend on them in the same way as melting or high-temperature metamorphism resets the simpler ^{87}Rb-^{87}Sr decay scheme. Each radioactive U isotope has a different decay rate that produces a different Pb isotope daughter (^{235}U to^{207}Pb; ^{238}U to ^{206}Pb), so it is possible to devise means of using present-day values of ratios between Pb isotopes, such as ^{207}Pb/^{206}Pb, ^{206}Pb/^{204}Pb and ^{207}Pb/^{204}Pb, to work back to such a 'closure' time. In short, that is the approach used by Connelly and Bizzarro. The most complicated bit of that geochemical ruse is estimating values of the ratios for the Earth's modern mantle and for the Solar system in general – a procedure based on what we can actually measure: lots of mantle-derived basalts and lots of meteorites. Cutting out some important caveats, the result of their model is quite a surprise: 'Year Zero' on their account was between 4426 and 4417 million years ago, which is astonishingly precise. And it is pretty close to the measured age of the lunar Highland anorthosites – products of fractional crystallisation of the Moon's early magma ocean – and also to that of the oldest zircons on Earth. But is also about 60 Ma later than previous estimates

The Connelly and Bizzarro paper follows hard on the heels of another with much the same objective (Snape, J.F. and 8 others 2016. Lunar basalt chronology, mantle differentiation and implications for determining the age of the Moon. *Earth and Planetary Science Letters*, v. **451**, p. 149-158. DOI: 10.1016/j.epsl.2016.07.026). Once again omitting a great deal of argument, Snape and colleagues end up with an age for the isotopic resetting of the lunar mantle of 4376 Ma to the nearest 18 Ma; i.e. an age significantly different from that arrived at by Connelly and Bizzarro. So the answer to the question, 'When was there a vestige of a beginning?' is, 'It depends on the model'… Thankfully, neither estimate for 'Year Zero' has much bearing on the big, practical questions, such as, 'When did life form?', 'Has there always been plate tectonics?'

More on the origin of the early Solar System and formation of the Earth-Moon system

The nearest Earth-like planet (*August 2016*)

What could be more exciting for exobiologists and planetary scientists than to discover that a nearby star is orbited by a planet approximately the same mass as the Earth and that may support liquid water: a world in the 'Goldilocks zone'? It seems that Proxima Centauri, the Sun's closest companion star (4.2 light years distant), might have such a planet (Anglada-Escudé, G. And 30 others 2016. A terrestrial planet candidate in a temperate orbit around Proxima Centauri. *Nature*, v. **536**, p. 437-440; DOI: 10.1038/nature19106). It is one of 34 candidates found to date with various levels of likelihood for having the potential to produce life and support it. To fit the bill a planet first has to orbit a star at a distance where the stellar energy output is unlikely to vapourise any surface water yet is sufficient to keep it at a temperature above freezing point, i.e. the 'Goldilocks' or circumstellar habitable zone is closer to a cool star than to a hot one. Note that the liquid-water criterion requires that the planet also has an atmosphere with sufficient pressure to maintain liquid water. It also needs to have a mass close to that of the Earth (between 0.1 to 5 Earth masses) and a similar density, i.e. a candidate needs to be dominated by silicates so that it has a solid surface rather than being made mainly of gases and liquids.



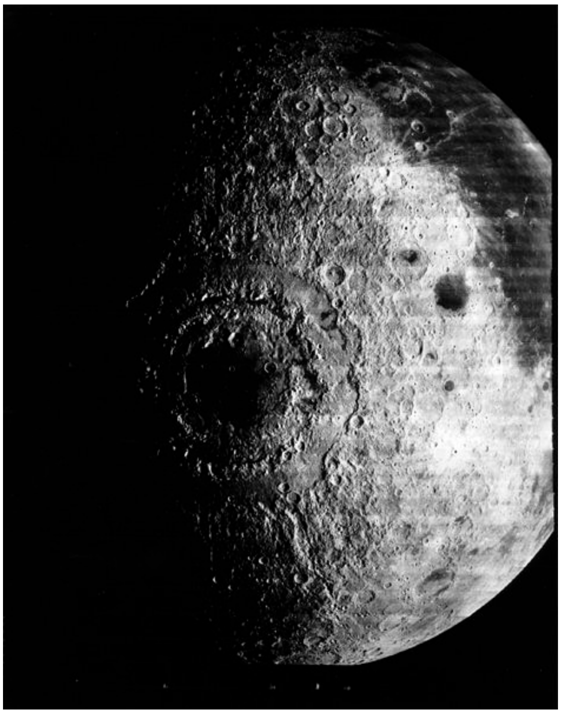
The location of Alpha Centauri A and B, Proxima Centauri and the Sun in the Hertzsprung-Russell (HR) diagram (Credit: Wikipedia)

Proxima Centauri b, as the planet is called, was not discovered by the Kepler space telescope using the transit method (drops in a star's brightness as a planet transits across its disk) but by terrestrial telescopes that measure the Doppler shifts in starlight as it wobbles because of the gravitational affect of an orbiting planet. As well as being close-by, Proxima Centauri is much smaller than the Sun so such effects are more pronounced, especially by planets orbiting close to it. The planet that has excited great interest has an orbital period of only 11.2 Earth days so is much closer to its star and may have a surface temperature (without any greenhouse effect) of 234 K (21 degrees less than that of Earth). The wobble suggests a mass and radius likely to be 1.3 and between 0.8 to 1.4 times those of Earth, respectively. So Proxima Centauri b is probably a silicate-rich world. But, of course, such limited information gives no guarantee whatever of the presence of liquid water and an atmosphere that can support it. Neither is it possible to suggest a day length. In fact, such a close orbit may have resulted in the planet tidally locked in synchrony with its orbit, in the manner of the Moon showing only one face to the Earth. Moreover, its star is a red dwarf and is known to produce a prodigious X-ray flux, frequent flares and probably a stream of energetic particles, from which only a planet with a magnetic field is shielded. All red dwarfs seem to have such characteristics, and the list of possible Earth-like planets show them to be the most common hosts.

It is too early to get overexcited as technologies for astronomical detection of atmospheres and surface composition are about a decade off at the earliest. Being so close makes it tempting for some space agency to plan sending tiny probes (around 1 gram) using a laser propulsion system that is under development. Anything as substantial as existing planetary probes and certainly a crewed mission are unthinkable with current propulsion systems – a one-way trip of 80 thousand years and stupendous amounts of fuel, maybe of the order of the total reserves of Saudi Arabia.

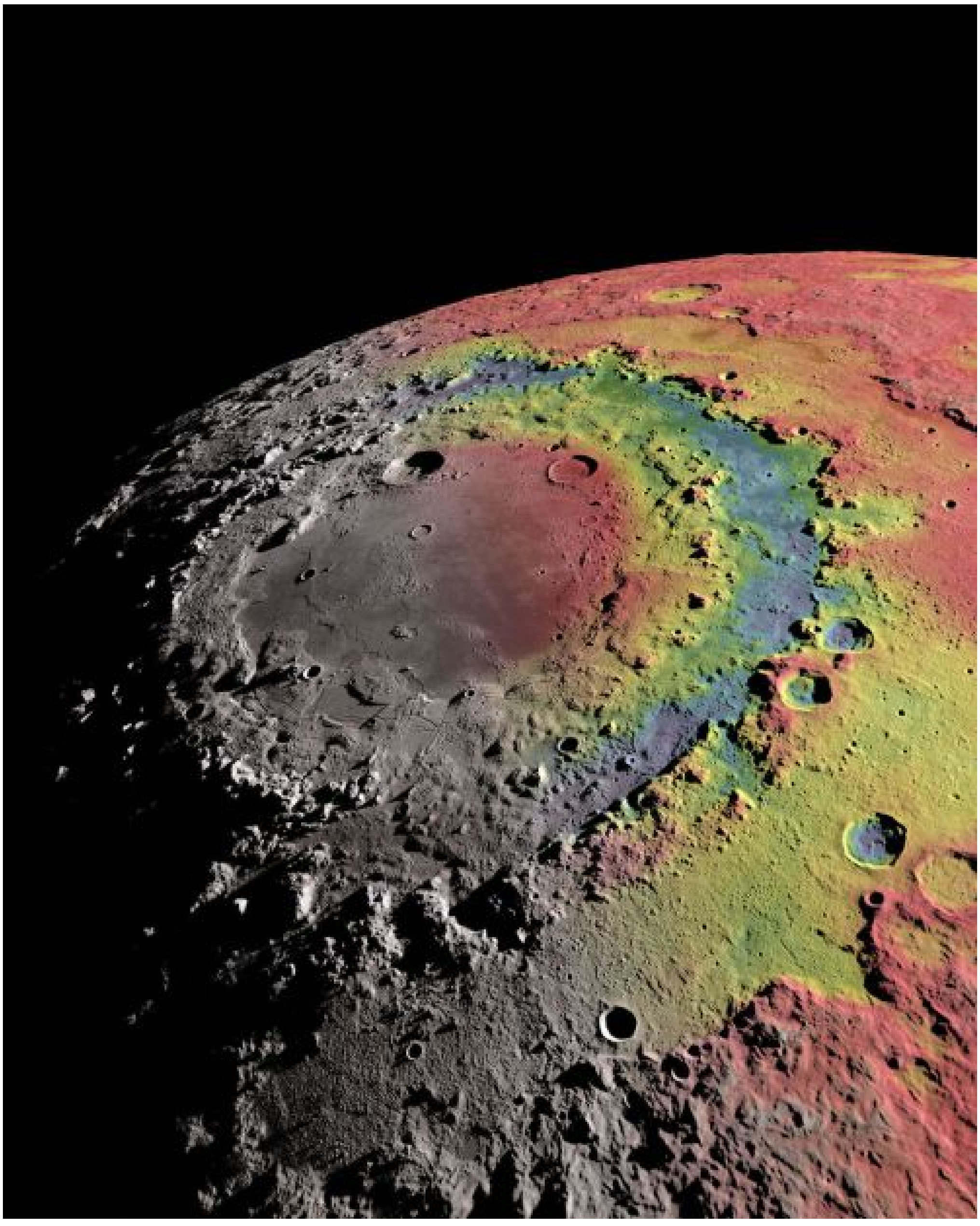
Lunar gravity and the Orientale Basin (*November 2016*)

Mapping the Earth's gravitational field once involved painstaking use of highly sensitive gravimeters at points on the surface, then interpolating values in the spaces between. How revealing maps produced in this way are depends on the spacing of the field sites, and that is still highly variable because of accessibility and how much money is available to carry out such a task in different areas. Space-borne methods have been around for decades. One uses radar measurement of sea-surface height, which depends on the underlying gravitational field. The other deploys two satellites in tandem orbits (the US-German Aerospace Centre Gravity Recovery and Climate Experiment – GRACE), the distance between them – measureable using radar – varying along each orbit according to variations in the Earth's gravity. Respectively, these methods have produced gravity maps of the ocean floor and estimates melting rates of ice caps and the amount of groundwater extraction from sedimentary basins. The problem with GRACE is that satellites need to avoid the Earth's atmosphere by using orbits hundreds of kilometres above the surface, otherwise drag soon brings them down. So the resolution of the gravity maps that it produces is too coarse (about 270 km) for most useful applications. If a world has no atmosphere, however, there is no such limit on orbital altitude, other than surface topography. A similar tandem-system to GRACE has been orbiting the Moon at 55 km since 2011. The Gravity Recovery and Interior Laboratory (GRAIL) mission has produced full coverage of lunar gravity at a resolution of 20 km. In a later phase of operation, GRAIL has been skimming the tops of the highest mountains on the Moon at an average altitude of 6 km; close enough to give a resolution of between 3 and 5 km.



The Mare Orientale basin on the Moon

This capacity has given a completely new perspective on lunar near-surface structure, about as good as that provided by conventional gravity mapping for parts of the Earth. The first pay-off has been for the best preserved major impact feature on the lunar surface: the Orientale basin that formed at the end of the Late Heavy Bombardment of the Solar System, around 3.8 billion years ago. The ~400 km diameter Orientale basin is at the western border of the moon's disk visible from Earth, and looks like a gigantic bullseye. Its central crater, floored by dark-coloured basalt melted from the mantle by the power of the impact, is surrounded by three concentric rings extending to 900 km across; a feature seen partially preserved around even larger lunar *maria*. The structure of such giant ringed basins – also seen on other bodies in the Solar System – has been something of a puzzle since their first recognition on the Moon. A popular view has been that they are akin to the rippling produced dropping a pebble in water, albeit preserved in now solid rock.



The Orientale basin superimposed by the moon's gravity field. Areas shaded in red have higher gravity, while blue areas have the least gravity. (Credit: Ernest Wright, NASA/GSFC)

GRAIL has allowed planetary scientists to model a detailed cross section through the lunar crust (Zuber, M.T. and 27 others, 2016. Gravity field of the Orientale basin from the Gravity Recovery and Interior Laboratory Mission. *Science*, v. **354**, p. 438-441; DOI: 10.1126/science.aag0519). The 40 km thick anorthositic (feldspar-rich) lunar crust has vanished from beneath the central crater, which is above a great upwards bulge of the lunar mantle mantled by about 2 km of *mare* basalts. The shape of the crust-mantle boundary beneath the rings shows that it has been thickened by anorthositic debris flung out by the impact. But the rings seem to be controlled by huge faults that penetrate to the mantle: signs of 2-stage gravitational collapse of the edifice produced initially by the impact.

More on planetary impacts

Related article: Mystery of How the Moon Got Its Bull's-Eye May Be Solved (space.com)