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Small Bodies of the Solar System Transcript

Date: Wednesday, 4 March 2015 - 1:00PM

Location: Museum of London



04 March 2015

Small Bodies of the Solar System

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Introduction

The Solar System is a surprisingly crowded place. Swimming through space alongside the major planets are a whole host of moons, moonlets, comets, dust particles, dwarf planets and asteroids, all also in orbit around the Sun. In today's talk I shall concentrate on some of these smaller bodies: the asteroids and the dwarf planets and how they contribute to the overall architecture of the Solar System.

An **asteroid** is simply a space rock (containing ice and metal too). The characteristics are known of over 100,000 asteroids, and there are most likely several millions in total. With sizes ranging from a few metres to 550 km in diameter, they are shaped more like potatoes than planets, and display battered and cratered surfaces. A **dwarf planet** is the stepping stone between these space rocks and the major planets. Larger and more massive than the asteroids, they have sufficient self-gravity to be pulled into a spherical shape, but not enough to have cleared their own solitary path round the Sun.

However, both the first asteroids and the first dwarf planets to be discovered were originally classified as planets and their role re-evaluated with time, as astronomers learned more about the contents and distribution of the Solar System. Now recognised as the remnant debris from the formation of the planets, they give us different perspective on how the Solar System came to be.

Discovery of Asteroids

Discovery of Uranus

The six planets out to, and including, Saturn have always been known to humanity, and their movements against the background of fixed stars have been monitored with the unaided eye since antiquity. A full understanding of these motions had to wait until the Renaissance, where intuitive science from Copernicus, Brahe and Kepler established the Sun at the heart of the Solar System, and the laws that dictate the orbital mechanics of the planets. The growing understanding of the shape of the Heavens was then consolidated by the first new data that emerged with the development of the use of telescopes for astronomical observations at the start of the 17th Century.

But the vision of a Solar System encompassing only six planets remained unchanged until 1781, when Sir William Herschel stumbled across Uranus as he was using his new state-of-the-art telescopes to chart the positions of faint stars. He observed an object that was extended in shape – not point-like, but showing a greeny-coloured disc – and too bright to be one of Messier's diffuse nebulae. The clincher was that it moved relative to the stars from one week to the next. His first, and entirely logical, interpretation was that he had found a new comet. Only as he calculated its orbit from the observations made over the next few months did he realise that it followed a circular path well out beyond that of Saturn. At such a great distance, the fact that the object appeared as a disc in his telescope immediately meant that it was much larger than a comet – indeed, it was bigger than any the terrestrial planets, although not quite on the scale of the giant planets Jupiter and Saturn. Quite accidentally, Herschel had discovered the first new planet.

Bode's law

One of the fascinating things about the discovery of Uranus was that the size of its orbit complied with a pattern known as the Titius-Bode 'law'. This observes that the relative distances of each of the planets from the Sun (in practice, the semi-major axis of their elliptical orbits) obey the mathematical formula $D = 0.4 + 0.3 \times 2^n$ for $n = 0, 1, 2, \dots$ and a $D=1$ corresponds to one astronomical unit (1 AU; about 150 million km), the separation of the Earth from the Sun. The only glaring inconsistency is that the law predicted that a planet should lie between Mars and Jupiter at around 2.8 AU, where none had been observed. Had something been missed?

Discovery of the brightest asteroids

At this point astronomers had a new hobby – who would waste time searching for comets when there might be new planets waiting to be discovered! The 'missing' planet between Mars and Jupiter seemed to have been found on the 1st January 1801, when the Italian astronomer Guiseppe Piazzi observed something moving within this gap, and named his discovery Ceres, after the Roman goddess of agriculture. But almost straightaway things began to get a little more complicated when the German astronomer Heinrich Olbers stumbled on another new object while studying Ceres in 1802. His discovery, Pallas, became the ninth planet. The strange thing, however, was that Pallas moved around the Sun in a similar orbit to Ceres. And the situation was further compounded by the subsequent discovery of two more planets occupying this gap: Juno, the tenth planet discovered in 1804, and Vesta, the eleventh found in 1807. But after that, and despite intense searching through the next decade, no more objects were found. The Solar System had ten planets.

Like Uranus, all four objects had required the development of powerful telescopes for their discovery as they are too faint to be seen with the unaided eye. But unlike Uranus, this wasn't because they were so far away, but because they were so small. Even with a telescope they did not appear extended, but star-like, and it was only their motion against the stationary stars that gave them away. On their discovery they were immediately accepted as planets, but there was debate about the role of these new bodies in the hierarchy of the Solar System. The main dissenter was Herschel, who proposed they be described by the term 'asteroid' meaning 'star-like' ... perhaps a not entirely impartial move from someone who might have a vested interest to be the only person to have discovered a new planet!

Discovery of Neptune

By 1846 Herschel was no longer alone in having been the first to find a major planet, when the discovery of Neptune was announced. For the first time, a new major planet had been discovered not by serendipity, but by detailed mathematical calculation comparing the observed and predicted motions of Uranus. Any discrepancies were assumed to be due to the gravitational effect of a hitherto undiscovered planet orbiting the Sun beyond Uranus. Neptune was found in the correct region of the Sky and found to be comparable to Uranus in size, and fully recognised as a planet, even if its orbital distance now broke with the pattern suggested by the Titius-Bode law.

and yet more asteroids

The arrival of Neptune into our knowledge suddenly confused the situation regarding Ceres, Pallas, Juno and Vesta. The ambiguity was further compounded by a deluge of new discoveries which started just a year before Neptune's discovery. A new small body was found in the gap between Mars and Jupiter a full 38 years after Vesta had been found; and then at least one further object added to the list each year after that. By the end of the 19th Century the growing accumulation of 'asteroid planets' all swarming in the same region in the Solar System had blurred the understanding of what and what was not a planet. A subtle consensus decision gradually moved from describing all these small bodies as planets to using Herschel's term asteroid, including even the largest and first four discovered; this reclassification acknowledging that there were differences between the planets and asteroids.

how we discover new asteroids now

The ability to detect asteroids in great numbers was enhanced by the development of photography as an astronomical technique at the end of the 19th Century. Either a camera was fixed to a telescope that tracks the motion of the stars across the sky so that a faster-moving asteroid is revealed as a streak on the image; or comparison of two images of the same part of the sky taken at slightly different times reveals an object which has changed its position in the meanwhile. Today's asteroid discoveries may employ computers and CCD imaging on telescopes that survey the sky continuously and methodically, but the basic principle remains the same. An asteroid is revealed by its motion relative to the stars.

Today there are over 200,000 named asteroids charted, following well-determined orbits, and many many more which have been discovered even if their orbits are not yet fully mapped out. A new asteroid is not just given a name (which the discoverer is allowed to choose, as long as there is no duplication), but it is also assigned a number. The numbers increase according to the chronological order of 'discovery', although the order of discovery point rests not necessarily on the first viewing, but also on the reliable determination of the asteroid's orbit. So each small space rock out there is uniquely identified with both a number *and* a name: 1 Ceres, 2 Pallas, 3 Juno, 4 Vesta...and even 134340 Pluto!

Properties of the Asteroids

The asteroid belt

The majority of asteroids are collected into a torus-shaped swarm that fills the space between the orbits of Mars and Jupiter and which is known as the main 'asteroid belt'. It contains millions of objects, and spans the region about 2.2 to 3.3 AU out from the Sun, where objects have orbital periods lasting between three and six Earth-years.

Physical properties of the asteroids

Nearly all but the largest of asteroids in the asteroid belt appear star-like in even today's large telescopes because they are physically small. They vary from the four largest: Ceres in 950 km in diameter; Vesta 525 km and Pallas 540 km and Juno 230 km; and decrease in size down to rocks barely tens of metres in diameter. As with so many natural distributions, there are fewer of the larger objects, and ever-increasing numbers at progressively smaller sizes. We expect that there are over a million objects larger than 1 km across, and many millions that are yet smaller. We can determine the size of an asteroid by the time taken for it to eclipse the light of a background star if it moves in front, in what is known as an *occultation*. If its orbital parameters are known - how far away it is, how fast it's moving - then the duration of the eclipse can allow you to estimate size of the

object.

There may be very many of them, but the combined mass of all the asteroids in the asteroid belt is small. A third of all the mass is contained within Ceres alone, with another third contributed from the next three most massive objects (Vesta, Pallas and 10 Hygiea) combined. Altogether all the asteroid belt would sum to make only 4% of the mass of the Moon. Accordingly, the self-gravity of any individual asteroid is also low; even for the most massive, Ceres, it's less than 3% the gravity at the surface of the Earth. Typically the escape speeds are less than 0.5 km/s (c.f 11 km/s for Earth, 2.4 km/s for the Moon) and asteroids don't have sufficient gravity to retain any atmosphere. This also accounts for the weird and wonderful shapes of asteroids, as only Ceres has enough mass for its self-gravity to pull it into a sphere; most asteroids are distinctly non-spherical, often elongated into shapes that resemble potatoes rather than anything planetary.

The small mass of the asteroids also means that most will not have had a molten core, or subsequent lava flows or volcanos. Only the very largest asteroids can have experienced any geological processing, with the rest remaining largely unaltered since their formation. Or would have done, if they had remained isolated in space. The uneven shapes of asteroids can be inferred by pronounced variations in their brightness as viewed from Earth. Asteroids are rotating, and as one spins it brings different parts of its surface to face towards us, changing the amount of sunlight it reflects towards us. Fly-pasts of or by asteroids have confirmed the irregular elongated shapes, showing their surfaces to be very heavily cratered, gouged and chipped. Like everything else in the Solar System, the asteroids date from just after the formation of the Sun, and over the ensuing billions of years they have undergone numerous collisions with each other that have ultimately proven disruptive. Whether these are head-on smashes capable of fragmenting an asteroid into much smaller pieces, or less dramatic impacts that have still steadily modified their surfaces - larger ones excavating craters, smaller ones pulverising the outside layers - the impacts that an asteroid experiences in its history are largely responsible for shaping their appearance today.

The pieces chipped away from an asteroid by the impacts create asteroid moons if they are not expelled with sufficient velocity to escape gravitational capture. For example, the first discovered moon was a 1.4km-diameter rock known as Dactyl, which orbits around its parent asteroid, twenty-times larger 243 Ida. Many more asteroid moons have since been discovered. Some asteroids may even develop ring systems, which are expected to be relatively temporary structures - when the asteroid 10199 Chariklo passed in front of a background star in 2013, dips in the stellar brightness that occurred both before and after the expected occultation showed that it is surrounded by two rings: one about 7km and one about 3 km wide, and separated by 9km at a distance of about 400 km from the asteroid.

rotation

The periodic brightness of an asteroid show that they have a lumpy shape, and enable us to learn something about their inner structure. Most asteroids rotate once every few hours (eg Pallas has a 7.8 hours period, Vesta every 5.3 hours), but some can take a several days to rotate once, while others take only a couple of minutes! While many space rocks spin about a single, well-defined axis, others tumble in a more chaotic fashion. The orientation of the asteroid's rotation axis can be estimated by the way that variations in the brightness change as it moves around the Sun, and presents different faces towards us. The fact that they seem to be randomly oriented (and not lined up with those of most of the planets) again points to the contributing influence of collisions in producing the characteristics of asteroids we see today). Sometimes the rotation periods are observed to change, presumably as a consequence of collisions that either push against or with the direction of rotation to decrease or increase the rate of rotation.

The relationship between an asteroid's diameter and its rotation period tells us how solid the object is. Empirical plots of the two properties suggest that any asteroid larger than about 300m in diameter can't rotate faster than once every couple of hours. This is because any light-weight, porous object can only rotate so fast before material is thrown off its surface, as there is not enough mass, and thus self-gravity to hold it together otherwise; if it rotates any faster, it will rapidly disintegrate. An asteroid which is a compact solid body will have a greater material strength binding it together, and it can thus spin much faster - up to once every couple of minutes! The faster spinner is the 20m-wide asteroid 2008HJ, which has a rotation period of only 42.7 seconds!

From the rotation periods, we can broadly divide the asteroids into two types: ones which are little more than piles of rubble - such as 253 Mathilde and 25143 Itokawa, where fragments of a smashed orbit are now only loosely held together through gravity and a coating of ice: and others such as 433 Eros, which are much more solid bodies, with a uniform internal composition.

Composition of asteroids

At the very simplest, the *albedo* (how much light it reflects) of an astronomical object immediately tells you something about how shiny it is. For example, Vesta reflects about 40% of the light that falls on it, whereas Ceres reflects less than 10%. Thus, despite being smaller, Vesta appears the brighter object. We learn details about the surface composition of asteroids from the spectrum of the sunlight reflected, and seeing which spectral features have been imprinted in this reflection (compared to the raw sunlight spectrum) reveal which minerals are inherent to the surface. While many asteroids are literally space rocks, simply composed of rocky

silicate material, others appear to be composed of pure metal such as nickel or iron, with a few showing evidence of volcanic basalt.

Generally, asteroids in the main belt show a gradient of chemical composition influenced by how close they are to the Sun. About 75% are *C-type* asteroids: black in colour, darker, and with a high carbonaceous content, such as the largest object Ceres. These dominate the outer side of the asteroid belt, facing away from the Sun (beyond 2.7 AU). The reflected spectrum shows absorption features due to water-rich clay-like minerals, suggesting the clays might have formed originally on a wet surface. About 15% of asteroids are the much redder *S-type*: brighter, drier, and containing silicates of iron and magnesium, these live to the sunward half of the belt (dominate at radii 2.2AU but still found out to 3AU). There are also much brighter metallic *M-type* asteroids that inhabit the middle of the belt – composed of pure metallic iron, with nickel, and a little silicate: and volcanic basalt *V-type* asteroids and many other less common types.

Origin of the asteroids

The diversity in the composition of the asteroids in the main belt reflects the initial conditions within the vast cocoon of dust and gas that gathered around the newly-formed Sun 5 billion years ago. Most of the material in the original cloud will have fallen to the centre, collapsing under its own gravity, where the gravitational energy released will have heated up the core until it reached sufficient temperature for nuclear fusion to be ignited. At the point that the proto-star starts shining, accretion of material to the centre is halted, and the left-over material forms a dusty cocoon known as the *solar nebula*. Dust particles within this disc begin to stick together, slowly aggregating into small clumps, which then gravitationally pull in more matter. The growth of the planets has begun. But in the region just beyond Mars, the normal accumulation of matter was continually disturbed by the gravitational influence of rapidly-forming massive Jupiter. While not strong enough to accrete the matter for itself, it nonetheless disrupted the process, stirring up the rocks so that they failed to coalesce into a single planet: either they are accelerated so that they collide so fast that they fragment rather than adhering, or they are thrown out of the inner Solar System altogether. This means that the asteroids are the raw material for a major planet that never formed in this region, and today only a fraction of the original debris remains here.

The shapes and battered surfaces demonstrate that they have undergone many collisions during the history of the Solar System, as does the identification of some of them as mere rubble piles.

The observed change in composition of asteroids through the main belt is a consequence of the way that temperatures in the early solar nebula fell with increasing distance from the Sun. The young Sun's heat and pressure would have vaporised any volatile material close to it, as well as pushing light elements out to further parts of the nebula. Thus the carbonaceous/water-rich minerals could only have condensed in the outer, cooler regions, whereas the rockier, metallic material is also able to condense on the inner, warmer side closer to the Sun. Some of the asteroids show evidence from being pieces of larger bodies that perhaps attained small proto-planet status before being completely fragmented by the impacts. These might have temporarily achieved sufficient mass to have internal heat, allowing 'differentiation', where heavier materials sink to the centre. Some asteroids now may well be fragments of the pure metal-rich cores of these larger bodies, while others could be the remains of the rocky mantles.

why asteroids are interesting

The fact that most of the material in the asteroid belt is from bodies that were never large enough to have undergone this geological processing means that they are of great scientific interest. Little changed since the very early stages of the Solar System, they give us much better route to understanding the raw material of the solar nebula – unlike analysis of the matter bound up in planets, which has been extensively modified by volcanic or geochemical processes. The distribution of their chemical composition with radius allows us to deconstruct conditions in the early solar nebula. The high fraction of metals in asteroids also means that they have the potential as a source of valuable raw materials – particularly metals – that could be mined in the far future, when we have exhausted such supplies on Earth.

Near-earth objects

Not all asteroids stay in the main asteroid belt. There are several hundred whose orbits intersect with that of the Earth, and which may potentially present a threat to us in the far future. This gives us another reason to study both the orbital dynamics and physical structure of asteroids in preparation to try and mitigate any such event.

radar observations of flypast asteroids

Indeed, every so often, an asteroid will oblige in coming close enough to Earth to enable us to scrutinise it closely as it whizzes past, by bouncing pulsed radio signals off their surface and then interpreting the echoes. A smooth surface reflects the radio energy differently than craggy ones, so we can detect cratered or rough surfaces as well as determining their overall size, shape and structure. If an asteroid is rotating, the Doppler effect will spread the wavelength of the signals received as they reflect off its moving surface. Most of these asteroids come within several hundred thousand km (which sounds close, but it is often at least a few times the Moon's distance away from us), and they travel so fast that they can only be studied very briefly.

Families of asteroids

The occurrence of Near-Earth objects shows that not all asteroids remain confined within the asteroid belt. Both within the belt and outside of it, we can identify *families* of asteroids. For example, there are even 3 families of near-Earth objects – the Apollos, the Atens and the Amors. The families contain asteroids that share similar orbital and physical (compositional) properties, hinting that they are often fragments of a larger single parent object that was broken apart by a major collision. Other families are dynamical groupings where the distribution of asteroids has been influenced by the gravitational pull of the major planets.

trojans

Beyond the asteroid belt, there are populations of asteroids that accompany Jupiter in its orbit around the Sun. Moving in two swarms, one following and one preceding the giant planet, each provides a third corner to an equilateral triangle with the Sun and Jupiter at the other apexes. They keep pace with Jupiter's motion and are known as the 'Trojans' (after the first discovered, 588 Achilles). The Trojans are here because they occupy a particular spot in orbital mechanics known as Lagrangian points, where the gravity of Jupiter exactly balances that from the Sun (one may be more massive, but it's much further away!). Individual asteroids hover around this spot in a cloud, oscillating gently to and fro, and because they are moving slowly along a well-determined path, they are expected to have undergone fewer collisions than objects in the asteroid belt.

Kirkwood gaps

The distribution of asteroids within the main belt itself is not even, and it contains 'Kirkwood' gaps at specific radii which remain clear of objects. Any asteroid in one of these spaces would travel round the Sun with an orbital period that is an exact fraction of Jupiter's, in *resonance*. For example, a 3:1 resonance implies an object moves round the Sun three times for every complete circuit by Jupiter – this means it would draw close to Jupiter every 11.86 years, and in the same place along its orbital path. The object would then experience a cumulative gravitational pull from Jupiter which eventually drags it out of this orbit. Asteroids not in resonance with Jupiter only have these encounters at random times, and at random places in their path, so the interactions don't amplify into a systematic effect. Thus regions within the belt that correspond to these resonances remain clear, and should any asteroid stray into one of these gaps it will rapidly (in astronomical terms...) be dislodged!

Missions to the asteroids

fly-pasts

Despite the asteroid belt sounding like a very crowded place, the sizes of the objects are far smaller than their average separations (of thousands to millions of km), so there is plenty of empty space to manoeuvre a spacecraft through the belt to the outer planets safely. As each of the *Pioneer 10* and *11*, *Voyager 1* and *2*, *Galileo* and *Cassini* missions to the outer planets passed through the belt, they used the opportunity to examine several asteroids up close en route to their main destination.

The *Galileo* mission was the first spacecraft to image an asteroid close-up, when it sailed past 951 Gaspra in October 1991, followed by 243 Ida and its moon Dactyl in August 1993, all on the way to its primary target of Jupiter. Similarly *Deep Space 1* visited 9969 Braille in 1999; *Stardust* flew past 5535 Annefrank in 2002 (practicing its flypast technique ready for Comet Wild); and more recently the *Rosetta* spacecraft flew within 800km of 2867 Steins (about 5-6 km across) in 2008 and 21 Lutetia in 2010 (100km across) on its way to Comet 67P.

These close encounters show the shapes and chipped and cratered surfaces of the asteroids very clearly. They also enable us to estimate the mass of an asteroid, if the flypast is close enough, by sensing any tiny deviations in the planned path of the spacecraft that reveal how much it has been affected by the asteroid's gravity. But of course a much better mass estimate can be obtained if a spacecraft is placed into a close orbit around an asteroid. This has been achieved in two spacecraft missions so far.

NEAR mission to asteroid 433 Eros

The first mission to orbit – and even land on! – an asteroid was the *NEAR (Near Earth Asteroid Rendezvous)* spacecraft which arrived at 433 Eros in 2000, having passed by 253 Mathilde in 1997 on its way. Mathilde is a typical small dark C-type asteroid about 65x50x50 km in size. Its mass density was measured to be low at 1.3 g/cm³, only just above that of water, and less than half what one might expect for a rocky body. It thus seems that Mathilde is a classic rubble-pile asteroid where fragments of a previous collision are held together loosely by gravity, and the object has a porous interior – up to half of it must be empty space.

Eros, on the other hand, is smaller (approximately 35x10x10 km in size), and it was the first near-Earth object to be discovered. It's a bright S-type (silicate) asteroid and the response of the spacecraft to its gravity showed it is definitely a single solid body of almost uniform composition, with a mass density of 2.6 g/cm³. After *NEAR* arrived at Eros it orbited the asteroid for a year before making a landing on its surface in February 2001. Eros displays four large craters, and most of the surface is strewn with loose boulders. As the spacecraft

descended to the surface, we could see the debris scattered across it in detail, and like the Moon, Eros is blanketed with a thick powder known as *regolith*, consisting of the pulverised remains of an asteroid surface under continual bombardment.

Hayabusa at Itokawa

A few years later, the Japanese spacecraft *Hayabusa* visited the tiny (530x290x210m³) near-Earth asteroid 25143 Itokawa in September 2005. Itokawa is another loose rubble pile – where two bulks of rough terrain are joined by a smooth saddle forming a peanut-shape. It is an S-type asteroid, such as is found in the inner part of the asteroid belt. After about a month observing the asteroid from a distance of about 7km, the spacecraft touched down for about 30 minutes in November to collect a sample of the regolith. The first attempt failed, but a second attempt a week later was successful: a tiny dart was fired into the surface of the asteroid to spray material up and out for collection in a canister. A sample of about 100 tiny particles (most smaller than 10 micrometres across) were gathered, and the canister returned to Earth in June 2010. This asteroid dust was subject to detailed scientific analysis, which confirmed the idea that Itokawa is composed of fragments of a larger asteroid that was smashed apart, and that the current surface had been exposed to space for about 8 million years.

Dawnmission

...at Vesta

The *Dawn* mission spent a year in orbit around 4 Vesta in 2011/2, mapping its geology in detail. Vesta was the fourth asteroid to be discovered and it is the second largest object in the main asteroid belt. Rotating once in just over 5 hours, it is shaped like a squashed football just over 500 km across. The object shows large craters, including where a particularly large chunk was gouged from the south polar regions in a massive glancing blow. The deep grooves that circle Vesta's equator may also be a consequence of the massive collision, which is also thought to have scattered a numerous small rocky chunks from Vesta out into space, many of which fall onto Earth as meteorites. They can be uniquely identified as belonging to Vesta because of their specific but matching mineral makeup (pyroxene). Spectroscopic examination of the mineral composition of Vesta's surface reveals that many regions are covered with volcanic basalt. It is thus one of the very few objects in the asteroid belt which is large enough to be differentiated – to produce lava flows it must have once had a hot core. We think it has a metallic core wrapped by the rocky surface. Detailed surface features shaped like gullies around Cornelia crater may have hosted a very brief flow of liquid water, and are assumed to have been carved after buried ice deposits were temporarily heated during impacts.

...and at Ceres

The *Dawn* spacecraft departed Vesta in September 2012, and it is due to arrive at the largest object in the asteroid belt – Ceres – this Friday (6th March 2015). At 950km across, Ceres is large enough to be spherical, and differentiated inside – so it has a crust, mantle and a core. Light reflected from the surface shows the crust to be water/ice-rich, although perhaps dusted with a thin layer of particles. Indeed, Ceres seems to have more water on its surface than Vesta – we can speculate that it took longer to reach its current state than did Vesta, so by the time it was fully formed it was cooler, and more receptive to any water deposited. Alternatively Vesta may have undergone more disruptive collisions that refashioned its structure and surface. There are suggestions that Ceres could harbour an internal ocean beneath the crust. We don't know so much about Ceres as we do about Vesta, but obviously that is due to change soon! So far the images have revealed plenty of craters, and curious white spots that could trace the presence of water ice... watch this space!

centaurs

Not only are there asteroids *within* the asteroid belt, and Trojans at Jupiter's orbit, but there are further populations well beyond that. The Centaurs orbit the Sun in paths that take them out as far as Neptune. The first of this population to be found was 2060 Chiron in 1977 which orbits between Saturn and Uranus. Centaurs are different from their asteroid cousins – and as the name suggests, they behave, if not quite as half horse, half human, then as half-asteroid, half-comet. They are able to brighten and grow a coma in the same way that a comet does if they approach close to the Sun; however, at sizes of 100-200km across some of them are too large to simply be cometary nuclei, and their orbits don't take them anywhere near as close to the Sun as many of the comets.

Pluto

discovery of Pluto

The idea that there could be other major planets persisted after the discovery of Neptune. Taking 165 years to complete a single orbit of the Sun, Neptune was moving too slowly to detect any gravitational disturbances in its orbit, so there was not the simple option of applying the same method to find the next object mathematically from its pull. Instead there was the hope that after taking out the effect of Neptune, there still might be some

residual perturbation to Uranus' orbit that could predict the location of any further planet. In practice when *Voyager 2* refined the estimate of Neptune's mass during its flypast in 1989, it was discovered that Neptune is responsible for all the irregularities observed in Uranus's orbit, and so there can be no massive planet out beyond there. Pluto was eventually discovered (more or less by chance, albeit in a dedicated search) in 1930 by Clyde W Tombagh from comparison of two (time-separated) images of the same part of the sky. Pluto was immediately hailed as the ninth planet of the Solar System

Orbital characteristics

However, its orbit was rather peculiar compared to those of the other planets. Tilted by 17° from the flat plane that contains the rest of the planets, it follows an elongated ellipse rather than the more normal circular shape, and moving between 30 and 50 AU. It is so distant from the Sun that it takes 248 years to complete one orbit, and for 19 of those years it is closer to the Sun than Neptune (although as Pluto and Neptune are in resonant orbits, despite their paths crossing, they never collide).

Pluto's companions

For such a small body, Pluto has a surprisingly rich coterie of companions. Its largest satellite is Charon, discovered serendipitously in 1978: in photos taken to refine the details of its orbit, Pluto appeared to be elongated at times, having a bulge that appeared and disappeared over periods of a few days. It was recognised to be caused by a large companion in orbit around Pluto. Charon is half as big as Pluto, and they orbit each other every 6.4 days at a separation of about 19,600 km. Being of similar mass, gravitational tides have locked them to face each other all the time. And like the Earth and Moon, their particular configuration may well be due to a giant collision of protoplanets. Further satellite moons have been found later around Pluto, the latest discovered only in 2012. All orbit further out than Charon. There are

Nix and Hydra, both around 50-60km across, and Styx and Kerberos each about 10 km across.

physical properties of Pluto

At 2400 km across, Pluto is much closer in size to the big moons of the giant planets than to the major planets themselves. No extended disc is visible through the telescope - so again we estimate its size by knowing its orbit and timing a stellar occultation. We can use the orbital kinematics of Charon to measure the mass of Pluto, and combined with its size, this yields the density. At 1.7 g/cm³ it is primarily a rocky body, and infrared spectroscopy of the light it reflects suggests that Pluto's surface is covered with a veneer of volatile icy material such as methane.

Stellar occultation has also revealed the presence of a very extended and tenuous atmosphere around Pluto. This is mostly composed of nitrogen, with carbon monoxide and a touch of methane. There are seasonal effects in the atmosphere due to the change in temperature - when Pluto is furthest from the Sun, much of the atmosphere will freeze onto the surface.

When it is closer to the Sun, gases will be liberated from the surface and some may even escape away into space given Pluto's low gravity. Light and dark markings on its surface seem to change with time - either they are geological features moving in and out of view, or they may show seasonal changes in on the small object.

the Kuiper belt

The Solar System doesn't come to an abrupt halt at Pluto. Beyond 30AU it changes into a disparate swarm of many small icy/rocky bodies - Pluto is just one of the nearest, and a typical member of the *Kuiper Belt* that wraps around the orbit of Neptune in a fat torus, much like the inner asteroid belt, only larger and more puffed up. The existence of such a population was originally proposed by the British astronomer by Kenneth Edgeworth in the 1940's and the Dutch astronomer Gerard Kuiper in 1951. The idea was that in such far-flung regions of the solar nebula, material is spread out into such a large volume, and moving so slowly that it takes a long while to form any proto-planets; meanwhile Neptune would form much more quickly. In the same way that the gravity of Jupiter stirred up the asteroids in the main belt to prevent them from coalescing into one body, Neptune's gravity also disrupted all the small rocky bodies at the outer edge of the Solar System so that they could not group into a single dominant planet.

The actual existence of the Kuiper Belt was not confirmed until Dave Jewitt and Jane Luu discovered the first known object out there, 1992 QB₁ in August 1992. Now thousands of Kuiper Belt Objects (KBO) are known beyond Pluto, and probably millions of small bodies inhabit the Solar System between 50 and 100 AU. Hundreds of thousands of them are expected to be over 100km across. This new architecture for the Solar System provides a new context for Pluto, and triggered reevaluation of it not as a planet, but as just one of the nearer and brighter members of a much larger population of trans-Neptunian objects. It turns out that Pluto's orbit is not that bizarre compared to other objects out there. Most of the KBO are in classical, almost circular orbits with periods of over 250 years. Some, like Pluto, re locked into orbital resonance with Neptunewhere since they never get close enough to Neptune to be scattered by its gravity, they can survive in regions that would otherwise

have been emptied of objects.

Scattered disc

Otherwise any KBO straying too close to Neptune could be thrown out of the Solar System entirely, or forwarded to the inner parts of the Solar System - perhaps to become a Centaur, or grabbed by the gravity of a giant planet to become a short period comet. Alternatively it is dislodged into a more eccentric and tilted orbit, to become part of the more chaotic *scattered disc*. Objects in the scattered disc have very elongated orbits (orbital eccentricities ranging as high as 0.8), taking them between about 30-35AU from the Sun at closest, and beyond 100AU at furthest, and with inclinations as high as 40°.

Dwarf planets

Buried within the Kuiper Belt more recently-discovered bodies that rival Pluto in size and importance, many of which have been discovered by the American astronomer Michael Brown and his team.

50000 Quaoar

The first of the large KBOs to be discovered was Quaoar in June 2002, which follows a fairly circular orbit about 42AU out from the Sun every 286 years, and which is tilted out of the plane of the planets only by about 8°. The 1100 km-wide is about half the size of Pluto, and its surface is one of ice and frozen methane.

136199Eris

Shortly afterward in 2003 the discovery of an object similar in size to Pluto was announced. Eris is about 25% more massive, and so heavy that it must be almost entirely rock - in contrast to Pluto which has a lot of frozen water inside. Eris has a very eccentric orbit ranging between 38 to 97 AU over a period of 558 years. It lies so distant from the Sun that its methane atmosphere freezes out onto the surface, leaving a highly reflective surface.

136472Makemake and 136108Haumea

These objects were followed by the discovery of Haumea in 2004 and Makemake in 2005. Makemake is 2/3 the size of Pluto, and the second brightest object in the Kuiper belt. Orbiting the Sun at an average distance of 46 AU, it again has a surface iced with large amounts of frozen methane. Haumea is also covered in pure ice, but it is significantly egg-shaped and spinning incredibly fast. It also seems to have an accompanying cohort of small satellites. Its shape, spin and the presence of several moons all strongly point to it having undergone a glancing blow with another KBO in the past - this is expected to have knocked off many chunks of icy rock, many of which remain in orbit around Haumea still, while others have spun off into space to form a separate cloud of small objects.

90377Sedna

One of the most exciting trans-Neptunian objects to be discovered was Sedna, in November 2003. It has a diameter of about 1000 km, but without any moons it's difficult to assess its mass. Like other KBO it has a very reflective surface coated with a mixture of frozen water, methane and nitrogen. However it's significantly red in colour - almost as red as Mars - thought to be due to a coating of hydrocarbons assembled from simpler organic compounds. Its orbit is less characteristic of other members of the Kuiper Belt: first of all, it's so large that it takes Sedna 11,400 years to go once round and still be considered part of the Solar System. Indeed its orbit resembles more that of a comet, although less extreme, and it is incredibly elongated, moving between 76 and 936AU from the Sun. Possibly it is an extreme member of the scattered disc, flung into this far-fetched orbit after a close approach to Neptune, or it could be a member of the very inner reach of the distant Oort cloud of cometary nuclei thought to mark the outer edge of the Solar System.

2012 VP113

Even Sedna is not alone - last year (2014) the discovery of 2012 VP113 revealed an objects about half the size of Sedna following a 4200-year orbit that is similarly eccentric - ranging between 80 to 265 AU.

Definition of a dwarf planet

Given the realisation a decade ago that there are other objects of comparable mass, size and orbit to Pluto at the edge of our Solar System, it seemed reasonable to reconsider its original classification as a planet. Indeed, it sparked off an international debate about the exact definition of what is, and what isn't a planet, and the final resolution combined geological and dynamical criteria:

- *Anything in orbit around the sun* - ie primarily orbiting the Sun rather than another planet, so as to exclude moons from the definition;

- *that is big enough to be round in shape* - i.e. with sufficient mass and thus enough self-gravity, to have undergone geological processes. This criterion includes many of the newly found KBO. Even though we can't see their shape, we can still mostly infer whether they have enough size/mass to be round, although it will depend on the combination of rock and ice in the interior. Ice is not as hard as rock, so it takes less force to make an ice ball round. Generally an icy body has to be somewhere between 200 and 400 km across, a rocky body somewhat larger;

- *and which has cleared the neighbourhood around its orbit* - in other words, is it solitary or part of a larger population? This last point is the key distinction that differentiates between the major planets and Pluto and its friend. At that point, if they are not planets, the phrase **dwarf planet** was introduced to distinguish them.

***New Horizons* mission**

We still have much to learn about these very distant denizens of the Solar System - and the ideal opportunity to do so by mid-July this year (2015). The *New Horizons* spacecraft was launched in Jan 2006 to commence a 9.5 year flight to Pluto. It is currently about 180 million km away from its rendezvous, and already returning navigation images of Pluto and Charon. By May the cameras will start to take better pictures of the system than possible from telescopes on Earth, and by June surface features should start being visible.

But it'll just be a temporary meeting of spacecraft and dwarf planet: *New Horizons* will fly to within 10,000 km of the surface of Pluto, 27,000 km from Charon, and pass through the system at a relative speed of 13.8 km/s. It has a total of seven science instruments, each designed to operate at different points in the flypast to maximise the science undertaken. There are high resolution cameras working in the visible, near-infrared and ultraviolet in order to obtain both images and spectra of the dwarf planet and its moons; a dust detector, as well as plasma and high energy particle detectors to measure the strength and content of the solar wind so far out. Radio science experiments will test the passage of radio beams (from Earth) through the atmosphere of Pluto to determine its temperature and pressure profiles. As Pluto takes a while to rotate, we'll only see one side of the planet in great detail during the close approach, so one camera will observe the far side of Pluto from long range on the way in, and on the way out.

And after Pluto?

After Pluto, *New Horizons* will sail on, but with sufficient fuel remaining to continue to at least one, and perhaps two, further objects in the Kuiper Belt as an added bonus mission, in 2018-2019. It has been difficult to find suitable targets close to the spacecraft's flight path, as can't be readily diverted from its course, but a couple of potential targets in the Kuiper Belt have been identified, each to have diameters between 20-55km, and to lie at distances of 43-44 AU from the Sun.