BACK down 2 EARTH

Exploring Asteroids, Comets, Impacts & Craters

Contents

Welcome to Back Down 2 Earth!

Back Down 2 Earth (BD2E) is an expansion of the existing Down 2 Earth (D2E) education project which teaches school students aged 11-19 about the geological side to astronomy. You will learn about the wonders of comets and asteroids and the possible destruction that these bodies can cause on places like our home planet.

So follow us on a journey through space, where our first stop will be at a comet - once we've travelled the long distances to the Kuiper Belt and Oort Cloud that is! After chasing and catching one of these 'hairy stars', we find out what comets are made of and take a peek into the missions that have been made to these icy bodies to learn more about their composition. What does the make-up of the comet mean with regards to how life formed on Earth?

Heading home, we meet the extensive Asteroid Belt between the orbits of Mars and Jupiter. Here we take our time to investigate these space-boulders that seem to litter the Solar System. With our knowledge from our space mission, we enter the Earth's atmosphere, where we take a trip to some of the most famous craters on our planet. At these craters, we also consider the extinction of the dinosaurs. On our travels we are met by a meteor shower – what are meteor showers and where do they come from? We take a look at what these shooting stars are made of, and consider the different types of meteorite.

Back in the UK, we chat with scientists who are involved in studying meteorites, impacts and the death of the dinosaurs. They tell us about their widely different careers after studying geology and hopefully give you some ideas for possible career paths in your future.

You can also get involved in the classroom with BD2E by visiting our website at http://education.down2earth.eu/ where there are downloadable activity worksheets to try (outlined in this booklet)- from creating your own impact craters to investigating the speed at which spacecraft impactors must hit a comet in order to learn about its composition. Don't forget to play with our Impact Calculator, which allows you to decide on the size and location of the impacts that are made by these foreign objects which trespass into our atmosphere – the fate of the Earth is in your hands!

Want to actually hold a meteorite? Well now you can! The National Museum of Wales supplies loan boxes to schools across Wales where you can touch some of the samples of meteorites, rocks and dinosaur fossils.

This project has been supported by the Beacons for Wales Public Engagement fund, Faulkes Telescope Project, National Museum of Wales and by the Science and Technology Facilities Council (STFC). We thank Astronomy Now magazine for supplying us with the resources that have made this booklet possible.

The five Ws of comets

Who?

The story of comets is one that spans the history of the Solar System, and to tell their story in full we have to consider the 'who?', 'what?', 'where?', 'when?' and 'why' of their icy nature.

Comets have held a fascination going as far back as the ancient Chinese, Greeks, and Romans, as well as Comet Halley's guest appearance on the Bayeux Tapestry as the Norman's invaded England and King Harold fell. Usually they were seen as portents of doom – Harold probably knew his time was almost up, just a few months after his coronation, when Halley began to streak through the sky. But others saw it as a sign, an opportunity, like William the Conqueror of course, who saw it as a chance to go to war and capture the throne he claimed was rightfully his. Others read religious symbols into the appearance of comets – when a bright comet outburst lit up the skies over Rome, Emperor Augustus claimed it was Caesar's spirit ascending to the afterlife.

With the Copernican revolution and Kepler's laws of planetary motion, astronomers in the sixteenth and seventeenth centuries began to better understand comets, and the superstitious grip that they held over humanity began to diminish. Nevertheless, the scientific fascination that we experience today, and the sheer wonder on the odd occasion when a passing comet illuminates the night sky, still matches the supernatural fear that the ancients felt as these 'hairy stars' (as the rough translation of the Latin word 'cometes' describes them) streaked across the stars. What would they have made of the great comets of our time, such as Hale–Bopp, Hyakutake, Holmes and McNaught?

Hale–Bopp Comet. Image: Kazuhiro Seto.

What?

If asked to picture a comet, you're likely to think of the fuzzy coma with a long, gaseous tail trailing behind it – the typical 'hairy star' mentioned above. Inevitably, if a comet is remembered, it is usually for its tail. Hyakutake (1996) and McNaught (2007) had amazing tails. The tail and coma actually only manifest themselves as the comet approaches the Sun. For the most part, away from the Sun, a comet is just a frozen nucleus. Observing cometary nuclei can be tough; they're either so far away that they are difficult to see in even the largest aperture telescopes, or they are surrounded by a thick, dusty coma. Despite that, "We actually know an awful lot," says Professor Alan Fitzsimmons of Queen's University, Belfast.

Our modern-day interest in comets is closely tied to our yearning to try and understand how the Solar System, including Earth, formed. Comets, as we now know, are constructed from primordial material generated during the dawn of the Solar System, 4.6 billion years ago. Comets are the detritus from that planet-forming period, and give insights into that distant time. They were forged before the Sun's heat or collisions with other bodies could alter them chemically, and as such they preserve the pristine material of the infant Solar System in their composition. If we can understand the materials inside comets, we can understand what the building blocks were that, piece by piece, formed the planets.

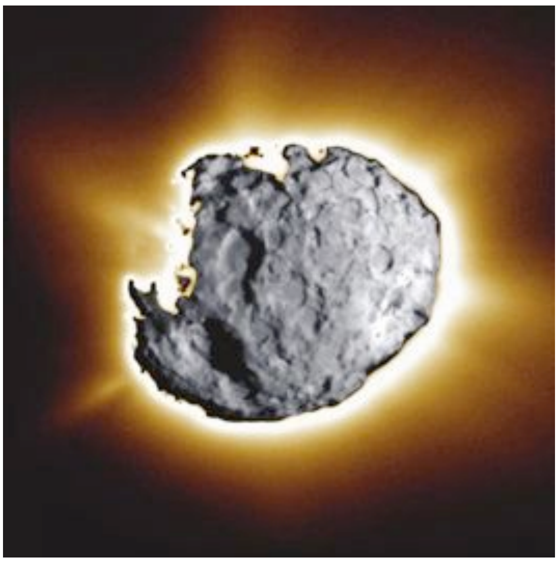
Comets aren't generic. "When we look closely we can actually see differences between comets: differences in composition and differences in the relative amount of ices to dust particles embedded within them," says Fitzsimmons. Besides water–ice, astronomers have detected in comets the likes of carbon monoxide, carbon dioxide, methane, ethane, ammonia, formaldehyde, ethanol, hydrogen cyanide, and even amino acids. Their discoveries either come through spectroscopic analysis of their light or through the Stardust sample-return mission.

Many of those aforementioned materials sound a lot like the constituents of the pre-biotic gloop found on Saturn's largest moon, Titan, or the very early Earth. Astrobiologists agree that these are the compounds that are required to be in place if life is to develop. The nuclei of comets are coated in these organic compounds, in the form of a thick, dark crust of organic tar, underneath which lies ice. One idea promoted by some scientists at the Cardiff Centre for Astrobiology is that as a comet nears the Sun, the ice beneath the crust melts, forming reservoirs that could act as havens for micro-organisms. Indeed, they even propose that comets crashing into the young Earth may have delivered life to our planet. This theory of 'panspermia' is certainly controversial and not entirely popular, but comets almost certainly at least delivered the organic compounds and, just as importantly, water necessary to begin the process of creating life on our planet. We owe our existence to comets.

The organic crust comes in the shape of a black, tar-like substance, so dark that comet nuclei are, surprisingly, some of the darkest objects in the Solar System. When NASA's experimental Deep Space One spacecraft made its ion-drive powered voyage past Comet Borrelly in 2001, it found the albedo of the comet was between 0.025 and 0.03 (i.e. it reflected between 2.5 and 3 percent of sunlight incident upon it). Giotto measured the albedo of Halley's nucleus to be 0.04.

Nevertheless, it is this dark surface that enables a comet to burst into life as it approaches the Sun, soaking up heat that bakes off the volatile gases on the surface, and causes outgassing. A gaseous cloud develops around the nucleus, and the solar wind sculpts this coma into a majestic tail, sometimes millions of kilometres long. The tail generally points away from the Sun, but if long enough it can appear to curve as the comet follows its orbit. A second tail, the ion tail, does point in exactly the opposite direction to the Sun and the solar wind. The ion tail is fainter, and is created when ultraviolet radiation from the Sun acts on the gaseous particles in the comet's coma. The particles, through the photoelectric effect, are ionised and the coma's subsequent positive charge helps induce a magnetic field around the comet that acts as a barrier to the solar wind, slowing it and forcing it to go around the comet. The ionised particles (ions) congregate away from the coma, upstream of the solar wind, forming the ion tail as the magnetic field lines carried on the solar wind drape around the comet.

Comets can have their ion tails snipped off too. If the magnetic field lines around the ion tail become too squeezed up, magnetic reconnection can take place (essentially, open



A composite image of Comet Wild 2, which the Stardust spacecraft sampled. In this particular image, a short exposure of the nucleus is combined with a longer exposure showing the glowing coma and jets of gas and dust streaming into space. Image: NASA/JPL–Caltech.

field lines 'reconnect' to form closed field lines, and they separate from the rest of the comet). In 2007 NASA's STEREO spacecraft watched one comet's ion tail be completely severed as it passed through a coronal mass ejection bubbling up out of the Sun's million degree corona.

The first photograph of a cometary nucleus was taken by the American astronomer Fred Whipple in 1950. It was Whipple who coined the term 'dirty snowball' to describe the nucleus (he also linked the Taurid meteor shower with Comet Encke and discovered six comets himself). Many comets have a density less than that of water, which perhaps gives some indication that they are not quite as solid as they might appear from the outside. As such, their porous structure can break up and fragment rather easily. Many asteroids are also loosely held together 'rubble piles', so did they form in similar fashion? Not really, explains Fitzsimmons. "The asteroids that we see in the Asteroid Belt are nearly all remnants of once larger bodies that have been broken up in collisions," he says. "We know that when a comet forms, it can't really have formed in a very violent way because when you smash things together you get heat, and that heat would have driven off all the ices that we see. So we know that comets must have formed in a much more gentle environment than asteroids."

Where and when?

The gentle environment that Fitzsimmons talks about had to be nowhere near the Sun. If they had formed too close to our stellar neighbour, the Sun's radiation would have driven off all the ices that coat the nucleus. No, comets had to form beyond the snow line – the region in the early Solar System where substances like water and ammonia were able to exist as ice grains rather than vapour. In protoplanetary nebulae the snow line occurs where temperatures drop below minus 123°C (150 K), dependent on density and pressure, and the boundary to the snow line was roughly where we find Saturn today. However, anomalous results from a recent NASA space mission have shown that not

The superb tail on Comet 2006 M4 SWAN. Image: Zdenek Bardon.

everything that goes into a comet came from beyond the snow line.

NASA's Stardust mission had the task of bringing comet dust back to Earth. Once on terra firma, in the sterile nature of the laboratory, scientists studying the recovered microscopic dust particles scooped up from Comet Wild 2's tail in January 2004 found a mystery developing. Here were particles of organic compounds that could only have formed in a high-temperature environment, specifically the region of the protoplanetary nebula nearest the Sun. How did they end up in a comet that formed billions of kilometres away? Are our models of how comets form all wrong? Not in the slightest, says Fitzsimmons. In fact, it sheds more light on what was happening in the protoplanetary nebula as the planets began to grow from embryonic planetesimals, which is precisely the aim of comet research.

"What this is telling us is that the Solar System was much better mixed than we possibly thought beforehand," he says. "There must have been a lot of motion, a lot of movement of material around the Sun when the planetary system was forming."

Imagine turbulent cells in the protoplanetary nebula transporting material from near the Sun out to where the comets were forming, or a conveyor belt of jets from the volatile young Sun that stirred up the nebula. Of course, there is the danger of misleadingly creating a global scenario from just one sample (Wild 2) but spectroscopic studies of other comets have shown similar results.

As the Solar System coalesced from the spinning, chaotic protoplanetary nebula, cometary bodies fell into distant orbits around the Sun, discarded from the planetary construction yard. Their new home was the Kuiper Belt – a disc of icy bodies beyond Neptune, extending up to 12 billion km from the Sun – or even further beyond that, the Oort Cloud, a spherical swarm of trillions of frozen comets that could possibly stretch out as far as half way to the nearest star. Today, not every comet hails from these distant locales; some pass regularly through the Solar System.

We divide comets into classes depending upon their orbits. Short period comets are split into two groups, Jupiter-family comets and Halley-family comets. The Jupiter- family comets typically have orbital periods of less than 20 years, and their elliptical orbits lie in the plane of the Solar System. They are dominated by the gravitational influence of Jupiter. The Halley-family comets, named after the most famous comet of all, have orbital periods of less than 200 years and can escape to as far away as Neptune's orbit before looping back towards the Sun. Halley, for instance, returns every 76 years.

Then there are the long period comets such as Hale-Bopp and Hyakutake, which we might be lucky to see every few millennia (Hale- Bopp's orbital period is 2,400 years, whilst Hyakutake's is 20,000 years). Finally there are the one-off comets that race through the Solar System on a parabolic trajectory, before the Sun's gravity ejects them from the Solar System on a one-way ticket into interstellar space.

Over 3,500 comets have been identified so far, 400 of which are short-period comets while 1,500 have been found to be Sun-grazers. These are comets that fly perilously close to the Sun, and some are even unfortunate enough to hit the Sun and be destroyed. The vast majority of Sun-grazers (Icarus would certainly have been proud of them) have been discovered by the joint NASA–ESA spacecraft, the Solar and Heliospheric Observatory (SOHO), as it stares continuously at the Sun.

Artwork depicting Deep Space One's 2001 encounter with Comet Borrelly. Image: NASA/JPL.

We can predict the orbits of the comets we know about, but one- off comets, or long period comets that are just swinging around in our direction for the first time in millennia, often come as a complete surprise. So it is not always possible to predict when the next great comet will be – some of the best, like Hyakutake in 1996, have come out of nowhere to amaze us. So when the next great comet will be is anyone's guess.

Why?

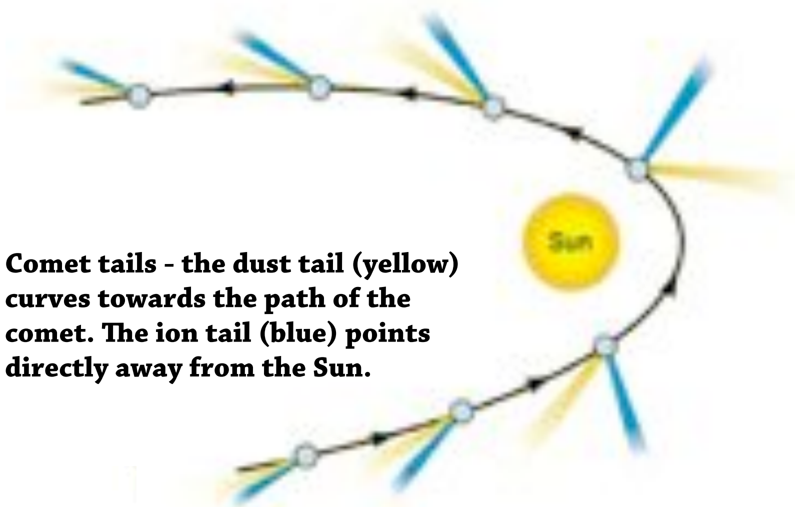
Out in the frozen depths of the Kuiper Belt and Oort Cloud, the Sun's radiation and gravitational grasp is diminished. Comets are vulnerable to other influences, such as the relatively close passage (perhaps by a light year or so) of another star. To give some indication of how close other stars can get, the red dwarf star Gliese 710 will get to within 70,000 astronomical units, or ten trillion km – that's actually inside the Oort Cloud, as far as we can tell – in around 1.4 million years time, before merrily going on its way. Its gravity will disrupt the orbits of millions of comets, slinging many of them our direction. The vast majority will pass harmlessly through the Solar System, although it is feasible that some may collide with Earth or other planets, much like when Comet Shoemaker–Levy 9 collided with Jupiter in 1994. Some astronomers, such as John Murray at the Open University, have even speculated that an as yet undiscovered planet lurks in the Oort Cloud, massive enough to disturb the orbits of comets. Either way, it is these perturbations that can cause comets to wind up on trajectories that bring them into the inner Solar System and link their fates inextricably with ours.

Quick facts about...

Comets

At a glance...

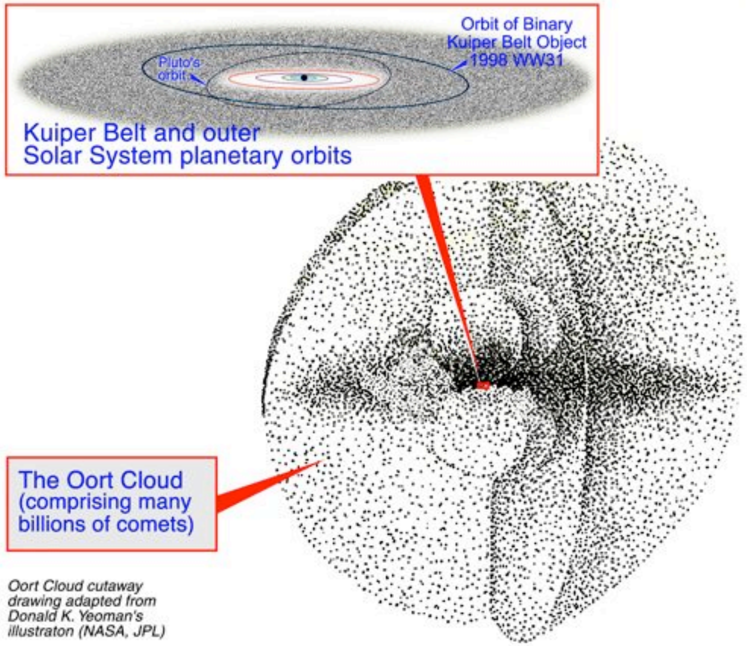
- Comets are made up of rock, frozen gases and ice
- Comets have 2 tails - a dust tail and a ion tail. These tails always point away from the direction of the Sun



Comet tails - the dust tail (yellow) curves towards the path of the comet. The ion tail (blue) points directly away from the Sun.

Image courtesy of NASA

A cracking comet - in March 2010, amateur astronomer Nick Howes discovered that Comet C2007 Q3 Siding Spring was breaking up during its orbit around the Sun. This image shows the fragments coming from the comet's centre (Image courtesy of Faulkes Telescope Project/ LCOGT)



Oort Cloud cutaway drawing adapted from Donald K. Yeoman's illustraton (NASA, JPL)

- Short-period comets, which take less than 200 years to orbit the Sun, originate from the Kuiper belt, around the orbit of Pluto
- Long period comets, which take more than 200 years to orbit the Sun, originate from the Oort cloud
- The Oort cloud lies at the edge of our Solar System, at a distance between 5,000-100,000 AU. That's 7.5×10^{11}-1.5×10^{13} km!

Asteroids: Boulders in space

Comets are not the only dangerous objects to us here on Earth. In the following pages we move into the part of the Solar System called the Asteroid Belt, where thousands of rocks litter the space between Mars and Jupiter.

What?

Asteroids are basically lumps of rock. Today they mostly reside in a band that circles the Sun called the Asteroid Belt, which lies between the orbits of the planets Mars and Jupiter (to be precise, the Asteroid Belt is found between 300 million km and 490 million km from the Sun; to compare, Earth is about 150 million km from the Sun). The biggest asteroid, called Ceres (pronounced seh-rez) is 974 km wide. The smallest asteroids are less than a metre across, and there are millions of them in the Asteroid Belt.

There are even some that lurk outside the Asteroid Belt, floating around the orbits of the planets. Sometimes they come close to the Earth, with the potential to crash into our planet. We call these Near Earth Objects, or NEOs. An asteroid colliding with Earth is thought to have been a major reason why the dinosaurs died off 65 million years ago, but we'll come onto that later.

How?

When the Earth and the rest of the planets were forming all those billions of years ago, the Solar System was full of asteroids. The asteroids were created from a dusty, gaseous disc that had formed around the young Sun. These asteroids then began to merge to form bigger and bigger objects called planetesimals, which then grew into planets like Earth and Mars. Life in this construction yard wasn't fun; colliding with other asteroids and gathering up debris, all the while trying to avoid getting pulverised by a larger object. The rocks in the Asteroid Belt are the leftover rubble from this construction period. Therefore asteroids are the building blocks of planets, which means they are made of the pure material from which the Solar System formed. Consequently, by studying what asteroids are made of, we can find out about the materials that originally built the Earth.

There are three ways we can discover what asteroids are made from. One way is by sending space probes to investigate them, taking pictures or even landing on them. This is what NASA's NEAR-Shoemaker spacecraft (Near Earth Asteroid Rendezvous; Shoemaker refers to Gene Shoemaker, the legendary planetary scientist and asteroid and comet discoverer) did when it arrived at the asteroid Eros in the year 2000. Alternatively, sometimes asteroids come to us, in the form of tiny chunks of rock blasted off their surfaces that then fall to Earth as meteorites. However, space missions are expensive and are few and far between, while you need a certain degree of luck to find meteorites. Astronomers therefore use a third method for measuring what asteroids are made of, and this method is called spectroscopy.

Different materials absorb and reflect light from the Sun at different wavelengths. By identifying these different wavelengths astronomers can work out the make-up of an asteroid's surface.

C-type, S-type and M-type asteroids?

In 1975, three astronomers – Clark Chapman, David Morrison and Ben Zellner – characterised asteroids depending on their composition by using spectroscopy, and put them into three main groups. The first group are the C-type asteroids. These are made from so-called carbonaceous materials, which are rich in carbon-based compounds. C-types are the most common, constituting around 75 percent of all asteroids in the Asteroid Belt, and are most numerous in the middle to outer regions of the Belt. They are generally coloured a ruddy, dark hue, reflecting less than 10 percent of the sunlight that falls on them, and they also contain a large amount of water molecules, but hardly any metallic elements.

The next type of asteroid is the S-type. The 'S' stands for the rocky silicate minerals that make up the majority of their composition – also large amounts of iron, magnesium and nickel are present, but barely any water, in contrast to the C-types. They are also a little bit brighter than C-types, and constitute 17 percent of the asteroids in the Asteroid Belt.

The third and final major type of asteroid is the M-types. Here, the 'M' stands for metals, as M-types contain more metallic elements than other types of asteroids. They also contain rare metals, such as platinum. Indeed, a large amount of the platinum on Earth comes from a giant impact crater called the Sudbury Basin in Canada, where a giant M-type asteroid struck the Earth 1.8 billion years ago.

The geology of asteroids can tell us a great deal, not only about conditions in the Solar System when they formed, but also what has happened to the asteroids since then. When it comes to the composition of asteroids, think of a bucket of sand, grit and pebbles, all shaken and mixed up. Believe it or not this is the typical composition of many smaller asteroids, just a loose jumble of rock and dirt. But then add sufficient gravity and over time the various types of material will begin to settle, with the largest pebbles sinking to the bottom, then the grit, with the lighter sand filtering to the top. This is what has happened to a few asteroids, such as Ceres, Pallas and Vesta, which grew large enough for their material to become layered – all the heavy iron sank to their centres, while the lighter, less dense material was nearer the surface. This process could only happen if the asteroids were hot enough for their rock to be soft and molten, a bit like the molten lava that spews from volcanoes. The heat for this may have come from their formation, but also from radioactive rocks deep within the asteroids.

Some of the larger C-types may have even contained some liquid water long ago when they were still warm. Evidence for this comes in the form of clay materials present on some asteroids that could only have formed in water. Meanwhile some of these asteroids were then smashed apart in collisions with other asteroids, and their fragments still bear the scars of these violent crashes, with minerals flash-heated to form other types of minerals. Spare a thought for poor old Vesta, which had large parts of its body smashed off in a collision. The chunks of debris now form the Vesta family of asteroids, some of which have found their way to Earth in the form of meteorites.

On a collision course

Sometimes asteroids don't just come to Earth in pieces; on occasion an entire asteroid has crashed into Earth. Sixty-five million years ago, a 10 km wide asteroid smacked into Earth in the Yucatan Peninsula in Mexico, leaving behind a 180 km wide crater called Chicxulub. The impact sent huge clouds of dust and ash into the sky, blocking out the Sun and sending temperatures across the world plummeting. The impact has been linked to the extinction of the dinosaurs, and although the impact may not have been solely responsible for their extinction, it almost certainly played a significant role. Several other extinctions in Earth's history have also tentatively been linked to asteroid impacts.

Should we be worried about being wiped out by an asteroid impact? Not especially. It turns out that an asteroid 50m in diameter will collide with Earth every thousand years, and asteroids this size are capable of creating a crater 1 km wide. The famous Meteor Crater in Arizona is a good example of an impact of this size. A crater is always bigger than the asteroid that creates it, simply because of the amount of kinetic energy in the asteroid as it hurtles towards the ground.

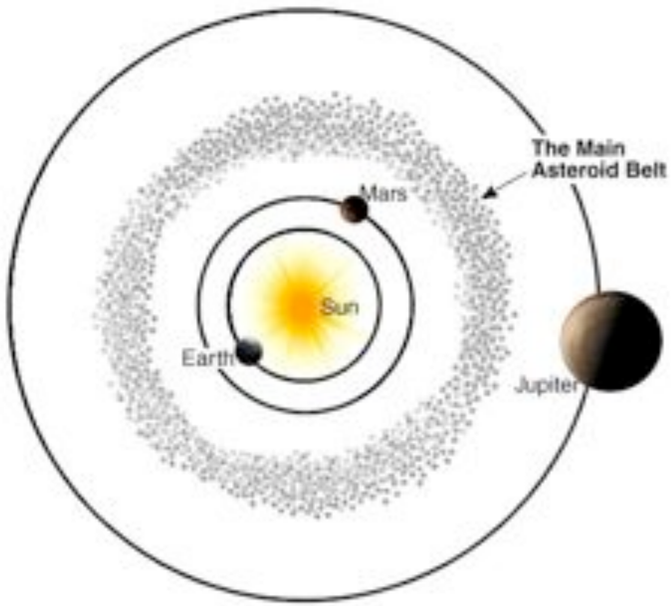
A larger asteroid 1 km across is estimated to hit Earth on average every million years. An impact this size would release a whopping 40,000 megatons, blasting a crater 17 km from one side to the other in the ground, with a blast wave that can carry debris, flatten buildings and burn trees up to 300 km away. An impact of this size, whilst capable of doing lots of damage (especially if it landed in the ocean, causing a giant tsunami), wouldn't threaten humanity with extinction. This threat lies with asteroids around 10 km in diameter, which impact on Earth on timescales of tens to hundreds of millions of years. So, based on those odds, we should be alright – for the time being at least.

Quick facts about...

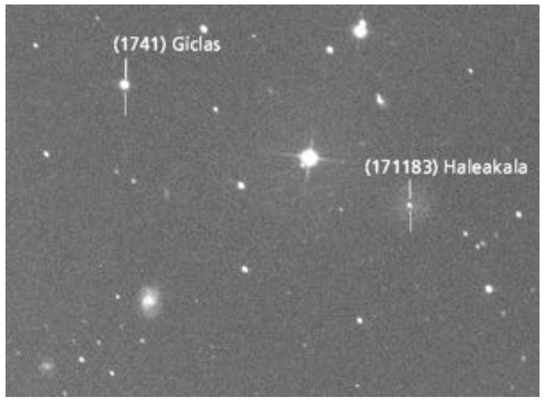
Asteroids

At a glance...

- Asteroids are rocky objects which orbit the Sun in our Solar System but which are too small to be considered planets
- They are thought to be leftover debris from the formation of our Solar System
- The majority of asteroids can be found in the 'Asteroid Belt' between Mars and Jupiter
- Hundreds of thousands of asteroids have so far been discovered and users of the Faulkes Telescopes have contributed to these discoveries!



Asteroid 'Snowdonia', discovered by users of Faulkes Telescope North



Asteroid 'Haleakala', discovered by users of Faulkes Telescope North. A second asteroid, Giclas, can also be seen in the image.

Activity

Measuring Impact Craters on Earth

In this activity you will be measuring craters of different sizes on Earth which are the result of an impact from space. The impacts causing these craters would result in a variety of climatic changes - small impacts would generally affect only the local area, whereas larger impacts could have massive changes in the global weather systems. To begin, download Google Earth, then follow the instructions below.

What will I need for this activity?

- Google Earth - download from: http://earth.google.com/

Finding and measuring impact craters

In order to find the impact craters that you will be measuring for this activity, you will have to enter the latitude and longitude of the craters into the 'Fly To' box in Google Earth.

- In the lat/long boxes, enter the co-ordinates of the place you wish to view. For example, to view the **Barringer Meteor Crater** click in the 'Fly to' box and enter 35 02 N, 111 01 W

- To measure the craters listed in the table below, you will use the Measure tool in Google Earth. To find this in the main Google Earth menu, click on Tools > Measure . Or, click on the  symbol at the top of the window. A pop up box will appear in which 'line' is already selected. Click on the units box to select km.

You can now measure the diameter of each impact crater in Google Earth by using the left button of the mouse and dragging the line across the width of the crater. The distance measured is shown in the pop-up box.

Measuring the sizes of impact craters

Find the impact craters listed in the table on the next page using Google Earth and measure their largest diameter (some of the craters are elliptical in shape, not round).

Crater Name	Latitude	Longitude	Size (km)
Barringer Meteor Crater This meteor crater was formed about 50,000 years ago by an iron meteorite impact. It is very easy to find in Google Earth.	N35 02	W111 01	
Manicouagan This impact crater is one of the oldest known craters on Earth. It was formed about 200 million years ago, and although some of the crater has been worn away by erosion, it is still very clear and easy to find in Google Earth.	N51 23	W68 42	
Clearwater Lakes These 2 impact craters were formed by a pair of asteroids hitting the Earth's surface. In one of the craters, a circular area of islands can clearly be seen. This is an elevated part of the crater, as seen in a complex crater. The central part of the second crater cannot be seen however as it is below the water.	N56 13	W74 30	
Upheaval Dome Originally thought to be a collapsed salt dome, this crater has all the features of a typical impact crater - a central peak, an inner crater and outer concentric shock rings. This makes it easy to identify in Google Earth.	N38 26	W109 54	

Comparing the sizes of impact craters with local distances

Once the size of each impact crater has been determined in Google Earth, a comparison can be made with distances local to your school or home. This will give some perspective on the sizes of these objects.

1. Enter the street name or postcode of your school/home in the '**Fly to**' box in Google Earth.

2. Once Google Earth has flown to your location, choose the measure tool once again by clicking on the ruler.

3. Using the mouse, left click on your location to mark the point where you would like your line to be drawn from. Make sure your units are in 'kilometres' again so you can make a proper comparison with the impact craters.

4. Zoom out of your location in Google Earth so that you can fit a line the size of one of the impact craters, onto your map.

5. Finally, extend your line until its length equals the size determined for each impact crater previously. This puts into perspective how big the impact craters really are!

Activity

Measuring Impact Craters on Earth

Bang!

During this activity you will be using the impact calculator to try and reproduce some of the real impact craters we see on Earth.

What will I need for this activity?

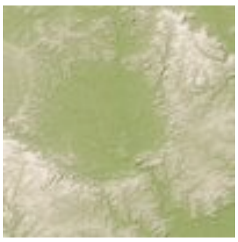
- Access to the Impact Calculator: http://education.down2earth.eu/impact_calculator

Method

Input the following data into the impact calculator to make craters similar to those on Earth. Set your distance from impact as 500km so that you are not destroyed by the larger impact events and record your results in the table.

Barringer Meteor Crater, USA

Projectile Diameter: 100 m
Projectile Density: Iron (8000 kg/m^3)
Impact Velocity: 20 km/s
Impact Angle: 45°
Target Density: Sedimentary rock



Ries Crater, Germany

Projectile Diameter: 1500 m
Projectile Density: Dense rock (2700 kg/m^3)
Impact Velocity: 20 km/s
Impact Angle: 30°
Target Density: Sedimentary rock

Chesapeake Bay, USA

Projectile Diameter: 3500 m
Projectile Density: Dense rock (2700 kg/m^3)
Impact Velocity: 20 km/s
Impact Angle: 45°
Target Density: Sedimentary rock

Crater Name	Impact Energy	Crater Depth	Crater Diameter	Other effects	Frequency of impact
Barringer					
Ries					
Chesapeake Bay					

Snap!

Below are 3 impact craters found on Earth. Using the impact calculator, can you fill in the gaps for the details of the impactor to match these craters?

Hint: There may be more than one way of forming each crater!

Crater Name	Projectile Diameter	Angle of impact	Object Velocity	Projectile Density	Target Density	Crater Diameter
Tenoumer crater – Africa		45°	20km/s		Sed. rock	1.8 km
Clearwater Lakes – Canada		45°	20km/s			30km
Chicxulub – Mexico						180km

The impact calculator which you used for the above activity is based upon equations and research carried out by scientists at Purdue University in the US.

But there are also scientists here in Wales who are interested in finding and identifying impact craters on Earth. On the next page, one of these scientists, Dr Iain MacDonald from Cardiff University, chats to us about his work and how he developed an interest in impact craters and finding bits of rock from space.

Career Profile

Name: Iain McDonald

Age: 41

Job title: Research Geochemist

Likes: (i) days when my instruments work perfectly; (ii) fieldwork in exciting places; and (iii) finding out things that are new and unexpected.

Dislikes: Bureaucrats and their endless quest to devise the most time-wasting tasks.

Place of work: Cardiff University

What qualifications do you have which enabled you to work in impact rocks and meteorites?
BSc Hons Chemistry & Geology (University of Glasgow)
PhD Geology (University of Cape Town)

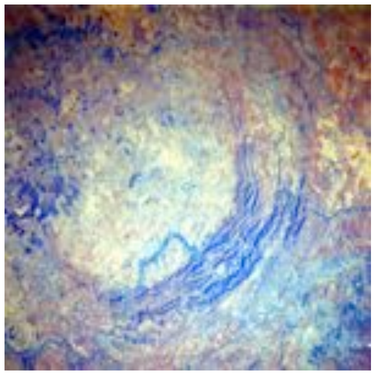


Image Credit: NASA

What sparked your interest in impact rocks and meteorites?
Field visits with my PhD supervisor, Rodger Hart, to the Vredefort impact crater in South Africa.

What are you working on at the moment?
Chemical analysis of impact ejecta from Greenland, Australia and South Africa. Platinum mineral deposits in South Africa.

Describe a typical day in the life of a Geochemist?
Preparation and analysis of samples. Collation and interpretation of chemical data. Lots of head scratching before the lightbulb comes on and I understand what it might mean.

What's the most exciting/interesting part of your job?
You never know what the next sample is going to throw up.

What advice would you give young people who are interested in a career in impact rocks and meteorites?
Don't take the easy option. Study pure science subjects like Physics, Chemistry and Maths. You can't get anywhere in this area without them.

What do you like doing outside of work?
Astronomy, football, studying early 20th century history.

Iain MacDonald, geochemist at the School of Earth & Ocean Sciences at Cardiff University, has been studying possible impact structures across the world, and using a group of elements found in the periodic table, known as Platinum Group Elements (PGEs) to help decide if the craters were formed by impacts from space.

Geologists and geochemists are especially interested in PGEs as they can be an indication that a projectile from space has impacted the Earth sometime in the past.

Almost all meteorites have concentrations of PGEs that are much higher than in the average crustal rocks of the Earth - 20,000-100,000 times higher! Even a small meteorite hitting the Earth would result in a large deviation from the normal measured concentrations of PGEs in the impacted area.

The ratios of each of the elements in PGEs also gives scientists an indication of the type of impactor that has struck the Earth, since different classes of meteorites contain differing ratios of elements.

Platinum Group Elements - What are they?

Platinum group elements are metals which have similar physical properties. They have high melting points, do not react to other elements and ions, and are amongst the rarest elements found in the Earth's crust.

The PGEs consist of:

- Ruthenium
- Rhodium
- Palladium
- Osmium
- Iridum
- Platinum

Their position in the periodic table can be seen below.

PGEs occur naturally on Earth, but they are very rare and precious. They are much more abundant in the asteroids in our Solar System, which are the leftover debris from the formation of the inner planets.

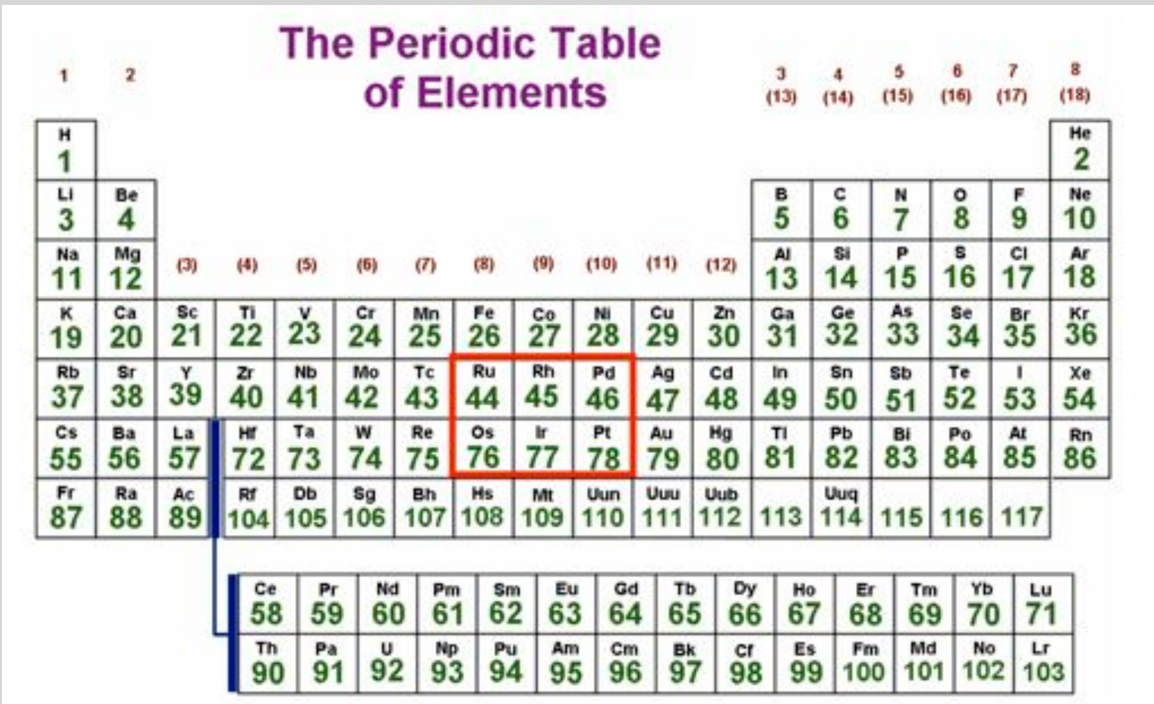


Image courtesy of US Geological Survey (http://www.usgs.gov/)

One of the impact craters studied by Iain is Chesapeake Bay in North America. This crater, discovered accidentally in 1983 by a deep sea drilling project, is thought to have formed about 35 million years ago during the time known to geologists as the Eocene epoch.

The start of this time period or epoch, approximately 56 million years ago is marked by the emergence of the first modern mammals. Scientists believe this epoch lasted about 22 million years, with the end occurring at a time when a major extinction event occurred on Earth, possibly due to an impact in both Siberia and at the site of the Chesapeake Bay crater.

Finding PGEs can help prove that a structure was formed due to an impact, so in 2009 Iain set about trying to find evidence of PGEs in rocks from a drilled hole in the Chesapeake Bay crater. The analysis of the rocks did not obviously identify any raised level of PGEs, so no firm conclusion could be reached. Although further work has been carried out on Chesapeake Bay by other scientists, who suggest it is an impact crater, Iain's work unfortunately couldn't corroborate their results and so the question of the nature of this structure, as yet, remains unanswered...

Meteorites

Meteor from Kappa Cygnid Meteor Shower.
Image credit: Jimmy Westlake

A falling star: The Meteorite

Have you ever seen a shooting star? If you've ever spent time looking up at the night sky, then you probably have – a streak of light flashing through the sky high above for a moment, and then gone – sometimes so quick you can't be sure if you have really seen something, or imagined it. But shooting stars are definitely real.

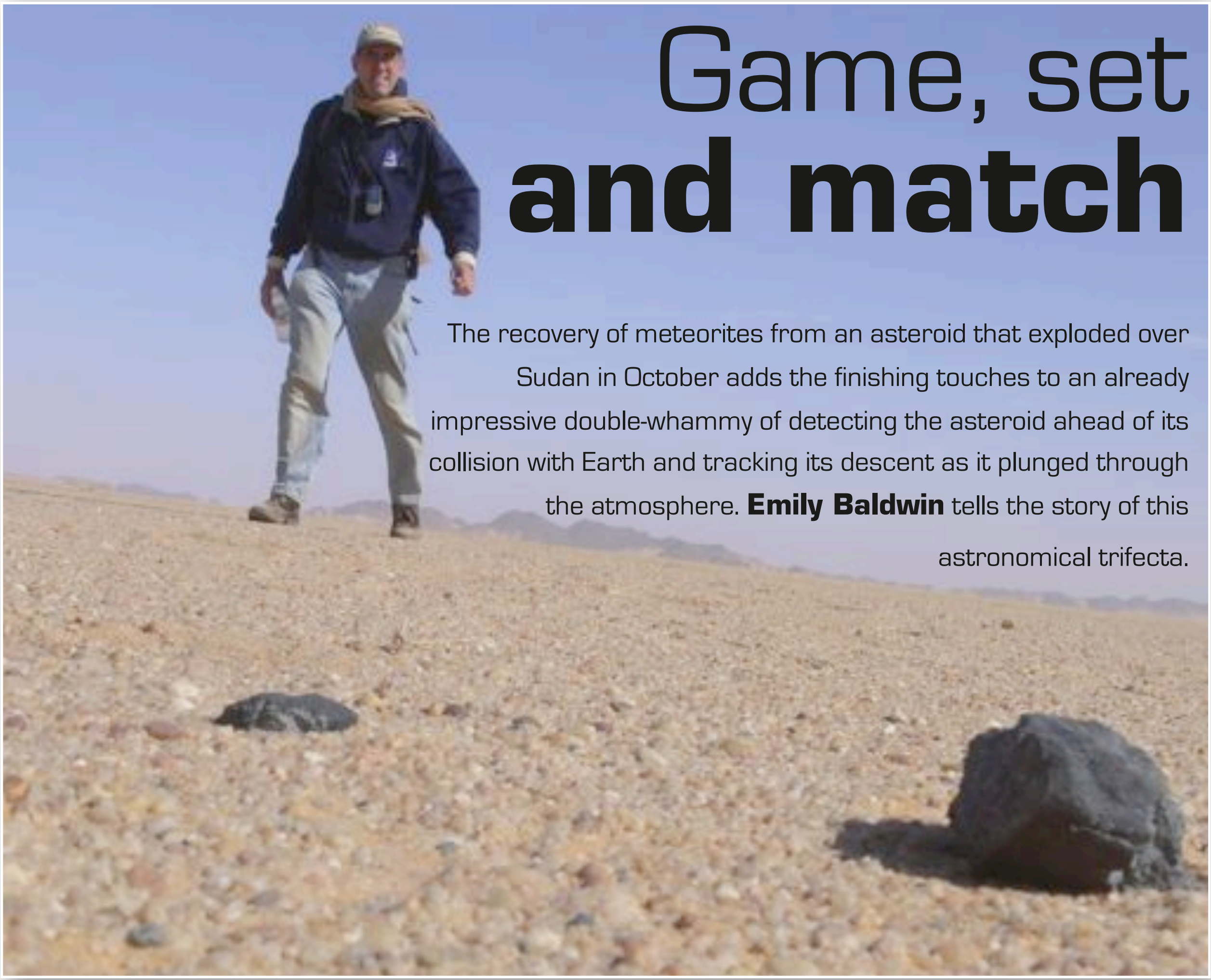
Next question, a little bit harder this time: do you know what a shooting star is? Its name is a little bit misleading. Shooting stars are not really stars. Our Sun is a star, our closest star, and the other stars are light years away, so we can count them out. Believe it or not, shooting stars are just tiny bits of dust entering our atmosphere from space. Tiny particles, like grains of sand, crash into Earth's atmosphere at 70 km per hour, between 50 and 100 km above our heads. The light we see is the glow of the heated air around them as they fly into the atmosphere and burn up.

Sometimes something a little bigger than a pebble will shoot through the atmosphere, and we see these as fireballs – if you are lucky enough to see a fireball then you might even see flames shooting from it. You can see video footage on the Internet of fireballs bright enough to cast shadows. But not to worry, fireballs are not dangerous – like shooting stars, they are high above us.

Occasionally, the bit of rock can be so big that it does not all disintegrate while entering the atmosphere - and it falls to the ground. We call these meteorites (while they are flying through the atmosphere as shooting stars we call them meteors, and while they are in space we call them meteoroids – it is important to remember the difference). A whopping 38,000 meteorites have been found on Earth so far, from all over the world, but most are found in the desert or in snowy Antarctica. This is because meteorites are dark rocks that stand out on the barren sand or snow.

Game, set and match

The recovery of meteorites from an asteroid that exploded over Sudan in October adds the finishing touches to an already impressive double-whammy of detecting the asteroid ahead of its collision with Earth and tracking its descent as it plunged through the atmosphere. **Emily Baldwin** tells the story of this astronomical trifecta.



Dr Peter Jenniskens stumbles across meteorites from asteroid 2008 TC3 in the Nubian Desert.

There are some 6,000 Near-Earth Asteroids (NEAs), most no larger than 1km wide, lurking in the Earth's neighbourhood, and at 6:39am UT on 6 October a small four-metre-wide object joined the gang. Attracting the attention of Richard Kowalski of the Catalina Sky Survey, who was using the Mount Lemmon 1.5-metre telescope to scan the sky, this asteroid clearly had Earth in its sights. Preliminary orbital calculations at the Minor Planet Center predicted an impact with the Earth above the skies of Sudan within 21 hours. A rapid observation campaign ensued, supported by amateur and professional astronomers alike, and sure enough, the asteroid – by this stage assigned its tag of 2008 TC3 – impacted right on schedule at 2:46am UT on 7 October. Eyewitness reports of a bright flash by a KLM airline pilot flying nearby were supported by observations from the Meteosat 8 weather satellite, which recorded a sudden localised heating in the atmosphere. Striking the atmosphere at 12.4 km/s and at a shallow 20 degrees above the horizon, the asteroid exploded at an altitude of 37 km with a force equivalent to around one kiloton of TNT.

Picking up the pieces

Soon after, mobile phone images captured by locals living in villages along the River Nile began to surface, showing that the impact left a cloud of dust in the atmosphere. Experts were skeptical that any fragments could have reached the ground intact, since meteorites have never before been collected from such a high altitude explosion. Even Dr Peter Jenniskens, who led the expedition that would eventually collect 280 fragments, was sceptical.
"I wasn't confident at all!" he told Astronomy Now. "It was just that if something could be collected it would clearly be very important for science. On my first trip to Khartoum at the beginning of December I really went with the expectation that the trip would be a success if I

just got the chance to talk to some of the eyewitnesses in the area."

Researchers at the University of Khartoum, led by Mauwia Shaddad from the Physics Department, were already prepared with a busload of 45 students and staff to help Jenniskens. The team set off into the Nubian Desert to an area where small pieces might have fallen.

"Since the material that came from the explosion was still moving at its original speed and pretty much unstopped by the atmosphere at this point, the pieces were really spread out," says Jenniskens. The first fragment was found by student Mohammed Alameen after two hours of searching and, after two more trips, almost 280 fragments were recovered in total from an area 29 x 9 km wide. "This was an extraordinary opportunity, for the first time, to bring into the lab actual pieces of an asteroid we had seen in space," says Jenniskens. "Sure enough, we found a material so fragile that it was not yet in our meteorite collection."

A match made in heaven

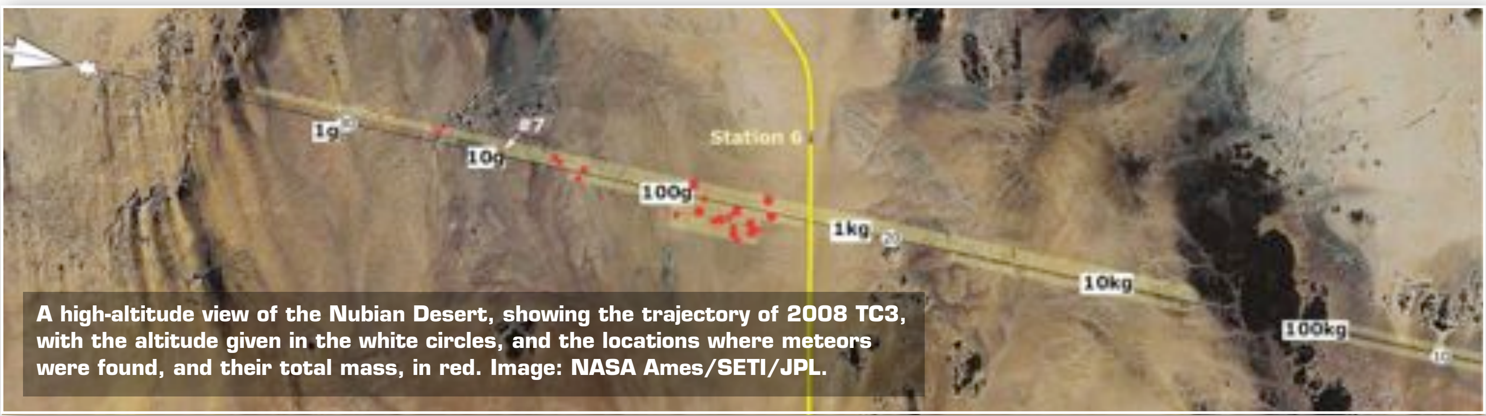
Before it met its demise in Earth's atmosphere, the asteroid was subject to intense scrutiny by ground-based telescopes, including the 4.2-metre William Herschel Telescope at La Palma. A team of British astronomers was already at the telescope when

Students and staff from the University of Khartoum criss-cross the desert in search of meteoritic fragments.

they received news of the asteroid's approach and, in the four and a half hours before the impact, they used the telescope's spectrometer to measure how light was reflected from its surface. Reflectance spectroscopy allows astronomers to categorise asteroids into some twenty classes, each having a slightly different spectrum and assigned a different letter of the alphabet. Around three-quarters of all asteroids are dark carbonaceous C-class asteroids, but until now it has been very difficult to link these asteroid classes to meteorite types.

"Astronomers measured 2008 TC3 coming in, and saw it was an F-class asteroid," says Dr Janice Bishop of the SETI Institute, who joined Jenniskens in measuring the reflection properties of the meteorite fragments in the

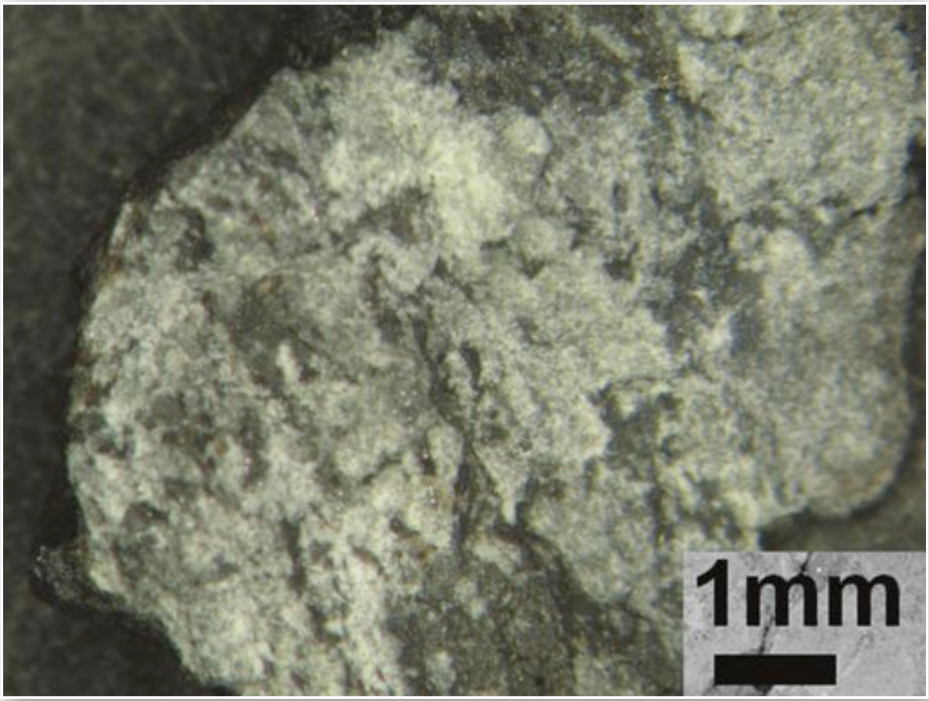
"STRIKING THE ATMOSPHERE AT 12.4 KM/S AND AT A SHALLOW 20 DEGREES ABOVE THE HORIZON, THE ASTEROID EXPLODED AT AN ALTITUDE OF 37 KM WITH A FORCE EQUIVALENT TO AROUND ONE KILOTON OF TNT."



A high-altitude view of the Nubian Desert, showing the trajectory of 2008 TC3, with the altitude given in the white circles, and the locations where meteors were found, and their total mass, in red. Image: NASA Ames/SETI/JPL.

laboratory and helped discover that both the asteroid and its meteoritic remains reflected light in much the same way. Marrying up measurements in this way is usually hampered by the fact that large asteroids have dusty, rubble-strewn surfaces that reflect light in spurious ways. Asteroid 2008 TC3, on the other hand, was only four metres wide with low gravity, and therefore offered a relatively clean surface for study. “Most lab rocks are between 20–40 percent reflectance, but these pieces were 2–3 percent, really dark.”

F-class asteroids are a sub-division of the C-class asteroids, accounting for just 1.5 percent of known asteroids, and the fragments of 2008 TC3 correspond to an equally rare group of meteorites known as ureilites. Futhermore, the newly found meteorites display a



The contrail left by the exploding asteroid, captured on a mobile phone camera. Image: Muawia Shaddad.

texture and composition unlike any other ureilite meteorites found on Earth before. Curiously, not all the meteorites from 2008 TC3 have the same composition, with some fragments exhibiting very fine grained texture and light material while others are very black and coarser grained.

“This particular asteroid had a wide range of materials in it and we are hoping that the fact that this is an anomalous material for this type of polymict ureilite will help explain the properties of ureilites and how these different meteorites were formed,” says Jenniskens. The textures suggest that parts of the meteorite were melted, while other parts escaped heating. “Was this heating a deep magma event inside the interior of the asteroid or was it a surface process associated with impact? Investigating the textures and compositions will be the next step in unravelling the history of the parent asteroid.”

Some clues can be gleaned from studying the orbit of the asteroid,

The contrail left by the exploding asteroid, captured on a mobile phone camera. Image: Muawia Shaddad.

A dark, rough-textured fragment of 2008 TC3.

which was quantified to a degree 10,000 times better than typical orbits derived from solely observing a fireball for a few seconds. From some 20 hours worth of measurements astronomers produced such an accurate orbit that 2008 TC3's journey through space could by traced back in time. Its orbit was highly elongated, with its furthest point in the Asteroid Belt and nearest point near Earth's orbit. But in the past the orbit was even more elliptical, stretching deeper into the Asteroid Belt.

"There is only one F-class asteroid that has such an orbit now and that is 1998 K2," says Jenniskens. That means 2008 TC3 and 1998 K2 could both originate from the same debris field in the Asteroid Belt, regions that have resulted from ancient collisions between asteroids. "What's interesting is that debris fields tend to consist of asteroids of one particular taxonomic class, so it may be possible to identify the exact debris field from which 2008 TC3 originated. By linking meteorites to asteroids in such a direct manner, this whole picture of where things are found in the Asteroid Belt becomes a geological map of the Solar System instead of just being a classification of objects. If we find a few more of these F-type asteroids it may take us back to the exact place in the Asteroid Belt where these come from, but that's only possible to do when the orbit is so well determined."

A lesson in planetary protection

Knowing the nature of F-class asteroids could contribute to designing ways of protecting Earth from possible future impactors that may pose a threat to civilisation. The fact that 2008 TC3 exploded so high in the atmosphere meant it was very weak, but striking such a fragile asteroid with an atomic bomb, for example, would merely turn it into a swarm of deadly impactors, highlighting the importance of selecting the right defence technique for certain types of asteroid. At this moment, surveys of large (approximately kilometre- sized) Near Earth Objects (NEOs) are nearly complete, and so the attention is shifting to smaller NEOs. The Pan-STARRS (the Panoramic Survey Telescope and Rapid Response System) project is set to catalogue up to ten million main belt asteroids and tens of thousands of NEOs down to a diameter of just 300 metres.

Such objects, while not capable of wiping out life on Earth, would still cause considerable local damage; the Tunguska asteroid of 1908 was just a few tens of metres across and yet flattened 2,200 square kilometres of forest. Jenniskens expects that as more small asteroids are uncovered in surveys like Pan-STARRS, there will be more incidents like 2008 TC3, where a dramatic prediction of an impact is followed up with an intense observation campaign as the asteroid approaches and enters Earth's atmosphere, culminating in the recovery of fragments by meteorite hunters.

Every new case will add another rung to the ladder that links meteorites to asteroids, and ultimately enable us to unravel the geological history of our Solar System with greater clarity than ever.

Activity

Following the Falling Meteorite

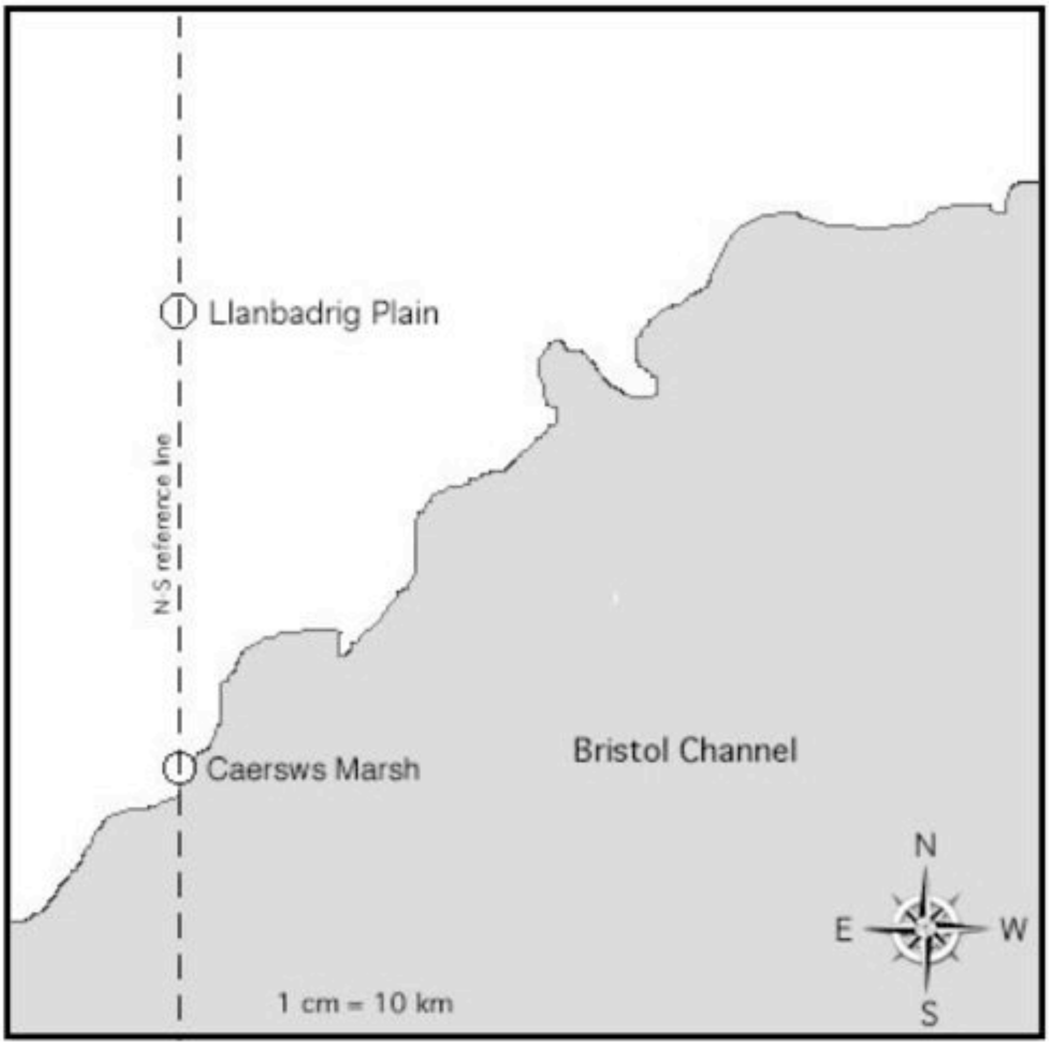
It's possible for a scientist to determine a meteor's original orbit in space and as you have just read, in one particular case, the recovery of meteorites from the disintegration of an asteroid has given experts some very detailed information indeed. In this activity, you will track a meteor's path using a techniques known as triangulation, where you measure the directions to an object from 2 known locations. From this you can predict where the meteorites might be found.

What will I need for this activity?

- Protractors
- Rulers
- Coloured pencils

Path and Speed of a Meteor

Using the map provided, triangulate the path and explosion of a meteor and work out the best area in which you should look for meteorites.



The map shows the location of 2 people when they saw the meteor. The observer in Llanbadrig Plain was looking 80 degrees East of North when she saw the meteor explode.

Method

1. From Llanbadrig Plain, measure an angle 80° East from the dashed N-S reference line, mark the angle, and with a coloured pencil draw a long line from Llanbadrig Plain through the mark you made.

The observer in Caersws Marsh was looking in a direction 40° East of North when he saw the meteor explode.

2. From Caersws Marsh measure an angle 40° East from the dashed N-S reference line, mark the angle. Using the same colour pencils draw a long line from Caersws Marsh through the mark you made.

Your challenge: find the Meteorite!

Q. Where do the two lines cross?

Q. Where did the meteor explode?

Both observers also saw the meteor shed a spark some time before it exploded (assume the meteor's path was horizontal). The observer in Llanbadrig Plain was looking in a direction 110° East of North when she saw the spark fly.

3. Using the same technique as in step 1 and a different colour pencil, draw a long line from Llanbadrig Plain in that direction.

The observer in Caersws Marsh was looking in a direction 60° East of North when he saw the spark fly.

4. Draw a long line from Caersws Marsh in that direction.

Q. Where was the meteor when the spark flew?

Q. Using the positions of the spark and the explosion, which direction was the meteorite travelling in?

Q. How far was it from where the meteor sparked to where it exploded?

Q. Where would you first look for meteorites that might have fallen from the explosion?

Q. If both observers counted 2 seconds between the spark and the explosion, how fast was the meteor going (km/hr)?

Meteor Showers

Why is space filled with these chunks of rock and dust? They are leftover bits and pieces from when the planets formed, over four and a half billion years ago. The biggest chunks of rock are called asteroids, which we have already come across. As we have already discovered, comets are also leftover debris from the planet-building phase, but they are made of dust and ice, rather than solid rock. When they swoop near the Sun they grow a tail of dust that's vaporised from their surface by the Sun's warmth. Periodically Earth will move through the path of one of these comet tails – the dust itself can linger for decades, long after the comet has been and gone – and we get a meteor shower, where there can be dozens or, during a particularly good meteor shower, hundreds of shooting stars per hour. The best meteor showers are the Quadrantids that peak on 3 January every year, the Lyrids that peak on 22 April, the famous Perseids on 12 August, the Orionids on 22 October, the Leonids on 17 November and the Geminids on 14 December. The Geminids, it is thought, are actually dust from an asteroid called Phaethon rather than a comet – and it has been shown that Phaethon was originally part of the second biggest asteroid Pallas, but was smashed off in a mighty collision with another asteroid billions of years ago.

How to watch a meteor shower

Watching a meteor shower can be one of the most enjoyable things about observing the night sky, waiting with tense excitement to see the next shooting star. The best meteor shower is the Perseids – not because it necessarily has the most meteors, although it does have as many as 100 per hour – but because you can sit out in the garden during the warm summer night to watch them, rather than having to wrap up in your scarf, bobble hat and gloves during the middle of winter, as you would have to for watching the Geminids in December.

For the best meteor viewing, find a dark corner of your garden or from wherever you are observing. Allow time for your eyes to adjust to the darkness, and use a red light torch rather than a normal torch, so that you do not ruin your night vision.

To avoid going back inside, bring a flask and some snacks with you and wrap up warm – even in August for the Perseids, it can still get chilly late at night. A hat is essential, as your body loses much of its heat through your head.

Now, you have probably discovered that when looking at the stars, straining your neck to look up all the time can quickly become uncomfortable. For meteor watching, a deck chair is ideal – you are angled comfortably upwards.

Simply watching for meteors and counting up how many you see in your head is fun, but if you want to be a proper scientist then you need to record your results, as you would during a real science experiment. With a clipboard, pen and paper, write down the time that you see each meteor, which direction the meteor comes from, its colour (if you can see any) and how bright it was (compared with perhaps the star Vega, or the stars of the constellation of Orion).

So you have spent some time out in the garden, watching and recording meteors. What do you do with your results? Send them to organisations such as the British Astronomical Association (www.britastro.org) and the Society for Popular Astronomy (www.popastro.com), who collate all the reports to look for trends in meteor showers – for example were they more or less active than in previous years, and if so, why?

By watching a meteor shower and reporting what you see, you could be contributing to real life science – how exciting is that?

Types of Meteorites

Chondrites

By far and away the most common type of meteorite is the chondrite – they number 27,000 out of the 38,000 discovered rocks from space. They're notable for their brilliantly coloured spherical crystals called chondrules, which are filled with all kinds of minerals such as olivine, pyroxene, iron and silicon. They are finished off with flecks of iron-nickel and sometimes calcium and aluminium too (the iron makes them slightly magnetic). Chondrites are thought to have formed at the same time as the inner planets, and preserve dust from the primordial protoplanetary disc that has been flash-heated to 1,000°C. Evidence of this is seen in the 'refractory inclusions' present in chondrites (refractory materials are elements that have condensed at high temperature but maintained their physical and chemical structure). The cause of this flash-heating is one of the many mysteries of the environment in which the planets formed; perhaps they were caught up in shock waves rippling through the disc, or got too close to the Sun, or were the victims of the constant onslaught of impacts as embryonic planets – planetesimals – smashed into one another.

Chondrites come in four divisions: ordinary, carbonaceous, enstatite and rumuruti. The latter two are quite simple; enstatite meteorites are oxygen poor, lack metals and number about 200 finds, whilst 900 rumuruti meteorites have been discovered, with a higher ratio of oxygen-17 to oxygen-16 than in Earth rocks, and totally devoid of any metals. Ordinary chondrites (which make up 90 percent of all chondrites) and carbonaceous chondrites are far more complex.

Meteorite NWA 801, a CR2 chondrite. Image: Meteorites Australia.

Achondrites

These are stony meteorites that have undergone a degree of thermal stress resulting in melting. Intriguingly, three of the most interesting types of achondrites – the howardites, eucrites and diogenites, or HEDs as they are collectively known – have been traced back to the second most massive asteroid, (4) Vesta, which was visited in 2011 by NASA's Dawn spacecraft. The theory is that HEDs are debris from a significant impact that Vesta suffered a few billion years ago, which ripped off about one percent of its mass. Howardites and eucrites are breccias (smashed rocks - howardites even contain bits of eucrites and diogenites), with the eucrites being basaltic and diogenites full of pyroxene that has settled out of cooling lava flows.

The Tatahouine meteorite, a pyroxene diogenite from Vesta. Image: Meteorites Australia.

The remaining categories of achondrite meteorites are the angrites and the aubrites. Angrites are very special. They have the same mineralogy as basalt (copious amounts of pyroxene and plagioclase), and less than twenty have been picked up worldwide, but that's not why they're special. It's the fact that they are incredibly old, having formed 4.556 billion years ago, which makes them so vital to studies of Solar System formation. Scientists have nailed the flag of the angrites to the masts of two asteroids, (289) Nenetta and (3819) Robinson, which are unprocessed lumps of primordial rock in the Asteroid Belt.

A slice of an iron meteorite displaying the Widmanstätten pattern. Image: Meteorites Australia.

Iron meteorites

The cores of large rocky bodies that are warm enough to become molten, or partially molten, will see all their iron sink to their cores. How then, do we find iron meteorites? The early Solar System was a dangerous place to be, with impacts and collisions a frequent occurrence. Over time some relatively large asteroids were chipped away, impacts smashing off their crusts and excavating their mantles to expose their metal core, which was also pulverised, sending shards of iron–nickel alloy spinning through the inner Solar System.

Iron is a somewhat more rare material than carbonaceous or silicate minerals, meaning that iron meteorite falls only account for five percent, and yet they are a popular member of meteorite collections. This is for a number of reasons; they actually look and feel like the stereotypical idea of a meteorite – dark, heavy and pitted – and for that reason they stand out more than stony meteorites when explorers are searching for them. Because of their density, they can also withstand atmospheric entry better than stony meteorites, and arrive in bigger lumps – all the largest meteorites found have been iron meteorites. They are also highly resistant to weathering, barring the odd spot of rust that can be easily cleaned off, and hence can survive for much longer on the surface of Earth than other types of meteorite.

Jargon buster

Aqueous alteration
The process by which minerals are altered following reactions with water.

Carbonaceous rock
Rock containing carbon-based minerals.

Isotopes
Variants of the same chemical elements that have differing numbers of neutrons.

Petrology
This is the study of rocks and how they form; hence petrological types.

Silicate rock
Rock containing stony, silicon-based minerals.

Volatiles
Materials that melt or boil at relatively low temperatures, such as carbon dioxide and water.

Slice an iron meteorite open and pour a nitric oxide/alcohol solution over the exposed innards, and you will be treated to an intricate pattern of criss-crossing bands known as a Widmanstätten pattern. These interlaced ribbons (called lamellae) occur when one of the two dominant minerals of iron–nickel meteorites, taenite, begins to cool and lose some of its nickel atoms, forming lanes of the second dominant material, kamacite, instead. This transformation takes place when the iron is solid but hot, from about 700°C down to about 450°C . When elements move from one mineral to another in solid rock, it is known as diffusion. The thicker the lamellae are, the slower the rock cooled.

Meteorites from Mars

The infamous ALH 84001 Mars meteorite, with its alleged microbial fossils, is unique in more ways than just its reputed evidence for Martian life. It also falls into a class of meteorite called an orthopyroxenite, of which it is the only member. More common Martian meteorites are the shergottites and the nakhlites, and both types have fascinating histories. The first known shergottite landed near Shergotty in India in 1865, and is a basaltic rock laced with pigeonite, augite and maskelynite, with much of the latter being transformed into plagioclase during the intense impact that dug the rock out of the ground on Mars and gave it enough energy to escape Mars' gravity and wind up here.

It turns out that there are two types of shergottite from two impact events, one 500,000 years ago and another three million years ago, and they can be identified based on whether they are coarse or fine grained. The fine grained material formed in lava flows, whilst the coarser material is rock that cooled slowly beneath the Martian crust, only to be erupted out onto the surface between 165 and 450 million years ago.

The nakhlites are even more interesting. Only seven are known, with the prototype having fallen in the Nakhla region of Egypt in 1911. Formed almost entirely from the green mineral augite, they also bear testament to the red planet's watery past, with small amounts of clays, carbonates and sulphates, and in one or two cases iddingsite, which forms from olivine that has been exposed to running water. Nakhlites have been dated back 1.3 billion years, and were wrenched off Mars in an impact some 12 million years ago.

The final known type of Mars meteorite are chassignites, of which only a pair are known, and they are rich in olivine having formed in Mars' crust. These little chunks of Mars, whilst no substitute for a bona-fide sample–return mission, help to bring the red planet to us.

Stony-iron meteorites and other oddities

A number of meteorites are a curious mixture of both stony and iron-based meteorites. Pallasites are extraordinary, with huge centimetre-sized gems of olivine called peridot, while mesosiderites contain half and half of iron and silicate. Both flavours of meteorite are suspected of having been spliced together underneath the vicious temperatures and pressures of large impacts with asteroids.

There are a handful of meteorites that don't fit in with any of the conventions, stubbornly refusing to be classified or their origin ascertained. Lead amongst these are the ureilites, which are made from olivine and pyroxene – fairly standard – but also contain curious veins of carbon-rich graphite and diamonds that can only form under high pressures, such as those experienced in impacts.

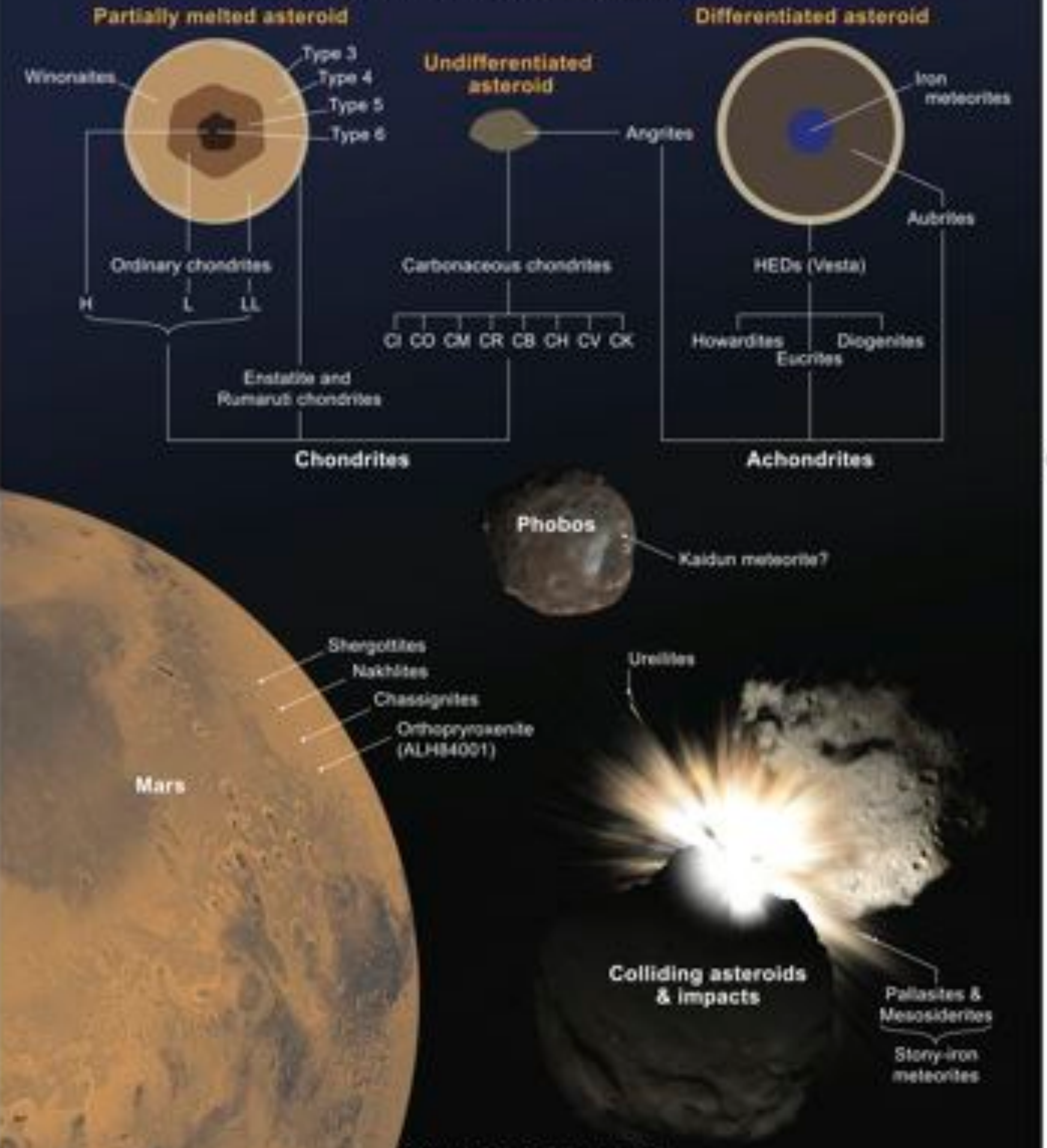
The problem is, impacts should transform delicate carbon-based material such as olivine. Another small group are winonaites, made mostly from low calcium pyroxene as well as a diverse mix of olivine, plagioclase, sulphides and metal. Winonaites are thought to arise from asteroids that started melting and forming differential layers of materials, before this was rudely brought to a halt by a large impact smashing the asteroid to pieces.

Finally, there are the brachinites, named after the Brachina meteorite that fell to Earth in southern Australia in 1974, and are composed mainly of olivine and basalt.

Meteorites

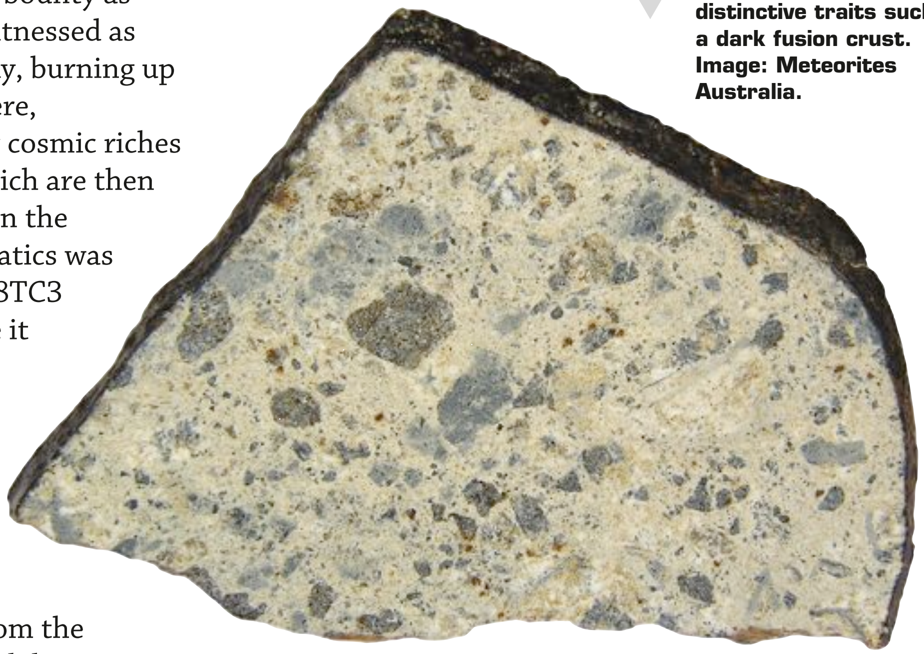
A FAMILY TREE

Meteorites hail from a variety of asteroids, some of which have completely melted and formed distinct cores, mantles and crusts (i.e. they have differentiated), others that have only partially melted, and some from lumps of rocks too small to have differentiated.



AN graphic by Greg Smye-Rumsby

A Meteorite Spotter's Guide



Some meteorites have distinctive traits such as a dark fusion crust. Image: Meteorites Australia.

Meteorite hunters classify their bounty as either 'falls' or 'finds'. Falls are witnessed as fireballs streaking through the sky, burning up with the friction of the atmosphere, fragmenting and showering their cosmic riches over many square kilometres, which are then hunted down. An example fresh in the memories of many meteorite fanatics was the chance event of asteroid 2008TC3 being identified just hours before it plummeted through Earth's atmosphere in October 2008, exploding about 37 km above the Nubian Desert in Sudan and spraying around four kilograms worth of rare ureilite-class meteorite over the desert. Around 300 fragments from the exploded meteorite were retrieved during subsequent expeditions weeks and months later. Finds, on the other hand, are often stumbled upon accidentally, many years or even centuries after they fell. Dedicated meteorite hunting trips, especially to places like deserts or the Antarctic, where the meteorites' characteristic dark black shell stands out against the desolate surrounds, turn up the majority of 'finds'. That's because these environments undergo slow change, preserving these rocks for tens of thousands to millions of years, compared with the 100 years or so it takes to break down a rock in wet climes, such as the UK, for example.

Meteorite or meteorwrong?

While you and I may not have the funds to spend six months on an Antarctic expedition to collect meteorites, all is not lost, for meteorites are found all over the world, with some 20 recorded falls in the UK over the last few hundred years. But how can you tell if you've picked up a piece of the early Solar System's history, or just a common garden rock? If you can answer yes to these questions you could have a national treasure in your hands:

Is it attracted by a magnet?

Meteorites have a high iron content so they will often attract a magnet. However, there are a lot of Earth rocks that are magnetic too, so you will need to answer some more questions to confirm your discovery.

Is it heavy for its size?

Because of their high iron content meteorites are quite heavy compared with Earth rocks of the same size.

Does it have a fusion crust?

When a meteorite careers through Earth's atmosphere it burns, forming a dark brown or black 'fusion crust'. If the rock is cracked open you will clearly see the thin veneer of the fusion crust against a pale interior. You might also see thin, wavy lines on the crust. These are flow lines caused by the surface having melted and flowed around the rock.

Does it have rounded corners?

Although meteorites are irregular in shape they will often have rounded corners, smoothed as they melted during their journey through the atmosphere. If a large flat surface is exposed, the other half of the rock may only be a stone's throw away (literally).

Does it have regmaglypts?

Regmaglypts, more commonly referred to as 'thumb-prints', are indentations in the meteorites' surface that look like a thumb has been pressed into a malleable material. While meteorites generally don't have holes, this thumbprint texture is often seen.

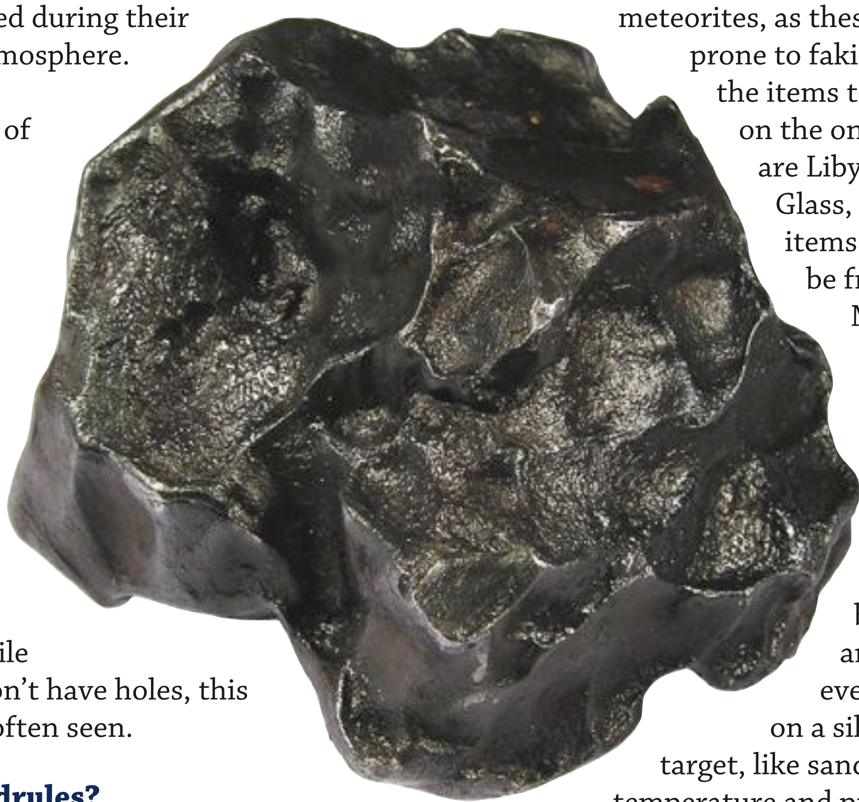
Does it contain chondrules?

If there are small round features inside the rock, which are sometimes exposed on the surface too, these might be chondrules. These spherical grains formed in the solar disc some 4.5 billion years ago and accreted to form the first rocky bodies in the Solar System and, ultimately, the planets.

Do you still think your rock might be a meteorite? In the UK you can take it along to the Angela Marmont Centre at the Natural History Museum in London where it will pass through their enquiry service for further examination.

A meteorite collectors' guide

Meteorite collecting is something of a hobby, and for some, a profession. David Bryant is an expert meteorite collector and trader, selling under the name SpacerocksUK. "When I was a boy back in the 1950s, meteorites were really scarce – actually owning one seemed pretty unlikely," he says.



The Sikhote-Alin meteorite displays fine examples of the 'thumb-print' texture known as regmaglypts. Image: Meteorites Australia.

Now it's as easy as logging onto eBay, although Bryant advises caution against using online auction sites to purchase meteorites, as these are very prone to faking. "Probably the items to be avoided on the online auctions are Libyan Desert Glass, moldavite, items claiming to be from the Moon or Mars, and Nantan irons," he says. Libyan Desert Glass is a by-product of an impact event occurring on a silica rich target, like sand; the high temperature and pressure conditions 'shocking' the silica into glass. Formed in a similar manner, moldavite is the name given to an olive-green glassy impactite associated with the Reis impact crater in Germany. Nantan irons, on the other hand, are named after the sixteenth century meteorite fall in Nantan, China, and most of the specimens on sale are highly weathered. "It's always best to buy from someone with a high profile or international reputation," continues Bryant. "Generally if you buy from a dealer with an International Meteorite Collectors Association (IMCA) membership (I'm number 1898!) that's a virtual guarantee of genuineness." He also suggests going to rock and gem shows (of which there are around two dozen a year in Britain), so you can see the meteorites 'in the flesh' and talk to the experts.

As with most hobbies, at a basic level collecting meteorites is fairly inexpensive, and you need very little equipment to get going. However, a hand lens or a USB microscope – the latter of which can be purchased for as little as £30 – will allow you to magnify features such as chondrules and perhaps give you that little bit of extra enjoyment from the hobby. In combination with a digital camera you can keep an online catalogue of your collection, too. Most meteorites don't require too much special care either, and are fine to leave exposed on a shelf for example, but pallasites and some etched iron meteorites have to be looked after in dry conditions, so if your collecting starts getting serious, you might want to invest in a cabinet with a dehumidifier.

In terms of the meteorites themselves you can buy small fragments of common meteorites at pocket money prices, and decent sized pieces for a few tens of pounds, but it will set you back a few hundred, if not thousands of pounds if you want something from the Moon or Mars. "The biggest lunar meteorite samples that I stock are just half a gram and cost £400, although I also stock smaller fragments for just £25," says Bryant. "A glassy tektite the size of a conker is just a few pounds, whereas a lunar meteorite of the same size would cost £20,000".

Tektites, along with other diagnostic products of impact events such as shatter cones (impact-affected rocks that display 'horsetail' patterns formed by shock waves from the impact passing through them) and impact breccias (rocks containing angular and melted fragments set in a matrix of material, perhaps of a different composition), are also commonly found in a meteorite collector's pocket, and can be picked up from any impact site. As for meteorites, says Bryant, "there's only a limited amount – prices are rising sharply as they are being outstripped by demand, especially since some countries have now embargoed their export."

Happy hunting!

Where in the Solar System?

Rocks from the Moon and Mars are easily distinguished from Earth rocks and other meteorites by their chemical compositions and age. Lunar meteorites have the same chemical make-up as the rocks brought back from the Moon by the Apollo astronauts, and gasses trapped inside the Martian meteorites are the same – and in the same proportion as – gasses in Mars' atmosphere that the Viking landers of the 1970s recorded. Furthermore, Martian meteorites are all igneous, which means they must have crystallised from a melt. They are also quite young, which means they must have come from a body that has been geologically active. Even melted asteroids had cooled off by about four billion years ago because they were too small to retain their heat – the youngest Mars meteorite is about 165 million years old, which implies it must have come from a planet- sized body. The internal textures can yield a lot of information too. Planetary meteorites and achondrites have no chrondrules, so must have come from fully differentiated bodies, while those with chondrules were formed in the nascent solar nebula.
Asteroidal meteorites can be matched up to specific asteroids by looking at the way they reflect sunlight, using telescopes on Earth. Their reflectance characteristics are dependent on composition, which has enabled astronomers to divide asteroids up into different groups such as rocky, metallic, rock and metal, and carbonaceous. By using this technique, an incredible 920 meteorites have been paired up with asteroid (4) Vesta.

Spacerocks UK stocks a range of meteorites, tektites and impact glasses. Image: David Bryant, www.spacerocksuk.com.

Shattering asteroids spilled many meteoroids into the Solar System, to one day fall onto Earth as meteorites. Image: NASA/JPL–Caltech/T Pyle (SSC).

What did meteorites ever do for us?

Meteorites tell us of a time long ago, when the planets were not even a twinkle in the Sun's eye.

If you've ever been to a construction site, you'll know they can be messy places, with leftover rubble and bricks scattered everywhere. Solar systems are pretty much the same, except there's no one around to tidy up afterwards. Instead, we still have the bits and pieces that went into building the planets floating around. Their compositions, amount of thermal processing and age open a window into the deep past and the formation of the Solar System. Four point six billion years ago, our Sun began to condense out of a cloud of gas. In the process, the gas settled into a spinning disc around the equatorial axis of the young star, condensing into dust as it cooled. Dust particles began to stick together, building up into larger pebbles, boulders, asteroids and protoplanets. During these early days there were dozens of protoplanets, some in chaotic orbits, and often colliding and scattering into a thousand shards. The early Solar System wasn't for the faint hearted.

Today things are much calmer, but as we've seen, some of this debris still falls to Earth. On a world where all the original rock has been melted down and reprocessed through volcanic and tectonic activity over billions of years, or weathered by wind water and air, meteorites are pristine samples of the construction materials that went into Earth. They tell us much about how our planet formed. Through radioisotope dating of meteorites, it is possible to begin chronicling our Solar System's early history and piecing together the different stages of planet formation.

Creation of the chondrules

First to cool out of the solar nebula, once temperatures had reached 1,200–1,400˚C, were the CAIs (Calcium-Aluminium-rich inclusions). They included corundum, melilite and perovskite. Imagine them as fluffy balls of dust, held together by a veneer of ice, just microns in size. As the solar nebula cooled further, components of the chondritic matrix came into being during chemical reactions with the CAIs – for instance, from corundum came spinel, which bequeathed both forsterite and enstatite, which were the precursors to olivine and pyroxene at about 400°C. Such minerals became part of the first chondrules, formed during intense flash heating events that raised the temperature to above 1,500°C, completely melting any dust balls nearby, before cooling by a 1,000 degrees in just an hour. Chondrules display textures indicative of multiple flash melting and refreezing events, but what, in the early environment of the Solar System, could have caused them?

There have been many theories, and it is possible that they all conspired to have an effect. Lightning in the solar nebula sparked by dust grains of different sizes with positive and negative charges, shock waves as clumps of gas and dust fell onto the accretion disc, bi-polar jets of radiation from the embryonic Sun or outbursts every 10,000 years or so, even a nearby recurrent nova, have all been suggested. Whatever their origin, the chondrules are survivors of a period when the Solar System was a hot, suddenly violent, and unforgiving place. The first truly solid bodies began to form from the disc a mere three million years after the formation of the Sun – that's about 4.568 billion years ago. Angrites (a form of achondritic meteorite) are a prime example. They wound up inside some of the first asteroids that, unlike today's frozen lumps of rock, were molten all the way through. Their soft, molten rock allowed the heavy elements such as iron and nickel to begin sinking towards the core, where they begin to swirl around, generating a magnetic dynamo. Today the only rocky bodies to possess a magnetic field are Mercury, Earth and Ganymede. Mars once had a magnetic field, but

An artist's impression of a dusty accretion disc around a young star with bipolar jets, possibly flash heating chondrules. Image: NASA/JPL-Caltech/T Pyle (SSC).

this has now since vanished, leaving behind only residual magnetic traces in some of its rocks in the same way that angrites preserve the magnetic field of the asteroids of which they were part. Judging from the residual magnetic traces in the angrites (and they're not the only magnetic meteorites, although the origin of some is difficult to interpret at present) asteroids as small as 160 km in diameter may have possessed magnetic fields 40 percent as strong as Earth's. Research by scientists at the Massachusetts Institute of Technology (MIT) has shown that differentiated asteroids give hints as to the condition of the young, growing Earth.

"Molten planetesimals would likely have formed metallic cores and rocky crusts before they accreted to Earth," says MIT's Dr Benjamin Weiss. "This would require that the material that had formed Earth's core was processed in a magma ocean on Earth before it went on to form the core."

What meteorites brought with them

As well as bringing heavy metals to Earth, asteroids and meteorites may have brought something even more valuable – the building blocks of life. The origin of life on Earth is a huge mystery, and its most basic components are the amino acids that go into building proteins, which build up into RNA that in turn builds up into DNA. Stanley Miller and Harold Urey famously showed that a soup of organic compounds, energised by lightning, could create amino acids, but there is also evidence that meteorites could also have brought large quantities of amino acids to Earth. In 2008, scientists at the Carnegie Institution in Washington DC found that two CR chondrites picked up in Antarctica in the 1990s contained higher concentrations of amino acids than had ever been seen in meteorites before. They contained 180 and 249 parts per million, compared to the typical 15 parts per million or less that most meteorites contain.

"The amino acids probably formed within the parent body before it broke up," says Carnegie's Dr Conel Alexander. He suggests that chemical precursors such as ammonia that wound up in asteroids could have interacted with water to create the amino acids. "After the break up, some of the fragments could have showered down onto Earth. These same precursors are likely to have been present in other primitive bodies such as comets, which were also raining material into the early Earth."

The amino acids b-alanine and glycine have also been found in the Ivuna meteorite, of which the largest chunk is now proudly on display at the Natural History Museum (NHM) in London. Ivuna – a CI chondrite, of which only nine have been found – shows evidence of aqueous alteration. "In fact," says NHM's Dr Caroline Smith, "CI meteorites are extremely water rich, which raises the possibility that they originate from comets." CM chondrites, such as the Murchison meteorite that fell in Australia, are also rich in organic material including amino acids. "They are very important as they show that the basic building blocks for life are possibly present in comets (if you believe that CI chondrites originate from comets), as well as asteroidal material."

The fact that there are meteorites – these little shards smashed off their parent bodies – is also testament to the chaotic, crowded environment that the proto-planets found themselves in. That organic molecules could not only form but also persist long enough to pollinate the planets is an amazing story, as is the fact that we can read, if not the whole story, then certainly chapters in the histories of the meteorites that we keep in our collections.

Career Profile

Name: Heather Jackson

Age: 36

Job title: Curator of Archaeopetrology

Likes: Wild swimming

Dislikes: Injustice

Place of work: Amgueddfa Cymru – National Museum Wales

What qualifications do you have which enabled you to work in Geology?
BSc Archaeology and Geology, MPhil Archaeopetrology

What sparked your interest in Geology?
Annual holidays on North Yorkshire coast as a child. I spent hours on rain-soaked beaches searching for fossils! I was also inspired by the Geological Museum in London, which had a great exhibition on the Formation of the Earth.

What are you working on at the moment?
Comparing rocks that I've collected from the Llyn Peninsula, North Wales, with a group of 5000-year-old stone axes. By comparing the detailed chemistry of the rocks using X-Ray Fluorescence and microscopic study of thin slices of rock, I can help archaeologists to establish exactly where the rock to make the axes was extracted.

Describe a typical day in the life of a Curator of Archaeopetrology?
Documenting stone samples from the Museum's collections, looking at rocks under the microscope, studying geological maps, going through archive material from archaeological excavations, teaching undergraduates about microscopic study of rocks, plotting graphs…

What's the most exciting/interesting part of your job?
When I'm doing research there's a thrill in getting to the core of a problem, but I also really enjoy working with the collections. Last week I was looking at a piece of Stonehenge!

What advice would you give young people who are interested in a career in Geology?
Get a field guide and go out and look at rocks. Geology opens your eyes to the landscape around you – other geologists will appreciate it if you're as enthusiastic as they are.

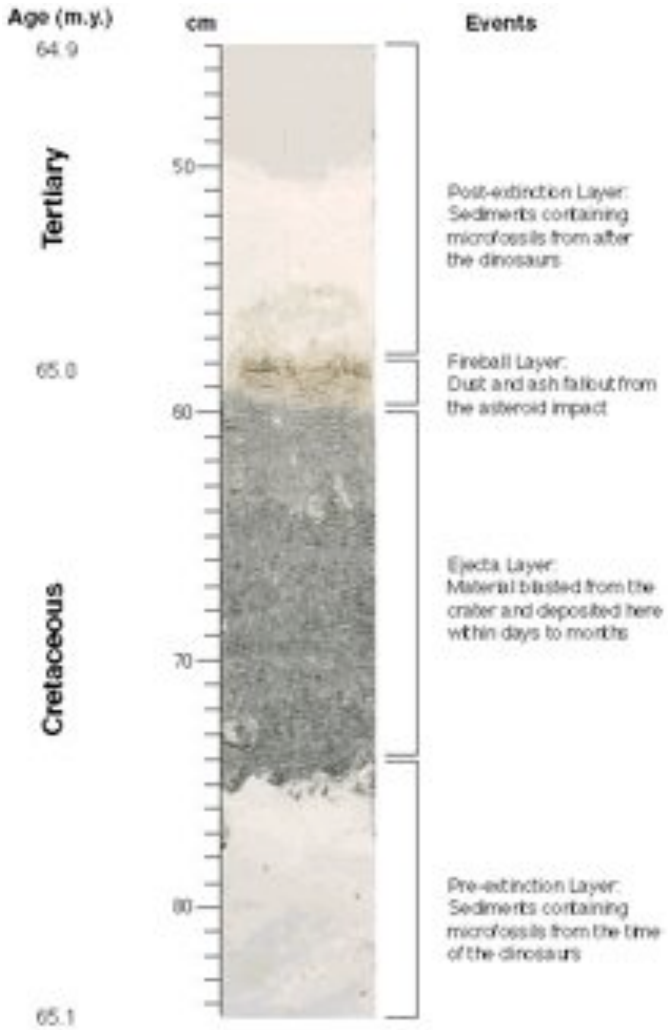
What do you like doing outside of work?
Walking in the mountains or along the coast. All the most beautiful landscapes just happen to be the most geologically interesting as well!

Death, Destruction and Dinosaurs

For over 100 million years, dinosaurs reigned supreme over all animals on Earth, but a global catastrophe 65 million years ago wiped them off the face of the planet forever. Their sudden disappearance from the fossil record sparked much debate amongst scientists as they tried to piece together the clues for their extinction.

But it wasn't only the dinosaurs who suffered from this event - over three quarters of the life forms on Earth became extinct; those species who survived were those that lived deep in the oceans or underground, and those who flourished as scavengers on the Earth's surface.

This extinction event 65 million years ago marks the end of the time of geological history known as the Cretaceous period and the beginning of the Tertiary period. As a shorthand, geologists call this geological instant the K-T boundary (K for the German word for Cretaceous; T for Tertiary). Rocks that formed during these distinct periods are recognisable by the fossils of tiny organisms known as foraminifera, within them.



A cross-section through the K-T boundary layers.

Tiny creatures - big clues

Foraminifera are single-celled organisms, similar to amoebas, which live in the oceans. Although tiny, they are extremely numerous, and can be found both along the shore, and far out at sea, near the surface and at the immense depths of the oceans. The vast abundance and extent of these creatures means that they are excellent indicators of global environmental changes, so are used by scientists interested in how the climate on Earth may have changed over the past 500 million years. Before the impact event 65 million years ago, scientists found evidence of larger foraminifera living in the oceans, but after the impact, only smaller organisms are seen in the fossil record, indicating that something catastrophic had occurred, causing the extinction of the larger members of this species.

However, the actual cause of the extinction event has been the subject of scientific speculation for some years. Not all scientists agree that it was caused by an asteroid impacting the Earth. Other suggestions have included:

- it wasn't a single event, but a series of unrelated local extinctions;
- the extinction was a slow decline in numbers and diversity, not a catastrophe;
- the extinction was caused by a rapid change in climate from warm and wet to cool and dry;
- the dinosaurs became an evolutionary dead end and could no longer adapt to minor changes in their environment;
- living things were killed by the effects of massive volcanic eruptions (specifically those in the Deccan region of India);

Evidence for catastrophic impacts

Until 1980, each of these hypotheses had strong supporters and there was no consensus at all. In that year, a crucial paper was published in 'Science' magazine that thrust the meteorite impact hypothesis into prominence and eventual acceptance by most scientists.
The K-T boundary had been investigated for many years as scientists searched for the cause of the extinctions. The rocks from this period seemed to indicate a global catastrophe, but at this boundary they are not exposed at the Earth's surface in very many places. Some of the best exposures are in Northern New Mexico, and in southern Canada, Italy, Spain, Denmark, and New Zealand. At all of these sites, the K-T boundary is defined by a thin layer of greyish clay. Rocks at these sites include sandstones from ancient river valleys, limestones from ocean reefs, and cherts from the ocean floor. The grey clay is present in all of them. Cretaceous fossils, marine or terrestrial, are present below the grey clay but are never found in rocks above the grey clay. The fact that the same grey layer with the same lack of fossils above, are found in rocks across the world shows that whatever happened at this time was a global event.


The KT clay layer is clearly visible here

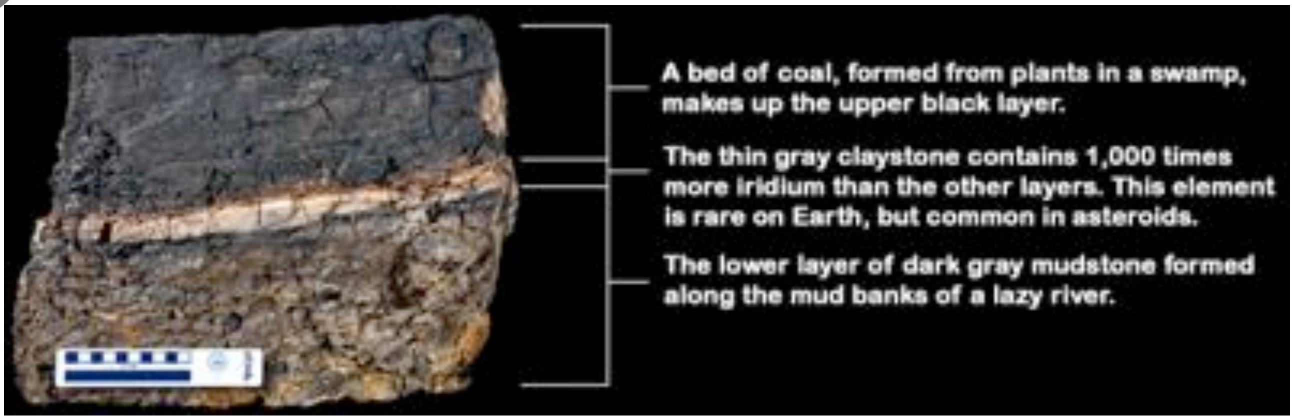
Material from outer space

Another piece of evidence from the study of the K-T boundary clay that gave particular credence to the theory that an asteroid had hit the Earth was the discovery of Iridium in the clay layer. Iridium is extremely rare in rocks from the Earth's surface, but is much more abundant in common meteorites (as explained on page 18). Scientists found that the layer of clay was extremely rich in this element, adding to the evidence that a large object from space did impact the Earth at the time of the extinction. From studying the amount of iridium at the K-T boundary, scientists estimated the size of the impactor in question to be about 10km in diameter.

More 'shocking' evidence

Scientists across the world have searched for additional evidence for an asteroid impact at the K-T boundary time. In the grey clay they also found other features consistent with a meteorite impact, including shocked quartz and tektites (melted rock).

Scientists also found soot in the clay layer — enough soot to suggest that enormous fires consumed much of the Earth's vegetation. In the rocks below the grey clay, they also recognized deposits from enormous ocean waves which might have been tsunamis caused by an impact. In addition, they found broken rock in unusual places that seem to have been the result of earthquakes (which again, could have been triggered by an impact).



The rock layers pre and post the KT event. Image courtesy of San Diego Natural History Museum

Crater

The impact of a 10 km asteroid or comet must have produced a circular crater, probably more than a 150 km in diameter. A crater that size would probably have multiple ring structures, like the larger craters on the Moon. Although remnants of a few large craters matching this description are known on the Earth, they are all much older than the 65 million year age of the K-T boundary. The lack of a known crater made many scientists suspicious of the whole impact hypothesis, and inspired others to look for the impact crater. Many features around the world were suggested and investigated as possible impact sites.

The work centred initially on North America because the largest fragments of shocked rock were found there. The Manson meteorite crater, beneath Iowa, was first targeted because it formed about 65 million years ago. But Manson is only 35 km in diameter, probably too small to have caused global devastation and too small to have been made by a 10 km asteroid.

The search then moved to the Caribbean area, because the clay layer was thickest there, and had the largest rock fragments and globules of melted rock. Finally, suspicion focused on an unusual sub-surface structure on the northern coast of Yucatan (Mexico), centered under the town of Chicxulub. Studying rocks from drill cores of the area and data from remote sensing methods (gravity measurements, seismic profiles) showed that the Chicxulub structure is a meteorite impact crater.

Its current size is estimated at 180 km in diameter, certainly large enough to have caused a global environmental catastrophe. As the asteroid hit, all life within about 300 km would be vaporized instantly. Then the hot blast wave from the impact explosion would kill all life for several hundred kilometres in all directions. Further out, the blast wave would kill, deafen and disorient many animals. In the ocean, the shock from the impact would generate enormous, world-wide tsunamis (mega-tsunamis), perhaps with waves a kilometre tall. Gigantic hurricanes (hypercanes) might also be

Shocked quartz is a form of the mineral quartz, but which, when viewed under a microscope, looks very different, with patterns of lines crossing the mineral. It was originally found in underground bunkers where nuclear bombs had been tested, and was thus confirmed to form in rocks where there has been a very sudden increase in pressure. It has subsequently been discovered in rock layers at various geological time periods, including the KT boundary time, giving further evidence to scientists that impacts occurred on Earth at these times.

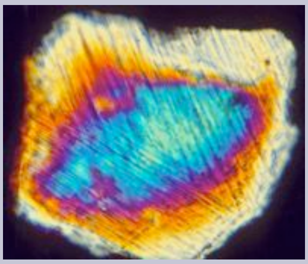
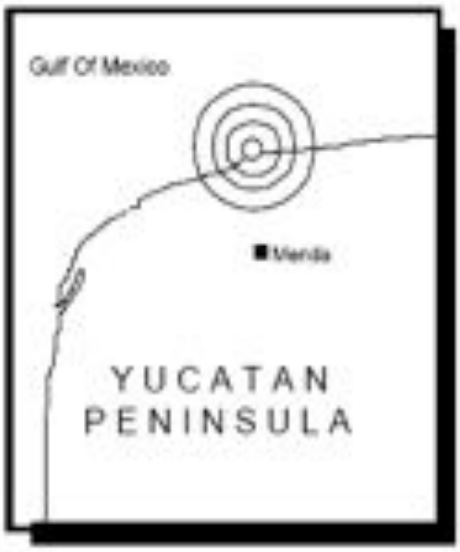


Image of shocked quartz - courtesy of the U.S Geological Survey triggered. In the Earth, the shock from the impact would be felt as huge earthquakes, and would set off other earthquakes over the whole globe.

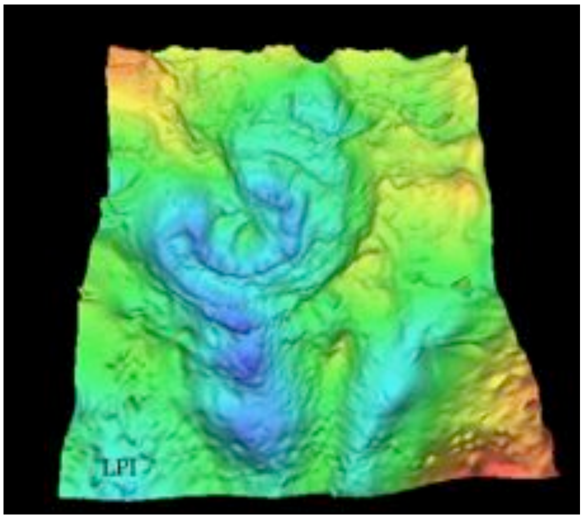


Location of Chicxulub crater

Ejecta from the impact (both sand-sized particles and larger) would shoot out and rain down for thousands of kilometres around. Other ejecta would leave the Earth's atmosphere but not Earth's gravity; it would return to Earth as meteorites so abundant that their heat would "broil" the Earth's surface and set off wildfires over the whole planet. Over the impact site, a mushroom cloud would rise, carrying dust from the explosion far into the stratosphere. This dust would mingle with the soot from wildfires to form a world-wide haze so thick as to block out all light from the sun. Over time, without the Sun's heat, surface temperatures on the Earth would drop 20-30°C.

The combined effects of the fires, the darkness, and the cold must have devastated life and caused the collapse of almost all ecological inter-relationships. Months later, when the dust cleared and the Sun finally shone again, only some seeds and the most enduring animals would still be alive. Three quarters of all species would die in the next few years, due to the loss of the ecosystems on which they depended. Early shrew-like animals were the only mammals so far discovered to have survived the disaster, and it is thought that birds may be the only direct descendant of the dinosaurs left living today.

Bristol University has a thriving undergraduate degree course on palaentology (the study of dinosaurs), as well as a popular outreach programme called the 'Bristol Dinosaur Project' which aims to educate the people of Bristol about their own local dinosaur. We chat to the learning officer of this project, Ed Drewitt, on the next page and learn how his interest in science enabled him to become involved in such an exciting project. Finally, we chat to Dr Jana Horak, head of Mineralogy and Petrology at the National Museum of Wales in Cardiff and find out what drove her interest in rocks and minerals.



Gravity and magnetic field data image of the Chicxulub impact crater. From NASA's Astronomy picture of the day, Feb 26th 2000 - courtesy of V.L. Sharpton, LPI

Career Profile

Name: Ed Drewitt

Age: 30

Job title: Learning Officer of the Bristol Dinosaur Project

Likes: Nature, dinosaurs (!), communicating with people and trying different foods and restaurants.

Dislikes: Bureaucrats and their endless quest to devise the most time-wasting tasks.

Place of work: Department of Earth Sciences, University of Bristol.

What qualifications do you have which enabled you to work in educational palaentology?
BSc Zoology and 10 years of experience working with schools and families.

What sparked your interest in zoology?
Being encouraged by family or friends at a young age.

What are you working on at the moment?
Developing a learning programme for schools on nature and wildlife.

Describe a typical day in the life of a Learning Officer?
Checking e-mails and preparing for the day, phoning back schools to book visits, meeting with partners to arrange projects and volunteers and taking resources and objects out to schools to do workshops.

What's the most exciting/interesting part of your job?
Meeting so many different people and engaging them in science in a way that works for them.

What advice would you give young people who are interested in a career as a learning officer?
Never give up on your dream. Get experience at college or university before you have to get a full time job - it gets harder to get the experience otherwise!

What do you like doing outside of work?
Scuba diving and bird watching.

Career Profile

Name: Jana Horák

Age: 48

Job title: Head of Mineralogy & Petrology

Likes: being inspired by other people

Dislikes: meat (all varieties)

Place of work: Amgueddfa Cymru – National Museum Wales

What qualifications do you have which enabled you to work in Mineralogy & Petrology?
BSc, PhD

What sparked your interest in Mineralogy & Petrology?
Having to find another A-level that fitted in with my others and finding out that geology is the most fantastic subject

What are you working on at the moment?
Dating some of the oldest rocks in Southern Britain that are found in Anglesey, N. Wales, and trying to use isotopes to date a sequence of rocks that we can't yet prove when they formed.

Describe a typical day in the life of being the head of Mineralogy & Petrology?
Answering enquiries from anyone from the general public to professional geologists, working on the collections, squeezing in some research time to keep current research projects moving forward, management – anything from staff or collections issues to contributing to committee work, both inside and outside the Museum.

What's the most exciting/interesting part of your job?
Working things out! Anything from interpreting new data to answering a difficult enquiry because you either have just the right piece of knowledge or you know where to locate the information.

What advice would you give young people who are interested in a career in Mineralogy & Petrology?
Get as much experience as you can. In geology a good general knowledge picked up from attending as many fieldtrips and lectures as possible always comes in useful.

What do you like doing outside of work?
Not answering enquiries! Reading, gardening.

Journey's End

That concludes our journey around our Solar System. We've learnt many interesting facts about asteroids, meteorites and comets including what they're made of and how scientists are still continuing to understand these fascinating astronomical objects. We have also delved into the careers of a few scientists who played their part in bringing the information that has made this booklet possible.

We hope that Back Down 2 Earth has sparked an interest, where perhaps one day you'll be a scientist using data to understand what enters our atmosphere or even finding out more about the extinction of the dinosaurs.

In the meantime, keep looking up - it's a vast Universe out there, full of mysteries yet to be solved!

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