This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 640190

EURO-CARES
A PLAN FOR EUROPEAN CURATION
OF RETURNED EXTRATERRESTRIAL SAMPLES

Work Package 8

Deliverable 8.8

MOOC: Space on Earth

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Space on Earth

Background: A MOOC (Massive, Open On-line Course) is a web-based, open access, stand-alone tailored package of material designed to enable guided study of a subject. Courses typically last between 4 and 8 weeks. A well-designed MOOC is often used by school teachers seeking enrichment activities for students, or to bring themselves up to speed on a specific subject area, although the main participants are usually the general public. The EURO-CARES consortium chose to produce a MOOC because it is a relatively easy way to reach many thousands of people globally, raising the profile of space science.

Description: The MOOC, **Space on Earth**, is designed to deliver 3 hours of study materials over a 6 week period. By the end of the course, students will have an understanding of the range of materials delivered to Earth (both natural and artificial), where it comes from and how it is collected. They will learn about current curation practices, and about the cutting edge analytical techniques applied to the materials. Finally, they will bring all this information together to gain a 'big picture' of why it is interesting and important to study extraterrestrial material. At the end of each week, there will be a quiz to test their understanding of the material, and then a final quiz that covers the whole course; we are still in debate about whether or not to award a Certificate of Completion to participants. There will be a forum for participants to ask questions or discuss issues, possibly through a twitter feed or facebook page. It will not be moderated by members, but will operate through peer pressure and be subject to the usual rules of netiquette. Consortium members will be encouraged to monitor the forum on a semi-regular basis to ensure that the discussions are sensible. The first presentation of the MOOC (now scheduled for April 2017) will be delivered in English; future presentations will be rolled out in French, Spanish, Italian and German.

Delivery Platform: The reason why the MOOC has not yet been launched is because of a delay in determining which platform would be most suitable to host the material. Originally, it was planned to use FutureLearn, *via* the Open University, but because that has not been possible (change in OU policy on funding of MOOCs), we have had to seek an alternative platform. The materials have been written in a format that is ready to be transferred to EdX (one of the largest MOOC platforms), but we are also considering the European SchoolNet Academy (http://www.europeanschoolnetacademy.eu/), which would then also link directly to our school education resources, and would also link in to the EuroPlanet network. There are pros and cons to both platforms: EdX has a higher and more varied audience of potential global participants, but the European SchoolNet Academy is closer to our target audience.

Target audiences: (i) secondary school and university students seeking additional challenges beyond their respective curricula; (ii) school teachers who wish to enhance their knowledge of space and planetary sciences, giving them additional material for their lessons and (iii) the section of the general public that maintain an interest in astronomy and planetary sciences.

Breakdown of Presentation:

Week 1: What is extraterrestrial material?
Meteorites, Cosmic Dust, Space Debris, Remote Observation

Week 2: Where does extraterrestrial material come from?
Asteroid Belt, Moon, Mars, Comets

Week 3: How do we acquire extraterrestrial material?
Fall, Find, Atmosphere, Ice, Sample Return Missions

Week 4: How do we look after extraterrestrial material?
Planetary Protection, Curation

Week 5: How do we analyse extraterrestaterrestrial material?
Non-Invasive, Invasive, Destructive

Week 6: Why is it important to study extraterrestrial material?
Solar System formation and Evolution, Impact possibilities

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Introductory page of the MOOC:

Free online course | Duration: 6 weeks | 3 hours pw | Certificates available

FUNDING

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ABOUT THE COURSE

What is the chance of the Earth being hit by a meteorite? Might we all be wiped out, like the dinosaurs? What would cause such a catastrophe?

In this 6 week course, you will find out about the range of materials that falls to Earth, where it all comes from and how it is collected. You will learn how scientists look after this valuable material, and the sort of equipment they use to study it. You will think about why it is interesting and important to study extraterrestrial material – and find the answer to whether you might suffer the same fate as the unlucky dinosaurs

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Outline of the content material for week 1:

1	**Week 1: What is Extraterrestrial Material ?**								
2									
3	**Segment**	**Section**	**Title**	**Image**	**Ref:**	**Video**	**Ref:**	**Other Assets**	**Time (min)**
4	**Hour 1**		**Meteorites**						
5	**Segment 1**	**1.1**	Introduction to the Course			MMG introduces course	N		5
6			Introduction to ET Material	Montage of meteorites	N		-		5
7			Observed to fall: forward look to W2		-	Chelyabinsk	Youtube		5
8			Found by chance: forward look to W3	Antarctic meteorite	MMG				5
9	**Segment 2**	**1.2**	Meteorites: unmelted	Allende hand specimen	MMG			Link to Virtual Microscope	20
10				Allende thin section	MMG				
11	**Segment 3**	**1.3**	Meteorites: melted, stone	Eucrite hand specimen	MMG				10
12				Eucrite thin section	MMG				
13			Meteorites: melted, iron	Iron meteorite (Gibeon or Henbury)	MMG				5
14			Meteorites: melted, stony-iron	Pallasite (Imilac)	MMG				5
15	**Hour 2**		**Dust and Debris**						
16	**Segment 1**	**2.1**	Cosmic Dust: Meteor		MMG				5
17			Cometary dust forward look to W2	Comet tail	MMG				5
18			Atmospheric and ice collection: forward look to W3	Melting ice, sieving water	Gounelle	Melting ice, sieving water	Gounelle		5
19			Fusion crust & micrometeorites		MMG				5
20	**Segment 2**	**2.2**	Space Debris: what is it?						5
21			Where does it come from?			Debris around Earth	NASA/Youtube		5
22			What can we learn from it?	Eureca foils	MMG				10
23	**Segment 3**	**2.3**	Practical session: Find the meteorite					OpenScience Lab	20
24	**Hour 3**		**Remote Observations**						
25	**Segment 1**	**3.1**	Ground-based telescopes						5
26			Space-based telescopes						5
27			Orbiters						5
28			Landers						5
29	**Segment 2**	**3.2**	Quiz and Feedback						20
30	**Segment 3**	**3.3**	Summary						10
31			Look Ahead						10

Week 1 | Week 2 | Week 3 | Week 4 | Week 5 | Week 6

1.1

Artist's impression of the inner Solar System, looking towards the Sun from the Asteroid Belt.

Space on Earth [Article]

What is the chance of the Earth being hit by an asteroid? Might we all be wiped out, like the dinosaurs? Would we be able to stop a collision?

In this six-week course, you will find out about the range of materials that falls to Earth, where it all comes from and how it is collected. You will learn how scientists look after this valuable material, and the sort of equipment they use to study it. You will think about why it is interesting and important to study extraterrestrial material – and find the answer to whether you might suffer the same fate as the unlucky dinosaurs

The course

You can get more of an idea about what's covered in the course from watching the following video, in which the course director, Professor Monica Grady, will tell you a bit about what you can expect to be doing in the next few weeks.

[In-line video] MMG introducing the course

The course is designed to run on desktops, tablets and mobile devices; however, some of the material is quite detailed and using a larger screen will enhance your experience. Materials are best viewed running the most up-to-date software available for your device and using the most recent version of the web browser.

Progress

Keep track of your progress by clicking ‘Mark as complete’ at the end of every step you read. This will help you to keep track of where you’ve got to in the course. You can see your progress at the Progress link at the top of each step.

Downloads

From time to time you’ll see downloadable PDFs at the bottom of a page. These are provided to help your learning. They include transcripts, extracts and information sheets that you may want to save for future reference.

Quizzes and tests

To test your knowledge at the end of the five weeks we’ve provided an end-of-course test. Your score will be available on the progress page that you’ll find a link to at the top right of this page. Quizzes pop up at the end of each week and look similar to tests but are not scored – they are included to help you learn.

Comments and discussions

There are plenty of opportunities to communicate with other learners. You’ll be able to make comments at any point in the course – just click on the pink plus symbol (+) to open the comments area. You’ll also notice discussion points, which offer a more structured dialogue with your fellow writers on key topics. Please join in!

Why not introduce yourself now by posting a comment below?

When making comments and participating in discussions, please remember that these will be visible to the thousands of learners registered on the course, so make sure you only share information that you would be happy to be publicly visible.

Profile pages

You can view the profile pages of your fellow learners, and ‘follow’ them to keep track of their comments. We recommend that you follow the lead educator, Monica Grady, and mentors X, Y and Z.

Get extra benefits, upgrade your course

You can now get extra benefits by upgrading this course, including:

Unlimited access to the course: Go at your own pace with unlimited access to the course for as long as it exists on XX.

Access to tests: Ensure you’ve mastered the material with access to tests on the course.

A Certificate of Achievement: To help you demonstrate your learning we’ll send you a Certificate of Achievement when you become eligible.

Find out more

The next two steps describe what is coming up during the five weeks of the course.

(Image: ESA/ATG Medialab / Text: © EURO-CARES)

1.2

Introduction to Extraterrestrial Material ? [Video]

[Video]: Chelyabinsk

Watch the video to see the type of damage that an incoming asteroid can cause. The footage is a compilation of material collected when the Chelyabinsk meteorite fell in February 2013. Nobody was hurt directly by the meteorite, but many injuries resulted from broken glass as windows were shattered.

In this first week, you will discover the different types of extraterrestrial material that fall from the sky every day. Most of it usually arrives unseen, as particles of dust no bigger than a grain of sand. The dust can be collected from high up in the atmosphere, or from Antarctic ice. Larger specimens of extraterrestrial material that fall to Earth and are recovered are known as meteorites.

Almost all meteorites come from the Asteroid Belt – a region of battered and cratered bodies that orbit the Sun between Mars and Jupiter. A few meteorites come from Mars, and a similar number from the Moon. You will learn more about the origin of meteorites and how we know where they come from in Week 2.

Fortunately, events like the spectacular Chelyabinsk fireball are rare, occurring about once every 10 – 20 years or so – you will find out more about meteorite impacts in Week 3.

The next section introduces you to why we might want to study meteorites.

1.3

Why is ET material important? [Article]

[Image] Clean Room

In the second half of the course, you will find out how we look after extraterrestrial material once it has been collected. In Week 4, you will learn about curation of meteorites. It is important to keep meteorites as contamination-free as possible, so that scientists know that they are making measurements on meteorites, and not on terrestrial contaminants. Extraterrestrial dust particles – known as Interplanetary Dust particles, or IDP, are kept in ultra clean rooms, like that shown above, at the NASA-Johnson Space Center in Houston, Texas.

The different types of analyses, and the instruments used to make them (like the Scanning Electron Microscope shown below) are covered in Week 5.

[In-line Image] SEM

In the final week of the course, the significance of meteorites in helping to understand the origin and evolution of the Solar System is discussed. You will also see how what you have learned about the Solar System can be applied to planetary systems around other stars. You will finish with a test that covers all of the course content – and if you are successful, you can apply for a certificate of completion.

Now you have heard about the treats in store, and the opportunities available through the course, it is time to find out about the difference between a meteor and a meteorite.

1.4

Meteors [Article]

[Image] Meteor

You found in Step 1.2 that most extraterrestrial material arrives on Earth as dust. The picture above is of a meteor – or a shooting star. These are grains of dust that become so hot as they come through the Earth's atmosphere that they evaporate away: nothing lands or is recovered from these grains. The particles are travelling extremely fast – about 20 km s^{-1} (45,000 miles per hour) – and the atmosphere ahead of the particle becomes compressed by the flight and heats up. This is the heat source that melts and evaporates the particles, not frictional heating as is often thought.

Sometimes the streaks or flashes of light of a meteor might be green or orange in colour. This is a result of the chemical composition of the dust grain.

If you can view the sky away from city lights, you should be able to see at least one meteor per hour. This is the background rate of sporadic (or random) meteors. At certain times of the year, many tens, or even hundreds, of meteors per hour may be observed – this phenomenon is known as a meteor shower. The picture below is a woodcut of the Leonid meteor shower of 1833

[In-line Image] Leonids 1833

If you were observing a meteor shower from the ground, from your perspective the meteors would seem to originate from a single point. This is the radiant, and a meteor shower is almost always named for the constellation in the sky where the radiant appears to be situated. So, for example, the radiant for the Leonid meteor shower appears to be in the constellation of Leo.

Sporadic meteors may be caused by dust from either asteroids or comets. Meteor showers, however, are associated with dust from a comet. The image below illustrates how the orbits of the Earth and a comet's tail intersect to produce the meteor shower

[In-line Image] Earth-comet orbits

In the next step, you will learn how to distinguish between a meteor and a meteorite.

1.5

Meteoroids, Meteorites and Fusion Crust

[image] Fireball

The image above is of a still from the video at the start of step 1.2, of the fireball that flew through the atmosphere in Chelyabinsk, Russia, in February 2013. A fireball may also be described as a **meteoroid** – a bright object that blazes its way down to the Earth's surface. When it lands, it is known as a **meteorite**.

[Inline-Image] Stannern hand specimen

One of the most important things to realise about meteoroids is that they do not get hot inside as they travel through the atmosphere. The heat is radiated away as droplets of melted rock and metal are torn from the surface of the bolide (another term for a meteoroid). Heating stops at a height of around 10 km, and the meteoroid travels the final distance to Earth under gravity. During this part of its journey, the outer surface of the meteoroid, which had been molten, quenches and solidifies, forming a fusion crust, which is usually less than about a millimetre thick. The appearance of a fusion crust can be characteristic of a meteorite – but meteorites that have been found, rather than seen to fall, may have had their fusion crust weathered away.

So now you know the difference between a meteor, a meteoroid and a meteorite. That makes you a meteoriticist – someone who studies extraterrestrial material. You are not a meteorologist – someone who studies the weather – although the words have the same language root. The Greek word *μετέωρον* (meteōron) means 'a thing lifted on high', interpreted as 'something in the atmosphere'.

That is probably sufficient etymology – better come back down to the ground and find out about meteorites.

1.6

Different types of Meteorite [Article]

[Image] Montage of meteorites

The image above shows four different types of meteorite – two look like stones, one appears to be solid metal, and the fourth seems to be metal with areas of transparent material. The image illustrates the most basic division of meteorites, based on the material from which they are made; stones (made of stone), irons (made of iron) and stony-irons (made of stone and iron).

This classification is useful – and served meteorite scientists for many years, because it was easy to distinguish between non-magnetic stones and magnetic irons. But it does not help us to understand the relationships between the four different types. A more modern system of classification is to distinguish between primitive, unprocessed materials and materials that have been processed through heating and melting.

In the image above, the sample at the top left, labelled (a), is a primitive meteorite, and the other three are all processed. Primitive meteorites are all stone in composition and also known as chondrites, after their main constituent, **chondrules** (pronounced kondrools). This comes from the Greek word, χόνδρος (khóndros), which means 'seed' or 'grain'. Chondrules are spherical droplets of silicate minerals, and you will hear more about them in step X.x. Processed meteorites are known as achondrites, because they do not contain chondrules. The can be stone, iron or stony-iron in composition, and you will learn about them in step x.x

There are many sub-divisions of primitive and processed meteorites – the link below allows you to download a meteorite classification 'family tree'. But don't worry – you aren't going to go through all the branches of the tree – it is just to show you that things can get a bit complicated once you start to take a detailed look at the different groups.

[Download] Meteorite classification family tree

You may well question why we bother to sub-divide meteorites into all these different groups and classes. You will come back to this question a bit later – but perhaps you would like to suggest some reasons on the discussion forum?

You will explore what a primitive meteorite is in the next step.

1.7

Meteorites: unmelted [Article]

[Image] Vigarano slab

A larger image of sample (a) from the previous step is shown above. This is a slab of the Vigarano meteorite, which fell in Italy in 1910. It is a beautiful example of a primitive meteorite. If you downloaded the meteorite classification tree, Vigarano is a member of the CV group. In fact, it is the 'type specimen' of the group – the V in CV stands for Vigarano (the C is for Carbonaceous).

Primitive meteorites have not been melted since they were first assembled into their parent objects at the dawn of the Solar System. This means that they have the same overall composition as the original dust grains from which they formed. They are unfractionated – this means that in all but the most volatile of elements (hydrogen and helium), they have compositions that are close to that of the Sun. The diagram below is a comparison between the composition of the Sun's photosphere and that of the smallest, but most primitive group of meteorites, the CI meteorites. (Here, I stands for Ivuna, the type specimen).

[In-line image] Photosphere vs CI chondrites (Atlas Fig, 2.1)

So primitive meteorites are undifferentiated – the parent objects have never been heated sufficiently strongly to melt and separate out into crust, mantle and core. Although the parent objects never melted, they are not necessarily unaltered: the minerals in some have been changed by fluids, whilst others have been mildly heated.

The main image of Vigarano shows that it has a texture of a random pattern of approximately circular objects, mixed with a much smaller number of irregularly-shaped objects. The circular objects are how chondrules appear in two dimensions –you are looking here at a slab that has been cut from a stone about the size of a large grapefruit.

In the next step, you will learn about chondrules, and the other components of primitive meteorites.

1.8

Components of Primitive meteorites [Article]

[Image] Chondrule

Chondrules are spherical to sub-spherical objects that can be up to about 2.5 cm across. Their shape and internal texture indicate that they formed in a high temperature process, and that they are quenched droplets of once-molten silicates. They are mainly formed of Fe-, Mg-silicates. Despite decades of study, and their abundance, the formation mechanism of chondrules is not understood. The location of chondrule formation, and the process that rendered solid grains of interstellar dust molten are uncertain: Scientists have described at least nine different processes that might have been responsible for chondrule formation, including mechanisms such as in the highly energetic wind flowing from the young Sun or in shock waves. It is possible that more than one mechanism was involved in chondrule formation, and that chondrules were produced by different processes at different locations within the nebula at different times.

[In-line Image] CAI

Calcium- and aluminium-rich inclusions (CAI) are irregularly-shaped objects. As their name implies, they are composed of calcium- and aluminium-rich minerals; these minerals are characterized by their refractory nature; their presence implies that CAI formed in high temperature processes (temperatures > 1800 K), probably in a region very close to the newly-formed Sun. The mineralogy and isotopic composition of CAI identified them as objects that formed very early on in the history of the Solar System.

Their irregular shape implies that they have not been through an extensive melting process, and for many years they were thought to have been produced by direct condensation from the cooling nebular gas. Whilst this is presumably correct for some CAI, others have textures that suggest formation from partially molten droplets. CAI are regarded as aggregates of primary nebula condensates that may have experienced several episodes of partial melting and alteration in the nebula prior to accretion into parent bodies.

In the next step, you will learn about melted stone meteorites, and how they differ from unmelted ones.

1.9

Meteorites: melted, stone [Article]

[Image] Eucrite hand specimen

Achondrites are meteorites that formed from melts, and thus have differentiated compositions. Achondrites traditionally only comprised stony meteorites that had lost a large fraction of their primordial metal content, their name emanating from the observation that such meteorites generally do not contain chondrules. However, the current convention is to regard all differentiated meteorites (stone, iron and stony-iron) as achondrites.

Stony achondrites differ from chondrites in their major element content, especially calcium and similar elements. They have almost no metal or sulphides, and neither do they contain chondrules. They are mainly composed of crystals that appear to have grown from a melt. There are many different groups of achondrites, some of which can be linked together to form associations allied with specific parents.

The **howardite-eucrite-diogenite** (HED) clan is a suite of generally brecciated igneous rocks ranging from coarse-grained orthopyroxenites (**diogenites**) to cumulates and fine-grained basalts (**eucrites**). The **howardites** are regolith breccias, rich in both solar wind gases and clasts of carbonaceous material. The HEDs all have similar oxygen isotopic compositions; a strong candidate for the HED parent body is asteroid 4 Vesta.

1.10

Meteorites: melted, iron [Article]

[Image] Polished slice of Henbury

Iron meteorites are a complete contrast to the types of meteorite that you have encountered so far. They are highly differentiated materials, presumed to be products of extensive melting processes on their parents. You will return to how these meteorites formed next week, but for now, you will focus on what iron meteorites look like and how that is related to what they are made from.

The image above is a slice of the Henbury iron meteorite that has been polished and then etched with dilute acid to show the distinctive pattern characteristic of iron meteorites. The pattern comes from intergrowth of two phases. The first, called kamacite, contains less than about 7 wt. % nickel; the second is taenite, with approx. 15–50 wt. % Ni. The intergrowth structure is known as the Widmanstätten pattern, and the width of the bands (or lamellae) of kamacite is related to the cooling history of the parent bodies. The wider the bands, the more slowly the meteorite parent body cooled. The pattern is named for Aloys J. B. von Widmanstätten, who, at the start of the 19th century, observed the pattern on several iron meteorites, although he probably was not the first to describe the structure.

As well as iron and nickel, iron meteorites contain many other elements, including the precious metals gold, silver, platinum, palladium and iridium. They are subdivided on metal composition into

12 different groups, although many irons defy chemical classification, and simply remain ungrouped. On the basis of compositions, it is estimated that iron meteorites might represent samples of at least 70 individual asteroids.

Melted stony-iron meteorites are also composed of kamacite and taenite, and they are the subject of the next step.

1.11

Meteorites: melted, stony-iron [Article]

[Image] Esquel

Looking at the meteorite family tree from Step 1.4, you will find the melted stony-irons lie next to the melted stones, and that there are two classes. similar only in their approximately equal proportions of silicate and metal. The two groups have very different origins and histories. The image above shows a polished slice from the Esquel (check) pallasite. These are perhaps the most strikingly beautiful of all meteorites. They are an approximately equal mixture of iron-nickel metal and silicate minerals, and the metal forms a continuous network, into which the silicates are set). Pallasites were thought to be from the core-mantle boundary of their parent bodies, but more recent modelling shows that they are more likely to come from XXXXX.

[In-line Image] Estherville

The other class of melted stony-irons, mesosiderites, are more diverse in their appearance and composition than pallasites. They are a mixture of varying amounts of iron-nickel metal with silicates, the whole assemblage of which seems to have been broken up, shocked and then re-assembled. Mesosiderites are thought to come from the surface of their parent objects, mainly because of their highly brecciated nature and their high content of solar wind gases.

1.12

Meteorites under the Microscope [Activity]

[Image] Allende virtual microscope

In the previous step, you learned about chondrules and CAIs, looking at images taken using an optical microscope. The picture above is of a CAI next to a chondrule in the Allende CV meteorite, also taken using an optical microscope. To obtain images such as this, a piece of meteorite has to be stuck to a small piece of glass. The meteorite is then ground down and polished until it is only 30 µm thick; the specimen is known as a polished thin section (often abbreviated to pts) and is transparent to light. The picture below shows what a polished section looks like.

[In-line image] Picture of a polished thin section

A petrological microscope (below) is a specialised microscope for examination of thin sections. It has two light sources, an upper one which shines on the top surface of the sample and is reflected back into the detector (in the picture above, the detector is a camera). This geometry gives a reflected light image, and is used for looking at opaque minerals, such as metal grains. The lower light source first passes through a filter that polarises the light (the polariser) and then through the sample. The light is transmitted into the detector, either directly, or through a second polarising filter (the analyser). The analyser can be moved in or out of the light beam, to generate an image in plane-polarised light (polariser only) or through crossed polars (polariser and analyser). This geometry generates transmitted light images used for looking at transparent minerals.

[In-line image] Picture of a petrologic microscope

Now you can obtain your own images of meteorite thin sections from a variety of different meteorite types using a petrologic microscope.

Read the **User Guide to the Virtual Microscope** (https://www.virtualmicroscope.org/about/user-guide) which introduces you to a petrologic microscope that can be accessed and operated over the internet (the Virtual Microscope), allowing you to look at polished thin sections of different meteorites.

Access the Virtual Microscope website (https://www.virtualmicroscope.org/), then move to the Europlanet and British and Irish meteorites meteorite collections (https://www.virtualmicroscope.org/collections). Play around with the different meteorites, changing the magnification, looking at the specimens in transmitted light (both under plane light and crossed polars) and reflected light. Be patient when you are loading the images and changing the magnification – the images take a few seconds to load.

Which meteorites show chondrules most clearly? Which ones require use of reflected light? Share your observations on the Discussion Forum below.

1.13

How much Extraterrestrial Material falls to Earth? [Discussion]

[Image]

The short answer to the question is 'a lot'. But since you would probably like to have something more specific, an answer of 'tonnes and tonnes' is not much better! And 'it depends' also leaves much to be desired.

Why don't you try and estimate a value for the amount of extraterrestrial material that is added to the Earth each year? Remember what you read in Step 1.2, that most extraterrestrial material arrives as dust, rather than as kilogram-scale meteorites. Post your answer on the Discussion forum – and no cheating by moving on to the next step to find the answer.....

1.14

Estimating the mass flux [Video]

[Video] Phil Bland explaining mass flux

Phil Bland runs an automated camera network in the southern hemisphere. In the video, he explains how that is helping us to understand how much material falls to Earth – and how he can work out if a meteorite has landed, and go and collect it

Fortunately, Phil hasn't seen any really big ones arriving – unlike the dinosaurs….

1.15

Death of the Dinosaurs [Article]

Approximately 65 million years ago, at the end of the Cretaceous Period, there was a dramatic drop in the numbers of species present on the Earth: about 60% of all species suddenly disappeared. This mass extinction has been linked with the collision of a huge meteorite (or bolide) with the Earth. The impact site was at Chicxulub, in the Yucatan Peninsula in the Gulf of Mexico. The crater is now buried, but geophysical surveys estimate its diameter to be between 180 and 320 km. Environmental effects caused by an impact of these dimensions include a darkening of the sky, due to ejected rock dust, followed by a rapid, global drop in temperature. In the case of Chicxulub, the impact was into a sedimentary rock formation, including evaporite deposits (i.e., sulphate-bearing rocks), resulting in tonnes of sulphur oxides ejected into the atmosphere. The energy of the impact fused nitrogen and oxygen from the atmosphere into nitrogen oxides. As the temperature dropped, sulphur and nitrogen oxides washed out of the atmosphere as acid rain. These consequences affected the entire globe, not just the local region, and for an extended period of time. It is entirely possible that the end result of these global environmental changes was the extinction of many species, including the dinosaurs, although this is by no means completely accepted by many palaeontologists.

[In-line image] Graphic of K-T impactor

1.16

What is the biggest meteorite to hit the Earth? [Article]

[Image] Graphic of Moon formation

As far as we know, the impact into the proto-Earth of a body about the size of Mars is the largest object to hit our planet (so far). The consequences of the impact were formation of the Moon. Models have shown that the Earth was differentiated by the time the impact occurred, and that much of the crust and mantle of the Earth was stripped away.

1.17

When will the next Big One hit Earth? [Article]

[Image] Graphic of time vs size of impactor

That is a very good question. Tonight? Next week? Next year? Over the past few years, as the realisation that asteroid impact of the Earth is a very real possibility, there have been many attempts to assess the amount of material that lands on Earth, particularly in terms of the size distribution of the objects that fall.

1.18

Week 1 [Quiz]

[This will not be included until the MOOC is published]

1.19

Summary of Week 1

You have begun your investigation of Space on Earth by learning the difference between a meteor, a meteoroid and a meteorite. You have seen that meteorites can be sub-divided into two types. Some meteorites have never been melted – these are primitive meteorites, or chondrites, are made of stone and still have the composition of the original material that formed the Solar System. The second type of meteorite are those that have been processed by heating and melting – these are the achondrites and may be made from stone, or iron or a mixture of stone and iron.

As well as finding out about the different types of meteorite, you have also discovered how much extraterrestrial material falls on Earth, and how frequently it falls. You should also realise that whilst the chance of us being wiped out like the dinosaurs is very small, it is still possible – and that even if we knew when it was going to happen, there was still not very much we could do about it.

In Week 2, you will explore where meteorites have come from, and how we know this.

Week 2: Where does Extraterrestrial Material come from?

2.1

Asteroid Belt

[Image]

Asteroids are by far the most abundant named objects in the Solar System. Over one hundred thousand asteroids have been detected, of which most orbit in the asteroid belt between about 2 and 4 AU from the Sun (between the orbits of Mars and Jupiter). The total mass of all the bodies in the current asteroid belt is only about one-thousandth of an Earth mass, although originally, a few Earth masses of material would have been available in the solar nebula in the region. The asteroids are thought to represent fragments of *many* small planetary bodies that never accreted into a single body. This is because of the strong gravitational influence of the newly formed Jupiter 'stirring up' the asteroid population, causing collisions which would repeatedly break up the bodies and so impede the formation of one single large object.

2.2

Asteroid Orbits [Article]

Jupiter continues to exert a strong influence on the asteroid belt. When we plot the number of asteroids against semimajor axis, a striking pattern emerges, as shown in the figure There are spaces, or gaps, where there are very few asteroids. These gaps, known as Kirkwood Gaps after their discoverer, are not random. They occur when the orbital period associated with a given value of semimajor axis, is a simple fraction of the orbital period of Jupiter. This is another example of orbital resonance, as you met with the Plutinos and Neptune.

2.3

Near Earth Objects [Video]

[Video] 60 Second Adventures in Astronomy. No. 14: Gaia and the killer asteroids

Near Earth Objects(NEO) are bodies that have orbits which come near (or indeed cross) the orbit of the Earth. In 2017, almost 17000 NEAs were known. Some objects in the NEO group can come very close to the Earth and could collide with the Earth at some time in the future. This subset, of which almost 2000 are currently known, are called Potentially Hazardous Asteroids (PHAs). The image below shows the orbits of PHAs in relation to Earth's orbit. Looking at the PHA orbits, it is perhaps not surprising that the Earth occasionally suffers an asteroid impact! **Video 2.1** is a short and light-hearted look at 'killer asteroids' prepared by OU staff.

It is all very well knowing that a 'killer asteroid' might be out there – but what should we do about it?

2.4

Disaster Management

[Image]

As you found in the previous step, there are many Potentially Hazardous Asteroids. It is now thought that a global catastrophe (which would wipe out humanity) would be triggered by impact of an asteroid or comet around 1 km across. Fortunately, almost all known objects of this size have been mapped; indeed, with specific monitoring programmes in progress, bodies down to diameters of 10 – 20 m have been traced. The issue of how to deal with a potential asteroid collision is one, which is currently exercising the minds of scientists and politicians all over the world.

[In-line Image] ISO/1 Oamuamua

Even though we are fairly confident that we are aware of almost all PHA, we should not relax our guard! In December 2017, an alien object, travelling at great speed, travelled through the Solar System, and remained undetected until it was on its way back out again. The object, named ISO/1, for Interstellar Object number 1 by the IAU, was on a hyperbolic trajectory, which astronomers have interpreted as meaning it came from beyond the Solar System. i.e., it was not from the Oort Cloud. The object showed characteristics of both an asteroid and a comet, but seems to have a very strange shape, being elongated and almost cylindrical in profile. This has led some of the more excitable astronomers to propose that it might be a faring from an interstellar spaceship.

We should turn away from the speculative, and move to consideration of comets, and whether or not they are a possible source of meteorites.

2.5

Comets

[Image] Orion step 4.17

There are two types of comet: long-period and short-period. Long-period comets approach the Sun from random directions.

Their elliptical orbits around the Sun can be very steeply inclined to the ecliptic plane, and take more than 200 years to complete. For example, the comet Hale-Bopp, which last appeared in 1997, has an orbital period of about 3000 years. Long-period comets seem to come from the outermost fringes of the Solar System, at least around 50,000 astronomical units away. This region is known as the Oort Cloud.

Short-period comets approach the Sun at fairly shallow angles and have much shorter orbits. For example, Halley's comet, which was closest to the Sun in 1985, orbits once every 76 years, so will return to the inner Solar System in 2061. Comet 67P/Churyumov-Gerasimenko, the comet studied by the Rosetta mission, has an orbital period of about 6.5 years. Short-period comets were once thought to be long-period comets that had been affected by Jupiter's gravitational pull and moved into different orbits. Now, however, it is recognised that short-period comets come from the Kuiper Belt, the region of the Solar System out beyond Neptune.

Another noted Kuiper Belt object is Pluto. For many years regarded as a planet but now regarded simply as one of the hundreds of thousands of rocky and icy bodies which form the Kuiper Belt.

2.6

Meteorites from Comets? [Video]

[Video] Matt Gounelle on Orgueil and comets

Matthieu Gounelle is Professor of Cosmochemistry at the Universite de Paris 6 (*nb, check new name)*. He has made a special study of the Orgueil meteorite, which fell in France in 1864. This is one of a group of only 6 primitive CI chondrites, and because they are so different from any other meteorite group, and are the closest in composition to the sun, there has been debate for many years about whether they might be the nuclei from comets that have lost all their ice. Listen to Matthieu explaining his opinion.

Moving away from primitive objects at the edge of the Solar system, let's now move closer to home, and our near neighbours.

2.7

Moon and Mars [Discussion]

[Image] Montage Moon and Mars

As you will have read several times, almost all meteorites in our collections come from the asteroid belt – although there is also a small but significant number of meteorites from the Moon, and a similar number from Mars. These samples were removed from the surface of their parent object by asteroid impacts, then ejected into space. Almost the first question that you would probably like answered is 'how do you know these meteorites didn't come from the asteroid belt?' You will find the answer over the next few steps – but before moving on, what do you think would be reasonable evidence to show that these meteorites came from the Moon or Mars? Share your ideas of how a lunar or a martian meteorite might be identified on the Discussion forum.

2.8

Lunar meteorites [Article]

[Image] ALH 81005

The first lunar meteorite to be described was ALH A81005, found in the Allan Hills region of Antarctica. Descriptions of this small (31.4g) specimen were remarkably consistent, and acceptance of its lunar origin was unanimous. The reason that consensus could be achieved so readily was because ALH A81005 could be compared with the Apollo and Luna samples returned directly from the Moon. The lunar meteorite was identical to Apollo and Luna samples in mineralogy, mineral chemistry and isotopic composition. Cratering of planetary surfaces by asteroidal impact had been considered as an important process for modifying planetary surfaces, but from the dynamics of such a process, the ejection of large amounts of material was thought to be unfavourable. Identification of

ALH A81005 as lunar showed that material could indeed be removed from the Moon and land on Earth.

2.9

Martian meteorites [Article]

[Image] EET 79001

In the previous step, you saw that a rock collected in Antarctica could be compared with samples brought by the Apollo astronauts, resulting in acceptance that meteorites could come from the Moon. Because astronauts have not yet visited Mars, we have no samples returned directly from our neighbouring planet to provide a benchmark against which potential martian meteorites could be compared.

The tale of how a group of meteorites, including the one pictured above, was accepted as martian is too long and complicated to be included here – but the pdf below, which can be downloaded, is of a review written several years ago that goes through the evidence for a martian origin. The number of different martian meteorite groups has increased since the paper was published in 2006, but the evidence has not changed.

A summary of the evidence for a martian origin is as follows: the meteorites are younger than asteroidal meteorites (the youngest is ~ 165 Myr old) so they cannot be from the asteroid belt, but must be from a volcanically-active body (i.e., a planet). Oxygen isotope composition shows that all the meteorites come from the same parent body (but do not indicate which body that is). Finally, some of the meteorites contain gas trapped within pockets of melt glass. The gas has the characteristic composition, in terms of CO_2, N_2 and noble gases, as Mars' atmosphere (as determined by orbiting spacecraft). It also has the same $^{40}Ar/^{36}Ar$ isotopic composition as Mars' atmosphere, which is very different from that of Earth's atmosphere. The gas was concluded to be a sample of Mars' atmosphere trapped when the meteorite was excavated from Mars' surface by impact. Hence the meteorites are from Mars.

You should be aware that there were originally only three sub-groups of martian meteorites, the type specimens of which were named Shergotty, Nakhla and Chassigny. On this basis, the martian meteorites used to be referred to as 'SNCs', but usage of this term is now discouraged since, as indicated above, several more sub-groups have been recognised.

You will return to consideration of martian meteorites in the final week of the course, and discuss the information about Mars that can be derived from the specimens.

2.10

Quiz and Feedback

[This will not be included until the MOOC is published]

2.11

Summary of Week 2

[Image] Main Image

Week 3

How do we acquire Extraterrestrial Material?

How de we acquire extraterrestrial material? That's easy – it just falls out of the sky….. Fair enough, that is true – but only about 5 meteorites a year are seen to fall. Fortunately, there are places where extraterrestrial material accumulates and can be collected. Before we consider where these places are, we'll look at why meteorite falls are highly regarded for analytical purposes.

3.1

Meteorites seen to Fall [Discussion]

[Image]

As you learned in Week 1, during the last few seconds of its flight to Earth, a meteoroid develops a fusion crust. This gives the resulting meteorite some degree of protection from terrestrial contamination. However, weathering of a meteorite starts immediately: transit from the vacuum of interplanetary space to an oxygen-rich atmosphere is a huge change in oxidation conditions, and even the most iron metal-poor meteorite has a complement of metal that is available to rust. So if a meteorite can be collected and safely curated immediately it falls, then the worst of any potential weathering will be avoided.

What other advantages are there for analysing a meteorite fall rather than a find? Share your ideas on the discussion forum.

Meteorites that are found are still an enormously valuable resource for study. In the next few steps, you will learn about why some places are better than others to search for meteorites.

3.2

Cold Deserts [Article]

[Image] Meteorite on blue ice

In 1969, a party of Japanese glaciologists found several pieces of meteorite on a blue-ice region in the Yamato Mountains of Antarctica. When the meteorites were analysed, they were found to be different types – it was not a single meteorite that had shattered on the ice. This finding was reported, but it was not until 5 years later, when a second expedition to the same area recovered almost 700 meteorites, that it was realised that the first finding was not unique. Since then, 42,400 meteorites have been found in Antarctica, from a tally of 57,000 meteorites in total. So Antarctica is an incredibly efficient storehouse for meteorites.

Why do you think this is? Share your thoughts on the Discussion forum, before moving to the next step

3.3

Blue Ice

[Image] Meteorite on blue ice

Part of the reason for the extraordinary trove of meteorites from Antarctica is the weather – it is very dry. Antarctica is the driest of all deserts, and so there is little free water to rust and breakdown meteorites. It is also very cold, so any weathering reactions are slowed down. However, by far the most significant reason for the success of Antarctica as a meteorite store is the ice – or, more specifically, movement of the ice. Glaciers move from the Antarctic plateau to the sea. But where their movement is impeded – for example, by a mountain – then the ice builds up. Ice build up is balanced by ice erosion through scouring by wind, and any rocks carried by the glaciers get deposited close to the mountain barriers. Since very few glaciers have many rocks on top of them – they are mainly dragged from the base of the valley that a glacier is carving out – then a very high percentage of the rocks in the blue ice compression regions are meteorites.

Another factor in favour of meteorites being found in Antarctica is that it is bare – there is no vegetation to obscure the landscape, and dark meteorites show up easily on the ice.

Next you will learn about a slightly different mechanism for concentrating meteorites.

3.4

Hot Deserts

[Image] Searching in Nullarbor Plain

After Antarctica, the Sahara is the most prolific source of meteorites, but the concentration mechanism there is very different. Again, the dry environment helps to preserve meteorites, but there is no concentration mechanism – other than time.

3.5

Searching for Dust [Discussion]

[Image] Cartoon of someone brandishing feather duster looking for dust

As you might imagine, looking for samples of extraterrestrial dust is not easy – not only because the grains are tiny, but also because of the enormous quantities of terrestrial dust that are generated every day. Anyone who has ever wielded a duster to clean behind a cupboard knows that dust accumulates very quickly.

Use the Discussion Forum to consider possible sources of terrestrial dust

Extraterrestrial dust must be collected from places where the concentration of terrestrial dust is low. In the next step, you will see how the use of high-flying aircraft revolutionised the study of cosmic dust.

3.6

Dust from the Stratosphere [Article]

[Image] U2 plane with dust collector

3.6

Dust from Antarctic Ice [Article]

[Image] Melting Ice

3.7

Cosmic Spherules from the Ocean Floor [Article]

[Image] Challenger Spherule

3.8

Other Sources of Extraterrestrial Dust [Article]

[Image]

3.9

Quiz and Feedback

[This will not be included until the MOOC is published]

3.10

Summary of Week 3

Week 4: Sample Return Missions

4.1

Sample Return Missions [Article]

[Image] Graphic of sample return mission

Last week, you learned about where meteorites can be found (or seen to fall) on Earth, and where extraterrestrial dust may be collected. There is a more certain way to acquire these samples – and that is to go to an asteroid or comet to collect it directly.

Sample return missions are among the most exciting of space missions, providing both scientifically unique information and an unparalleled mechanism for inspiring the public. Returned samples allow us carry out sophisticated analyses using a wide range of scientific equipment that can enhance remote sensing measurements from spacecraft. Some scientific studies can only be done in laboratories on Earth rather than remotely or with spacecraft. These investigations include precise isotope measurements that allow age dates to be determined or a chemical history to be unravelled. Similarly, detailed measurements of organic material can help us understand whether life has been present elsewhere in the Solar System.

4.2

Previous Sample Return Missions [Activity]

[Image] Astronaut collecting on the Moon

Currently, we have samples that have been collected directly from three Solar System bodies: the Moon, a comet and an asteroid, as well as material trapped from the Solar Wind. Lunar samples (almost 300 kilograms in total) from the Apollo and Luna missions have been available for analysis for over 30 years. As you found in Step 2.x, it was comparison with Apollo samples that confirmed the validity of a lunar source for the first lunar meteorite to be identified.

[Activity] Using a microscope to look at the Moon

It is more usual to use a telescope or a pair of binoculars to study the Moon – but because we have samples from the Moon here on Earth, we can use a microscope to look at different parts of the Moon in detail. You used the Virtual Microscope in Week 2 (Step 2.x) to look at meteorites in thin section. Follow the link below to pay another visit to the Virtual Microscope website. The link will take you directly to the lunar sample collection, where you can select specimens from each of the 5 Apollo missions to investigate.

You can download the PDF below for a guide to the different features to look out for in the three main rock types found on the Moon.

Next you will find out about samples brought back from a comet

4.3

The Stardust Mission [Article]

[Image] NASA graphic of Stardust spacecraft

[In-line Image] The Stardust aerogel collector

[In-line Image] Stardust particle track

Asteroid (XXXX) Itokawa was the target of the Japanese Space Agency's Hayabusa mission in 200x. You will learn about the problems that the spacecraft had to overcome to bring material back to Earth in the next step.

4.4

Hayabusa mission to Asteroid (xxxx) Itokawa

[Image] Itokawa

[In-line image] Itokawa grains

Next you will learn about the Genesis mission to capture the Solar Wind.

4.5

Capturing the Solar Wind

[Image] Genesis collector (prior to launch)

Genesis, an operation to collect samples of the solar wind, returned to Earth in September 2004; although the landing was less successful than planned, it is anticipated that almost all of the mission science will be recoverable. Stardust, the mission to comet Wild2, will return cometary, interplanetary and interstellar dust in 2006, and Hayabusa, the mission to asteroid Itokawa, will bring back a sample of the asteroid in 2007. Beyond these missions, both ESA and NASA are planning Martian sample return missions within the next decade. The much lower masses of returned material required for analysis from post-Apollo missions are a result of major advances in the sensitivity, precision and resolution of analytical instrumentation.

4.6

Future Sample Return missions [Video]

[Video] Youtube

Check out the EURO-CARES youtube channel – there are several short video clips of planetary scientists saying where they would like to send a mission to return a sample.

Over the next decade, there are clear opportunities for Europe to lead a sample return mission to the Moon, and to collaborate with other space agencies on sample return missions to asteroids and to Mars and its moons (Phobos and Deimos). ESA, as well as national and other international space agencies, have several missions under study to these bodies. It is essential that a sample receiving and curation facility is considered as a critical element of the mission architecture and that its planning and design requirements are fully incorporated during the earliest phases of planning for each sample return mission. Previous work has indicated that from site selection to full-readiness for receiving Mars samples takes 8 - 11 years.

4.7

Planetary Protection

[Image] person in PP suit

One of the most important issues surrounding sample return missions is the requirement for Planetary Protection (PP). This guides the design of a mission, aiming to prevent biological contamination of both the target celestial body and, in the case of sample-return missions, the Earth. The Committee on Space Research (COSPAR) has the mandate from the United Nations to maintain and promulgate the planetary protection policy. Planetary protection is essential to preserve our ability to study the astrobiologically-interesting planets and moons of our Solar System by preventing contamination with terrestrial micro-organism or organics and thus removing the possibility of false-positive results (forward PP). The second aspect of planetary protection aims to protect the Earth's biosphere from extra-terrestrial agents, which might be harmful if released into the Earth environment (backward PP). Both aspects have been considered, forward PP on samples collected and then returned, and backward PP during transport and curation phases.

COSPAR defines five planetary protection categories with subcategories dependent on the target of the mission and the type of mission (fly-by, orbiter or lander). All missions which will return extra-terrestrial samples to Earth for further analysis belong to category V. Depending on the origin of the extra-terrestrial material a category V mission can be an unrestricted Earth return mission (e.g. samples from the Moon) or restricted Earth return mission (e.g. samples from Mars or Europa).

Once returned to Earth, samples have to be stored under specific conditions (depending of their origin) so they remain as pristine as possible. At the same time, for restricted missions, the Earth environment must also be protected from potential hazards. Currently, worldwide, no single facility exists that allows containment of restricted materials, as would be required for a sample receiving facility for materials returned from objects such as Mars. Since it is impossible to foresee the actual risk factor of returned samples, the facilities need to have the most stringent containment level presently afforded to the most hazardous biological entities known on Earth. The infrastructure, procedures, protocols and instrumentation, sample handling, as well as staff training all have to be adapted to PP requirements.

So, once we have brought material back to Earth and made sure it isn't hostile, what happens to it next?

4.8

Curation of samples returned from space missions [Article]

[Image] Lunar lab at JSC

Curation is defined as:

'The collection, handling, documentation, preparation, storage and preservation (into the indefinite future) of samples and distribution of a sub-fraction of samples for research'.

While dealing with samples returned from space, the purpose of a sample receiving and curation facility is to take delivery of the returned spacecraft, open it up and extract the sealed sample container, open the sample container and recover the samples (rock, dust, headspace gas, etc.) from the sample container, and then to transfer samples to the curation laboratory. If applicable, depending of the origin of the samples, biohazard and life detection tests would also be conducted within the facility.

Sample curation facilities are currently operational at the NASA Johnson Space Centre in Houston, Texas (USA) and at the Planetary Material Sample Curation Facility (PMSCF) of the Japan Aerospace Exploration Agency (JAXA) in Sagamihara (Japan). As previously stated, neither of these facilities meet all the requirements for sample return missions from Mars (i.e. these facilities are not currently capable of handling restricted samples).

4.9

Unrestricted Laboratories [Article]

[Image] Clean-room glovebox

Laboratories for unrestricted samples are cleanrooms designed to eliminate the possibility of contamination of the sample from the terrestrial environment (particulate, organic, microbiological, etc.). The usual approach for the design of a cleanroom is to start with the ISO norm for particulate contamination (relying on filtering the incoming air with high-efficiency filters and keeping the room under positive pressure), and to restrict as much as possible potential contamination from the materials and instruments used in the cleanroom. Buffer corridors and increasing levels of cleanliness are used to step up to the cleanest part of the laboratory. This approach is already implemented at NASA JSC and JAXA.

4.10

Restricted Laboratories [Article]

[Image] PHE lab

Laboratories for restricted samples must address two big challenges: keeping the precious samples as pristine as possible (in the same way as for unrestricted samples), whilst also avoiding release of a potential biological or hazardous agent to the environment.

Containment of biological agents is a well-known process, with levels of containment adapted to known pathogens. The concept of a containment laboratory is to use successive layers of protection, safe practices of work and engineering controls (primary, secondary and tertiary) to ensure that aerosols of agents are not released to the environment or to workers.

Containment is provided by a high level of redundancy, by access control, barrier minimization and by an approved decontamination methodology; safe practices of work are also required to ensure these measures are used correctly and the worker reduces any possible risk of contamination from the start. For unknown pathogens, it is recommended that the highest level of containment, BSL-4, is adopted, and remains at this level until the samples are proven to be devoid of biohazard, or sterilised using a validated method.

4.11

Quiz and Feedback

4.12

Summary of Week 4

[Image] Main

You have spent the past 4 weeks finding out about meteorites and cosmic dust: where the material comes from, how much there is, where we find it and how we curate and analyse it. In the final week of the course, you will bring all this information together to see what you can learn from extraterrestrial samples.

Week 5: What can we learn from Extraterrestrial Material?

[Image] Main image

Study of meteorites gives us information about the origin of the Solar System. Knowledge of the composition and age of individual components within meteorites help us to interpret the processes and timescales of Solar System evolution. Insights into planetary formation processes can be applied to understanding of exoplanets and exoplanetary systems.

In this final week of the course, you will discover some of the specific ways in which measurements made on different types of meteorites can teach us about how the Sun and planets formed – and how they might also be implicated in the origin of life on Earth!

5.1

Solar System Formation [Video]

[Video] Planet formation {https://www.youtube.com/watch?v=UNPj7e6XJCQ}

The video shows how a swirling cloud of gas and dust gradually evolves to produce a central star surrounded by a series of orbiting planets. The video is, of course a simulation. The image below is not a simulation – it is a real picture of a star in the process of formation and was captured by the ALMA telescope.

[In-line Image] HL Tauri from ALMA

At this stage in the Sun's evolution, the gas and dust cloud is known as the solar nebula; it is also called a protoplanetary disk. Looking back to Week 1, can you think what sort of extraterrestrial materials are likely to be being formed at this stage in Solar System history? What is the overall composition of the solar nebula? Post your suggestions to the Discussion forum below.

Next, you will find out how to determine the age of the Solar System

5.2

Finding the Age of the Solar System [Video]

[Video] Sara Russell

Mineralogy, plus major, minor, trace element and isotopic chemistry of mineral grains allows inference of condensation sequences, nebular oxygen fugacity and irradiation history, as well as thermal evolution. Isotopic composition of primary components has been particularly successful in delineating the heterogeneous nature of the presolar nebula. An absolute chronology for primary components has been outlined on the basis of high precision Pb-Pb dating; the results provide a marker to which all other processes can be related. The presence of decay products from short-lived radionuclides has been used to infer relative chronologies for the different non-metallic components in primitive chondrites, assuming production of the nuclides by an external source just prior to collapse of the nebular cloud. However, scenarios involving spallation by neutrons close to an energetic young sun have upset the chronological argument. Distinction between the two competing hypotheses is still awaited, and, we hope, almost resolved, as increasing instrumental precision allows measurement of ever smaller quantities of decay products from radionuclide systems with shorter and shorter half lives.

5.3

Solar System Evolution[Article]

5.4

Thermal and Aqueous Alteration [Article]

Following on from aggregation into planetesimals, the first planetary epoch encompasses the time during which mild to moderate heating of the planetesimals took place, as well as collisions between planetesimals. As with the nebular and accretion epochs, most of the information for this period is obtained from components within chondritic meteorites. In theory, the recognition of secondary components in chondritic meteorites should be fairly straightforward. Melting of ice, and the subsequent reactions between solid and fluid on parent bodies led to the formation of secondary minerals such as carbonates and magnetite, the alteration of primary silicates (olivine, pyroxene) to phyllosilicates and oxidation of metal and sulphide grains. Carbon-rich planetesimals, such as the parent objects of CM2 meteorites, had an additional suite of secondary alteration products, resulting from hydrous pyrolysis of organic compounds. As heating continued, or reached higher levels in planetesimals with little or no ice, thermal alteration took over from aqueous alteration, and dehydration and thermal metamorphism produced a different crop of secondary minerals. It has been recognised for many years that textural and mineralogical changes brought about by secondary alteration helps to sub-classify chondrites into petrologic types. Analysis of secondary minerals yields information on the extent of alteration, fluid composition and alteration temperature. Radiogenic isotope systematics, such as I-Xe, of secondary minerals, reveal the timing of fluid alteration. Variations in oxygen isotope composition of different components (carbonate, magnetite, phyllosilicates) show the extent of fluid-solid interaction, constrains the fluid composition and alteration temperature.

5.5

Differentiation [Article]

Continued thermal evolution of asteroidal parents eventually resulted in melting of the silicates, differentiation between metal and silicate, and segregation of metal into planetesimal cores; collision between asteroids also continued. All these processes can be traced through analysis of components from achondrites.

Trace element and isotope variations in silicates from achondrites record the magmatic processes that they have experienced, and allow associations of complementary igneous rocks to be recognised. So, for instance, it is clear that the howardites, eucrites and diogenites form a sequence of rocks that sample different depths from a single asteroid class (e.g., Mittlefehldt et al., 1998). An interesting development of recent years has been recognition of primitive achondrites as bridges between melted achondrites and unmelted chondrites; this recognition has been based on the analysis of mineral chemistry, as well as textural variations and oxygen isotope relationships. Radiogenic isotope systems, such as Mn-Cr, Fe-Ni and Sm-Nd record the onset of planetary differentiation and its duration.

5.6

Core formation [Article]

[Image] Iron Meteorite

The most extensive planetary melting ultimately leads to metal extraction and core formation and iron meteorite and pallasites help us to trace these processes Components within iron meteorites available for study include the major iron-nickel alloys (kamacite and taenite), plus minor components such as sulphides, phosphides and graphite; many iron meteorites also contain silicates, allowing connections to be made with less differentiated materials. Shock-produced phases, e.g., diamonds, record collisional history for iron meteorite parents. Radionuclide systems, such as Pd-Ag, Re-Os and Hf-W, are used to understand the differentiation and cooling histories of melted meteorites. The chemistry of silicate and metal fractions in pallasites give information about processes occurring within their source regions, although the location of this source region, at the core-mantle interface, or at a more shallow depth below a thick regolith is still debated.

5.7

The Presolar Epoch [Article]

A volumetrically insignificant, but scientifically critical component within chondrites is their complement of interstellar and circumstellar grains. The family of grains that is the most recent to be analysed in the laboratory is that of grains formed prior to the accretion of the solar nebula. Lumped together in the broad category of 'presolar grains', these materials have a variety of origins. The grains thus pre-date the major chondritic components, and occur as several populations of grains with different grain sizes. The presence of the grains was first inferred in the late 1970s to early 1980s, on the basis of the isotopic composition of noble gases. The unusual isotopic signatures of the noble gases implied the existence of several different hosts; analyses of acid-resistant residues suggested that the hosts might be carbon-rich. In 1983, combustion of a set of residues yielded the first carbon and nitrogen isotopic compositions of the grains. Individual grains of all of these types, except diamonds are now analysed routinely by ion microprobe. Individual crystallites of nanodiamonds are only ~ 3nm across, thus isotopic measurement of discrete grains is not yet possible (and may never be possible), even with the most sensitive of techniques.

The isotopic compositions of minor and trace elements associated with specific nucleosynthetic processes are also measured by ion microprobe or resonance ionisation mass spectrometry, whilst the identification of sub-grains within grains has been recognised through analytical transmission electron microscopy, and can now be analysed by ion microprobe. Meteorites are not the only objects that are host to presolar grains: interplanetary dust particles contain species that were irradiated prior to accretion, and which might therefore be interstellar in origin. These sub-components, known as GEMS (Glass with Embedded Metal and Sulphides) contain silicates, a few of which have unusual oxygen isotopic compositions indicative of a preserved circumstellar component. IDPs contain other presolar components, including circumstellar forsterite crystals and organic compounds with large enrichments in deuterium and nitrogen. The organic species are similar to those observed in molecular clouds, and along with the presence of inorganic presolar grains imply that IDPs are the most isotopically primitive materials available for laboratory investigation.

Apart from the GEMS, the measurements outlined above have, almost exclusively, been undertaken on populations of grains produced after extensive demineralisation of whole rock primitive chondrites. Less destructive separation techniques have been developed, and analysis of individual presolar grains *in situ* within a meteorite is now possible.

The foregoing discussion focuses on inorganic (although still mainly carbon-bearing) populations of presolar grains. There is also a vast range of organic presolar components available for measurement. These components are present in the most primitive chondrites (CI, CM and UOC) as well as in IDPs. They are characterised by elevated D/H and $^{13}C/^{12}C$ ratios and encompass a range of materials from simple aliphatic to complex aromatic. Laboratory analysis of presolar organic materials tends to be the domain of organic chemists, and their range of techniques, including pyrolysis and combustion GC-IRMS.

5.8

End of Course Test

5.9

What next?

[image]: Mooc Main image

Over the past five weeks, you've learned about the origin and evolution of the Solar System, the meteorites and dust, comets and asteroids that yield valuable information about our beginnings, the collection places we find extraterrestrial material – and the places we would like to bring samples back from.

Whatever you decide to do next – we hope that you have enjoyed learning about Space on Earth, and that you will be ready to explain to friends why they need not worry (too much) about an imminent impact from an asteroid!