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THE AGE AND COMPOSITION OF THE SOLAR SYSTEM

A Lecture by

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The Age and Composition of the Solar System

One of the most valuable properties that meteorites have for "historians" is their incredibly persistent memory. When dealing with nucleosynthesis of the elements in stars, we saw how their construction upto iron was based on the use of building blocks of 4 units of mass as helium nuclei were cemented into various atoms. Carbon had particular significance because of its role in burning hydrogen to helium during the production of nitrogen and oxygen. Two carbons fuse to give magnesium which in turn adds a helium to produce silicon. Two silicons join together to afford iron. A plot of the relative abundance of the elements against their atomic number shows very well the way in which this chain of events progresses. After hydrogen and helium which are by far the most abundant, because of their overwhelming primordial production in the Big Bang, the next most important elements in order of decreasing yield are ^{16}O, ^{12}C, ^{20}Ne, ^{14}N, ^{24}Mg, ^{28}Si, ^{32}S and ^{56}Fe; other major players are ^{40}Ca and ^{60}Ni. With the exception of nitrogen, which as we know has a special place in the CNO catalytic cycle, all these elements have masses divisible by four, confirming the involvement of the helium subunit.

Relative abundance of the Elements

Position	Element	Abundance (rel to Si 10^6 atoms)
1	Hydrogen	2.79×10^{10}
2	Helium	2.72×10^{9}
3	Oxygen	2.38×10^{7}
4	Carbon	1.01×10^{7}
5	Neon	3.44×10^{6}
6	Nitrogen	3.13×10^{6}
7	Magnesium	1.07×10^{6}
8	Silicon	1×10^{6}
9	Iron	9×10^{5}
10	Sulphur	5.15×10^{5}
12	Calcium	6.11×10^{4}
15	Nickel	4.93×10^{4}

Out of our top ten elements, five (H, O, C, N and S) are the essential ingredients of the organic world (life). Similarly five from the top twelve are the most important in the inorganic world of rocks. The two we have not considered are helium and neon, which are always gases and, because of their inertness, take part in no chemical combinations. It is interesting that oxygen, the third most abundant element holds the key place in both the organic and inorganic domains; it is the most prevalent by mass in living things and easily the most significant species when it comes to constructing rocks and minerals.

The organic chemistry of the solar system and the Earth will be considered in detail in a future lecture but how element abundance manifests itself in inorganic situations can be appreciated by looking at the most abundant minerals in the solar system. Two families of silicate minerals with different structures are found to make up sixty percent of the fabric of meteorites. The olivines are solid solutions (unresolvable mixtures produced when one element substitutes for the other in crystals) of magnesium and iron silicates with the general formula $(MgFe)_2\ SiO_4$ whereas the pyroxenes are solid solutions of iron, magnesium and calcium with a common formula of $(MgFeCa)\ Si_2O_6$. Some typical important minerals are listed below:

Formula	Mineral name
Mg_2SiO_4	forsterite
Fe_2SiO_4	fayalite
$MgSiO_3$	enstatite
$(CaMg)Si_2O_6$	diopside
$(MgFe)Si_2O_6$	pigeonite
$(CaMgFe)Si_2O_6$	augite

It has been well worked out how minerals would condense from a hot gaseous cloud such as might have constituted the primitive solar nebula. The sequence is given below with the first few percent being given over to some very refractory oxides containing calcium and aluminium (more of these later). As can be seen a major part of the condensate is Fe/Ni metal, a species we never see free metal on Earth because it all migrated to the core by density settling when the Earth was hot and molten. As we heard in a previous lecture almost completely metallic meteorites are well known.

Condensation Sequence of minerals

Temp(K)	Name	Formula		Abundance
1758	corundum	Al_20_3	}	
1647	perovkite	$CaTiO_3$	}	5%
1513	spinel	$MgAl_2O_4$	}	
1471	iron/nickel	Fi/Ni		25%
1450	pyroxene	$(MgFeCa)Si_2O_6$	}	60%
1444	olivine	$(MgFe)_2SiO_4$	}	
<1000	rest			<10%

Although almost all the production of abundant elements can be accounted for by organic matter, or the major inorganic minerals of the silicate world, what about all the other elements out of the total of 82 known to exist naturally? One way of getting at the abundance of these is to study the spectrum of the sun; another route is to investigate the most primitive meteorites of all, the carbonaceous chondrites, obviously so-called because of their relatively high abundance of carbon. The two approaches had an almost simultaneous start. Solar spectroscopy was begun in the 1860s and one of the first scientists to attack the problem was Sir Normal Lockyer. He also decided to investigate meteorites after observing Coggia's comet in 1871. The rationale for his work, published as a book called the Meteorite Hypothesis in the 1890s, was that he believed the energy to drive the Sun (and to provide the light of comets and other stars) emanated from collisions between swarms of meteorites. Remember at this time the world was not yet aware of radioactivity, so the possibility of fusion reactions was in the distant future. Lockyer's efforts are a perfect example of what frequently occurs in science: the right experiments are done for the wrong reasons. Lockyer's first major success was to discover a new major element in the sun which he called helium. Although nearly thirty years were to pass before his discovery was confirmed, by the finding of helium on Earth by Ramsay, we all know how important ^4He is in our story. In 1889, two of Lockyer's assistants were the first people to find carbon outside the solar system in the Andromeda nebula.

Lockyer did investigate carbonaceous chondrites; by the time he was pursuing his goals several important ones, including perhaps the most vital of all in the current context, had fallen. During the evening of May 14th of 1864, practically the whole of France, from Paris to Pyrenees, was to witness one of the most spectacular of all meteorite fireballs. Twenty stones, the largest the size of a man's head, came to Earth around the village of Orgueil, Tarnet-Garonne. Translated from the French orgueil means "pride" and whilst pride is one of the seven deadly sins, the villagers of Orgueil have every reason to be proud of their meteorite. Modern analyses, compared to spectroscopic studies of the sun, show that the CI carbonaceous chondrites (almost always Orgueil data are used) are the nearest match there is in terms of chemical composition for our star. The agreement is so good that until some better method comes along (plans are in hand to analyse the sun's corona *via* a space mission) if we want to know the abundance of any minor or trace element in the early solar system we turn first to the Orgueil meteorite. There is just one problem with this method: according to other criteria Orgueil is not the most primitive sample we believe we have, so why does it approximate the sun so well?

The most important aspects of a meteorite's ability to remember its past perhaps comes from the mass spectrometeric study of isotope compositions. Whereas rocks on Earth only record the chronology of major geological events, for example their crystallisation age or some subsequent metamorphic processing, meteorites have an enormous variety of ages including those listed below.

Ages acquired from meteorites

Age	**Examples of Isotopes used**
Terrestrial	^{14}C, ^{36}Cl
Cosmic Ray Exposure	^{3}He, ^{21}Ne, ^{38}Ar etc.
Catastrophic events	$^{40}Ar/^{39}Ar$
Crystallisation	$^{87}Rb/^{87}Sr$
Earth/Solar system	$^{207}Pb/^{206}Pb$
Relative Formation	$^{129}I/^{129}Xe$
Formation interval	^{26}Al

Of these only ^{14}C specifically involves an element of life, so even though life forming elements are indirectly involved elsewhere, we will start with terrestrial ages since they allow certain principles to be explained. The mass 14 isotope of carbon is radioactive and decays away by loss of an electron, with a half-life of *ca* 5500 years, to nitrogen. On this basis there should be no active ^{14}C left in any meteorite since they are all much older than a few times 5500 years. However, in space a meteorite is subject to bombardment by cosmic particle fluxes; these convert elements in the meteorite heavier than carbon by spallation (a kind nuclear smashing and grinding process) to ^{14}C. Because the exposure in space is sufficiently long, the ^{14}C reaches an equilibrium amount when it is being freshly added and decaying away at equivalent rates. For various meteorite compositions, laboratory experiments are able to suggest the equilibrium concentration of ^{14}C which will have been produced quite accurately. Once a meteorite enters Earth's atmosphere the cosmic flux is cut off and the ^{14}C will decay away to nothing. However, if in them period following the the meteorite is discovered as a find, by measuring the amount of ^{14}C remaining and comparing this to what ought originally to be present, the terrestrial age can be calculated.

The technique is not an easy one to carry out since the amounts of ^{14}C are extremely small; a very large mass spectrometer called an accelerator is involved. Nevertheless from a study of a key element of biological life we regularly ascertain the lifetimes of a meteorites on Earth. This is actually more true than it might seem because in temperate climates meteorites only survive for about 3500 years before being eroded away to dust. In hot dry deserts this lifetime against degradation is extended to about 50,000 years (the limit of ^{14}C dating). There are older meteorites on Earth but these are found in cold dry deserts when their decomposition is stopped by sealing in the ice; their ages are measured by longer lived isotopes, such as ^{36}Cl but the principle is the same as for ^{14}C.

Other dating techniques work on various premises, all slightly different, but are still dependent on nuclear reactions. Cosmic ray exposure ages are estimated from measuring the production of isotopes by spallogenic reactions which have not necessarily gone to equilibrium. The ages are obtained *via* measurement of how much of the product has been found in the sample; the method of course does not work if the product decays away like ^{14}C.

Dating the time a meteorite formed is frequently carried out just as for terrestrial samples. Many different decay schemes are used. One of the most useful involves measuring the formation of ^{40}Ar from ^{40}K. The method is particularly clever in that some of the potassium remaining undecayed is first converted by a nuclear reaction in the laboratory into another argon isotope, ^{39}Ar. The ratio of the two argon isotopes measured by mass spectrometry, after using heat to release them from the rock, gives the age directly. Because argon and K are of different volatilities it is very useful to observe the release pattern to see if the rock has been disturbed since its formation. This allows processes like the destruction of the meteorite parent body or ejection of a meteorite from a planet's surface to be studied.

One of the most fundamental ages we can obtain from meteorites is that of the solar system itself. Before scientists thought of using meteorites for this purpose, the focus of their attention was the age of the Earth which would approximate the required number if the solar system all formed at about the same time. The earliest ages were arrived at using historical literature or hypothetical events (the flood) and this almost always implicated religious works. Upto the end of the eighteen century, the age of the Earth from the scriptures was believed to be an incredibly young 6000 years. With the birth of the Natural Sciences in the nineteenth century various new analytical routes to estimating the age of the Earth were suggested. For example people tried to calculate how long a molten Earth would take to cool and arrived at orders of magnitude longer than the Bible supposed the age of the Earth to be. But even their estimate of 20 to 100 x 10^6 years was superceded by theories based on the dissolving capabilities of water. Here the premise was to assume that the universal solvent for everything including life began as pure water; how long then would the oceans have taken to reach their present salinity? A common place upper estimate was ca 300 x 10^6 years. A variation on this theme was to work out how long it would take to accumulate the thickest layers of sedimentary rock; again the estimated age of the Earth went up, passing a billion years for the first time.

At the turn of the twentieth century fortunately for science, radioactivity was discovered and it was realised that natural helium on Earth, was a break down product of uranium. Even though helium easily leaks out of rocks, estimates based on the production of helium by radioactive decay caused the ages to go up again. They did yet again when the abundance of non-volatile radioactive decay products were compared to parent isotopes. Whilst in theory, the search for older and older rocks on Earth might eventually have led to an authentic birth certificate, in practice it could not because no rock has ever been found on Earth which is as old as the planet. Because of plate tectonics, the Earth has been continuously resurfaced. The oldest rocks yet found are 3.95 x10^9 years old sediments from Greenland, which are younger by about half a billion years than the actual age of the Earth.

How do we know we are still short of the goal? Again we have to thank the meteorites and in particular an idea which was to come from using lead isotopes. The radioactive decay sequence of uranium, which has two radioactive isotopes, gives final products which are different isotopes of lead. It provides a way of calculating ages even though the rocks may have been disturbed (see ^{40}Ar, above). In fact, by measuring lead isotope ratios $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ it is possible to obtain what is called an isochron, the slope of which will give the age of the samples. A complicating factor arises because not all lead derives from the decay of heavier radioactive isotopes; some lead is primordial, it was made as the element lead during stellar nucleosynthesis. To correct for this we need to know the $^{207}Pb/^{206}Pb$ composition of something which contained no radioactive uranium. The solution to the problem for meteorites came when it was discovered that iron sulphide (troilite, a mineral of an essential-to-life element sulphur although not the biological version of iron sulphide-pyrites) in iron meteorites provided the necessary correction point. Using the troilite data for Canyon Diablo (the meteorite from "Meteor Crater"), in 1956 Claire Patterson was able to come up with a formation age for a group of meteorites which suggested an age for the solar system of $4.55 \pm 0.07 \times 10^9$yrs. How does this however give us the age of the Earth? To provide that Patterson needed to show that Earth was relatedto his meteorites; he had to find a sample which as near as possible approximated the bulk Earth. He speculated that this might be material collected from deep marine sediments which would be mixtures of uranium minerals derived from many sources in the Earth's crust. When he measured a suitable sample, it fell right on his meteorite isochron.

Nowadays the age of the solar system has been refined even further by studying internal isochrons (based on individual mineral separates of a single meteorite) of the most primitive samples. The type CV3 carbonaceous chondrite Allende is one such specimen, it gives an absolute age of $4.553 \pm 0.004 \times 10^9$ years. Many meteorites have been measured by different techniques and they do not all have exactly the same age, suggesting that the actually building up of the solar system took a finite time. Of course working out this interval is important for knowing the mechanism of construction.

Another equally important time needed for the solar system is how long was it between formation and when the constituent elements were produced? We can not exactly answer this question but we do know that elements produced by supernovae, only a very short time before our star was created, are present in meteorites. To see this evidence we have to turn to the oxide minerals which we observed as the first species to form in the condensation sequence discussed earlier. Oxides (and some other high temperature species) occur in what have become known as CAI (Calcium-aluminium-rich inclusions). They are distinguishable by their having a very unusual oxygen isotope signature. By selecting the CAI minerals which do not contain Mg, it is possible to look for the presence of ^{26}Mg which is the daughter of ^{26}Al, a radioactive element produced in supernovae as confirmed by observations of supernova 1987. Since ^{26}Al only has a half-life of 700,000 years, it means that the time between supernova going bang and the formation of the solar system was quite short. According to one hypothesis, a supernova explosion may even have triggered the formation of the sun and its family of planets, comets asteroids and most importantly meteorites, which provide the cosmochemical memory of the event.

Further Reading

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