G R E S H A M

C O L L E G E

WHERE DO METEORITES REALLY COME FROM?

A Lecture by

PROFESSOR COLIN PILLINGER BSc PhD DSc FRS
Gresham Professor of Astronomy

22 November 1996

GRESHAM COLLEGE

Policy & Objectives

An independently funded educational institution, Gresham College exists

- to continue the free public lectures which have been given for 400 years, and to reinterpret the 'new learning' of Sir Thomas Gresham's day in contemporary terms;

- to engage in study, teaching and research, particularly in those disciplines represented by the Gresham Professors;

- to foster academic consideration of contemporary problems;

- to challenge those who live or work in the City of London to engage in intellectual debate on those subjects in which the City has a proper concern; and to provide a window on the City for learned societies, both national and international.

Gresham College, Barnard's Inn Hall, Holborn, London EC1N 2HH
Tel: 020 7831 0575 Fax: 020 7831 5208
e-mail: enquiries@gresham.ac.uk

Where do meteorites really come from?

People have only accepted the concept of meteorites as extraterrestrial objects for rather less than two hundred years. In fact if anecdotal evidence is accepted, Thomas Jefferson, the US President, when told of the Weston Connecticut meteorite, is reputed to have said he would rather believe that Yankee Professors lie than stones fall from the sky. Was it then a giant leap of faith for the American Presidency to have Bill Clinton pronouncing from the White House lawn on August 7th 1996, that NASA scientists had discovered possible fossil evidence of life processes in a meteorite from Mars? The answer to that question is a resounding NO! The Mars story is worthy of special attention and it will be the subject of an extra Gresham Astronomy Lecture (December 11th, 1996). Here we discuss more generally how we have learnt to find meteorites scientifically rather than casually wait for them to find us. The knowledge of where they ultimately come from before reaching Earth is very dependant on our ability to measure precisely the stable isotope ratios of some of the elements of life, particularly oxygen.

The very first meteorites to come into our collections were all "falls". That is to say they were seen to fall by their collectors and it has become tradition to name them after the nearest Post Office, which seems to be a tacit assumption that they are somehow messengers. In the early nineteenth century, however a major step forward was made through the chemical analyses by Edward Charles Howard. He recognised that a suite of samples assembled by Sir Joseph Banks from all over the World contained metallic iron contaminated with several wt‰ nickel. Free iron is almost unheard of in terrestrial rocks and nickel is so rare that methods to analyse for it had only relatively recently been worked out in 1802, when the experiments were performed. The fact that rocks, coming from thousands of miles apart, appeared to be related by a common thread, argued extremely strongly that they shared a similar origin from beyond the Earth. Thus supporting an hypothesis put forward by Ernst Chladni in 1794.

The availability of a technique to recognise meteorites which had not been seen fall led to the identification of so called "finds" to augment the collections beginning to accumulate in European museums. Less than half a dozen meteorites are seen to arrive from space every year and in two hundred years about twice that number have been accidentally discovered by members of the public and subsequently identified, mainly by those involved in museum curation.

Meteorite in Museum collections in 1984

Falls	Finds	Total
905	1706	2611

Good sources of "finds", were areas where European led activities were taking place for the first time in the 19th and early 20th centuries. Thus construction of the Trans-Siberian Railway led to many meteorite discoveries along its route. The best example of a person recognising the possibilities for acquiring meteorites, by exploiting the advance of agriculture through virgin territory, is H.H. Nininger, a biology school teacher who was one of the founders of the Meteoritical Society. Nininger hit on the idea that farmers in the mid-west of America, bringing the praires into cultivation, would have found meteorites on their property. By touring the appropriate parts of the United States lecturing and exhibiting his specimens he added some 300 new meteorite "finds" to his collection.

Nininger's philosophy can be exploited to its fullest by considering hot dry deserts. Using data recorded by continuously observing cameras, it can be calculated that there are 9 events involving a meteorite of >1kg/10^6km^2/year and a total of 54 kg/10^6km^2/year for all samples in the size range 0.01 to 100kgs. Given that many hot desert areas on Earth are favourable for the survival of meteorites, and may have been arid for 1 to 4 x 10^4 years, there are locations to be found where a square kilometre of desert contains 2kgs of meteorites, with a 1kg sample every 3km^2. The trick is to find the areas; these have to be free of sand and preferably with a local background rock which is light in colour (limestone). There are very suitable locations in the Sahara and Western Australian which have been very well exploited to enhance meteorite collections.

Hot desert meteorite collections

Roosevelt Co	Nullarbor Plain	Sahara
147	>1000	875

After classification as "falls" and "finds", the next simplest level of taxonomy divides meteorites into stones, irons and the intermediate category, rather unimaginatively called stony irons. Irons and stony irons are much more easily recognised as "finds" for the obvious reason that lumps of metal just do not exist as terrestrial rocks; further more iron is very difficult to weather away. Irons however do not predominate amongst the "falls" so they clearly are not the most prolific meteorites in space.

Meteorite types in museums in 1984

	Stones	Stony-irons	Irons
samples all	1813	73	725
falls only	901	10	42

This excess of stones over irons can be readily seen when the huge accumulations of meteorites regularly collected from Antarctica are considered. The realisation that Antarctica was a happy hunting ground for meteoriticists came about entirely by chance. A Japanese party of glaciologists visiting the southern polar ice cap in 1969 collected a few stones from a relatively small area where there was no apparent geological outcrop. Believing this might be the debris from a meteorite, it was returned to Tokyo for identification. Imagine the delight when it was recognised that not one meteorite had been collected but 9, all different.

Something obviously unanticipated was going on: a very efficient meteorite concentration mechanism is working. Meteorites falling on the top of the polar plateau, at the rates mentioned for the hot deserts above, are incorporated into the accumulating ice and transported by glacial action downward and outwards towards the coast. If for any reason the ice flow becomes impeded and stagnant, the surface can be ablated by ferocious winds. Ice is removed much faster than the rate at which fresh snow falls and compacts into new ice. Consequently, tens, even hundreds of thousands of years of meteorite infall, over a wide area, is moved to, a relatively small tightly confined area and regurgitated from the ice. Since this concept was worked out, teams of scientists from Japan, the USA and Europe have made annual pilgrimages to Antarctica to look for blue ice fields and go meteorite hunting. Their success rate may be judged from the numbers of samples which have been brought back.

Antarctic meteorite collection

Japanese (JARE)	US (Ansmet)	European (EUROMET)
9006	7298	598

Unfortunately this treasure trove is not all it seems since (i) the average size of an Antarctic meteorite is only 10 grams, (ii) the pairing of samples (many are fragments of a single fall, this reduces the numbers of distinct meteorites by at least a factor of ten and probably more) and (iii) over 90% of the collections are a very common type of specimen called "ordinary chondrites" which do not greatly enhance our knowledge of the solar system. Ordinary chondrites are a conundrum; despite being such a large part of the collection, no one has the faintest idea of where they come from, except that their source is the asteroid belt.

This brings us to the question of the real provenance of meteorites. It seems somewhat ironic that the Meeting of the Royal Society which heard Howard report his iron/nickel data also heard about the astronomical discovery of the first asteroid Ceres, in the gap between Mars and Jupiter. Whilst Howard's report was being published, the second asteroid Pallas was found. Questions addressed to Howard were not recorded so we do not know if anyone asked whether the new asteroids could be a source of the stones which fell from the sky. The prevailing view taken at the time was that they must have come to Earth ejected from lunar volcanoes. A very good map of the Moon had just been drawn by the society artist John Russell who "moonlighted" as an astronomer. It was to be nearly a hundred and eighty years before an actual lunar meteorite was authenticated (see below).

The idea that meteorites were lunar rocks was soon discarded as more and more asteroids, the planet-that-never-was, were discovered. Direct links between meteorites and the asteroid belt were made by obtaining observations of the path of infalling meteorites, from two or more locations, and computing orbits which lead directly back to various appropriate aphelia. Another way of linking meteorites to asteroids is via their respective spectral reflectance curves. Whilst this has been successfully done to match some types of meteorites to some types of asteroid, it has never been achieved for the hugely prolific ordinary chondrites.

The most spectacularly successful matching has been done in respect of the fourth biggest asteroid Vesta which has an almost singularly distinct spectral curve, directly comparable with a group of meteorites named howardites in honour of Edward Howard. The supposition must be therefore that howardites came from Vesta. Now things become really very exciting geologically because howardites can be shown to be part of a much bigger family by studies on Earth in the laboratory, using the techniques of stable isotope geochemistry.

The key to the investigation is an ability to measure very precisely the oxygen isotopic composition of the meteorite silicates. This was first proposed in 1934 and suggested as a way of seeing whether some meteorites came from beyond the solar system rather than just the asteroid belt. The idea is based on the fact that oxygen is the most abundant element in any rock making up 45wt‰ of stone meteorites; its composition should be diagnostic of the sample. Oxygen has three isotopes, the most abundant being ^{16}O but there are two minor ones: ^{18}O about 500 times less abundant than ^{16}O and ^{17}O at even lower (a factor of 2000) concentrations. In any geologically sized body which has been thoroughly mixed these isotopes will have achieved some kind of homogeneity, considered as a fixed starting point. Any chemical or physical reaction which affects oxygen is capable of changing (fractionating) the ^{18}O and ^{17}O relative to the ^{16}O, but it will do so in proportions which are dictated by the mass difference between the isotopes. Therefore anything which affects the ^{17}O relative ^{16}O (mass difference 1) will affect the ^{18}O twice as much (mass difference 2). As a result any sample which has a common origin but was subsequently processed will define a line with a slope of $\frac{1}{2}$ on a plot of $^{17}O/^{16}O$ vs $^{18}O/^{16}O$.

The differences are exceedingly small but the techniques used to make the measurements are now very sophisticated. Oxygen is liberated from the rock by heating samples, in an atmosphere containing gaseous fluorine, using a laser. The gas released is obtained in very high yield, almost 100%, and after purification it is measured by a mass spectrometer specially designed so that the small differences from a standard are obtained, not absolute results. For this reason data are reported as differential or so called delta functions, where

$$\delta^{18}O\ (‰,\ \text{parts per mille}) = \left(\frac{(^{18}O/^{16}O)\ \text{sample}}{(^{18}O/^{16}O)\ \text{standard}} - 1 \right) \times 1000$$

$$\delta^{17}O = \left(\frac{(^{17}O/^{16}O)\ \text{sample}}{(^{17}O/^{16}O)\ \text{standard}} - 1 \right) \times 1000$$

This concept was first suggested by Nobel prize winner Harold Urey to avoid the problem that mass spectrometers all over the world over have their own idiosyncrasies , which can be consequently ignored to allow investigators to compare and discuss their results.

This has worked exceedingly well for investigations involving $\delta^{18}O$, $\delta^{13}C$ and $\delta^{15}N$ etc. Very few people have been able to make $\delta^{17}O$ measurements which are very difficult but nevertheless $\delta^{17}O$ vs $\delta^{18}O$ plots for meteorites have become obligatory. All Earth samples as might be expected define a distinct slope $\frac{1}{2}$ line. The idea was employed as a means of showing that Earth had received a small proportion of lunar rocks, not thrown from volcanoes but, of secondary meteorites ejected when a primary impact caused craters to form on the face of the Moon. Because we already had rocks returned from the Moon we were able to make a direct comparison, when the first lunar meteorites were proposed at the beginning of the 1980s. There are now well over ten known to be in existence, all except one from Antarctica.

The various asteroid meteorite families define different lines but still with slopes of $\frac{1}{2}$. The line on which the howardites fall is one which is common with some other meteorite groups the eucrites, the diogenites and the mesosiderites. The mesosiderites are a class of stoney iron meteorites, with easily enough silicate to make oxygen measurements for comparison with howardites etc. Many other iron meteorites have a small amount of silicate as tiny inclusions and this enables other families to be assembled. In situations where there is no silicate we can appeal to measurements of nitrogen isotopes. Iron has a great affinity for nitrogen and various families of iron meteorites have been linked together from the similarities of $\delta^{15}N$. In this way far from having to thank of every asteroid as a separate entity, we can begin to try and identify a relatively small number of parent bodies for our meteorites.

In respect of Vesta, we have on Earth some very distinct rocks, which are known to be related and these can be used to work out the geological history of the fourth biggest asteroid without ever having been there. It is not without good reason that meteorites have been called "the poor man's space probe".

Further Reading

R.Hutchison. The Search for our beginning. *Oxford University Press* (1983),
R.T.Dodd. Thunderstones and Shooting Stars. *University Press* (1986).
H.Y.McSween. Meteorites and their parent plants. *Cambridge University Press* (1987).

Research Papers

C.T.Pillinger. Light element stable isotopes in meteorites - from grams to picograms. *Geochim. Cosmochim. Acta* **48** 2739-2766 (1984).
C.T.Pillinger and J.M.Pillinger. The Wold Cottage Meteorite - not just any ordinary chondrite. *Meteoritics and Planetary Science* **31** 589-605 (1996).
R.N.Clayton and T.Mayeda. Oxygen isotope studies of achondrites. *Geochim. Cosmochim. Acta* **60** 1999-2017 (1996).

