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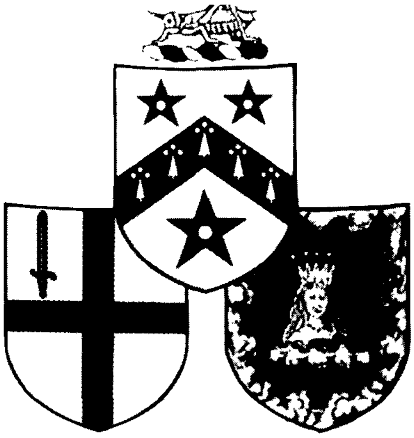

HAIRY STARS

A Lecture by

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GRESHAM COLLEGE

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- to foster academic consideration of contemporary problems;
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Hairy Stars

Hung be the heavens with black, yield day to night!
Comets, importing change of times and states,
Brandish your crystal tresses in the sky,
And with them scourge the bad revolting stars ...

So speaks the Duke of Bedford, Regent of England and France, in the opening lines of Act I, Scene I of Shakespeare's Henry VI, part I.

The cometary phenomenon has captured the minds of playwrights, poets, painters and the common people since time immortal. On each occasion that a comet passes into the inner solar system, the sun disentangles molecules which have been held in cold storage for probably 4.55 billion years.

In the last year or so we have been fortunate to have had visits from one good and one spectacular comet: Hyutake and Hale-Bopp respectively. The last time the latter was with us the Egyptians were a power in the ancient World. It is therefore prophetic that a European Space Agency (ESA) space mission now in the making was sometime ago given the name Rosetta after the stone which led to the deciphering of hieroglyphics. This project intends to establish in detail the nature of processes which make comets such spectacular manifestations, and discover whether these bodies are primitive matter left over from the formation of the solar system. Stones are going to play a part in the Rosetta mission too. The techniques employed in the laboratory by meteoriticists to make "stones which accidentally fall from the sky" give up their secrets are to be extensively used, for the first time in space experiments, to unravel the mysteries of comets.

Funnily enough two men who played important roles in the founding of meteoritics as a science Sir William Hamilton (husband of Lady Hamilton) and Edward Daniel Clarke, first Mineralogy professor at the University of Cambridge, were witnesses to the Rosetta Stone being handed over to the British by the defeated French Army in streets of Alexandria. Moreover, it was a British physician, Thomas Young, turned physicist, who provided the guiding light to the translation of the text. Young's name is forever associated with his Modulus the parameter measured by stretching materials; to commemorate his involvement with the Rosetta Stone, Modulus is used as the name of the British led experiment designed to understand the origin and evolution of comets.

Modulus, *M*ethods of *d*etermining and *u*nderstanding *l*ight elements from *u*nequivocal stable isotope compositions is a joint venture involving the Planetary Sciences Research Institute at the Open University and the Rutherford Appleton Laboratory's Space Science Department.

Everyone has been waiting for a long time for a sensational comet to look at and write about. Neither Halley 1985/6, and the much vaunted Khoutek were exactly breathtaking, so Hale Bopp in 1997, was the first really good viewing opportunity since Halley came round previously in 1910, and it was certainly worth waiting for. Considered against that nearly ninety year break, the fact that we are going to have to live in anticipation for fourteen years, until the Rosetta mission comes to fruition, is just about bearable. In fact the Rosetta idea stretches back much further, it was first conceived as a sample return in the mid-1980s but now in its final form, it will perform the most comprehensive investigation yet conceived for any cometary space project. The mission will take off in January 2003 and wind itself out through the solar system *via* swing-bys of Mars and Earth to get to a little known comet called Wirtanen in 2011, which will then be close to its aphelion. While, Wirtanen is still quiescent, a probe, produced by a German led consortium, will land on its surface; the main spacecraft will go into orbit around the nucleus. Together these two packages of instruments will travel with the comet on its journey through the asteroids, past Mars and Earth and round the Sun. As it goes it will monitor many fundamental properties as a function of the time and distance from the heat source which causes the tiny ball of dust and ice to release its volatiles to space.

As already said Wirtanen is a little known comet; it hardly rated study before it was selected as a candidate for the Rosetta Mission. If the publicity attached to a landing in a 200km x 150km region of Mars is anything to by Wirtanen is going to a household name in the not too distant future. Until recently, the only known picture was one taken by the British astronomers Iwan Williams and Alan Fitzsimmons: they turned the Johannes Kepler telescope in Wirtanen's direction when faced with a spare few minutes during an observing session on La Palma. During the next few years Wirtanen is expected to come under intense scrutiny as it makes several passes through the inner solar system. Its period is only 5.5 years so it has just completed one such trip past Earth, round the sun and back out to the icy wastes. This has made it possible to establish some very important facts about Rosetta's target so that it will not be entirely a blind-date. Wirtanen has a radius of only 0.6 to 0.7km (Hale Bopp was *ca* 30 times larger) and its rotation period is probably between 6.5 and 7.5 hours. It emits the characteristic species of comets: water and parent molecules which give rise to CN and C_2 spectroscopic bands. The production rate for H_2O is around 7 x 10^{27} molecules/sec at 1.16AU which means about a bath full of dirty water thrown into space every second, most environmentally unfriendly. The cyano and C_2 precursors are 10^3 to 10^4 less abundant. Such a comet is never likely to be a naked eye observable event but Wirtanen suddenly increased by two orders of magnitude in intensity at 3.5 AU, from 20 to 18, and its light curve altered again at 2 AU; the speculation being that these changes are due to the various molecular sources switching on, when heat absorption allows trapped species to become volatile. Wirtanen's dust environment is one in which 99.4% of the particles are smaller than 0.06μm but most of the mass (72.6%) is in grains upto 0.3mm.

Of course the above models will be refined as Wirtanen (twice more), and other comets are observed from the ground or from telescopes in Earth orbit, but it will be the Rosetta results which provide definitive data even though NASA is to have its own comet mission around 2006 called Stardust. This Discovery class launch aims to return dust grains captured by impact into collectors of the incredibly light material silica aerogel flown through the coma of comet Wild-2, which a recent close encounter with Jupiter has put on a trajectory which makes a return visit feasible and economic.

Although telescope observations have been much more prevalent as a result of Hale Bopp and Hyutake our best knowledge concerning the composition of the icy wanderers probably still comes from ESA's Giotto probe to Halley. All the most prolific species involve light elements which are those which constitute biologically derived species on Earth; this does not imply any direct connection with life on our planet but comets could have been the source material life needed to develop.

Molecule	**Source strength**	**Molecule**	**Source strength**
H_2O	100	CH_3OH	0.8
CO	12*	NH_3	1.5
CO_2	3.5	HCN	0.1
CH_2	<0.01	NO	0.2
CH_4	<0.01	N_2	0.02
C_2H_2	1	H_2S	0.1
C_2H_4	0.3	Heavy organic molecules	0.01
H_2CO	3.8+		

* 67% may be due to HCHO, +90% due to breakdown of polymeric material

Standard models currently suggest that there may be 10^{11} to 10^{12} comets in the Oort cloud, the region of our solar system which stretches beyond Pluto half way to the next star. Even with a mean mass only in the range of 1 to 8 x 10^{16} kg, the sheer weight of numbers means that the total bulk of comets is equivalent to 1000 Earth masses, more than the total of the giant planets and equal to the Sun's complement of elements heavier than helium. Thus a very strong case can be made for accurately quantifying light element compounds identified as present in comets. A full description of the compounds made up from H, C, N and O should include precise compound specific isotopic information. Such compositional detail is of immense importance because it can differentiate between the contributions made to the early solar system and provide direct evidence relevant to the origin of comets.

Accurate absolute and relative abundances of various cometary constituents will only be established by analysis of pristine material and for this reason a drill on the Rosetta lander will be used to acquire samples hopefully unaltered by evaporation, sublimation and condensation processes caused by the solar heating/cooling cycle. Although volatiles require drilling, refractory organic species, sometimes called CHON because they have this element composition but of unknown structure, are less likely to be affected by the solar warming. CHON could turn out to be a tar-like substance or something akin to the macromolecule which constitutes the material called kerogen in petroleum source rocks on Earth. To establish their nature CHON grains will be loaded into ovens and be decomposed for analysis by gas chromatograph - mass spectrometric analysis techniques.

The qualitative and quantitative examination of major, minor and trace constituents will undoubtedly teach us much about comets however the Modulus experiment as its acronym suggests is a whole lot more than that. It seeks to use isotopic compositions in the first instance as a means of recognising where the constituents came from. And of course the big question is whether we can detect the existence of material which is so exotic isotopically that it could be deemed to be from beyond the solar system. Traces of presolar matter have been found in meteorites for about 10 years now. One well characterised species consists of tiny (nanometre sized) diamonds of supernova origin. Presolar diamonds are flagged by low ^{15}N abundance; they could be a major constituent of Wirtanen. To recognise them will require combustion of samples. Even water which comprises the greatest part of the comet could have an isotopic composition, suggesting that it was never homogenised into the solar system. Primitive meteorites regularly afford water with a D/H ratio that is indicative of a method of formation involving ion-molecule reactions observed in dark molecular clouds and such a process would be very applicable to cometary species.

But isotopic compositions are much more versatile than simple tracer studies. Events modifying molecular abundances will change isotopic compositions since these are governed (fractionated) by both chemical and physical changes, e.g. the preferential removal of species enriched in light isotopes during evaporation or by preferential deposition of those rich in heavy isotopes during condensation. The most pertinent example the sort of thing which can happen to the isotopes of water is the Earth's own precipitation cycle. The processes which move water from the equator to the poles on Earth cause effects in both the isotopes of both oxygen and hydrogen. Similar occurrences could happen in cometary water as a function of evolution. Thus mass dependent fraction is a process which could drastically disturb the isotope systematics of species in the developing coma. Far from being disadvantageous; the magnitude of fractionation, and the rate at which it takes place, will supply indispensable information with respect to making sense of the cometary apparition itself. Thus monitoring isotopic compositions as heliocentric distance changes and study temporal variations will be important investigations. However such measurements will also allow us to address problems of comet heterogeneity which cannot be attempted from just one landing site.

Essential to achieving the goals of the Rosetta mission is the quality of the isotope measurements, accuracy and precision must approach the levels reached by ground-based laboratories, far exceeding anything reported previously for space experiments. So far where comets are concerned isotopic compositions are quoted by astronomers from spectroscopic features as an absolute ratios or, for example carbon, ^{12}C: ^{13}C. A major problem with all the ground based data is that they are for species which are of secondary importance (see Table) and even the parent molecules are unknown; no information can be obtained by telescopes for CO and/or CO_2. A similar situation prevails in other systems. The value quoted by astronomers for D/H ratio of Hale-Bopp is 2×10^{-4} (for a flux of 10^{30} molecules/sec); in astronomical terms it is said to correspond to the same ratio on Earth. A meteoriticist however would say that the D/H value for standard mean ocean water (SMOW) is 155.6×10^{-6} so, to the meteoritics fraternity, Hale-Bopp water and SMOW are possibly different.

The reason for this disparity is that in the laboratory isotope ratios are always measured to much higher precision. Modulus will strive to achieve on the comet the same kind of results as can be gathered on Earth, where stable isotopes instead of being talked of as a ratio are discussed in terms of small differences from a standard according to a differential convention which states that

$$\delta^{H}E = \left[\frac{(H/L)\text{sample}}{(H/L)\text{standard}} - 1\right] \text{ x } 1000(\text{permil}, ‰)$$

Where H and L are the heavy and light isotopes of the element E respectively, and the standard is an agreed homogenous reservoir, for example standard mean ocean water (SMOW) for hydrogen and oxygen.

To ensure that the kinds of precision desired can be achieved, it is vital to only measure the isotopic species of interest as ions in a mass spectrometer; other spectroscopy techniques are so far inappropriate. Mass spectrometers themselves are not perfect, they suffer from the problem of isobaric interferences. An example of the difficulty which arises is water, where multiple species exist, some of which have the same nominal mass: an ion of integer mass 17 could be ^{17}O or ^{16}OH whereas 18 could be ^{18}O, ^{17}OH, $^{16}OH_2$ or ^{16}OD and so on. It can easily be seen that unravelling the matrix is difficult but essential. Ions are not really of integer mass (m), they have both positive and negative mass discrepancies but these are small and it requires a very substantial mass spectrometer to resolve them (resolution here being defined as $M/\Delta M$, with values of 8000 necessary in the water system). The size of the magnet in magnetic sector or the length of trajectory in a time of flight instruments would make such a mass spectrometer far too big, massive and power hungry to be contemplated for a space mission.

Modulus gets round the problem by doing exactly what any self-respecting meteoriticist working in the laboratory would do. It converts water chemically to pure oxygen where isobaric interferences do not become an issue. The method used is to pass the water over a reagent cobalt trifluoride to extract the hydrogen, therefore just $^{16}O_2$, $^{16}O^{17}O$, $^{16}O\ ^{18}O$ etc. are measured by a very simple and low mass/low power mass spectrometer of unit resolving power <100. The processing of water is only a typical example of the Modulus philosophy; it will use other chemical reactions to probe important molecules such as CO, CO_2, formaldehyde for their complete isotopic makeup. It will take with it to the comet standards to utilise the time honoured ploy of routinely comparing sample and standard to iron out the calibration idiosyncrasies of mass spectrometers. The most challenging parts of building the instrument are that everything has to be achieved within a mass budget of less than four kilograms, a power requirement of only a few watts and miniature valves have to channel gas around a system by diverting the flow of a helium carrier. There are many technical firsts to be demonstrated but on June 2-3rd this year Modulus passed its evaluation tests and was selected and funded for the Rosetta Mission.

Further Reading

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