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HOW HIGH THE MOON?

A Lecture by

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How High the Moon?

It is of course a toss up whether the Moon or the Sun is the oldest astronomical object. Given that astronomers usually study the night sky, perhaps the Moon should be given the benefit of the doubt, particularly, as compared to the Sun, it does change in appearance and can be studied with the naked eye without risk to the observer. Even so most of the earliest known maps of the Moon are from telescopic studies. An exception is that by William Gilbert, a contemporary of Sir Thomas Gresham, whose effort predates Galileo's 1609 version. Naming of the major features on the Moon, and the practice of honouring famous scientists (although not always), derives from the 1640s and stems from the work of the Italian Jesuit Riccioli and his pupils. It was Riccioli who introduced the term Mare for the dark regions of the surface and the concept that areas, such as the Sea of Tranquillity, were dried up oceans. By the end of the eighteenth century however, when the first "professional" telescopes were being built (i.e. by Herschel), mapping the Moon had become the province of the amateur, for example, the crayon portrait painter John Russell.

Professional scientists again began to take an interest in our satellite with the advent of the space race of the 1960s, prompted by President Kennedy's promise "to put a man on the Moon by the end of the decade". The Apollo programme had so many firsts that it almost seems unfair to single out Neil Armstrong for taking the first "small step" in man's greatest adventure of exploration to date. Scientifically, the legacy of Apollo was nearly half a ton of lunar soil and rock which was returned by six missions over a period of three years. At the peak of activity, some 160 groups world wide were in receipt of sample allocations from NASA, including fifteen in the UK. The studies carried out range from investigating the physical properties of the Moon, characterising the petrology and chemistry of the minerals, through radiometric age determinations of all manner of events, to addressing a problem which is still fascinating us today - is Earth unique in supporting or having supported life?

Before we consider the last question, and the possibilities which opened up because the Moon turned out to be unambiguously barren in terms of evidence for life processes, we should look at another equally ancient conundrum. The centuries old puzzle of where did the Moon come from was also on the agenda of the scientists who study the elements of life and their isotopes. Firstly there was the fission hypothesis which suggests the Moon separated from the Earth as a result of tidal forces. Then there was the idea of capture of a roving asteroid and finally coaccretion. The measurement of oxygen isotopes cannot unambiguously distinguish between the three ideas but the very close similarity of the $\delta^{18}O$ and $\delta^{17}O$ of lunar rocks to those of the Earth definitely mitigates against the capture theory. From the total absence of volatiles e.g. H_2O in lunar rocks, light element investigations also rule out coaccretion. This leaves fission but the dynamics of fission as originally conceived are all wrong, so that the currently accepted best guess at the origin of the Moon is the giant impact hypothesis, which requires a collision between the primitive Earth and a Mars sized object to spall off the infant Moon. It seems that none of the impactor was incorporated into the new Moon or one might have expected to see a slight difference in the oxygen isotope systematics but this has never been detected even by the most precise modern methods. The possibility that the Pacific Ocean is the scar left after the collision has no scientific foundation whatever.

Now to return to investigations related the idea that the Moon had once been life bearing: in fact, it was not just past life which was sought during the Apollo programme but contemporary life as well. Immediately, after splashdown of the Apollo 11 return capsule, the first lunar samples were quarantined and rigorously tested for signs of viable organisms, pathogens or otherwise, but of course none were found. Also a preliminary scientific examination team was set up to establish which were the best samples to issue for the various investigations. It instantly recognised that the rocks which filled the Mare basins were not the sorts of things found at the bottom of the sea, but extremely low viscosity basalts which had flowed from volcanic vents to flood giant impact craters made in the outer crust of the Moon during the last stages of its formation. Nevertheless, since more than ten percent of the teams which had been assembled to characterise lunar materials were organic geochemists (scientists who identify and study the traces of biological molecules found in ancient and modern marine sedimentary environments) the detailed evaluation of lunar materials still went ahead. A whole panoply of techniques was used to test the samples for the presence of hydrocarbons, fatty and amino acids, carbohydrates etc. and even porphyrins (molecules related to for example chlorophyll) to set threshold levels for the presence of these compound classes of no more than a few parts per billion. On this basis, biologically significant molecules were assumed to be absent, except perhaps for porphyrins which might have been accidentally synthesised from the hydrazine rocket fuel used by the lunar landing module. Absolutely no life on the Moon, and the end of generations of speculation!

Although none of the molecules traditionally looked for as chemical fossils could be found, the preliminary analysis showed that Apollo 11 lunar soil had something like 150 parts per million(ppm) total carbon, whereas the pristine lunar rocks had virtually none. Some exterior agency must be operating on the Moon to add carbon to the soil. With the sample distributed worldwide two hypotheses were advanced: (i) that the carbon derived from implantation of the solar wind or (ii) it was a non-solvent extractable meteorite residue. Strangely the two sets of investigators propounding these theories hit on the same experiment, dissolution of the samples in acid, to prove their hypothesis. Each group reasoned differently, as follows: a team from Bristol argued that if the solar wind was responsible then a large excess of hydrogen which would accompany the carbon and lead to the generation of trapped methane, whereas some US investigators at NASA believed that the carbon might be carbide from iron meteorites, which would react with the acid to give methane. Both did the experiment of dissolving lunar soil in hydrochloric acid and claimed to have successfully obtained methane to support their ideas, announcing the results in January 1970, at the first Lunar Science Conference held in Houston. Of course the data were ambiguous, but within a few weeks of the Conference, the Bristol team, in a simple but elegant experiment, used a deuerated reagent for the dissolution and showed that the approximately 25ppm of methane released could be resolved into 5ppm trapped gas and 20ppm reaction product. One might think honours even, but it ultimately turned out the problem was much more complex than believed; the solar wind was also responsible for the deutromethane from a component which became known as hydrolysable carbon (see below).

Once a method was available to distinguish the two forms of carbon, it was an obvious step to try to characterise the processes which led to their formation and accumulation in the lunar soil. First however, some observations on what was being established about the lunar environment by Apollo. We have already inferred that the solar wind, the multi-element stream of atomic particles constantly ejected into space from the solar corona, with energies of one kev/atomic mass unit, could reach the lunar surface; infact this had been postulated some years before Apollo by a German scientist Heinrich Wänke. He predicted that, if the Moon had essentially no atmosphere and probably no magnetic field, lunar soils might be loaded with noble gases from the sun, like a group of meteorites he was studying which came from the very surface of a variety of asteroids. Indeed to prove Wänke's theory a group of Swiss experimenters sent an aluminium foil collecting device with each Apollo mission to trap solar wind flux actually hitting the Moon whilst the astronauts were involved in extravehicular activities. A glance at the Moon's face through a pair of binoculars will tell you that it is pitted and pock-marked by aeons of bombardment by meteorite impacts. The light coloured highlands (light because they are mainly a low iron mineral called plagioclase) of the Moon are of the order of 4.5 billion years old, whereas the dark Mare (iron rich pyroxenes, ilmenites and olivines) are between 3.2 and 3.8 billion years old, so catastrophic destruction of the original rocks has been going on ever since the Moon (and the Earth) formed. Large scale impacts are much less frequent now but micrometeorite activity continues more or less unabated. The outcome of all this erosion has been to reduce lava flows to boulders, boulders to pebbles and pebbles to dust. Concurrently however impact events melt rock to glass which is splashed around the surface aggregating cinder like material and the heat generated in explosions sinters the contacts between the ground down mineral grains to weld them back together again. The secondary rocks made in impacts by these two mechanisms respectively are known as glassy agglutinates and breccias. Billions of years of recycling has conspired to produce a soil (like exists on Earth through water, wind, freezing and thawing etc.)called the regolith. The whole series of events which go towards creating the presently encountered fine grained layer being referred to as "lunar gardening".

If trapped methane and hydrolysable carbon were added to the soil by the outside agencies of the solar wind and micrometeorite impact, then as a result of lunar gardening both should increase as a function of exposure at the surface, what is known as maturity. In the jargon which has been developed for lunar science, a freshly created coarse soil was called immature, whereas one which had been reworked countless times by microprocessing, broken done and rebuilt as agglutinates and breccia, was termed mature. Methane and hydrolysable carbon ought also to correlate with other species which were unambiguously from extralunar sources for example the noble gas ^{36}Ar, a species of nucleosynthetic origin which had to come direct from the sun.

Experiments of all types where performed to show that CH_4 and hydrolysable carbon could be found enriched in very fine grains or aggregates of fine grains within agglutinates, consistent with production on the very surfaces of grains, small particles having a greater surface area/unit mass. Theoretically the solar wind would only penetrate 50 nanometres into rock minerals, and splashed meteoritic remnants would coat surfaces, so these were exactly the sorts of results which would be expected for both extralunar origins.

Naturally as more and more lunar material came back from different Apollo missions to different sites on the Moon, specimens were tested for the existence of methane and hydrolysable carbon. The correlations for methane itself with other solar wind diagnostic elements (^{36}Ar) always worked well but with hydrolysable carbon they were less good. By the time of Apollo 16, NASA had grown confident enough with its equipment to fly to the lunar highland mountains to collect the plagioclase rich, low iron rocks. The samples returned from that mission contained hydrolysable carbon but it did not correlate with other parameters, whereas methane data still quite happily plotted on all the appropriate graphs; something was wrong with the overall hypothesis or a factor was not being taken into consideration.

The missing factor was the composition of the lunar soils themselves. If it was taken into consideration, normalising the measurements for hydrolysable carbon by the amount of total iron in the specimen, then a direct correlation could be obtained by plotting against the favourite solar wind indicator ^{36}Ar. The explanation was that hydrolysable carbon was not being added from outside the Moon by meteorites, but was being made on the surface from lunar resources and the influence of the solar wind. The rationale had to be that iron oxide was being reduced to iron metal and incorporating the carbon; there was insufficient iron in highland rocks for an efficient production. One way could simply be chemical reaction with the solar wind hydrogen but there was another process, which was much more original and exiting to explore. Fortunately, the British Steel Corporation invested the resources which allowed the possibility of the mechanism, which became known as preferential sputtering, to be considered.

When ions enter a target it's rather like smashing the cue ball into the pack of reds on a snooker table; the target balls fly off in all directions. In snooker all the balls are the same mass only their colours are different. Unlike snooker however, some atoms are completely lost or sputtered. In a geological sample the atoms or the balls are of varying size and mass and what is more they are held together by different bonding forces. Nevertheless the atoms obey some very simple theories, one involving transfer of momentum and the other thermodynamic properties of solids. These theories predict that the surfaces of mineral grains subjected to atomic sand blasting by the solar wind will become enriched in certain elements by preferential sputtering (loss of one atom relative to another) and that iron, and only iron, will be reduced to metallic form. When the theory is compared to what is seen on exposed lunar grains the match is exact. Perhaps most important, to the idea of preferential sputtering being accepted as the mechanism for producing metallic iron and associated hydrolysable carbon, are the enormous enrichments in heavy oxygen isotopes which are encountered in the relevant samples. Momentum transfer processes such as are involved in sputtering are very efficient at isotopic fractionation whereas high temperature chemical reactions are not.

The findings above argue very strongly that meteorites are not involved at all in adding carbonaceous material to the surface of the Moon. It was therefore important to consider whether all the carbon found in the soil could be explained by a solar wind source. Again it is important to turn to theory and laboratory simulation experiments. Although it was said earlier that the penetration depth of the solar wind into lunar material was about 50 nanometres, it transpires that some minerals are more easily entered than others and the different species are eroded at varying rates. Because implantation and degradation go on simultaneously at a single surface as competing processes eventually an equilibrium will be established when as fresh atoms enter the system others which have reached the advancing surface are knocked (sputtered) out. The equilibrium concentrations can be worked out for different kinds of minerals and a model for each. Apollo landing site made from the average bulk chemical composition of the soil. The concentration of carbon in lunar soils can be predicted. Calculated values turn out to agree very well with the measured values.

Because of the absence of biological processes and as a result of the way the Moon was formed, it is quite possible to accept that all the carbon currently there is from our Sun. The amount existing as hydrolysable carbon has been established as the best way of estimating the cumulative exposure of soils at the very surface of the Moon (the maturity of the sample).

This means that ultimately it might be possible to work out how the regolith has built up by analysing core samples.

Everything which has been said above for carbon also applies to another important light element nitrogen which ought to be simpler because unlike carbon it does not incorporate into iron. Nothing could be further from the truth! When nitrogen is studied in lunar soils it shows some very perplexing effects. Firstly the nitrogen abundance is apparently much greater than one would predict from the present day solar wind. Even more intriguing is the observation that lunar breccias which were sealed to the Sun some 3 billion years ago have nitrogen which is isotopically quite different (300‰ enriched in ^{14}N) from what is seen in soils which are still an open system. One explanation is that the Sun and hence the solar wind composition has changed during the history of the Solar System. No theory for the Sun is able to explain how or why - so there is every chance that some other as yet undreamed explanation is appropriate.

Although the Moon is a sterile object in terms of biology, the elements of life have still been able to tell us fascinating things about its environmental conditions; just as the Moon reflects the Sun, so too has it shed light on our understanding of our local star, and some unusual but universal effects it causes.

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