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The record of solar and galactic radiations in the ancient lunar regolith and their implications for the early history of the Sun and Moon

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A variety of techniques are available for studying past variations of solar wind, solar flares, galactic cosmic rays, and micrometeorites. Lumar rock results which average over the recent past (~10 Ma) indicate no major changes in any of these components. At longer times, recent data suggest secular changes in the $^{15}N/^{14}N$ ratio in the solar wind, possibly due to enhanced solar flare activity. With the deployment of new techniques, it now appears possible to measure solar wind, solar flare, and micrometeorite records in individual grains removed from different layers of lunar cores. Such grains have been exposed for brief intervals of time (10^3–10^4 a) for times extending at least 10^9 a in the past. Lunar and meteoritic breccias are promising candidates for extending the record back still further, perhaps close to the beginning of the solar system.

A major goal of lunar research has been to determine the nature and history of the lunar environment as recorded in lunar rocks and core samples. For this study, we and others have used a variety of effects that are produced by the energetic nuclear particles that constitute the solar wind, solar flares, and galactic cosmic rays. This work also has been linked with the study of impact features ranging from microcraters $\lesssim 1$ μm in size to craters many kilometres in diameter.

The basic motivation for this work is, of course, to look for temporal variations in the lunar environment. Such changes might represent variations in the overall environment of the solar system – the passage from one spiral arm to another or the traversal of a dense interstellar dust cloud, for example – or strictly local changes such as enhanced solar activity. Even if the Sun and solar system remained the same, changes in the Moon itself could also be reflected in the historical record; a very modest past dipole magnetic field would, for example, be sufficient to shield the Moon from the 0.5 MeV/nucleon iron nuclei that produce characterstic track gradients and high track densities in samples exposed on the present lunar surface.

We briefly summarize here the highlights of prior work; some new results are also included. Additional information can be found in recent reviews by Walker (1975) and Crozaz (1975).

Solar wind, solar flare, and galactic cosmic ray effects in lunar materials

These three types of radiations, whose chemical compositions (85–90 % protons, 10–15 % helium nuclei, ~1 % heavy nuclei) are roughly the same, have very different energies; their effects are thus recorded at distinct and characteristic depths.

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The solar wind directly implants large concentrations of solar ions into surfaces exposed to the Sun. Accompanying the implantation is a radiation damage process that results in an amorphization of crystalline surface materials. Both effects are restricted to a depth of a few tens of nanometres.

Measurable solar flare phenomena, on the other hand, are produced at depths up to ca. 5 g/cm^2. The major effects are as follows: (*a*) The production of stable and radioactive nuclei by inelastic nuclear collisons ($E \geqslant 10$ MeV), (*b*) the formation of nuclear particle tracks by heavy nuclei ($Z \geqslant 20$), and (*c*) the production of trapped electrons by ionization. Solar flare ions are also implanted but this is a phenomenon that has received little attention. An important phenomenon, first discovered by Price, Hutcheon, Cowsik & Barber (1971) in a comparison of a sample of Surveyor III glass (returned from the Moon by Apollo 12) with satellite measurements is that, in solar flares, as one goes to low energies ($E < 10$ MeV) the proportion of the very heavy elements with respect to helium increases. Although this effect is not yet understood, it must reflect the basic physics of solar flare production. This result comes as a disappointment to those who have hoped to use elemental abundances in solar flares as a measurement of the composition of the Sun.

Galactic protons and heavy nuclei have larger characteristic penetration lengths of *ca.* 400 and 40 g/cm^2 respectively. The most studied effects are the production of stable and radioactive isotopes in inelastic nuclear collisons as well as the formation of particle tracks by heavy stopping nuclei. Isotopic anomalies caused by nuclear reactions of secondary cascade particles, principally neutrons, play an especially important role in the studies of lunar cores.

All the radiation effects have been used to study the nature of the radiations themselves and their possible variations with time. A complementary aspect is the use of these effects to measure temporal changes in the lunar surface. The present paper focuses on the first aspect.

Properties of the lunar environment from studies of lunar rocks

Lunar rocks are exposed at the very lunar surface for at most a few tens of million years before being disrupted by local impacts. Furthermore, the impacts of micrometeorites produce an erosion of the order of a few mm/Ma, which complicates the interpretation of the radiation record and set an upper limit of a few tens of Ma to the time interval that can be studied in lunar rocks. As a result, lunar rocks have been used to study the relatively recent past.

Although some authors have claimed to have found evidence for variations in the fluxes of solar wind, solar flares, and/or micrometeoroids in the past, it is our view that the bulk of the available data suggests rather a remarkable constancy of the lunar environment at least in the recent geological past.

Radioisotope data indicate that the average flux and energy spectrum of solar flare particles has not changed appreciably in the last several million years (Finkel *et al.* 1971). Hoyt, Walker & Zimmerman (1973), using the thermoluminescence method which averages over the last 5×10^3 a, reached the same conclusions for that time interval. For galactic cosmic rays, a constancy has been obtained for periods up to 10 Ma by the study of radioactive isotopes (Finkel *et al.* 1971) and up to 50 Ma by the study of heavy nuclei particle tracks (Yuhas & Walker 1973).

Morrison & Zinner (1975) recently completed a combined study of solar flare track gradients and microcrater densities in two lunar rocks with the purpose of setting limits on the micrometeoroid flux and detecting possible directional variations in the flux of both micrometeoroids and solar flare particles. Crystals were examined in cavities of known and different orientations and with small solid angles. By selecting samples with limited exposure to space, one avoids the complications of rock erosion in the interpretations. No evidence for a change in the flux of particles producing submicrometre craters is found in the last 1 Ma. The authors find no anisotropy between the lunar north and the plane of the ecliptic in the flux distribution of micrometeoroids in contrast to the observation by Hutcheon (1975) of an anisotropy between lunar south and the plane of the ecliptic. In all samples, Morrison & Zinner find similar pit/track ratios significantly different than that measured by others (Hutcheon 1975). This discrepancy remains to be resolved.

Although disagreement exists as to the absolute flux of solar flare particles, the shape of the average solar flare energy spectrum during the last 1 Ma seems established at depths in excess of 30 μm in lunar rocks. The agreement between groups which measure track density *vs*. depth in lunar rocks is quite satisfying at these depths but below 30 μm (< 10 MeV/nucleon) confusion still prevails, both flat and steep spectra being reported in different samples. The reasons for the differences observed by various experimenters are not understood. They may be real and represent differences in the properties of low energy solar flares at different epochs.

Extending the radiation record back in time: lunar cores

Our knowledge of the radiations can be extended much further back in time by the analysis of lunar cores and lunar and meteoritic breccias (see next section).

Most of the cores from the Apollo missions exhibit a more or less distinct layering structure. In some, individual layers are easily indentifiable by the naked eye; in others, careful measurements of various parameters indicate the presence of distinct units. Although the exact number of layers is debatable, there is no question that many discrete units, with different irradiation histories, exist.

There is also no question that some crystals that are now found at the deepest depths reached (3 m) were once exposed on the lunar surface to free space. The very high track densities observed cannot be explained by galactic cosmic rays; further, many of the crystals (*ca*. 10 % in a 'well-irradiated' layer) have track gradients characteristic of those produced by solar flares with a steeply rising energy spectrum.

The growth of the regolith at a given place is a complex, stochastic process that is beginning to be understood as a result of recent computer simulations models (Arnold 1975; Duraud *et al*. 1975). At least some cores indicate a relatively simple history of a buildup by the accretion of a succession of layers several millimetres to several centimetres in thickness produced by local impacts.

As an example, in the Apollo 15 core, Gd isotopic anomalies (Russ, Burnett & Wasserburg 1972) are consistent with a model in which the 2.4 m core accreted slowly (as required by the very high track densities found at all levels) and then remained largely undisturbed for the last 500 Ma. This figure has been recently revised upward by Burnett & Woolum (1974) based on their direct measurement of the neutron depth profile in the lunar surface at the Apollo 17 site. The analysis of lunar cores thus offers the unique opportunity to extend the record back at least a billion years and perhaps even longer in time.

By using track indices, Lal and his colleagues (Arrhenius *et al*. 1971) and Fleischer and his colleagues (Fleischer, Hart & Giard 1974) have established a chronology of core deposition.

Although both methods are subject to severe criticism (Crozaz & Walker 1975), they give results in fair agreement with the neutron results leading to regolith growth rates on the order of 2–5 mm /Ma.

All cores can certainly not be explained on this simple basis. For example, thick unirradiated layers are occasionally found. The best example is the ~1 m coarse-grained layer in the uppermost part of the 3 m deep Apollo 17 drill core. Track results show that it was deposited in one event, less than 10 Ma ago, and has lain largely undisturbed since then (Crozaz *et al.* 1974).† This layer offers a unique opportunity to gain information about the ancient galactic cosmic rays at much higher energies than has been possible before.

The amorphous coatings produced by the solar wind on lunar crystals have been measured in 1 μm grains removed from the Apollo 15 and 16 deep drill cores (Maurette & Price 1975). In a given layer, the thicknesses vary by up to a factor of 4, indicating changes in solar wind energy; however, no systematic trend was found over a time on the order of 1 Ga.

A recent very interesting observation is an apparent secular change in the $^{15}N/^{14}N$ ratio with time in the solar wind related nitrogen. Kerridge (1975) noted an apparent decrease of the $^{14}N/^{15}N$ ratio with ^{21}Ne cosmic ray exposure ages and also with the depth in drill stems. Similar results on surface correlated nitrogen were also observed by Becker & Clayton (1975). Both groups have suggested that the $^{15}N/^{14}N$ ratio of the solar corona has changed, possibly related to a greatly enhanced solar flare activity in the past.

Obviously, indications of changes in the solar wind are important: intense solar winds have been proposed as a heating mechanism in the very early solar system (Sonett 1974). Geiss (1973) has also suggested that lunar core data can be interpreted as implying a larger solar wind flux in the past. However, this conclusion is critically dependent on an assumed abundance of Xe in the Sun. It has also been suggested that solar fluctuations could explain the unexpected negative result of the solar neutrino experiment (Davis 1972).

Much of the track work in crystals removed from lunar soils and cores has consisted of large numbers of measurements on grains chosen at random. Recently, we have focused on individual grains that have been exposed to *free* space some time in the past as attested by the presence of micrometeorite impact craters. The overall goal of the work is to measure the relationship between micrometeorites, solar flares, and solar wind during narrow windows of time at different epochs in the past. One aspect of the work has included the systematic investigation of hundreds of grains with the scanning electron microscope (Poupeau, Walker, Zinner & Morrison 1975). Some 20–40 % of the grains have microcraters, some having crater densities in excess of $10^6/cm^2$. The size distribution of impact pits in grains from soils and cores is similar to that in crystals recently exposed (Morrison & Zinner 1975). Assuming that the micrometeorite flux has been constant in time, the results show that individual grains in the lunar soil were exposed to the solar wind for some 10^3–10^4 a. The ratio of craters/tracks is 10^{-2}–10^{-3} of that found in surface rock crystals. It is, of course, possible that the micrometeorite flux capable of producing these craters has fluctuated in the past with the present time being one of greatly enhanced flux. However, the following experimental evidence seems to point to another more likely, and less sensational, hypothesis: in lunar soils, there is a striking *lack* of correlation between either the total track densities or track gradients and the presence or absence of impact craters. This is probably because lunar grains accumulate most of their tracks while covered with a few tens of micrometre of overlying material.

† See note added in proof.

A way to check this hypothesis would be to measure, by another method, the surface exposure of individual grains. We are currently developing a new technique based on the use of the ion probe to study the ions implanted by the solar wind in individual grains of lunar materials (Zinner & Walker 1975). The technique depends on the use of implanted marker ions of known energies. For different bombarding energies, distinctly different depth profiles are obtained and it seems that, at the very least, the ion probe will be useful in studying the redistribution of solar wind-implanted materials by heat, or subsequent irradiation by low energy solar flare particles. The detection of naturally implanted solar wind species appears more difficult but still possible. Sensitivity and background considerations require that individual grains be exposed to the solar wind for 10^3–10^4 years in order for most ion species to be studied. Certainly, nature has not been very kind because she has, as mentioned above, arranged to expose the lunar dust grains for between 10^3–10^4 a. However, several ions, notably ^{52}Cr, are exceptions requiring $\lesssim 5 \times 10^2$ a exposure for study.

Finally, the low energy enhancement of heavy ions in solar flares observed in the Surveyor glass is also found in the record of ancient solar flares stored in lunar cores (Goswami & Lal 1975).

Extending the radiation record still further in time: lunar and meteoritic breccias

Other samples, obvious candidates to take us much further back in time, are the lunar and meteoritic breccias.

In a number of Apollo 14 breccias, ^{244}Pu gas excesses have been observed (Drozd, Hohenberg & Morgan 1975), indicating that they probably formed a long time ago. The same holds true for gas-rich meteorites. At the present time the record in both types of samples remains largely untapped.

Brownlee & Rajan (1973), in a careful survey of rare, chondrule-like spheres discovered in the gas-rich achondrite Kapoeta, found micrometeorite craters similar to those observed on lunar rocks and grains. It is possible that the constituent grains of at least some gas-rich meteorites were bombarded with hyper-velocity micrometeorites. Furthermore, the presence of agglutinate-like objects, similar to those commonly found in the lunar soil, in another gas-rich meteorite, Bununu, seems to indicate that the gas-rich meteorites were exposed at the surface of some parent body and not in space as previously proposed (Price, Braddy, Hutcheon & Macdougall 1975).

Track gradients in lunar and meteoritic breccias cannot be distinguished from each other. They exhibit a tremendous variation, ranging from track gradients as steep as those seen in the Surveyor glass, indicative of an exposure right at the surface of a planet body, to no detectable gradients, indicative of a shielded irradiation.

The time of compaction of soil grains into a breccia can now be dated by a variant of the fission track method (Price *et al.* 1975) where fission tracks originating from a high-U phase are measured in a neighbouring low-U phase. This method was used by the above authors to study carbonaceous chondrites for which they inferred a compaction time of less than 4.2 Ga ago.

Summary

A variety of techniques are available for studying past variations of solar wind, solar flares, galactic cosmic rays, and micrometeorites. Lunar rock results which average over the recent

past (~10 Ma) indicate no major changes in any of these components. At longer times, recent data suggest secular changes in the $^{15}N/^{14}N$ ratio in the solar wind, possibly due to enhanced solar flare activity. With the deployment of new techniques, it now appears possible to measure solar wind, solar flare, and micrometeorite records in individual grains removed from different layers of lunar cores. Such grains have been exposed for brief intervals of time (10^3–10^4 a) for times extending at least 10^4 a in the past. Lunar and meteoritic breccias are promising candidates for extending the record back still further, perhaps close to the beginning of the solar system.

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Note added in proof (*August* 1976)

Recent more extensive data now lead to a more complex history. The layer was probably emplaced ~ 100 Ma ago and covered by variable amounts of shielding material. See Crozaz & Plachy, *Proc. of the 7th Lunar Science Conference* (to be published) for a fuller discussion.

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