THE PREDICTED IRRADIATION RECORD OF ASTEROIDAL REGOLITHS AND THE ORIGIN OF GAS-RICH METEORITES. J.C. Dran*, J.P. Duraud*,**, Y. Langevin*, M. Maurette*, *Laboratoire René Bernas, 91406, Orsay - **Service de Chimie-physique du C.E.A., 91120, Gif/Yvette

I - INTRODUCTION

The existence of regoliths on asteroidal surfaces is supported by recent telescopic observations. On the other hand the constituent grains of gas-rich meteorites have been clearly irradiated as individual grains in both the ancient solar wind (SW) and solar cosmic rays (SCR). This irradiation could have occured within an asteroidal regolith, before the compaction of the grains into a "brecciated" meteorite. The major purpose of this paper is to apply our analytical model of regolith evolution (1) for predicting the irradiation record of gas-rich meteorites in this case. It is shown that the comparison between the predicted and observed irradiation record gives useful clues about the origin of these interesting meteorites.

II - ACCUMULATION OF IRRADIATION EFFECTS IN THE REGOLITH OF A SMALL ASTEROID

In our analytical model of regolith evolution a small asteroid with a radius, $R_s \sim 10$km, reaches an equilibrium thickness, $\Delta_e \sim 2$m, in less than 100my, and then recesses to the interior with a speed ~ 10m/by. Such a speed then implies a duration, $T_a(i)$, for the exposure of the grains in the various fluxes of nuclear particles existing in the interplanetary medium (i = SW, SCR, GCR), which are at least 10 times smaller than those, $T_M(i)$, inferred for the Moon. If we now assume that the constituent grains of gas-rich meteorites also accumulated their irradiation record in such a regolith, we can already qualitatively predict that they should be much less irradiated than lunar dust grains. In addition they should originate from a relatively "fresh" regolith, formed and consequently irradiated over the last few 100my. We now further define this predicted irradiation record with respect to that already measured in lunar dust grains.

II.1 - Galactic cosmic rays effects

The GCR induce cosmogenic nuclides such as spallation products up to depth of ~ 1m in the asteroidal regolith. As both the GCR intensity only very slightly increases up to $\lesssim 30\%$ from 1 au to 3 au and $T_a(GCR) \lesssim 0.1\ T_M(GCR)$, the concentration of spallation product like Ne^{21} should reach an upper limit at least 10 times smaller than the average concentrations observed in surface lunar soil samples. Such a predicted trend is so far compatible with that observed for gas-rich meteorites. In particular the Ne^{21} concentration measured in Kapoeta is about 10 times smaller than the lunar value ($\sim 50.10^{-8}$ cc STP/g).

II.2 - Solar cosmic ray tracks

Recent satellite data (2,3) reveal two distinct types of SCR : the flux of the low energy ($E \lesssim 1$ MeV/uma) "solar" cosmic rays (LESCR) increases by a factor ~ 10 between 1 and 3 a.u (2), whereas that of the more energetic particles, considered as the solar flare cosmic rays (SFCR), decreases by a factor of ~ 30 over the same distance (3).

The iron-group nuclei in the LESCR and SFCR can produce tracks in silicate grains that we already investigated in lunar samples with the following results: 1. the track densities, $\rho(1\mu m)$, measured in μm-sized grains are mostly due to the LESCR and they peak at 10^{10} t.cm^{-2} ; 2. in 100μm-sized grains the $\rho(100\mu m)$ values at the center of the grains are produced by SFCR. Their distribution well fits a very peculiar theoretical distribution computed by using our Monte-Carlo model of lunar regolith evolution, and showing both a sharp maximum at 2.10^9 t.cm^{-2} and a large plateau extending down to 10^7 t.cm^{-2} (4).

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For the asteroidal regolith, T_a (SCR) $\lesssim 0.1\ T_M$(SCR), for both the 1μm and the 100μm-grains. From the variation of the LESCR and SFCR intensities with the heliocentric distance we thus deduce that ρ_a(1μm) $\sim\rho_M$(1μm) whereas ρ_a(100μm)$\sim \frac{1}{300}\rho_M$ (100μm), and this last conclusion is further illustrated by the results of a more elaborated Monte-Carlo computations (5) dealing with the distribution of the ρ_a(100μm) values. Only a single peak at $\sim 5.10^6$ t.cm^{-2} appears in the distribution, as the plateau observed in the corresponding lunar distribution, and which reflects the cycling of the grains through thick ($\gtrsim$1cm) ejecta blanckets, is suppressed when the deposition of the regolith grains only involves a "steady rain".

In a variety of gas-rich meteorites these predictions for the 1μm-grains are well verified by the ρ(1μm) values of $\sim 10^{10}$ t.cm^{-2} reported by the Berkeley group. In addition we measured the experimental distribution of the ρ(100μm) values obtained for >200 grains extracted from the Kapoeta meteorite (5). About 80% of the grains fit very well the single peak of the predicted distribution. However $\lesssim$ 20% of the grains show much higher ρ-value ($\sim 5.10^7$ t.cm^{-2}), which are probably due to their SFCR pre-irradiation history on the external surface of a parent regolith rock (5).

It is generally assumed that the low density peak in this experimental distribution does in fact reflect the irradiation of the whole meteorite in the iron-group nuclei of the galactic cosmic rays, during the flight time of the meteorite to the Earth, which is assimilated to the spallation age, T_s, of the meteorite. We offer an alternative interpretation for this peak, which looks more plausible than the previous one for at least Kapoeta. In fact, in this peculiar meteorite characterized by a very small value of $T_s \sim$2my, the maximum track density expected from the GCR irradiation of the whole meteorite does not exceed $\sim 10^6$ t.cm^{-2}. In addition very detailed computations of the characteristics of GCR-tracks in meteorites (6) show that the ρ(GCR)-values should differ at most by a factor of 2 for grains extracted within a distance $\lesssim$1cm. This is not compatible with the much larger experimental spread ($\gtrsim$10) observed in the experimental distribution, which is well predicted by the SFCR regolith irradiation of the grains.

II.3 - Solar wind ion implantation effects

In lunar silicate grains the solar wind induces both ultra thin amorphous coatings of radiation damaged material (AC) and surface concentration (C_s) of solar wind implanted species. Our lunar studies indicate that the 1μm-grains are exposed on the average only once in the ancient solar wind for about 5,000yr during their lifetime. As the formation of homogeneous AC on silicate grains requires an exposure of ∿2,000 yr in the contemporary solar wind, a high proportion ($\gtrsim$70%) of the 1μm-grains extracted from an average lunar soil does indeed show an AC.

On a small asteroid where T_a(SW) $\lesssim 0.1\ T_M$(SW) the grains should be exposed only 500yr in the solar wind, which is about 10 times less intense than at 1 a.u. Consequently in gas-rich meteorites formed in the regolith of a small asteroid no μm-sized grains should show an AC. This conclusion is well supported by the unsuccessful attempts of the Orsay and Berkeley groups to detect one grain with an AC in a population of $\gtrsim$500 silicate grains hand-picked in several gas-rich meteorites. Finally the C_s values observed in gas-rich meteorites should be much smaller than the corresponding lunar values, and this general trend again agrees with experimental observations (6).

III - DISCUSSION

Our "small-recent" asteroid scenario for the origin of gas-rich meteorites simultaneously accounts in a simple way for the very delicate balance observed

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between the irradiation effects associated with 4 very different fluxes of nuclear particles, that vastly differ with respect to their intensity, their variation with the heliocentric distance, their range in matter, etc... However this scenario has implications which have still to be tested with respect to various observations, such as the relative abundance and the preatmospheric sizes of gas-rich meteorites, their long flight times to the Earth, as deduced from spallation "model" ages that neglect the regolith pre-irradiation of the grains, and the very old "compaction" ages reported for the constituent grains of several gas-rich meteorites.

The following origins have already been proposed for gas-rich meteorites :
1 - In the most exotic scenario (7) the meteoritic grains were individualy irradiated at a much earlier time, when they were freely floating in the primitive solar nebula. They were then rapidly accreted into large asteroids, in which they were shielded from any subsequent irradiation. This primitive asteroids were subsequently fragmented into smaller bodies from which the meteorite was finally excavated and injected into an Earth crossing orbit in recent times. We believe that this scenario is very unlikely. Indeed for insulator grains in the same size fraction freely floating in space, the exposure times of the grains in the ancient SW, SCR and GCR should be roughly similar. In striking contrast for an asteroidal regolith subjected to a meteoritic rainfall, $T(GCR) \gtrsim 1000T(SCR)$ and $T(SCR) \gtrsim 100T(SW)$, and only these peculiar relationships can account for the very delicate balance observed between the very distinct irradiation effects recorded in gas-rich meteorites.
2 - In another scenario (8) the individual irradiation of the grains took also place at a much earlier time ($\gtrsim 4$ by ago), in the "megaregolith" of a large asteroid, most likely formed when the accretionary tail was still active in the solar system. This large asteroid then followed the fragmentation history just outlined hereabove. By taking a radius $\gtrsim 100$km for this primitive asteroid, we obtain Δe values $\gtrsim 200$m, that are sufficiently high to allow the shielding of the meteoritic grains from subsequent irradiations. But this megaregolith was exposed to a meteoritic flux (the accretionary tail) characterized by an intensity probably at least 100 times higher than the contemporary value used in our model of regolith evolution. As a result of the faster turn-over rates triggered by the accretionary tail, the exposure of the grains on the surface of this megaregolith, and consequently their degree of irradiation in the SW, SCR and GCR, was much smaller than that predicted in our "small-recent" asteroid scenario. Thus the "megaregolith" scenario cannot account for the irradiation record experimentally measured for a typical gas-rich meteorite like Kapoeta, and which is only compatible with the predictions of our model. However a variety of carbonaceous chondrites show an irradiation record, as illustrated by their SW rare gas contents and their proportion of SCR irradiated grains, which looks much weaker than those observed in the Kapoeta type meteorites. It could thus be argued that such a weak irradiations record originated at a much earlier times in an ancient megaregolith. This interesting possibility should be further investigated by tackling the problems of measuring low SW rare gas contents, small proportion of SCR irradiated grains and a larger variety of cosmogenic nuclides in these weakly irradiated meteorites.

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