Irradiation history and atmospheric ablation of meteorites: Results from cosmic ray track studies*

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Abstract. The dominant component of nuclear tracks observed in meteoritic minerals poor in uranium is produced by cosmic ray very heavy (vh: $Z > 20$) nuclei. Studies of cosmic ray tracks and other cosmogenic effects in meteorites give us information on the irradiation history of these meteorites and enable us to estimate the extent of ablation during their atmospheric transit, and hence their pre-atmospheric masses. In a specific type of meteorite, known as *gas-rich* meteorite, one finds individual grains and xenoliths that have received solar flare and galactic cosmic ray irradiation prior to the formation of these meteorites. Detailed studies of these exotic components give insight into the accretionary processes occurring in the early history of the solar system. Some of the important results obtained from such studies and their implications to meteoritics are summarized.

Keywords. Tracks; cosmic ray; meteorite; ablation; solar flares; irradiation history; exposure age; accretionary processes.

1. Introduction

The nuclear tracks observed in silicate grains from extraterrestrial samples (e.g. lunar samples and meteorites) are produced by one or more of the following components:

- (i) stopping solar flare and galactic cosmic ray (GCR) very heavy (vh: $Z > 20$) nuclei,
- (ii) spontaneous fission of ^{238}U and, in some cases ^{244}Pu ,
- (iii) induced fission of U and Th, and
- (iv) nuclear reaction-induced spallation recoils.

In the case of uranium-poor silicate grains in meteorites and lunar samples, the dominant source of tracks is the stopping solar flare and GCR heavy nuclei. The spallation recoil tracks have extremely short range ($< 1\mu$) and are relatively unimportant except for lunar samples and meteorites with very long exposure ages. This can also be distinguished from the vh nuclei tracks, which have recordable track lengths of $\geq 10\mu$ in common silicate grains. The low-energy (1-100 MeV/amu) solar flare particles have a maximum range of about a millimetre equivalent of silicate material, and as such solar flare vh nuclei tracks can be seen only in soil grains and rocks exposed on the lunar surface. In the case of meteorites, the solar flare track records are completely lost due to the atmospheric ablation processes which remove, on an average, a couple of centimetres of the surfacial material. A specific meteorite type, the *gas-rich* meteorite, is however, an exception, and one can find solar flare track records in silicate grains extracted from the interior of these meteorites, indicating that these grains were exposed to low-energy solar flare radiations prior to their incorporation into these meteorites. The nuclear tracks observed in most of the meteo-

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ritic silicate grains are thus produced primarily by VH nuclei in galactic cosmic rays. A detailed study of the track records in meteorites along with studies of other cosmogenic records (*e.g.* noble gas and radionuclide concentrations) gives information on: (i) the exposure and irradiation history of meteorites in space and (ii) the extent of atmospheric ablation and hence their pre-atmospheric masses. The study of individual components in gas-rich meteorites, that have received pre-compaction solar flare irradiation, on the other hand, offers us the unique opportunity to investigate possible changes in solar activity in the past and also to understand the accretionary processes occurring in the early history of the solar system. The present paper deals with some of the important aspects of the above studies and the present status of our understanding in these fields.

2. Irradiation history of meteorites

The cosmic ray exposure history of the meteorites, in general, is considered to be a single stage process involving removal of these objects from their parent bodies at some time in the past, and their exposure in space as small objects before being captured by the earth in recent times. It is generally assumed that while they were present in their parent bodies (the asteroids being the most probable parent bodies of meteorites) the meteorites were well shielded from cosmic rays. Such an assumption is justified since the mean attenuation length of various cosmogenic interactions varies from less than a micron (for solar wind interaction) to, at best, a couple of metres (for production of stable isotopes and radionuclides). There are, however, exceptions to the single stage exposure of meteorites, the gas-rich meteorites being one example. There are also other meteorites that have probably experienced multi-stage exposures, resulting from their presence in the nuclear active zone in the parent bodies, and collisional fragmentation in space after being ejected as small objects from the parent bodies. Exposure histories of each of the above types of meteorites will be discussed separately.

2.1 *Meteorites with single-stage exposure history*

In meteorites with single-stage exposure history, the cosmogenic records observed in them (*e.g.* tracks, spallogenic stable- and radio-nuclides, etc.) can be interpreted in terms of two parameters: (i) the intensity of the galactic cosmic rays, and (ii) the cosmic ray exposure durations. Studies of cosmogenic effects in both lunar and meteorite samples have shown that the long-term average intensity of both the proton and heavy ion components in GCR, responsible for production of cosmogenic nuclides and nuclear tracks respectively, has essentially remained constant for the last few tens of millions years (Arnold *et al* 1961; Lal 1972; Walker 1975; Reedy *et al* 1981). We shall therefore assume a constancy in galactic cosmic ray intensity in the past in the discussion that follows.

Assuming a constancy in GCR intensity it is possible, in principle, to obtain the duration of cosmic ray exposure T of a meteorite by studying the cosmogenic records in it. However, the process of atmospheric ablation, which results in the removal of variable amounts of near surface material in different meteorites, introduces an additional uncertainty regarding the shielding depths of the analysed samples within the

original meteorite, and hence on the exposure age estimates. Also, because of the extremely depth-sensitive production rate of nuclear tracks, the track records in meteorites alone *cannot* be used to estimate the duration of cosmic ray exposure. The problem is less severe in the case of cosmogenic stable- and radio-nuclide studies, since their production rates as a function of depth do not vary too much, and one can use an average production rate, independent of the shielding depth of the analysed samples, to obtain approximate exposure ages of meteorites. Examples of typical production rate profiles for nuclear tracks and stable isotopes and radionuclides in spherical meteorites of different sizes are shown in figure 1. One can immediately note the large difference in the production rate profiles for tracks and cosmogenic nuclides. An added advantage in the case of cosmogenic nuclides is the possibility of studying more than one radionuclide or more than one isotope of the same element in the case of stable-nuclides, which gives an additional clue for introducing shielding depth corrections to the exposure age estimates (Eberhardt *et al* 1966). Studies of exposure age distribution of meteorites, based on measurements of cosmic ray produced stable isotopes using mass-spectrometric techniques, have led to groupings in the exposure age distributions of different meteorite types (Wanke 1966; Crabb and Schultz 1981). These groupings have been attributed to discrete collisional events involving the parent body/bodies of the different meteorite types at different times in the past.

An accurate knowledge of the shielding depths of the analysed samples and the size of the original meteorites is however important for a better understanding of the exposure and irradiation history of individual meteorites, and particularly in the case of small meteorites where the production rates of cosmogenic nuclides vary signi-

Figure 1. Production rate of cosmic ray produced tracks, radio-nuclide (²⁶Al) and stable isotope (²¹Ne) in meteorites of chondritic composition. The $P(^{21}\text{Ne})$ values are in the unit of 10⁻⁸.

ificantly at a given shielding depth for different sizes of meteorites (figure 1). It is therefore essential to understand the magnitude of atmospheric ablation of meteorites, and for this purpose, the study of nuclear track records would be ideal because of its extremely depth sensitive production rate.

3. Atmospheric ablation of meteorites

The magnitude of atmospheric ablation of meteoroids during their passage through the earth's atmosphere depends on various parameters *e.g.* velocity, angle of entry, mass, density, shape etc. of the meteoroids. Analytical treatment of this problem to determine the dependence of meteoroid ablation on the above parameters has been carried out by various authors (Opik 1958; Baldwin and Sheaffer 1971; Revelle 1978). The discussion in this paper will be confined to studies based on the nuclear track method.

The basic principle involved in determining the extent of atmospheric ablation of meteoroids using the nuclear track method has been discussed by Fleischer *et al* (1967) and Bhattacharya *et al* (1973). The first step is to obtain the values of shielding depths (depth of the sampling point from the original (pre-atmospheric) meteoroid surface) for different sampling points within the recovered (post-atmospheric) meteorite. This involves determination of cosmic ray track densities in silicate grains taken from the sampling locations and evaluation of the rate of production of tracks, TPM (no. of tracks per *m.y.*), using the information on cosmic ray exposure age of meteorites obtained from stable isotope and/or radio-nuclide studies. Since the track production rate at a given depth X is not very sensitive to the size of the meteorite (see figure 1), one can easily evaluate the shielding depth ΔX of any given sampling point. Bhattacharya *et al* (1973) have generated a set of graphs, using the track production profile shown in figure 1, which directly gives the shielding depth ΔX as a function of both TPM and *effective* recovered radius of the meteorites and can be used conveniently to obtain ΔX values. In generating these ΔX vs TPM graphs, Bhattacharya *et al* (1973) assumed that the ablation is symmetric. However, the error introduced in the estimate of shielding depths, because of this assumption, is not serious since for a $\pm 100\%$ error-estimate in the actual radius of the meteorite, the error in shielding depth is less than $\mp 10\%$.

The methods of estimating pre-atmospheric size and radius of the meteorites for different ablation characteristics, based on shielding depth values obtained from nuclear track studies, have been discussed in detail by Gupta and Lal (1978). They have considered cases involving both symmetric and asymmetric ablation, and also survival of meteoroids as single or multiple fragments. The important results obtained in the work of Gupta and Lal (1978) are summarized below:

- (i) In the case of a single surviving fragment, it is possible to accurately reconstruct the pre-atmospheric size and shape of the meteorites if the centre of the pre-atmospheric body is contained within the recovered fragment.
- (ii) If the centre of the original meteorite is not contained within the recovered body, reconstruction of pre-atmospheric size is not possible in a straight-forward manner. However if a large data set for shielding depths at various points of the recovered fragment can be obtained, one can estimate the pre-

atmospheric size by comparing the expected and observed probability distributions of shielding depths for meteorites of different sizes which have suffered different degrees of ablation.

- (iii) In the case of meteorite fall involving multiple fragments one can estimate approximate pre-atmospheric size from the lowest track density value, obtained after extensive analysis of a large number of samples, assuming that the lowest density sample represents the centre of the original meteorite. Another approach is to estimate mass-loss for different track density intervals based on the observed and expected recovered masses for different track density intervals.

Earliest studies of atmospheric ablation of meteorites using the nuclear track method were carried out by Fleischer *et al* (1967), and more extensive studies were carried out to determine pre-atmospheric sizes of different meteorites by Price *et al* (1967), Cantelaube *et al* 1969, Lal *et al* (1969), Lorin and Pellas (1975), Bull and Durani (1976), Goswami *et al* (1978) and Bagolia *et al* (1977, 1978, 1980). The ablation phenomena in more than 150 meteorites have been studied recently by Bhandari *et al* (1980). Following the methods of Bhattacharya *et al* (1973) and Gupta and Lal (1978), Bhandari *et al* (1980) have obtained 'good', 'model' and 'limit' estimate of pre-atmospheric masses for a large number of meteorites, classified into four sub-groups, based on the frequency distribution of the shielding depths of samples analysed from each meteorite. 'Good' estimate for pre-atmospheric masses could be obtained only for about 20% of the analysed meteorites, since extensive sampling is necessary to obtain such estimates. They have found that the mass-ablation estimate ranges between 25 to 99.9% of the original mass, with a weighted mean of ~85%. The frequency distribution of pre-atmospheric masses (M_0) was found to follow a distribution of the type $dN \propto M_0^{-1} dM_0$. There is also a suggestion in the data that a relation between the mean mass-ablated and the atmospheric velocity of the meteorite exists in the velocity range 14 to 20 km sec⁻¹.

The frequency distribution of minimum shielding depths for different meteorites grouped as a function of percentage mass-ablation, obtained by Bhandari *et al* (1980), is shown in figure 2. The small values of minimum shielding depth, even in the cases of high ablation mass loss, indicate multiple fragmentation in the initial part of the trajectory since the outer regions, corresponding to low ΔX values, will be ablated away in the absence of fragmentation. The results obtained from nuclear track studies of the Dhajala shower (Bagolia *et al* 1977) illustrates such a phenomenon. The frequency distribution of the pre-atmospheric masses for the 'good' estimate cases is shown in figure 3. The roughly equal populations in the mass interval, $M_0 = 10\text{--}1000$ kg, indicate a power law distribution of the type $dN \propto M_0^{-1} dM_0$, as noted earlier. Such a distribution is distinctively flatter than the estimated index of about -2 for meteoroids in the mass-range $1\text{--}10^8$ g (Gault *et al* 1974), and of about -1.6 for meteoroids in the mass range $10^3\text{--}10^7$ g (McCrosky 1968). However, as Bhandari *et al* (1980) have noted, the lower efficiency in recovering small meteorites introduces a definite bias in the track based data towards meteorites of larger sizes.

The estimation of shielding depth by the track method has also been proved to be extremely useful in obtaining accurate production rates of cosmogenic nuclides in meteorites of various sizes. A combined study of nuclear track and cosmogenic nuclides in several meteorites, carried out recently by Bhattacharya *et al* (1980),

Figure 2. Frequency distribution of *minimum shielding depth* ($\Delta X_{\min}$) values for meteorites in three different ablation intervals. The no. of cases for which $\Delta X_{\min}$ exceeds 20 cm are combined together (from Bhandari *et al* 1980).

Figure 3. The number of meteorites in equal logarithmic mass interval is shown based on data for 28 meteorites for which reliable estimates of pre-atmospheric masses have been obtained using the nuclear track method (from Bhandari *et al* 1980).

led to the estimation of the parameter defining the hardness of energy spectra of cosmic ray primary and secondary nucleons at different depths within the meteorites of different sizes. This information is crucial in obtaining the production rates of cosmogenic nuclides as a function of depth for meteorites of different sizes.

The temperature gradient within a meteorite generated during the atmospheric ablation process also leads to partial annealing of tracks in the near surface (crusted) region of the recovered meteorite, and partial fading of low-temperature thermoluminescence. Studies of these effects coupled with laboratory data on track annealing and thermoluminescence fading characteristics can, therefore, give valuable insight into the atmospheric ablation process itself. Some work on these lines have recently been initiated (Jha and Lal 1981; Singhvi *et al* 1981).

4. Meteorites with multiple exposure histories

In the preceding discussion on the atmospheric ablation of meteorites it has been assumed that the meteorites have had a simple (one-stage) cosmic ray exposure in space as small objects. However considering the fact that collisional events (both cratering and catastrophic disruption of large objects) play an important role in the generation of meteorites, one expects some of the meteorites to have multiple cosmic ray exposure histories, prior to their exposure in space as a small object in the recent past. Such pre-irradiation could take place if the meteorites resided within the nuclear active zone (the upper few metres) of the first or second generation parent objects from which they were finally removed during collisional events. Monte-Carlo calculations of collision processes taking place among inner solar system objects (Turner 1979; Wetherill 1980) indicate that instances of multiple exposure of meteorites may be quite common. For example, in the case of meteorites with pre-atmospheric masses in the range 10–1000 kg, the probability of multiple exposure could be as high as 50% (Wetherill 1980). This result, however, depends on the assumed values of certain parameters characterizing the number distribution of small-size objects in the inner solar system and the collisional processes involved, and thus may be somewhat uncertain. Nonetheless, an analysis of meteorites with multiple exposure history offers a unique opportunity of studying the finer details in the evolutionary processes of solar system objects.

Although gas-rich meteorites can be cited as a specific case of meteorites with multiple exposure history, pre-irradiation in this case primarily refers to short-duration solar wind and solar flare irradiation of a few percent of the constituent components of these meteorites. Further, the records of solar wind and solar flare irradiations can be easily detected using particle track and mass-spectrometric methods. However, in non-gas-rich meteorites, devoid of solar wind-solar flare irradiation records, it is rather difficult to pinpoint cases of multiple exposure history, since, in the absence of any *a priori* knowledge of probable multiple exposure, the records of any given cosmogenic products (e.g. track, spallogenic stable isotopes and radionuclides) could be explained by considering an 'effective' single stage exposure. A method has been suggested recently by Bhandari and Potdar (1981) to detect cases of meteorites with multiple exposure history from a combined analysis of nuclear track and cosmogenic noble gas data. Based on the calculation of neon isotopic ratio ($^{22}\text{Ne}/^{21}\text{Ne}$) in meteorites of different sizes, and comparing the results of these calculations with measured values of this ratio in meteorites, whose pre-atmospheric masses have been determined by the track method, Bhandari and Potdar (1981) concluded that for a shielding depth < 30 cm, meteorites in all sizes show a (22/21) ratio of ≥ 1.08 . Thus meteorites with measured (22/21) ratios of < 1.06 indicate a deep seated (> 30 cm) exposure in larger size parent bodies. Their approach, shown in figure 4, is to study the relationship between cosmogenic neon isotopic ratio and the measured track production rate (assuming an 'effective' single stage exposure) and to identify meteorites having probable multiple exposures histories. They have reported that $\sim 20\%$ of the meteorites for which data have been analysed so far could have had multiple cosmic ray exposure histories. A more elaborate discussion of this topic will be found in the accompanying paper by Bhandari (1981).

A very strong case for multiple cosmic ray exposure histories of a couple of Antarctic meteorites was presented by Imamura *et al* (1979), based on a combined analysis of

Figure 4. Correlation plot of cosmic ray produced neon isotopic ratio ($^{22}\text{Ne}/^{21}\text{Ne}$)_{sp} and track production rate (TPM) for chondritic meteorites of different sizes and with a simple single stage cosmic ray exposure history. The hatched portion indicates forbidden zones. Data for meteorites with multiple exposure histories should deviate from the trend lines towards the upper left.

radionuclide and stable isotope data. Further work in this direction based on combined studies of nuclear track, noble gas and radionuclides is extremely important for a proper understanding of the collision-controlled evolutionary history of the small objects in the inner solar system.

5. Irradiation and evolutionary history of the gas-rich meteorites

The gas-rich meteorites can be considered as a special meteorite type having multiple exposure history. They contain individual components that have received solar-wind and solar flare irradiation prior to their compaction into the meteorite bodies. The irradiation records survived the compaction/brecciation processes leading to the formation of these meteorites, and can be easily detected using the nuclear track and mass spectrometric methods. In figure 5 are shown tracks due to solar flare heavy nuclei in grains from two gas-rich meteorites. The occurrence of such grains varies from ~ 1 to 20% among the grains present in these meteorites.

Gas-rich meteorites are present in varying proportion in different stony meteorites—both chondrites and achondrites. All the type 1 carbonaceous chondrites (CI), and 65% of the type-2 carbonaceous chondrites (CM) are gas-rich. Among other chondritic type the percentage abundance of gas-rich meteorites varies from zero (C3(0) chondrites) to $\sim 20\%$. Among the achondrites, the aubrites and the howardites have gas-rich members.

Figure 5. Solar flare tracks in individual grains from the gas-rich Kapoeta howardite (a) and the CM chondrite Murchison (b). The scale bar is 10 micron in both cases. Note the gradient in track density (with high track density near the edge of the grains to the left), reflecting the steeply falling energy spectrum of the solar flare heavy nuclei.

Since the solar wind and solar flare irradiation of individual components of gas-rich meteorites, comprising both single grains and xenoliths (rock fragments), preceded the compaction of these meteorites, the study of the irradiation records in these components provide the unique opportunity for obtaining information on the solar activity at different epochs in the past. Although it is difficult to obtain information about the time of compaction of the gas-rich meteorites, the available data suggest that the compaction of the CI and CM chondrites took place more than 4 b.y. (billion years) ago (Macdougall and Kothari 1976) and it could be about 1.4 to 3.7 b.y. ago for other types of chondrites and achondrites (Schultz and Signer 1977; Rajan *et al* 1979). Information on the intensity and composition of solar flare particles during the early history of the sun, based on studies of gas-rich meteorites, has been summarized by Rajan (1974), Goswami *et al* (1980) and Crozaz (1980).

Apart from obtaining information about the activity of the ancient sun, studies of nuclear tracks and other cosmogenic effects in samples of gas-rich meteorites also provide valuable insight into the dynamical accretionary and evolutionary process of solar system objects. There is a general consensus at present that most of the gas-rich meteorites are regolithic* breccias from an asteroidal surface, and that the individual components of these meteorites received their solar flare and solar wind irradiation while residing in the asteroidal regolith. This scenario which was postulated quite some time back (Suess *et al* 1964) gained wider acceptance only after the analysis of lunar samples and the observed similarity in the solar wind-solar flare records of the gas-rich meteorites and the lunar soils and soil breccias, which are definitive regolith products, and some of which are gas-rich in character (Lal and Rajan 1969; Pellas *et al* 1969; Wilkening 1971; Pellas 1972; Poupeau and Berdot 1972; Rajan 1974; Poupeau *et al* 1974). Detailed comparison of solar flare irradiation records in lunar soil grains and track-rich grains in gas-rich meteorites and the observed anisotropy in the track irradiation pattern in the track rich grains ruled out the possibility that these grains were irradiated individually in free-space prior to their compaction into these meteorites (such an irradiation would have led to an isotropic track irradiation pattern). As the case for regolith evolution of gas-rich meteorites has been strengthened, attempts have been made to characterize the nature of the asteroidal regolith and the associated impact processes, and model the dynamical evolution of the asteroidal regolith (Anders 1975, 1978; Price *et al* 1975; Housen *et al* 1979; Langevin and Maurette 1980), based on our present understanding of processes taking place in the lunar regolith (Gault *et al* 1974; Arnold 1975; Langevin and Arnold 1977). The effect of several important parameters *e.g.* differences in gravity field and the flux and velocity of bombarding objects etc., in the lunar and asteroidal cases, has to be considered in these calculations. The results obtained indicate much higher values for the regolith thickness on asteroidal objects, extending upto several hundreds of metres, as opposed to about ten metres in the case of the moon. Although there seems to exist a *qualitative* agreement between the observed solar wind-solar flare irradiation features in gas-rich meteorites and those predicted on the basis of regolith evolution models, it must be noted here that in all the attempts made so far to explain the cosmogenic features seen in gas-rich meteorites, the *pre-compaction* exposure

*The term 'regolith' refers to the upper layers of dust and rocklets produced by impact processes on atmosphereless bodies of the solar system (*e.g.* moon, asteroids). The thickness of this layer depends on the physical characteristics of the bodies and the impacting objects, and can vary from a few metres to a few hundred metres.

duration of individual components of these meteorites within the 'nuclear-active' region in the asteroidal regolith, has been considered as a free parameter or equated to the total cosmic ray exposure duration. Based on a re-evaluation of this problem Goswami and Lal (1979) postulated that the regolith irradiation scenario for gas-rich meteorites is not compatible at least in the case of the CI and CM (carbonaceous type 1 and 2) chondrites. They have based their argument on the fact that the pre-compaction irradiation durations, during which the individual components of the gas-rich meteorites must have received their solar flare and solar wind irradiation, is extremely short ($< 10^5$ yr) in the case of CI and CM chondrites, and have shown that such short duration irradiation in the asteroidal regolith cannot lead to the observed solar flare irradiation features in these meteorites. Goswami and Lal (1979) considered the difference between the exposure ages based on cosmogenic stable isotopes and radionuclides as the measure for pre-compaction irradiation duration. Such an approach is appropriate since the stable isotope age of a gas-rich meteorite will represent both the pre-compaction irradiation duration and the recent exposure duration of the meteorite as a small object in space, while the radionuclide exposure age will represent only the recent exposure duration in space.

As an alternative to the regolith scenario, Goswami and Lal (1979) have proposed that the solar flare and solar wind irradiation of individual components of gas-rich carbonaceous chondrites took place while they were residing in the surface or near surface regions of centimetre to metre size objects, prior to the formation of asteroidal size parent bodies. This must have happened in the very early stages of the evolution of the solar system. Lack of evidence for irradiation of individual grain in space requires that the pressure in the solar nebula was sufficient ($> 10^{-10}$ Atm.) to shield the grains from solar flare and solar wind particles until their incorporation into cm to metre size objects. Some of our recent studies (Goswami and Lal, unpublished) indicate that it is probable that some individual grains received direct solar flare irradiation, while being partially shielded by the gas pressure in the nebula itself. The centimetre to metre size bodies must coalesce to form larger size objects ($\geq$ km), within a short duration of 10^{4+1} yr, to effectively cut-off further solar flare and galactic cosmic ray irradiation, so that the constraint on the short pre-compaction irradiation duration can be satisfied. Collision among these large objects will finally lead to the formation of larger size parent bodies of CI and CM chondrites, which will thus form out of an irradiated swarm of objects, and shall contain 'irradiated' material throughout its entire volume. This feature can readily explain the high percentage of gas-rich meteorites among the CI and CM chondrites. While impact-induced regolithic activity will definitely be present in the parent bodies of these meteorites and may lead to excavation, fragmentation and redistribution of material, the solar-wind and solar flare records seen in individual components from the gas-rich members in these groups were essentially those imprinted prior to the formation of the parent bodies.

In view of the above development, a re-evaluation of our present understanding of the irradiation features seen in gas-rich meteorites as due to their exposure in asteroidal regoliths is becoming necessary. Work is currently in progress (Goswami and Nishiizumi, unpublished) to accurately determine the pre-compaction irradiation durations of gas-rich meteorites belonging to other chondritic and achondritic groups, based on measurements of noble gas and radionuclide exposure ages (on aliquots of the same sample). This approach, however, is feasible only in the case of meteo-

rites with low exposure ages (e.g. H chondrites) since for meteorites with recent space exposure age exceeding 10 m.y., the radionuclides (^{26}Al , ^{53}Mn) generally used for exposure age determination suffer from saturation effect. Additional experiments to determine the possibility of very different exposure histories of the irradiated and un-irradiated components in gas-rich meteorites are also necessary to get insight into the finer details of the exposure history of these meteorites. Future work along these directions could be expected to give us valuable information on the accretionary and evolutionary history of small objects in the early solar system.

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