CLUSTERS AND CYCLES IN THE COSMIC RAY AGE DISTRIBUTIONS OF METEORITES

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ABSTRACT

Statistically significant clusters in the cosmic ray exposure age distributions of some groups of iron and stone meteorites are observed, suggesting epochs of enhanced collisions and breakups. Fourier analyses of the age distributions of chondrites reveal no significant periods, nor does the same analysis when applied to iron meteorite clusters.

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Introduction. Cosmic ray interactions in meteorites produce a variety of spallation products which depend on the target element abundances, the size and location within a meteorite. Radioactive and stable cosmogenic nuclide pairs with half-lives ranging from a few years to 10^9 years can be used to determine the cosmic ray exposure history of an object. The radioactive nuclides with half-lives short, compared with the time interval of exposure to cosmic rays, are in secular equilibrium and define the production rates. For a constant exposure geometry measured amounts of the stable integrating nuclides coupled with radionuclide measurements are used to obtain the integral time of exposure to cosmic rays. The advantage of this approach is that reliable exposure age information can be obtained in samples reflecting variable degrees of cosmic ray shielding as in large meteorites or in cases of incomplete development of the secondary cascade typically observed in small meteorites. A number of methods were developed for the calculation of production rates and of cosmic ray exposure ages (e.g. Voshage, 1962; Nishiizumi et al., 1980; Marti, 1984; Lavielle et al., 1984). Exposure ages for iron meteorites based on ^{40}K-^{41}K and ^{38}Ar data indicate some clustering of exposure ages for several groups of irons (e.g. Voshage and Feldmann, 1979; Lavielle et al., 1984). Exposure age distributions for chondrites were studied several times (e.g. Wänke, 1966; Crabb and Schultz, 1981). Noble gas data were recently compiled by Schultz and Kruse (1983).

Methods of Analysis. To test the significance of a cluster of M samples within a given group of N (>M) meteorites, we first assign an age span, T, to the group as a whole, based on the rough appearance of the age distribution of the group. We then select a value, W, much shorter than T, similar to the age spread of the candidate cluster. Under the assumption that the N group members are uniformly and randomly distributed over the age interval [0,T], we calculate the probability of finding at least M samples within some subinterval of duration W.

The cluster probabilities were computed by performing Monte Carlo simulations on a vax 11/780 computer. For each trial of the simulation, N pseudo-random numbers were generated on the interval [0,T]. A set of overlapping subintervals, each of duration W, were defined so that their starting points form a uniform grid in which successive subintervals overlap by 90% so as to cover the interval [0,T]. If at least M of the N random numbers is found in one or more of the subintervals, a "success" is recorded. The estimated occurrence probability for a cluster of M meteorites is the number of successes divided by the total number of trials.

Various tests of the Pseudo-random number generator have been made, including a comparison with a direct calculation of the cluster probability in a limiting case where a simple analytic expression applies.

We have also searched for periodicity in the age distributions of both individual meteorite groups and in the age distributions of clusters. A discrete time series is formed by assigning to each of a set of uniformly-spaced time bins, the number of samples lying within the bin. A Fourier spectrum is then computed for these time series and is examined for outstanding peaks, the significance of a peak in the power spectrum is evaluated by computing the probability of finding a peak at least as high as the real one in the spectrum of a randomly generated age distribution (using a Monte Carlo procedure quite analogous to the above method of establishing cluster probabilities.

Results. A cluster is designated "probable" if its probability of occurrence, by the previously described test, is less than 10% and "very probable" if the probability is less than 1%. Groups of probable and very probable clusters are listed in the table below.

Table List of Significant Exposure Age Clusters and Calculated Probabilities.

Group	N	T (Myr)	Average Age of Cluster (Myr)	M	W	Probability
H Chondrites	95	20	7	45	3	$0/10^5$
Enstatite Achondrites	9	115	60	5	8	$94/10^4$
Irons IA	13	10^3	440	5	50	$20/10^3$
Irons IIA	7	10^3	25	4	50	$111/10^4$
Irons IID	3	10^3	360	3	50	$60/10^4$
Irons IIIA	19	10^3	650	7	50	$2/10^3$
Irons IIIE	6	10^3	475	3	50	$104/10^3$
Irons IVA	13	10^3	375	10	150	$1/10^4$
			400	6	75	$60/10^4$
			400	4	40	198/2000
Irons IVB	5	10^3	875	3	50	$50/10^3$

Column 1 gives the group containing the cluster, columns 2 and 3 give the size of the group, N, and its age span, T. Column 4 gives the estimated age and column 5 the number of samples in the cluster. Columns 6 and 7 give, respectively, the age span, W, of the cluster and the probability of random occurrence (the latter expression displays explicitly both the number of successes and the total number of trials from which the successes were derived). The table does not list all clusters found because some of these overlap in time.

A Fourier analysis of the H chondrite group, using only meteorites with exposure ages between 10 and 40 Myr (i.e., ignoring the big peak at 7 Myr) yielded no significant periods. Similarly, no significant peaks were found in the fourier spectrum of the L chondrites between 0 and 40 Myr. A power spectrum of the age distribution of the iron meteorites (see table) also yielded no significant periods.

Discussion. We regard the clustering as real since probable or very probable clusters occur in most of the major subgroups. The statistical significance assigned to the clusters depended on the assumed test model of a uniform distribution over the stated ranges, T. For instance, for each of the iron groups T = 1000 Myr is roughly the cutoff age for the irons as a whole. A more realistic hypotheses against which to test cluster significance might be to distribute the samples exponentially, to simulate the gradual decrease in the number samples of increasing age.

To obtain some idea of the sensitivity of the results to our assumptions, we have also computed the cluster probabilities by choosing a width W in excess of the apparent age range of the cluster, thereby overestimating the probability, for example, for the iron IIIE subgroup, changing W/T from 5% (corresponding to the result in the table) to 7% increases the probability from ~10% to ~20%, therefore, this cluster must be considered marginal. On the other hand, the probability of the cluster in the IA iron group increases from ~2% to ~9% when the assumed width of the cluster changes from 5% to 8%. The IA cluster and most of the clusters listed in the table are at least probable even when their age ranges are overestimated.

One interpretation of the clusters is that they represent epochs of increased meteorite formation resulting from individual collisions of asteroids or comets. In this case, one would expect to see a cluster of width corresponding to uncertainties in the age values. However, secondary breakups of the original collision products, complex exposure histories, and spatial variations in the cosmic ray flux, can all degrade the sharpness of the clusters. Thus it is important to know whether the actual spread in the ages of samples from a given cluster can be accounted for by any of the above factors.

Multiple collisions with asteroids might produce meteorites over an extended period. One possible example of such an enhancement is the iron IVA cluster at 400 Myr, extending over an age interval W = 150 Myr. The fact that this interval, containing 10 samples is exceptionally long leads us to suspect that two or more clusters are present. Belonging to the aforementioned 10 are 6 samples of average age 400 Myr, which themselves constitute a very probable cluster listed in the table. The remaining four samples do not constitute a cluster by our criterion, however a more sophisticated test might reveal a second cluster.

Conclusions. The record of cosmic ray effects in iron and stone meteorites was studied. Statistically significant clusters in the exposure age distributions of these objects were found, suggesting epochs of enhanced meteorite formation, possibly as the result of collisions and breakups. Significant exposure age clusters are found or confirmed for the following groups of meteorites: H-Chondrites at 7 Myr, enstatite achondrites at 60 Myr, iron group IA at 450 Myr, IIA < 50 Myr, IID at 350 Myr, IIIA at 650 Myr, IIIE at 475 Myr, IVA at 400 Myr and IVB at 875 Myr. A Fourier analysis of the age distributions of both H and L chondrites reveals no significant periods, nor does the same analysis when applied to the age distributions of iron meteorite clusters

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