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Evidence for Comet Storms in Meteorite Ages

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Abstract

Clustering of cosmic-ray exposure ages of H chondritic meteorites occurs at 7 ± 3 and 30 ± 6 Myr ago. There is independent evidence that comet storms have occurred at the same times, based on the fossil record of family and genus extinctions, impact craters and glass, and geomagnetic reversals. We suggest that H chondrites were formed by the impact of shower comets on asteroids. The duration of the most recent comet shower was ≤ 4 Myr, in agreement with storm theory.

1. INTRODUCTION

The cosmic ray exposure age of a meteorite is based on the amount of an isotope such as ^{21}Ne, which is produced at a known rate by energetic cosmic rays hitting the meteorite. The exposure to cosmic rays begins when the meteorite is broken out of a parent body which had previously shielded it, and ends when the meteorite lands on the Earth. Since most meteorites that are found have fallen recently (on a geologic time scale), the exposure ages give us the times the meteors spent orbiting in the solar system since their creation. In this paper we report evidence that a class of meteorites called H chondrites ("H" indicates High iron, approximately 28% by weight; chondrites are named after the round silicate bodies they contain called *chondrules*) broke from their parent bodies at the same times that comet showers left evidence of their existence directly on the Earth in the form of mass extinctions of species, impact cratering, and geomagnetic reversals.

The distribution of cosmic-ray exposure ages for meteorites has pronounced peaks. Crabb and Schultz (1981) reported clusters of H chondrite meteorite ages at 4.5 Myr and 20 Myr, but they noted that if they used the revised value of the ^{21}Ne production rate P_{21} proposed by Nishiizumi et al. (1980), then the calculated ages would be approximately 50% greater. (The technical considerations are as follows: The new value is $P_{21} \approx (0.29 \pm 0.02) \times 10^{-8}$ cm^{3}STPg^{-1}Myr^{-1} for H chondrites with a shielding parameter of ^{22}Ne/^{21}Ne = 1.114. It was based on ^{53}Mn, ^{81}Kr-^{83}Kr, and ^{22}Na-^{22}Ne calibrations that all agree with each other and with the findings of other researchers (Moniot et al. 1983; Müller et al. 1981) but disagree with the $P_{21} \approx 0.441 \times 10^{-8}$ value found for the ^{26}Al age calibration. The lone discrepant calibration which all researchers find for the ^{26}Al age is still unexplained, and the existence of this discrepancy should prompt continued caution in accepting the ^{21}Ne dates.)

Figure 1 shows the data of Crabb and Schultz (1981), adapted from their paper to reflect the revised production rate, using their identical logarithmic binning, but with Poisson error bars added. The H chondrites show peaks near 7 Myr and 30 Myr. Crabb and Schultz assumed that the younger peak was from meteorites produced in a single large event, and that the width of the peak was due to the uncertainty in the age determinations. This conclusion is consistent with the observation that the two peaks have comparable fractional widths, as is evident in the figure because of the logarithmic time scale. The L chondrites (L for Low iron, typically 22%) show a broad distribution of ages with no narrow peaks, although Crabb and Schultz note that the broad structure observed could be the sum of numerous small peaks.

Figure 1 also shows the dates for which there is the strongest evidence of comet storms on the Earth. Comet storms (or "showers") result when the comets normally orbiting the sun at great distances are perturbed (for example, by a passing star) so that a large number of them enter the planetary system together (Hills, 1986). The experimental evidence that suggests comet showers in the history of the Earth comes from a variety of sources:

(1) *Extinctions*. Peaks in the rates of extinctions of marine families were reported by Raup and Sepkoski (1984) who found that they were separated by a regular 26-30 Myr periodicity. They later found that peaks could be seen at the same ages in the extinctions of fossil genera (Raup and Sepkoski, 1986). A similar periodicity had been found earlier by Fisher and Arthur (1977) based on a qualatative analysis of geophysical data. In figure 1, the horizontal bars labelled "extinctions" indicate the geologic stages in which there are local maxima in the family extinction rates, based on Fisher and Arthur (1977). Specifically these bars cover the period 5.1-14.4 Myr (mid and late Miocene), 38-50 Myr (mid and late Eocene), and 65-73 Myr (Maastrichtian); the extinctions are not resolved to a finer time resolution than this. Several theories were proposed to explain the periodicity (Rampino and Stothers, 1984; Whitmire and Jackson, 1984; Davis et al., 1984) and they all involved the impacts of comets on the Earth during comet storms. Muller (1984) pointed out that if the extinctions were caused by comet storms rather than by individual impacts (as originally proposed by Alvarez et al.(1980) for the Cretaceous/Tertiary boundary) it would resolve the apparent conflict between the sudden extinctions expected from single impact models, and the extended period of extinctions claimed by paleontologists (Stanley, 1984) who said that the mass extinctions took place over several million years. Hut et al. (1987) present paleontological evidence that the mass extinctions are indeed stepwise, as expected from the multiple impacts that take place during a comet storm, and that these extinctions are consistent with known cratering rates on the Earth and other astronomical considerations.

(2) *Impact Craters and Impact Glass on the Earth.* Rampino and Stothers (1984) and Alvarez and Muller (1984) found that impact cratering on the Earth over a 250 Myr period matched the extinction cycles of Raup and Sepkoski (1984). The bars labelled "crater fit" in Figure 1 were drawn centered at 12.5, 40, and 69 Myr (the peaks of the cyclic fit of Alvarez and Muller); the bars cover the range ±2.5 Myr around the central values; this range is somewhat arbitrary, and it represents our guess to the the uncertainty in the fit. Craters younger than 5 Myr were not included in the work of Alvarez and Muller in order to reduce potential systematic bias from the large number of craters surviving from the recent past. In a recent analysis, Hut et al.(1987) argue that the strongest grouping of impact craters and impact glass occurs near the present, near 35 Myr, near 65 Myr, and near 90 Myr; we have plotted these with horizontal bars labelled "crater clusters." The width of the bars was estimated from the FWHM of the clusters (Hut et al., 1987). Raup and Sepkoski (1986) note that there is a "possible" extinction in fossil genera in the period 1.6-2 Myr.

(3) *Geomagnetic Reversals.* The rate of geomagnetic reversals shows maxima at approximately 30 Myr intervals (Negi and Tiwari, 1983); Raup (1985A) pointed out that these maxima roughly coincide with the marine family extinction peaks, although he later indicated that

the statistical significance of the effect was marginal (Raup, 1985B). The horizontal bars labelled "reversals" in Fig. 1 indicate the bins in which Raup (1985A) found maxima in the reversal rate, centered at 10 Myr, 40 Myr, and 70 Myr. Note that these bars represent bin widths and not one standard deviation error estimates; in both the first and third peak mentioned above there is an adjacent data point nearly as high. Muller and Morris (1986) proposed a theory to explain how impacts could cause some magnetic field reversals; their theory explained several features of the reversal morphology, as well as the evidence linking impacts to reversals.

There are only two strong peaks in the H-chondrite age distribution, yet the extinctions, impact data, and geomagnetic reversal rates all suggest that there was a third comet storm at about 65 Myr. An overall decrease in the numbers of stoney meteorites with age, usually interpreted in terms of a lifetime for such meteorites in the solar system, makes any statistical analysis marginal. In Figure 1 there is a suggestion of an excess in the region 56-70 Myr, (11 meteorites in 3 age bins), but additional events will be necessary to determine whether there is a peak.

The centers of the H chondrite peaks do not agree exactly with the times of comet storms deduced from the other data, but the discrepancy is within known systematic uncertainties. Cosmic ray exposure ages calibrated by several methods (Moniot, 1983; Müller et al., 1981; Nishiizumi et al., 1980) give values that differ by about 10%. The discrepancy in the ^{26}Al age suggests that there may still be unknown systematic errors in this age determination. Small variations in the intensity of cosmic rays with time, or age-dependent corrections for the diffusion of ^{21}Ne from the meteorites, for example, may slightly shift individual peaks. After taking into account these additional systematic uncertainties, our best estimates for the ages of the peaks in the H chondrite distribution are 7 ± 3 Myr, 30 ± 6 Myr, with the possible excess at 62 ± 8 Myr.

2. MODEL

The 7 Myr peak in the H chondrite age distribution has previously been interpretted as the result of the breakup of a single parent asteroid (Crabb and Schultz, 1984). The single parent was assumed because of the homogeneity of the meteorites, and because it appeared unlikely that several asteroids would break up at the same time. However the correlation with comet storms now suggests that the peak could be due to the impacts of a storm comets on the asteroid belt.

The total cross-sectional area of the roughly 2 x10^6 large asteroids (radius > 1 km) in the asteroid belt is about 5% the area of the Earth. This is sufficiently small that few comets with radius > 0.5 km would hit; small comets (if they exist) probably dominate the production of meteorites. Using the comet size distribution of Weissman (1983), we find that the ratio of small (10 m) comets to large (0.5 km) comets is 5 x10^3. Each impact releases meteoritic material with a volume up to 10^5 times that of the impacting object (Shoemaker and Wolfe, 1982). Because of the high energy of the collision, a large fraction of the material can fall out of the asteroid belt into orbits near the Earth.

To account for the absence of distinct peaks in the L chondrite age distribution, we hypothesize that the H and L meteorites originate in two distinct streams of parent asteroids, which we will call the H asteroids and the L asteroids. (Anders (1965, 1978) has shown evidence that the L chondrites had a common parent body that underwent outgassing 500 Myr ago; this could be the time of the creation of the L asteroid belt.) In this model, the H chondrites are produced in collisions between comets and the H asteroids; these collisions occur primarily during comet storms, and are sufficiently energetic to inject the H chondrites directly into orbits or gravitational resonances (Wetherill and Shoemaker, 1982) that eventually lead to the Earth. In contrast, we assume that the production of L chondrites is dominated by continuous collisions, perhaps between pairs of L asteroids. If the L asteroid stream is compact, then self collisions could dominate. If the L asteroid stream is close to a gravitational resonance, the L chondrites produced in the low velocity asteroid-asteroid collisions could reach the Earth. Although this model is ad hoc, we presented it to show that there is no *fundamental* mystery in the different distributions of the H and L chondrites.

The moon has a larger cross-sectional area than the asteroid belt, and yet few lunar meteorites have been discovered. Lunar meteorites have a much shorter lifetime in the solar system because of the close proximity of the earth, so the absence of such meteorites reflects the fact that they were swept out of orbit soon after the last comet storm. Recently fallen meteorites from the asteroid belt would have begun in orbits that did not cross the orbit of the earth, but which were gradually perturbed into our path by the effects of Jupiter and Saturn.

3. CONSEQUENCES

Once we accept a comet storm origin for the H chondrites, we can use the width of the age peak to place an upper limit of 4 Myr for the duration of the most recent storm. (The FWHM spans 4 Myr, but part of this width may be due to uncertainties in the age analysis.) This limit is incompatible with the long-duration comet storms inherent in the Planet-X theory (Matese and Whitmire, 1986), but it is consistent with the 1-3 Myr storms triggered either by random passing stars (Hut et al., 1987) or by a solar companion star (Muller, 1984).

In order to understand the role played by comet storms in such phenomena as mass extinctions and geomagnetic reversals, it is important to know what fraction of the impacts of comets on the Earth took place during the comet storms, and what fraction took place during the relatively quite 26-30 Myr time intervals in between. We can estimate this ratio by assuming that it is the same as the ratio of meteorites produced during those same intervals. We estimated the number of H chondritic meteorites in each of the three peaks by drawing a smooth background curve, and counting the number of meteorites above and below it. We found the number of meteorites in the peaks to be 66 ± 14 (at 7 ± 3 Myr) and 20 ± 14 (at 30 ± 6 Myr). The errors are primarily systematic uncertainty in the level of the background. The possible excess at 62 ± 8 Myr consists of 7 ± 3 meteorites. The total number of meteors in storms is 93 ± 30, and the fraction of meteors created in comet storms is 0.46 ± 0.15. We then conclude from our model that 0.46 ± 0.15 of the comets that hit the Earth do so as part of the relatively brief comet storms. This value is consistent with the qualitative observation that a substantial fraction of impact craters on the Earth are part of the periodic signal (Muller, 1986; Trefil and Raup, 1987). If the comet storms last for 3 Myr (Muller, 1984; Hut et al., 1987) then the flux of comets during a storm (assuming 26 Myr spacing between storms) increases by a factor of 8 ± 3. Note that this value does not depend on the (highly uncertain) number of impacts on the Earth during a storm.

Extraterrestrial impacts should leave evidence in the form of iridium layers, as was pointed out by Alvarez et al. (1980), who found a large iridium excess at the Cretaceous/Tertiary boundary (65 Myr old). Two (and possibly three) smaller layers have been found near the Eocene/Oligocene boundary (about 35 Myr old) (Ganapathy, 1982; Alvarez et al. 1982). The most comprehensive search for iridium has been made by Kyte and Wasson (1986) who examined sedimentary rock spanning the period 33 to 67 Myr. They estimated that 20% of their iridium signal came from cometary dust and 80% from terrestrial sources, so for the storms we are discussing here they should have observed an increase in the iridium by a factor of (0.2 x 8) + 0.8 = 2.4 ± 0.6. The iridium data in their paper does have factor of 2 fluctuations in the vicinity of 33-35 Myr, but these variations could be due to changes in sedimentation rate. Thus Kyte and Wasson did not have sufficient sensitivity to detect the magnitude of comet storm that is indicated by the H chondrite age data. Improved experiments are underway at Berkeley that should be able to see the expected iridium levels from these comet storms.

4. SUMMARY

The clustering of cosmic-ray exposure ages of H chondrites meteorites had previously been interpreted as evidence that most of them were created in two relatively brief events. By using the best calibrations available in the literature, we place these events at 7 ± 3 and 30 ± 6 Myr ago, with possibly a third event at 62 ± 8 Myr. There is independent evidence that comet showers have occurred at the same times, based on the fossil record of family and genus extinctions, impact craters and glass, and geomagnetic reversals. This agreement can be understood if the H chondrites were formed by the impact of storm comets on asteroids. The L chondrites, which do not exhibit these peaks, must have a different origin. The width of the youngest peak implies that the duration of the most recent comet shower was ≤ 4 Myr, in agreement with comet storm theory.

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Figure Caption: The cosmic ray exposure ages of chondritic meteorites, based on the work of Crabb and Schultz (1981), but using the calibrations of Nishiizumi et al. (1980) for the time scale. Since the meteorites are all recent falls, the age indicates the time that the meteorite was created. The bars indicate the times for which there is independent evidence of comet storms, based on extinctions of fossil families (Raup and Sepkoski, 1984), rates of geomagnetic reversals (Raup, 1985) and impact cratering (and impact glass) on the Earth (Hut et al., 1987; Alvarez et al., 1984). The bars agree with the ages of the the peaks in the H chondrites, within the systematic undertainties of the age determinations. This agreement suggests that the H chondritic meteorites were created during comet storms, perhaps from impacts of comets on asteroids. The L chondrite ages do not show sharp peaks; they are presumed to come from another mechanism (e.g. asteroid-asteroid collisions), not comet storms. The decrease in the number of meteorites older than 30 Myr indicates a finite lifetime for chondrites in the solar system of approximately 30 Myr. The logarithmic time axis and binning is identical to that used by Crabb and Schultz (1981). From the data we estimate that approximately half the comets entering the solar system do so during the relatively brief (≤ 4 Myr) comet storms.

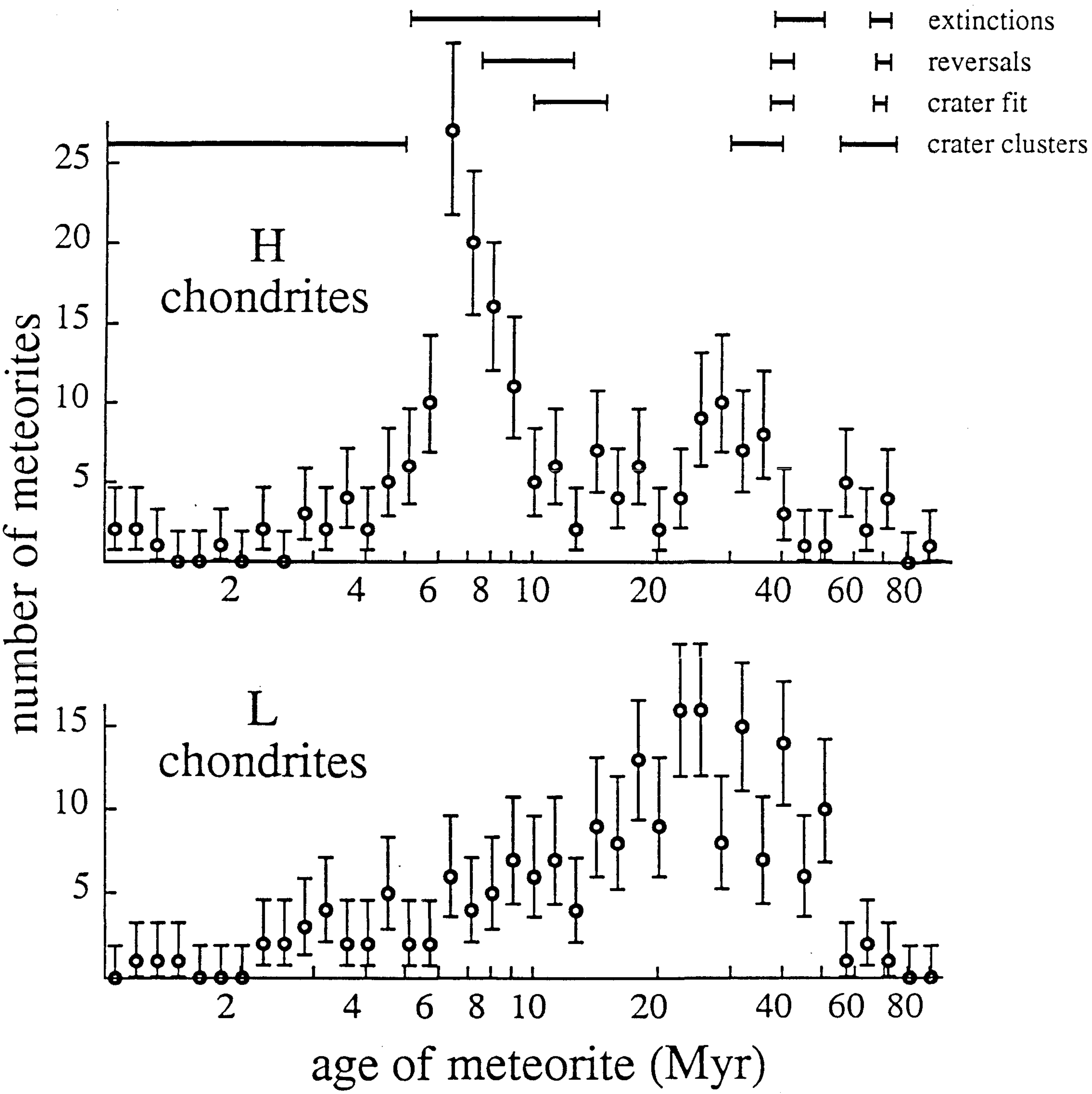
extinctions
reversals
crater fit
crater clusters
H chondrites
L chondrites
number of meteorites
25
20
15
10
5
2
4
6
8
10
20
40
60
80
age of meteorite (Myr)

Figure 1