Solar System impact rates measured from lunar spherule ages

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ABSTRACT

Solar System impact rates back to about 3.5 billion years ago have been determined by measuring the ages of 155 individual lunar spherules from the Apollo-14 lunar mission. Statistical analysis shows that most (> 90%) of these spherules come from different craters. The distribution of spherule ages shows a gradually decreasing rate of impacts from 3.5 billion years ago, to a low about 0.5 billion years ago, followed by a sharp increase by a factor of 3.7 ± 1.2 in the last 0.4 billion years.

Until recently, lunar impact rates have been derived from crater counting, supplemented by radioisotopic dating of a few craters (BVSP, 1981; Horz et al., 1991). Such methods give good estimates of average rates, but can not resolve fine structure. In 1993 we postulated that that greater detail could be obtained by the measurement of the ages of individual lunar spherules (Muller, 1993), although we did not then fully appreciate the difficulty imposed by the need to incrementally heat tiny samples of low K-content. Spherules are droplets of surface material that melted in an impact, were thrown from several meters to hundreds of kilometers, and solidified by radiative cooling before they landed; it is possible to recover more than a hundred of these glass spherules from a single gram of lunar soil. The diameters of these spherules ranged from less than 100 microns to greater than 500 microns. The measurement of the ages of these tiny samples was made possible by the development of the laser step-heating method of $^{40}Ar/^{39}Ar$ dating, first applied to terrestrial materials by York et al. (York et al., 1981) at the University of Toronto. We expected that most of the spherules in a given sample would come from different craters, so that a histogram of their ages would reflect the history of lunar impact rates. Of course, we would not know the age of the craters that we dated, or the size distribution.

An initial program to measure the ages of individual lunar spherules has been completed. Initial results from Apollo-11 and Apollo-12 samples showed that the spherules were compositionally similar to those of local rocks, which suggested that the majority of them were formed by relatively small impacts (Culler and Muller, 1999). We chose the location for the final samples to be Apollo 14, because the relatively high potassium concentration in the local soil (and hence in the spherules) allows more accurate dating.

We hand-picked155 lunar spherules from the Apollo-14 soil sample #14163. The samples were irradiated with fast neutrons for 100 hours at the Oregon State University Reactor. Each spherule was stepwise degassed using an 8-Watt argon-ion laser in 5 to 30 steps, and the argon isotopes measured using a MAP 215-C noble gas mass spectrometer. Spherule ages were determined using the $^{40}Ar/^{39}Ar$ isochron technique; for details, see Culler et al. (Culler et al., 2000). In Figure 1, we show a plot of the ages for these spherules..

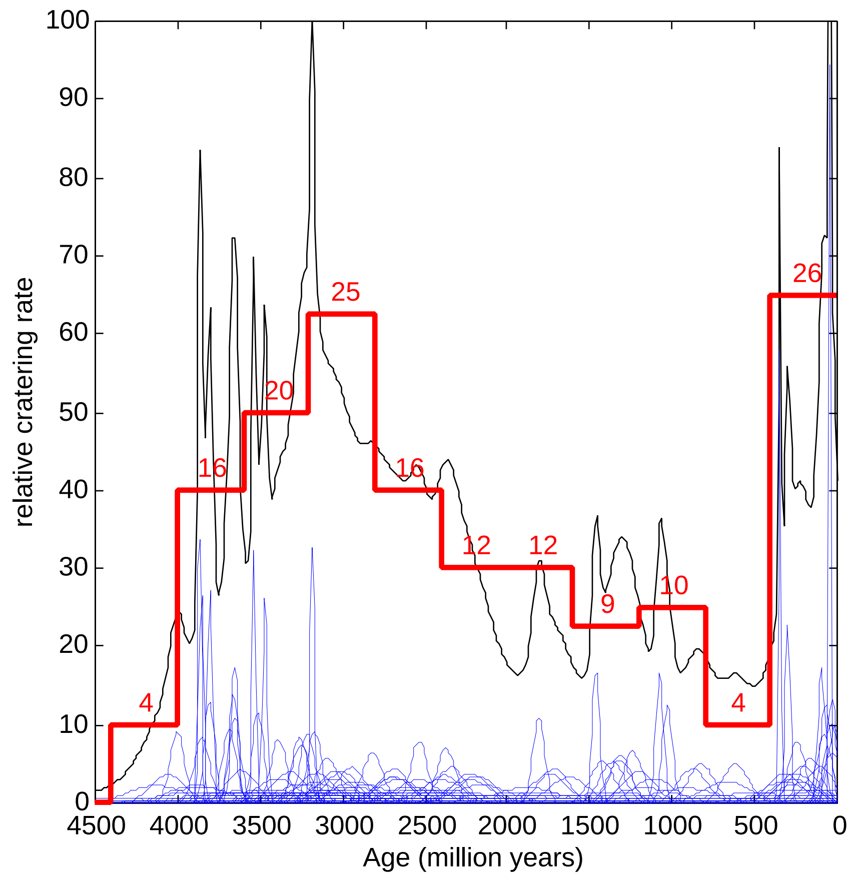

Figure 1. Age distribution of 155 spherules

Individual spherules are represented by Gaussians (at the bottom of the plot) with unit area and width equal to the age uncertainty of that spherule. The sum of these Gaussians forms the smooth ideogram which is, in a statistical sense, the best estimate for the cratering rate. However, when a crater has an extremely accurate age, it appears in this plot as a sharp spike; this should not be misinterpreted as a high rate. We also show a histogram of the spherule ages. Over each bin is printed the number of spherules that contributed to that bin.

In Culler et al. (Culler et al., 2000) we analyzed the potential biases in these data, including the effects of lunar gardening and the creation of the Apollo-14 region (the Fra Mauro formation) at about 3,850 Myr. We conclude, based on these data, that the cratering rate decreased from 3000 Myr to 400 Myr by a factor of 2 to 3. We also concluded that the cratering rate increased in the last 400 Myr by a factor of 3.7 ± 1.2, relative to the rate in the prior 800 Myr years. Previous evidence for a recent increase in impacts has been published by McEwen et al. (McEwen et al., 1997). We point out that our measurements are made on small craters, and we don't know if the results would be similar for larger craters.

We will now address the question of whether the spherules were independent, or whether clusters of them might have been created in single impact events. We do this by studying the statistical independence of their ages. For each spherule, we determined σ, the uncertainty in its age determination, and counted the number of other spherules N_1 whose ages were within 1σ of this age, and N_2 the number that fell between 1σ and 2σ. If spherule ages were associated with each other, then we expect $N_1 > N_2$; for a normal distribution, 68.3% would be between 0 and 1σ, and 27.2% would be between 1 and 2σ. If the ages are independent, then we expect $N_1 \approx N_2$. We estimate[1] the total number of non-independent "associated" spherules in the sample to be approximately $2.3(N_1–N_2)$. We calculated $\Delta N = N_1–N_2$ as a function of the spherule age uncertainty, and plotted the results in Figure 2. From this graph we can see, for example, that there were 142 spherules that had an age uncertainty less than or equal to 250 Ma. For these spherules, $\Delta N = 8$, and the number of "associated" spherules, i.e. the excess with clustered ages, is 18. Of course, this counts many associated spherules twice, since if A is associated with B, then B will be associated with A, so that the number of *excess* spherules in Figure 1 (for the purpose of estimating cratering rate, we don't want to double count) is approximately 18/2 = 9. Thus,

[1] The value N1-N2 also subtracts some associated spherules, since for every associated spherule within 1σ, we expect 0.4 between 1 and 2σ. To compensate for this, we must multiply ΔN by 2.3.

we estimate that 142 – 9 = 133 = 94% of our events come from different craters. This number could include spherule that are associated in time (e.g. arrive from a comet shower) but from different craters, so it may overestimate the number of events arising from individual craters. The absence of any particular trend in the associated spherules plot in Figure 2 implies that this estimate is not particularly sensitive to our choice of age uncertainty.

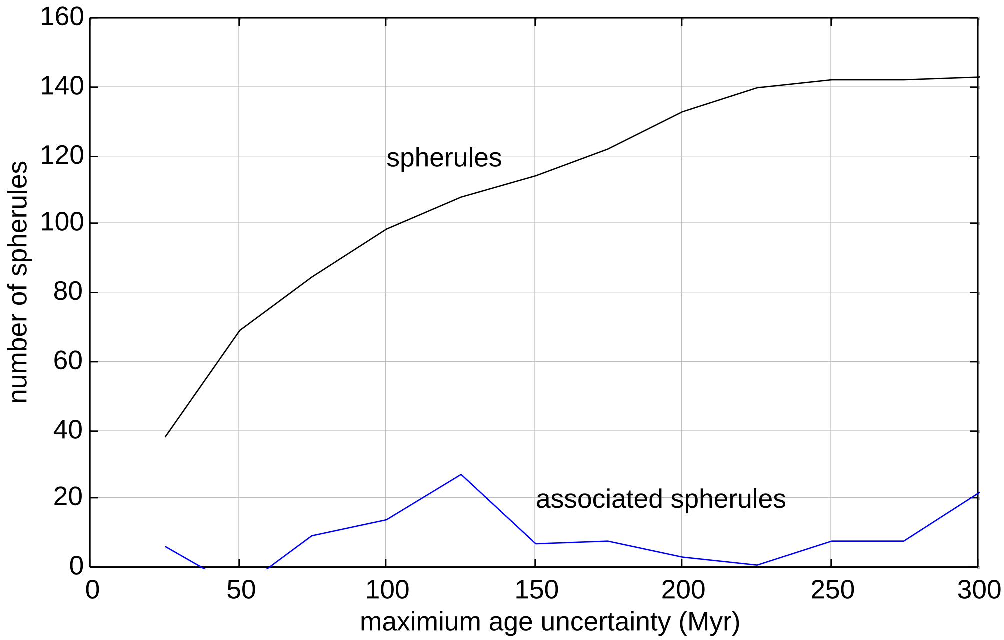

Figure 2. Estimate of spherule age clustering.

To study possible clustering further, for each spherule in this group, we can plot the individual excess, i.e. the number of spherules within 1σ minus the number of spherules between 1σ and 2σ. We show the results of this calculations in Figure 3.

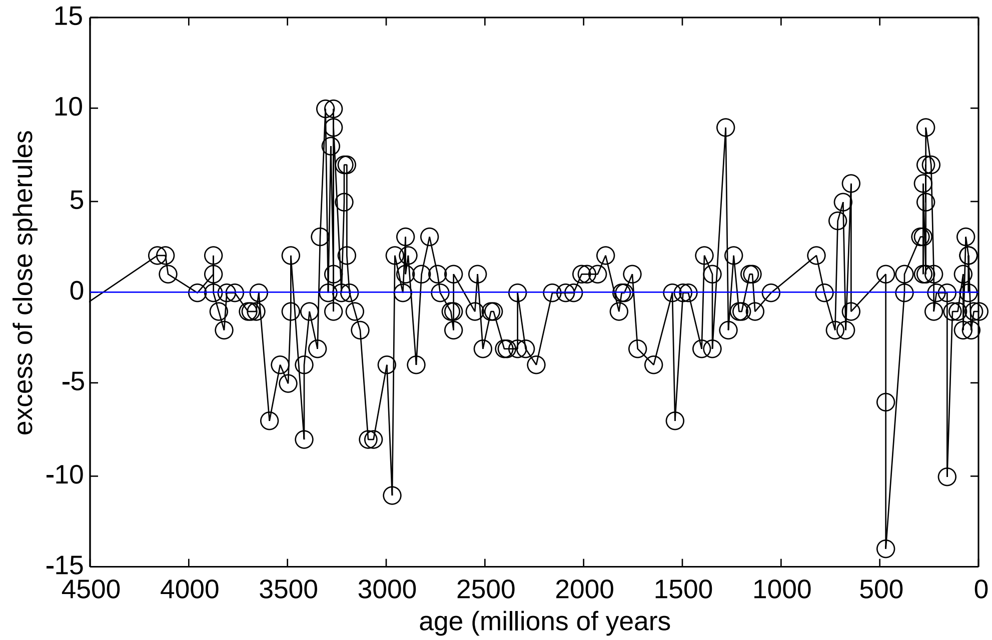

Figure 3. Excess of close spherules, vs spherule age (for σ < 250). Each point represents one spherule; the x axis is the spherule age, and the y axis is the excess of nearby neighbors for that spherule.

. The data are plotted as a function of time so they can easily be compared to the histograms. Of course, we do expect to see some excess in clustered regions, such as the last 400 kyr, when a large number of events occurred near the same time. To facilitate this comparison, we plot the distribution of ages for these spherules with age uncertainty < 250 Myr in Figure 4, using a smaller bin size of 250 Myr, because of the more accurate dates.

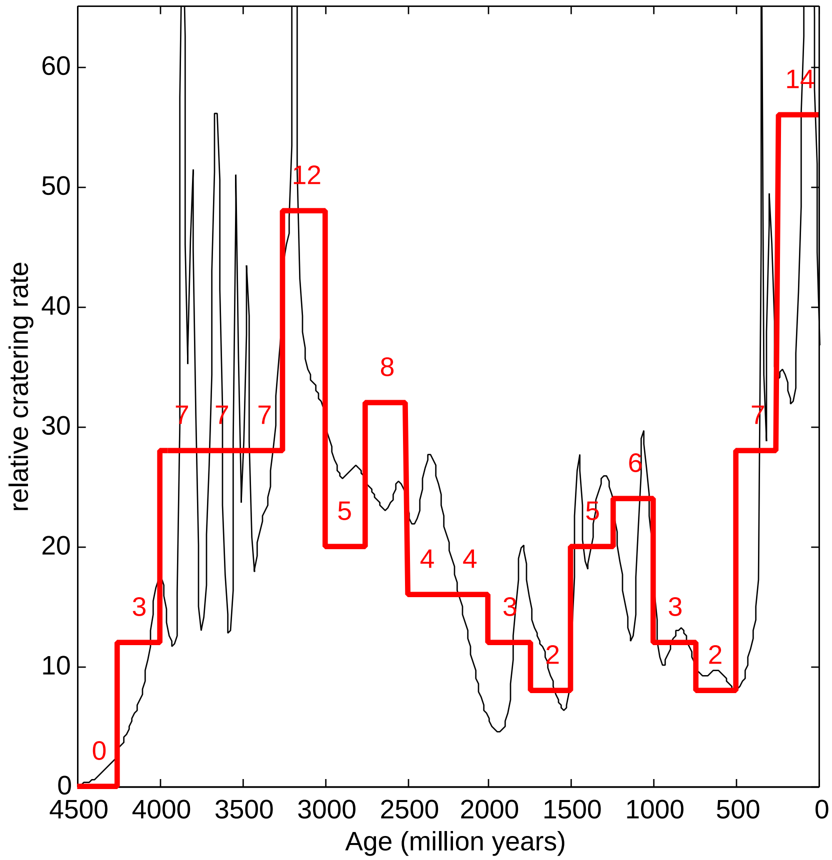

Figure 4. Ages of spherules with σ(age) < 250 Myr

The low number of impacts prior to 3500 years may be associated with the fact that the Fra Mauro formation, the site of the Apollo 14 landing, was created at about 3850 Myr. The fact that the peak occurs closer to 3200 Myr may be a statistical fluctuation. In Figure 5 we plot the ages of the 74 spherules with age uncertainties less than 150 Myr. In this plot the cutoff near 3850 Myr appears more abrupt. The few spherules at older ages could be spherules outside of their 1σ limits, or they could be secondary spherules, i.e. spherules created in a distant and older region that were thrown to the Apollo 14 site by a large impact.

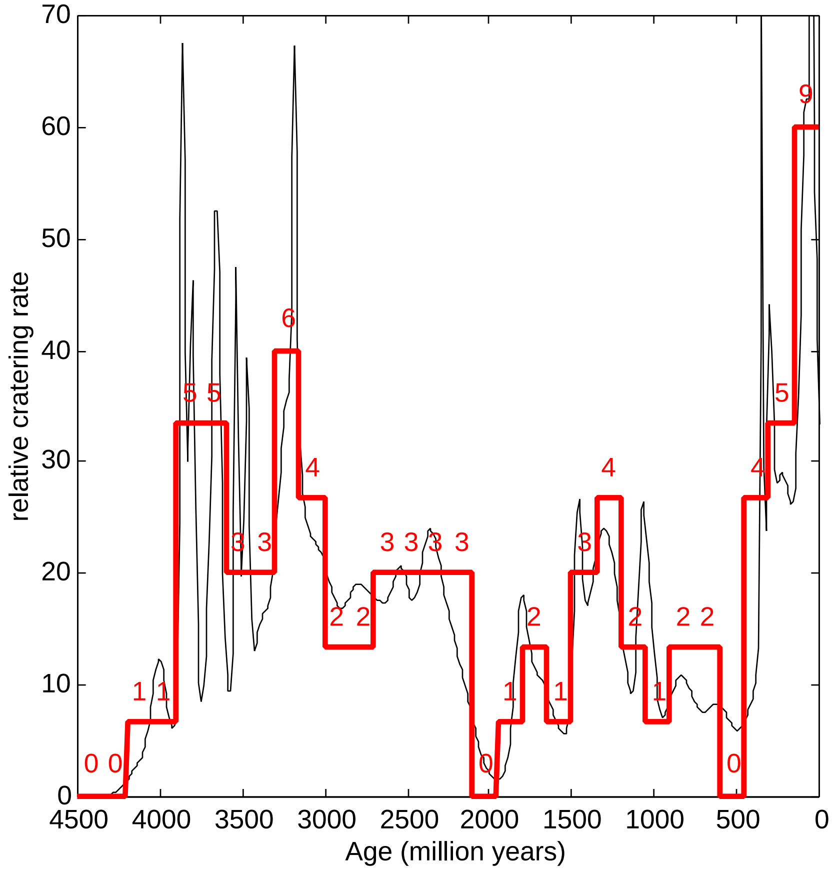

Figure 5. Ages for spherules with σ < 150 Myr

The gradual decrease in cratering rate from 3000 Myr to 500 Myr is present in all the age distribution plots. This is not surprising, as it may reflect a gradual decrease in the debris of the solar system, comets, asteroids, and meteors, as they are perturbed by interactions with Jupiter and the other planets into the sun, or to infinity.

The most intriguing feature of the data is the recent (last 400 Myr) increase in implied rate of impacts. We estimated this increase be a factor of 3.7 ± 1/2 compared to the immediately preceding period (Culler et al., 2000). Such an increase could come about if there were a large object in the outer solar system whose orbit was changed (perhaps by a close encounter with a passing star) so that it began 400 million years ago to exert a greater perturbation on the Oort comet cloud. It is fascinating to speculate on the increase in cratering, since the Cambrian explosion of life of life took place at about the same time. It is conceivable that the additional trauma from increased impacts on the Earth had an accelerating effect on evolutionary diversification.

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