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Measurement of the lunar impact record for the past 3.5 b.y. and implications for the Nemesis theory

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ABSTRACT

Measurements of the ages of 155 lunar spherules from the Apollo 14 site suggest that the solar system impact rate over the past 3.5 b.y. first gradually declined, and then increased starting at 0.4 Ga, back to the level it had been 3 Ga. A possible explanation is offered in terms of the Nemesis theory, which postulated a solar companion star. A sudden change in the orbit of that star at 0.4 Ga transformed a circular orbit (which does not trigger comet showers) into an eccentric orbit (which does). The Nemesis theory is speculative but viable; contrary to prior assertions, the orbit is sufficiently stable to account for the data.

INTRODUCTION

A new approach to estimating past impact rates has been developed by our group at Berkeley: rather than measuring the ages of identified craters, the ages of small glass droplets called spherules that are produced from unidentified impact craters are measured (Muller, 1993). Most lunar spherules are formed in impacts; others are primarily from pyroclastic eruptions. From analysis of the spherule ages, it was concluded that most of the spherules come from separate craters (Culler et al., 2000; Muller et al., 2000a). Even though we do not know the crater from which a spherule originates, the distribution of spherule ages gives us information about the rate at which craters were formed.

Even 1 g of lunar soil, collected from the Apollo missions, typically contains more than 100 spherules in the size range of 150–250 μm diameter. At the Apollo 14 landing site, the spherules contain sufficient potassium to allow $^{40}Ar/^{39}Ar$ measurement of their age to a mean accuracy of 221 m.y.; half of the spherules had age uncertainties $<$132 m.y. Larger spherules, which have higher total potassium contents, yielded the most accurate ages.

The original goal of the experiment was to test the Nemesis theory (Davis et al., 1984), which predicts that the impact rate will have a large component from periodic comet showers, events in which multiple impacts occur within short (1–2 m.y.) time spans. Moreover, the theory predicts that the comet showers will recur whenever the cause (Nemesis, the hypothetical companion star to the Sun) reaches perihelion, which is once per orbit. The spacing between comet showers would be regular, with a 26–28 m.y. spacing, matching the period seen in paleontological extinctions; however, due to perturbations in the orbit from passing stars, there are expected variations of several million years in the timing of the showers, as pointed out by Davis et al. (1984). Herein I review the status of the Nemesis theory, including the critical issue of the stability of the Nemesis orbit.

In March 2000, Culler et al. (2000) reported the measurement of the chemical composition and ages of 155 spherules from the Apollo 14 site. Based on the belief that the soil sample at our site was well mixed, we (Culler et al., 2000) argued that the observed spherule age distribution reflects the cratering rate on the surface of the Moon and the Earth. Additional aspects of our study of these issues are discussed in this chapter.

The spherule age distribution is shown in Figure 1. At the bottom of the plot are 155 Gaussian curves, one for each

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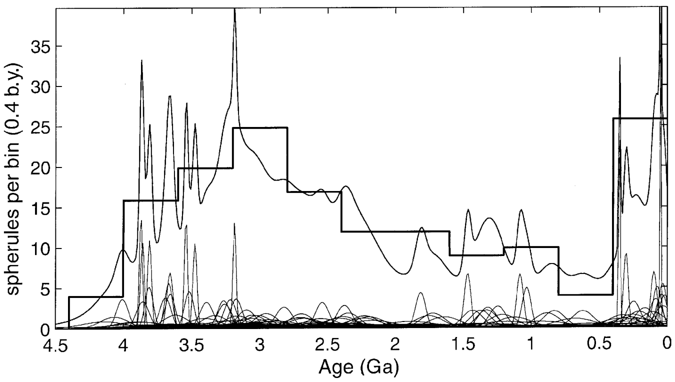

Figure 1. Distribution of spherule ages found at Apollo 14 site. Histogram shows number of spherules found in each 0.4 b.y. age bin. At bottom of plot, age measurement of each spherule is depicted by 155 separate Gaussian curves. Area of each Gaussian is constant (representing one spherule each), but width represents 1 standard deviation uncertainty in age. Continuous curve is sum of these Gaussians (ideogram). Ideogram is best estimate, in statistical sense, of age distribution of spherules. Note, however, that sharp spikes in ideogram are artifacts of spherules with highly precise ages.

spherule. The areas of each Gaussian are equal, but the width (root mean square deviation) for each is set equal to the 1 standard deviation error in the age uncertainty for that spherule. The sum of these individual Gaussian curves, the ideogram, is the smooth curve. The ideogram represents the best estimate, in a statistical sense, for the spherule age distribution. Note, however, that the sharp peaks are artifacts of several ages that were determined with high precision. The uncertainties in the ages were determined by a least-squares analysis of the isotope correlation plots, and represent the 1 standard deviation in the ages of those fits.

The spherule age distribution shows a broad peak near 3 Ga (3000 Ma). The smaller number for older ages is likely due to the relatively young age of the Apollo 14 landing site, estimated as 3.85 Ga. All spherules produced at the Apollo 14 site must be younger than this. The older spherules are presumed to be secondary, i.e., created and first deposited at distant sites and subsequently transported to the Apollo 14 site from secondary impacts.

There is a gradual decrease in spherule number from 3 to 0.4 Ga. This is consistent with previously reported estimates of a decrease in cratering rates during the same interval (BVSP, 1981; Ryder et al., 1991). The decrease could be due to gradual reduction in the number of impactors in the solar system as asteroids and comets are ejected by Jupiter's gravitational perturbation or deflected into the Sun.

The most surprising feature of Figure 1 is the sharp increase in the number of spherules with ages between 0 and 0.4 Ga. A recent increase of a factor of two had previously been suggested on the basis of measurements on the Earth and crater counting on the Moon (Grieve and Shoemaker, 1994; McEwen et al., 1997; Shoemaker et al., 1990). In the Berkeley data, the rate in the last 0.4 b.y. increased by a factor of 3.7 $\pm$ 1.2 (compared to the preceding 0.8 b.y.), back to the level that it had been 3 b.y. earlier.

There are several systematics that could create a difference between the spherule age distribution and the lunar impact rate. The most important of these is the fact that the lunar surface is mixed over time (lunar "gardening"). Older spherules are more likely to be buried, so it is more likely that we would find recent spherules at the top of the soil (where our sample was collected). This possibility is discussed in the next section.

SPHERULE AGES AND ANALYSIS

At the beginning of this study, two 1 g samples of lunar soil from the lunar missions Apollo 11 and Apollo 12 were obtained. The spherules were separated from the soil and the ages measured at the Berkeley Geochronology Center using the $^{40}Ar/^{39}Ar$ isochron technique. Poor precision was achieved because of the low potassium levels; several individual age uncertainties were $>$1 b.y. However, based on a chemical analysis of these spherules, we (Culler and Muller, 1999) deduced that most of the spherules came from local impacts. It was known that the Fra Mauro Formation at the Apollo 14 landing site was enriched in potassium by a factor of 5–10 compared to that at other Apollo landing sites. We requested and obtained samples from this location, and found that the spherules did have the higher potassium content expected from a local origin: with this higher potassium, higher precision ages were obtained. The median age uncertainty (1σ) for our 155 Apollo 14 spherules was 0.13 b.y.

A statistical analysis was done to estimate the number of craters represented by the 155 spherules. To understand the method used, assume for the moment that every spherule had an age that differed significantly from that of every other spherule. Then we could conclude that the spherules all came from different craters. Of course, this condition was not met, as can be seen in the overlapping Gaussian plots in Figure 1. However, we could still estimate the independence of the spherules from the ratio of spherules that occur within 1σ versus between 1σ and 2σ. If the spherules are truly independent, then these two numbers should be equal. To the extent that they are different (i.e., there are more close ages), we can conclude that there are multiple spherules from the same age. Using this method, we estimated that $\sim$146 of the spherules all came from separate craters (Muller et al., 2000b). This was consistent with a previous conclusion that most of the spherules were from different craters based on a chemical analysis of spherules (Culler and Muller, 1999).

The samples were collected from the lunar surface, and this creates a potential bias in favor of recent ages. The lunar soil is constantly overturned through impacts of meteoroids, a process referred to as lunar gardening. However, shallow soil is gardened more rapidly than deep soil. We might expect that old spherules would be uniformly mixed down to the base of the regolith, but recent spherules would be found primarily at the surface. This would result in an excess of recent spherules in our samples, which is what was found.

To minimize the systematics of lunar gardening, we chose a sample that had been collected in the vicinity of a very recent (25 Ma) impact that formed Cone crater. Calculations (Heiken et al., 1991; McGetchin et al., 1973) and seismic data (Chao, 1973) imply the presence of a 10–50-cm-thick ejecta layer from Cone crater at the location where the sample was collected. Because the sample was scooped from the surface of the regolith, it may consist almost entirely of Cone crater ejecta, which is thought to be well mixed. Because Cone crater is much deeper than the local regolith (which is ~8 m deep), these spherules may contain an approximately uniform sample of the cratering history of the landing site.

Despite the conclusion that the best model was that no gardening correction was necessary, several standard gardening corrections were applied to see their potential effect on the conclusions. The corrections consisted of power-law models in which the density of spherules at any given depth is assumed to depend on age, with young spherules concentrated near the surface, and older spherules more uniformly distributed. However, none of the gardening corrections yielded acceptable models in the sense that they suppressed the recent (0.4 Ga) peak, and yet had a cratering rate between 0.4 and 3 Ga that was compatible with previous limits based on crater counting (BVSP, 1981; Grieve and Shoemaker, 1994; Shoemaker et al., 1990). The failure of the gardening corrections can be traced to the fact they all assumed a smooth correction, and any smooth function that suppresses the recent peak results in an unacceptably high cratering rate in the region near 3 Ga.

Lunar gardening at one special location need not follow a simple power law, because it could be significantly affected by a few events. The standard gardening corrections are meant to reflect average changes, not the gardening at every location on the lunar surface. Additional information about gardening can be obtained, in principle, by measuring cosmic ray exposure ages, and such work is in progress.

The specific possibility that the 0.4 Ga increase could be due to spherules coming directly from Cone crater was examined, and we discussed this analysis in Culler et al. (2000). Of the 11 spherules that had ages compatible with that of Cone crater age (25 Ma), 3 are black, 3 are yellow, 3 are orange, 1 is green, and 1 is white. This diversity of color suggests that they did not all come from the same (Cone) crater. Moreover, removal of all 11 spherules compatible with the Cone crater age leaves 15 spherules in the 0–0.4 Ga bin, still a significant increase in the past 0.4 b.y., although the statistical significance of the effect is reduced from just over three standard deviations (3.7 ± 1.2) to just under two (2.1 ± 1.2). The first of these results is considered to be more accurate, because the spherule colors suggest that the 11 spherules discounted were not from Cone crater, as the reduced statistical significance requires.

Hörz (2000) suggested that the increase in spherules in the past 4 b.y. does not reflect an increase in cratering, but simply an increase in the efficiency of spherule production. His model is consistent with the data, but requires several ad hoc assumptions. Nevertheless, until measurements are made at other locations, it cannot be ruled out. For a discussion, see Muller et al. (2000a).

ROBUSTNESS

The data were analyzed in many different ways to see if our conclusions are robust to the method of analysis, and to seek correlations that could help us to understand systematic biases.

The use of the ideogram to represent the spherule age data avoids potential biases due to binning. However, because the ideogram is unfamiliar to many scientists, the data were also analyzed using the histogram method with different size bins: 400, 200, 100, and 50 b.y. The 0.4 b.y. increase is robust under these different binnings. In Figure 2 the histogram uses 50 m.y. bins. With very large 1 b.y. bins, as shown in Figure 3, there is no significant increase in cratering in the last bin; see the discussion in Muller et al. (2000a). In this plot, the recent increase is averaged with the period of low impact rate that immediately preceded it, and they cancel. Thus, without the age precision afforded by the measurements, the variations in the cratering rate (assuming it is real) would have been missed. Figure 4 shows the age distribution of the 58 spherules that had age uncertainties <0.1 b.y. In this plot, the 0.4 b.y. increase is still strong.

In the initial sorting of spherules, each was visually inspected and assigned a color in one of six categories: black or opaque (85 total spherules), yellow (36), gray (13), orange or red (10), green (9), and white (2). These variations in color are thought to relate to the concentration of titanium and to a lesser extent iron in the glass of the spherules. To search for possible biases, the age distribution of each color group was plotted separately. The 0.4 Ga increase was present (within the limited

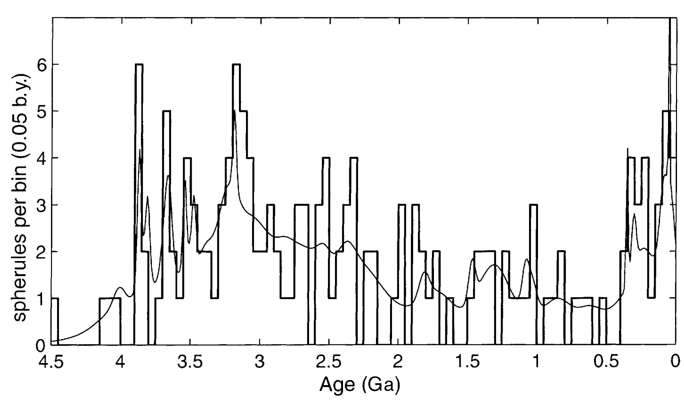

Figure 2. Distribution of spherule ages, plotted in 0.05 b.y. (50 m.y.) bins. Ideogram is identical to that in Figure 1. Plot illustrates that recent 0.4 Ga (400 Ma) increase is not artifact of choice of bin size.

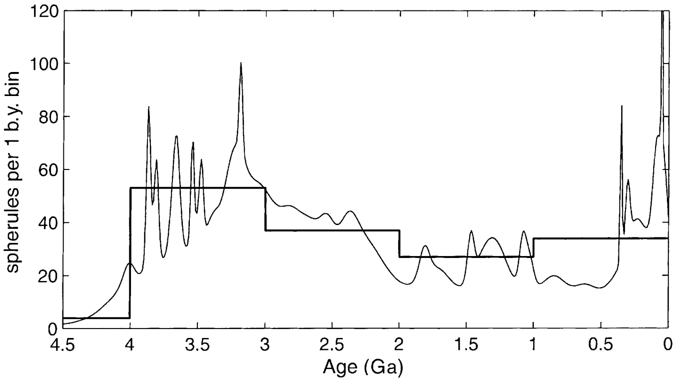

Figure 3. Distribution of spherule ages, plotted in 1 b.y. (1000 m.y.) bins. This plot shows no statistically significant increase in last 1 b.y. vs. previous period 3 to 1 b.y. Recent 0.4 Ga peak disappears because it is averaged with preceding bins, which were low. This plot illustrates that with poor age resolution, recent increase would have been missed. Ideogram is identical to that in Figure 1.

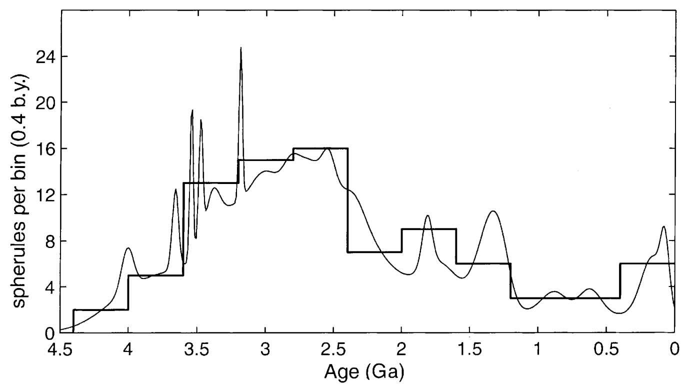

Figure 5. Distribution of spherule ages for black and opaque spherules. In our search for systematic anomalies, this plot deviated most from others. Number of events in past 0.4 b.y. is only 6, well below peak level at 3 Ga of 16. Based on Figure 1, we would have expected 13.3 events in this bin. Probability of obtaining 6 or few events when 13.3 are expected is ~2%. Plot shows small increase in final bin, and anomaly could be presence of unusual number of black and opaque spherules near age 3 Ga.

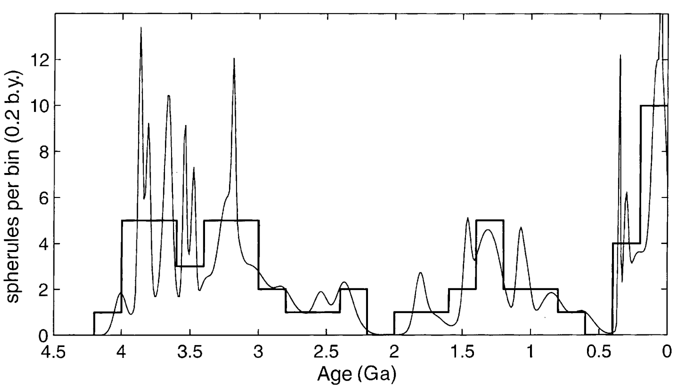

Figure 4. Distribution of spherule ages for most accurately dated spherules, those with age uncertainties (1 standard deviation) of 0.1 b.y. (100 m.y.) or better. Ideogram also contains only this subset of spherules. Recent increase is still evident.

statistics) in all groups except the black and opaque spherules. The age distribution for these spherules is shown in Figure 5. There is a slight increase present in the most recent bin of this plot, but it appears to be significantly less than in the other plots. I do not have an explanation for this discrepancy: the estimate of the probability of observing the 6 events in this last bin, when 13.3 were expected (based on the number of black and opaque spherules), is 2%. Perhaps it is simply that if there are 50 different plots (about this many were generated), to find one that is deviant at the 2% level is expected. It is also possible that there was a more efficient mechanism for generation of black and opaque spherules at 3 Ga. The statistics of the last three bins are very low, but they are compatible with a rise in the last 0.4 b.y. when compared to that of the previous 0.8 b.y.

The most likely model is that the spherule age distribution is proportional to the cratering rate near the Apollo 14 site. We do not know the size distribution that contributes to the spherules, and whether this matches the same craters that are measured in the crater counting methods. However, if we specifically degrade our age resolution, the results are consistent with those previously reported (Muller et al., 2000a). A final conclusion about the solar system cratering rate based on lunar spherule ages should wait until additional lunar sites are measured. Such measurements are underway. For the remainder of this chapter, the 0.4 Ga increase is assumed to be real.

NEMESIS THEORY

The Nemesis theory postulates that there is a companion star to the Sun, orbiting at a distance of ~3 light years, with a period of 26 m.y. If this orbit has an eccentricity >~0.5, then it passes close enough to the Oort comet cloud to trigger a comet shower once per orbit. Such periodic showers could lead to periodic extinctions of life on Earth, and to periodic increases in the cratering rate on the Moon.

The 3 light year orbit is larger than known for any double star system, and there has been considerable speculation that the orbit is unstable. The original paper (Davis et al., 1984) stated that the orbit had a stability time constant of about 1 b.y., and that small orbit to orbit variations of a few million years should be expected. Many subsequent analyses of the Nemesis orbit stability have been published, and these are summarized in the following.

A detailed study of the Nemesis orbit stability was published by Hut (1984), based on extensive computer simulations of the effects of passing stars, using a realistic distribution of star masses and velocities. Hut concluded that the Nemesis orbit was unstable unless it was close to the plane of the galaxy. For this orbit, however, the stability he found agreed with the estimate of ~1 b.y. in the original Nemesis paper. Hut also reiterated a surprising discovery about the lifetime of the orbit, i.e., that it decreased linearly with time. This is in contrast to other well-known behavior, such as the lifetime of radioactive particles. For radioactive particles the lifetime is independent of time; e.g., the ^{14}C nuclei that remain after 100 k.y. still decay with the same 5.7 k.y. half-life as the original nuclei. For Nemesis, the behavior is different. At formation, the expected lifetime of Nemesis would have been 5–6 b.y. Now that 4–5 b.y. have passed, the residual lifetime is only 1 b.y. Of course, this is just the average behavior, and the actual behavior of Nemesis (shown in specific simulations in Hut, 1984) could show sudden changes from the nearby passage of one massive star. (The 0.4 Ga increase is interpreted herein in terms of such a change.) The importance of the Hut calculation is that if estimates of the present lifetime of the Nemesis orbit are less than the lifetime of the solar system, it does not mean the star could not have survived for that period. This subtlety has been missed by many.

The Nemesis theory was based on the idea that passages of the solar companion star Nemesis through the Oort comet cloud would trigger comet showers. The same issue of *Nature* that contained the Hut article, contained several other articles on the same subject. One was by Hills (1984), who had originally discovered the possibility of "comet showers" (Hills, 1981). Hills (1984) showed that in its present orbit, the stability of Nemesis would be about 1 b.y., the same value obtained by Hut (1984).

Torbett and Smoluchowski (1984) also analyzed the stability of the Nemesis orbit. They assumed (incorrectly, as argued herein) that a stability time of 4–5 b.y. is needed for the present Nemesis orbit, in order for it to have survived. They also raised the possibility that passing giant molecular clouds, much more massive than stars, would dominate the orbital perturbations, and make the Nemesis orbit even more unstable. We (Morris and Muller, 1986) pointed out in a subsequent paper that their molecular cloud calculation had ignored the fact that giant molecular clouds are not only massive but also very large and diffuse, and thus only part of their mass (effectively that between Nemesis and the Sun) contributes to the tidal field that disrupts the orbit. When the diffuse nature of these clouds is taken into account, their effect on the stability is less than that of passing stars.

The stability of the Nemesis orbit was also analyzed by Clube and Napier (1984). Unfortunately, this article confused the parameters of the Nemesis theory with those of a similar theory by Whitmire and Jackson (1984), which had been published simultaneously with the Nemesis theory. Whitmire and Jackson also postulated a companion star to the Sun; however, they assumed a very small star, and this required them to postulate an extremely eccentric orbit, one that would be truly unstable. In contrast, the eccentricity assumed in the Nemesis theory was taken to be the median for stochastic orbits, i.e., 0.7. Clube and Napier argued (correctly) that the highly eccentric orbit is unstable, but they mistakenly ascribed that to the Nemesis theory. They also invoked the giant molecular cloud perturbations, and also ignored (as did Torbett and Smoluchowski, 1984) the large size of these clouds that reduces the effect they have on the Nemesis orbit (Morris and Muller, 1986). They stated that if the effect of molecular clouds were ignored, then the residual Nemesis stability would still be only 1 b.y., and they considered that insufficient. This estimate is the same as that determined by Hut, and it agrees with the estimate in the original Nemesis paper. It appears that Clube and Napier were confusing the present expected lifetime with the past expected lifetime.

The confusion about the stability of the Nemesis orbit was made worse by an editorial comment that appeared in the same issue of *Nature* as the articles by Hut, Hills, Torbett and Smoluchowski, and Clube and Napier. The comment was by Bailey (1984, p. 602), and it was titled *Nemesis for Nemesis*." Bailey stated: "the Nemesis proposal is extended and shown, in fact, to be quite incapable of producing the strictly periodic sequence for which is was originally designed." This was a misreading of the original Nemesis paper (Davis et al., 1984), which explicitly pointed out that the period would not be constant but would have orbit to orbit variations of several million years. Bailey's comment also characterized the paper by Hut (1984), as a "near retraction" of the Nemesis theory. Yet Hut (1984, personal commun.) considers his paper to be a vindication of the original Nemesis calculations, not a retraction. M. Bailey (1984, personal commun.) later said that he never wrote the words "near retraction," but that they had been inserted by the editor at *Nature*. An informal and unscientific survey of astronomers who discredit the Nemesis orbit (taken by me, over the following decade) showed that none of them had read the Hut paper. This is not surprising; why bother to read a paper when, according to the accompanying comment, it amounts to a near retraction?

The strongest argument against the Nemesis idea is not any difficulty with its orbit. It is the fact that the theory predicts that most of the mass extinctions of Raup and Sepkoski (1984, 1986; Sepkoski, 1989) should have been caused by impacts, and yet little evidence has been adduced since 1984 in favor of this conclusion. If we ever understand the origins of the other extinctions, and they are shown to be unrelated to impacts, then the Nemesis theory loses its only reason for existence. However, the Nemesis theory makes definite predictions, and thus is falsifiable. We should be able to find the star (the search has been stalled by telescope difficulties), and there should be a periodicity in impacts that can be seen in the crater data. Unfortunately, the age accuracy achieved thus far in the lunar spherule project is insufficient to see the expected 26 m.y. cycle.

NEMESIS INTERPRETATION OF THE 0.4 GA INCREASE

I assume for the purposes of the following discussion that the increase in the number of lunar spherules after 0.4 Ga reflects an actual increase in cratering rates. The Nemesis hypothesis can readily accommodate the increase. Hut's theory of Nemesis stability (Hut, 1984) described the average behavior of the orbit, which was an ensemble of many individual simulations. In reality, the orbit is very unlikely to have followed the average behavior. Let us hypothesize, therefore, that the orbit was relatively circular during the period 2–0.4 Ga. As shown in Figure 6A, the orbit does not enter the Oort comet cloud, but remains outside. In such an orbit, comet showers would not be triggered, and the rate of impacts on the Earth would reflect a background level from distant comets and asteroids.

If a passing star gave a major perturbation to Nemesis at 0.4 Ga, the orbit could have been perturbed into the postulated eccentricity of 0.7, as shown in Figure 6B. This would require a relatively close encounter with a passing star, probably <1 light year; however, the calculations of Hills (1981) and the simulations of Hut (1984) show that such an encounter is likely to happen sometime during the life of the solar system. If we postulate that it occurred at 0.4 Ga, from then on, the impact flux on the Earth would have two sources: a steady-state background, and a component from periodic comet showers. This could accommodate the observed increase.

Ultimately, the existence of Nemesis must be confirmed by direct observation. In the original theory, we assumed that Nemesis is a red dwarf star, and should be readily visible from the Earth. The Hipparcos satellite, unfortunately, surveyed only about 25% of the known candidates. Future parallex surveys, if they reach stars as dim as 10th magnitude, should find the star if it is there, or prove (by lack of discovery) that it is not there.

FUTURE SPHERULE MEASUREMENTS

The spherule method has had an initial success that suggests significant potential for future measurements. The increase in the past 0.4 b.y. has important implications, so it must be confirmed (or shown to be wrong) by making measurements at a different lunar site. This requires another high-potassium site, and/or the use of larger spherules. Use of such spherules may also allow sufficient improvement in the age determination that we could directly test the prediction that there is a significant component of impacts that occur in showers. A search for periodicity could yield evidence for or against the Nemesis hypothesis. In addition, measurements in the lunar highlands could potentially determine older cratering rates, and answer lingering questions about the existence and intensity of the late heavy bombardment.

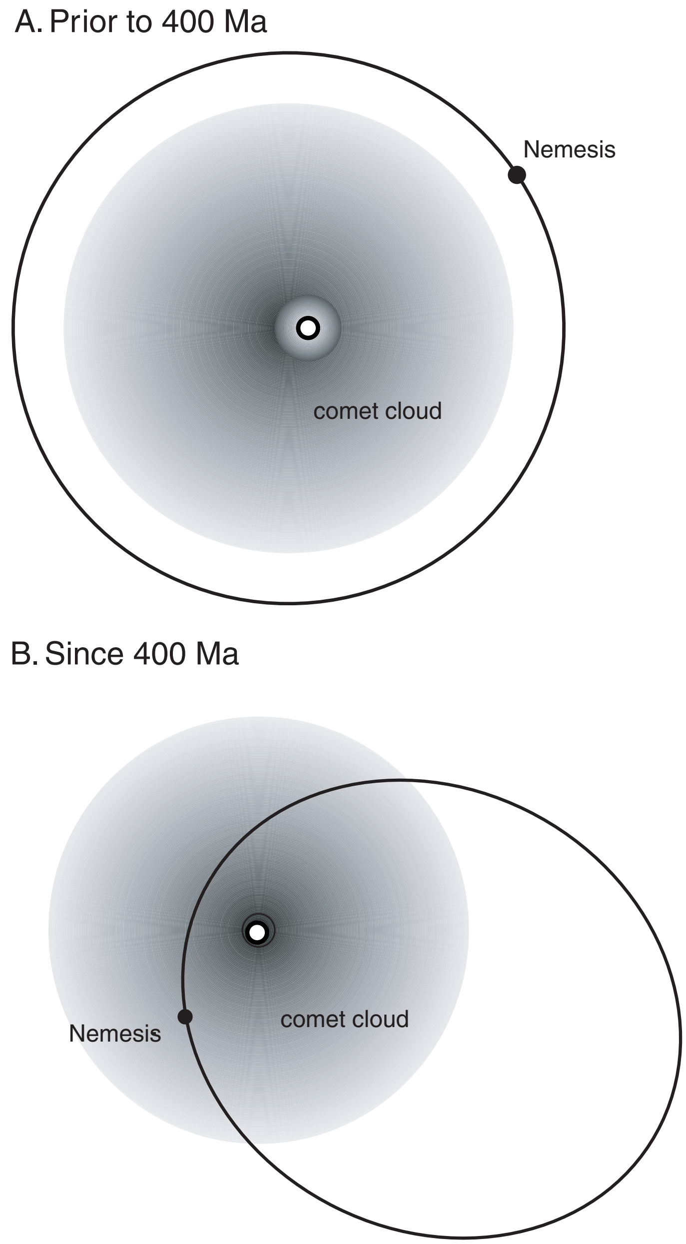

Figure 6. Hypothesized orbits of Nemesis. A: Circular orbit with 26 m.y. period, hypothesized as orbit prior to 0.4 Ga. B: Present orbit, with eccentricity 0.7. Change in eccentricity is attributed to close passage of star, as in calculations of Hut (1984). Inner Oort comet cloud is depicted in gray. Clear region near center in (A) represents depletion in orbits that pass close to Sun; size of depleted region is exaggerated for purposes of illustration. Depletion of these comets is result of perturbations of Jupiter. There is no depleted region in B, because of recent perihelion of Nemesis that perturbed comets into this region of space. Comets fill inner "eye" until they are kicked out (or into Sun) by gravitational perturbations of Jupiter. Expected duration of comet shower is few million years (Muller, 1985).

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