of a symmetrical comet shell model[14]. The contribution to terrestrial cratering while in this orbit is found from equation (3) with $q = 1$ AU. For $M_* \leqslant 0.07$, $\dot{N} \leqslant 66$ comets yr^{-1}, which is not significantly greater than various estimates of the current flux. These crude estimates are model-dependent and are only intended to show that the suggested evolutionary scenario is not necessarily in conflict with the present existence of the inner cloud and the cratering record. A detailed analysis of the evolution of the comet cloud plus companion is beyond the intent of this paper.

As noted above in connection with Hill's analysis, the intrinsic mass distribution of comets is uncertain. Density functions implicitly refer to observable comets of average size since normalization is based on the estimated number of observed long-period comets per year. Here we assume (as did Hills) that the relevant average-size comet has a radius of ~1 km and that the estimate of $\sim 5 \times 10^8$ comets per impact applies to this average comet. Qualitatively, we expect that there are intrinsically many more comets of smaller size. For every 1 km comet that strikes the Earth there will statistically be numerous smaller impacts, as observed in the cratering record. A large 10 km comet will similarly require on average more than $\sim 5 \times 10^8$ comets per impact. We thus anticipate a variation from cycle to cycle in the magnitude of the biological extinctions, depending on the maximum size impact comet as well as variations in the companion's perihelia. However, each cycle could always produce a number of collisions with $\leqslant 1$ km comets. The size and number of comets necessary to significantly perturb the biosphere is uncertain[15], although in the case of the major Cretaceous–Tertiary extinction, estimates suggest that the impacting body or bodies had the equivalent mass of a single ≈ 10 km asteroid or comet[18].

A black dwarf at a distance of $\langle r_* \rangle \approx 1.3 \times 10^5$ AU is potentially observable in the IR (for example, see refs 19–21). Such objects evolve along a vertical Hyashi track in the HR diagram until a final radius of $\sim 0.1\ R_\odot$ is reached, after which they cool radiatively[22]. For example, a dwarf of mass $0.02\ M_\odot$ and age 5×10^9 yr has an absolute 2.2–μm magnitude of 21.3 (refs 19, 22) and a corresponding apparent magnitude of 15.3 at 1.3×10^5 AU. The entire black dwarf mass range could similarly be observed at this distance. A recent search for black dwarfs around nearby stars concluded that these objects must be rare as companions[19]. However, the area searched around the candidate stars was 65×65 arc s or typically $\leqslant 10^3$ AU and more distant dwarfs (as well as dwarfs at distances $\leqslant 10$ arc s) were not excluded by this search. Although the companion's orbital period, semi-major axis, eccentricity, present distance and mass are all reasonably bracketed by the model, its orbital inclination and aphelion direction are unknown. Nonetheless, the companion is expected to be sufficiently bright in the IR for it to be observable in a full sky survey at the appropriate wavelength. The recent IRAS survey has thus far not found a tenth planet or solar companion, however most of the data analysis is still in progress[23].

The 2.6×10^7 yr extinction period has not as yet been detected in the cratering record (see below) on the Earth or Moon, although there is some evidence for a mean interval of 5×10^7 yr between major impacts[2,3,24]. Finally, we note that the various arguments[20,25–29] invoked to exclude the existence of an hypothesized[30] solar companion at $\sim 10^3$ AU are not applicable to the much more distant low-mass companion considered here.

Since submission of this paper we have received a preprint from Alvarez and Muller[31] reporting the discovery of a periodicity in the terrestrial cratering rate with a period and phase that closely match the extinction period. The cratering period has subsequently been confirmed in an independent analysis by D. Raup and J. Sepkoski (personal communication).

We thank Dr John J. Matese for helpful discussions and Dr M. E. Bailey who made several valuable suggestions.

Received 3 January; accepted 16 March 1984.

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Extinction of species by periodic comet showers

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A 26-Myr periodicity has recently been seen in the fossil record of extinction in the geological past[1]. At least two of these extinctions are known to be associated with the impact on the Earth of a comet or asteroid with a diameter of a few kilometres (refs 2, 3). We propose that the periodic events are triggered by an unseen companion to the Sun, travelling in a moderately eccentric orbit, which at its closest approach (perihelion) passes through the 'Oort cloud' of comets which surrounds the Sun (ref. 4; see ref. 5 for a review and ref. 6 for a more recent analysis). During each passage this unseen solar companion perturbs the orbits of these comets, sending a large number of them (over 1×10^9) into paths which reach the inner Solar System. Several of these hit the Earth, on average, in the following million years. At present the unseen companion should be approximately at its maximum distance from the Sun, ~2.4 light yr, and it will present no danger to the Earth until approximately AD 15,000,000.

The possibility that major extinctions occurred in a periodic manner was suggested by Fischer and Arthur[7], who believed that the periodicity was driven by a terrestrial mechanism, but it was only the detailed statistical analysis of Raup and Sepkoski[1] that eliminated many questions regarding systematic bias. They weighted each of the 39 customary stratigraphical stages according to the percentage of families in the preceding stage that were extinct in the following stage. A 26-Myr period is evident in the weighted data, and this period was shown by Fourier analysis and Monte Carlo simulation to be statistically significant with a confidence level better than 99%. The boundaries separating stages with large family extinctions are termed 'extinction events', although there is no direct evidence that the extinctions actually occurred at these boundaries. Large excesses of iridium had been found near two of these boundaries by Alvarez *et al.*[2,3], who concluded that the events were triggered by the impact of an asteroid or comet of a few kilometres diameter. Such impacts throw a large amount of dust into the atmosphere, and the extinctions could have been caused by the resulting lack of sunlight, temporary changes in climate, acidification of rain, or by some combination of such factors[8,9].

While impacts on the Earth by asteroids or comets provide plausible explanations for the individual events in which many species are extinguished, it is difficult to explain the precise periodicity of such collisions. Napier and Clube[10] had proposed that periodic catastrophies could be triggered by the capture of comets as the Sun passed through the spiral arms of the Galaxy (for a more recent discussion, see ref. 11). However, it is difficult to reconcile the Napier–Clube model with the relatively stable periodicity discovered by Raup and Sepkoski, in which the last four of the extinction events occurred within 2 Myr of the time predicted by an exact 26-Myr cycle. In addition, as pointed out to us by the Alvarez group, their measurements of isotope ratios of iridium and rhenium imply that the material that hit the Earth was of Solar System origin. The oscillations of the Sun in and out of the plane of the Galaxy have a half-period that roughly matches that required, and one might hypothesize, for example, the presence of an extremely thin layer of debris in the galactic plane that is encountered by the Solar System on each passage. This has the same difficulty as the Napier–Clube model; it predicts impacts with extra-Solar System material. In addition, the Sun is presently near the galactic plane, moving upwards with the relatively high velocity of $\sim 6\ \mathrm{km\,s^{-1}}$. As the last extinction event occurred 11 Myr ago, we are almost half-way between extinctions; thus we have the wrong phase for such an explanation.

If we try to account for the periodicity by postulating an object that orbits the Sun and comes close to the Earth every 26 Myr, perturbations from nearby stars will prevent the orbit from coming into the inner Solar System more than once. An object with this period has a large semi-major axis of ~88,000 AU (where 1 AU is the mean Earth–Sun separation of $1.5\times10^{13}\ \mathrm{cm} = 1.6\times10^{-5}$ light years). If this object passes within 10 AU of the Sun, then its orbit is highly elliptical, with an eccentricity greater than 0.9999. An equivalent way of saying this is to note that the object has very low angular momentum—this not only requires an unlikely fine-tuning of the orbit, but it is also unstable. Within one orbital period the gravitational perturbations of passing stars will cause the orbit to gain enough angular momentum to increase the perihelion distance to more than 100 AU, virtually eliminating its direct effect on the inner Solar System.

However, an unseen solar companion need not come close to the Sun to perturb the cloud of comets that surrounds the Sun at large distances. Oort and others[4–6] showed that there must be about 10^{11} comets in such a cloud with semi-major axis greater than or equal to 30,000 AU. There may be considerably more comets around the Sun than this, as comets with smaller orbits are not significantly perturbed by most passing stars and therefore would usually not be observed on Earth. Hills[12] has estimated the total number of comets to be closer to 10^{13}; even so, the total mass of these comets is probably less than that of Jupiter. The unseen solar companion would perturb such smaller orbits in a periodic manner even if its perihelion were as large as 30,000 AU. With a semi-major axis of 10^5 AU, the orbital eccentricity, e, is 0.7 or greater. Such an orbit requires no 'fine tuning'; in fact, one expects a distribution of eccentricities which uniformly fill phase space to be flat in e^2, with the fraction of orbits having eccentricity greater than e given by[13]

$$N/N_0 = 1 - e^2 \tag{1}$$

Thus the r.m.s. value of a random distribution of binary orbits has a mean value for the eccentricity of $(0.5)^{1/2} = 0.7$, and this eccentricity is adequate for our orbit. Of course, the larger the eccentricity, the shorter the duration of close passage to the Sun and the shorter will be the periods of maximum perturbation. However, no very tight bounds have been derived from the fossil records on the precise localization in time of the extinction events, so eccentricities as small as 0.7 are still possible. Passing stars will still perturb the orbit of this companion, but they will only gradually change the period and the perihelion. The present orbit, with a semi-major axis of 10^5 AU, will be significantly disturbed and possibly disrupted on a time scale of $\sim 2\times10^9$ yr. (Different authors find slightly different values between 1 and 4×10^9 yr; refs 13–15. This orbit has probably evolved through a stochastic process, perturbed by random passing stars, from an initial orbit with a shorter period and smaller semi-major axis. Over the past 2×10^8 yr the semi-major axis may have increased by ~10%, and the period by 15% (from Kepler's third law) as the orbital energy decreases linearly on average[13,14]. The uncertainties in the extinction dates are large enough to be compatible with such a drift in period. Once better data are available, it will be useful to test a parabolic fitting to the dates of major extinctions, although purely stochastic 'jitter' from individual stellar passages will always remain in the data even with absolutely perfect dating methods.

What effect will a single passage of a solar companion have on the comets in the Oort cloud? We will follow the detailed analysis of Hills[12] who considered the effects of random (non-periodic) stars passing close to the Sun. Normally the orbits of the comets are distributed isotropically within the cloud, except for orbits that enter the inner Solar System. Orbits which pass close enough to the Sun to be perturbed by Jupiter or Saturn (which have masses of order $10^{-3}\ M_\odot$) are swept out of the Oort cloud, either ejected into hyperbolic orbits or captured into short period (recurrent) orbits. The region in velocity space that is empty because of this effect is known as the 'loss cone', and it contains all the orbits which reach the inner Solar System from the Oort cloud. When a star or other massive object passes through the Oort cloud, the orbits of the comets will be perturbed and the loss cone will begin to fill. Hills showed that the fraction of the loss cone that will be filled is given by:

$$F = \left(\frac{27}{8}\right)\left(\frac{M^2}{M_\odot^2}\right)\left(\frac{a^4}{P^4}\right)\left(\frac{GM_\odot}{qv^2}\right) \tag{2}$$

where M is the mass of the perturbing star, v is its velocity (assumed by Hills to be $\sim 30\ \mathrm{km\,s^{-1}}$), and P is its distance of closest approach to the Sun; $M_\odot$ is the mass of the Sun, a is the semi-major axis of the comets affected, q is the minimum distance from the Sun that the comet must reach (1 AU if it is to hit the Earth), and G is the gravitational constant. Normally the Earth sits in the quiet 'eye' of the storm of comets, and the comets we see are those that have been perturbed into this normally quiet loss cone region by randomly passing stars.

Hills analysed the particular case of a star with mass similar to that of the Sun passing within 3,000 AU of the Sun, an event that should occur roughly every 500 Myr. For this situation, each of the bracketed terms in equation (2) is of order unity, and the loss cone will be filled. In less than a hundred thousand years a 'shower' of 10^9 comets will reach the inner Solar System. Using the estimates of Weissman[16] and Everhart[17] for the probability of comets hitting the Earth, Hills concluded that for the duration of the shower (10^5–10^6 yr), between 10 and 200 comets will hit the Earth. He mentioned the possibility that such a shower, triggered by the rare passing star that comes within 3,000 AU of the Sun, could be responsible for the Cretaceous-Tertiary extinctions.

One can arrive at a value similar to that of Hills for the number of impacts on the Earth from a comet shower from the following simple considerations. For a comet moving in an ellipse of eccentricity e and semi-major axis a, the distance of closest approach q is given by

$$q \quad a(1-e) \tag{3}$$

The fraction of comets with e between 1 and e is given by equation (2). Combining these two equations gives

$$N/N_0 = 1 - e^2 = 1 + (a-q)^2/a \approx 2q/a$$

where we have neglected the term $(q/a)^2$. Most of the $N_0 = 10^{13}$ comets in the cloud will be between 10^3 and 10^4 AU. Taking $q = 1$ AU and $a = 10^4$ AU, we find $N = 2\times10^9$ comets showering within the Earth's orbit. (The number of comets that will reach Jupiter's orbit at 5 AU is 10^{10}.) The probability that an individual comet will hit the Earth on a single pass is roughly the projected area of the Earth divided by the area of its orbit, or 1.6×10^{-9}. Each comet will make, on average, four trips to the inner Solar System[12], and on each trip it has two opportunities to hit the Earth. Taking these values together, we find that the total number of comets expected to hit the Earth is $2\times10^9\times1.6\times10^{-9}\times4\times2=25$. Of course this number depends directly on the number of comets in the inner part of the Oort cloud, for which we have no direct evidence.

Using equation (2) we now extrapolate from the case of a random passing star to the situation of a companion to the Sun passing within 30,000 AU at perihelion. The distance of closest approach P is now 10 times larger than for the random passing star case, but the velocity of a companion at this distance is ~0.2 km s^{-1}, 150 times less than the velocity assumed by Hills. Thus, the loss cone will be filled for the same value of a, the comet semi-major axis, of 3,000 AU, and roughly the same number of comets will enter the inner Solar System and hit the Earth, that is, 10–200. Although the impulse approximation assumed by Hills breaks down here, the effect is still of the same order of magnitude. If the mass of the companion is much smaller than 0.1 $M_\odot$, the loss cone will not be completely filled and only a few comets will hit the Earth. Of course, our estimates are approximate, and we probably know the number of comets in the Oort cloud only within one or two orders of magnitude. The calculations do show, however, that the model is plausible. Fluctuations in the eccentricity of the orbit (and hence in the perihelion distance) could conceivably account for the slow overall modulation seen in the intensity of the mass extinctions.

The major difficulty with our model is the apparent absence of an obvious companion to the Sun, and the existence of such an object is its most important prediction. We take this prediction seriously largely because of our inability to find any simpler explanation for the periodicity consistent with known facts. Unfortunately, the data are insufficient to allow us to determine where in the sky to look for the as yet unseen solar companion. The known stars nearest to the Sun have been discovered either because of their high apparent brightness, their large proper motion, or their association with other nearby stars. Unfortunately, our proposed companion star is likely to have none of these characteristics. In his review of the known nearby stars[18], van de Kamp explicitly states that the existence of a "distant dwarf star companion (for the Sun) is not excluded".

Harrison[19] considered the possibility of a nearby solar companion affecting apparent pulsar frequencies but his analysis indicated a star too close to the Sun to have the long period we require. (An additional analysis of Harrison's suggestion can be found in ref. 20.) If the solar companion is a black hole or a brown dwarf (a small star which never heated to ignition temperature) then it may be difficult to find. An intense X-ray and γ-ray source, Geminga, has been proposed as an object that may be very close to the Sun, although the present limits place it at less than 1,000 light yr[21]. If the companion is a hydrogen-burning M dwarf, its apparent magnitude will be between 4 and 12. There are over 10^6 stars in the sky within this range, and one of them may be the Sun's companion. The companion will have negligible radial velocity; from our estimate of its present distance (2.4 light yr, calculated assuming that the mass of the star is substantially less than that of the Sun) we expect an annual parallax motion of ±1.4 arc s and a proper motion of 0.01 arc s per year. The large parallax is probably the key to finding the star. The parallax and proper motion are not large enough for the companion to have been spotted in full-sky surveys that use large proper motion to identify nearby stars[22]. It is possible that the companion may not have been identified as such even if it were as bright as 9th magnitude, and a careful search of star catalogues may provide some candidates, but we suspect that it would have been noted years ago unless it is at the faint limit. Analysis of the IRAS data base may yield a candidate brown dwarf. Weakly bound binaries with a semi-major axis of 1.4 light yr are rare in the Galaxy. The observations show a steep drop-off above 0.7 light yr[23] and theoretical arguments (refs 13–15 and I. R. King and J. M. Retterer, in preparation) predict that separations greater than this should occur in fewer than 10^{-3} of star systems. It is possible that the conditions which drive evolution on the Earth are rarer in the Galaxy than had been supposed previously.

The number of comets that arrive in a single shower may be as much as one or two orders of magnitude greater than the number that arrive between showers. This has important implications for our understanding of Solar System physics and evolution. Since the comets fall in from many regions of the Oort cloud, their arrival in the vicinity of the Earth will be spread out over a considerable period of time, perhaps a million years or more. Thus, we do not expect the periodicity in comet impacts to be exact, but instead it should have a slight 'jitter' or variability of about a million years. One should be able to find evidence in the geological record, perhaps by looking for closely spaced iridium layers or by further studies of isotope ratios, that in the average extinction the Earth was hit by more than one comet.

If and when the companion is found, we suggest it be named Nemesis, after the Greek goddess who relentlessly persecutes the excessively rich, proud and powerful. We worry that if the companion is not found, this paper will be our nemesis.

After this paper was submitted, W. Alvarez and R.A.M.[24] found a periodicity in the ages of large impact craters on the Earth, with a period and phase that closely match those of the mass extinctions. In addition, we became aware of evidence in micro-tektite records[25] that there were at least two separate impacts near the Eocene–Oligocene boundary.

We thank numerous colleagues for critical discussion and helpful suggestions and, in particular, L. W. Alvarez, J. N. Bahcall, F. Crawford, J. Kare, I. King, H. Spinrad and S. Perlmutter. During this research R.A.M. was supported by a fellowship from the John D. and Catherine T. MacArthur Foundation. It was partially funded by the NSF Alan T. Waterman Award, by NSF grants EAR-81-15858 and PHY82–17352, and by the Department of Energy under contract DE-AC03-76SF00098.

Received 3 January; accepted 8 March 1984.

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