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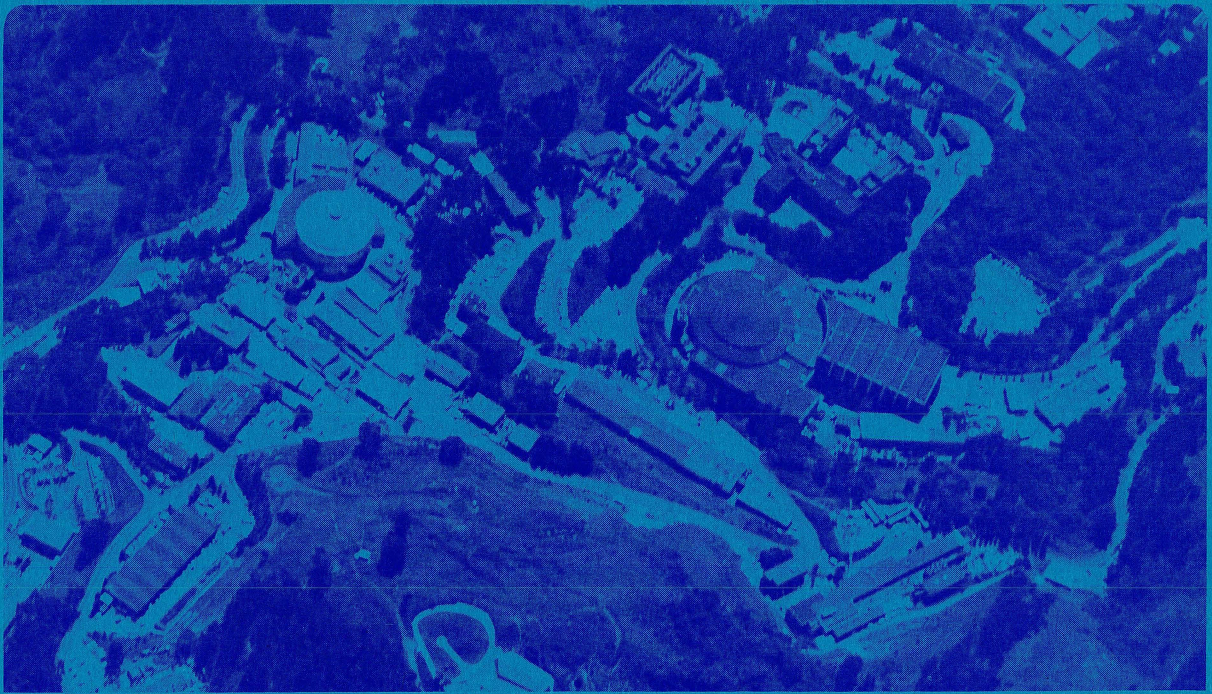

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Extinction of Species
by
Periodic Comet Showers

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The observed 26 million year periodicity in the fossil record of extinctions can be explained if we postulate the existence of an unseen companion to the sun which triggers a shower of comets when it is near perihelion. Possibilities for testing this hypothesis are discussed.

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A 26 million year periodicity has recently been seen in the fossil record of extinction in the geologic 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 5 to 10 km.[2] We propose that the periodic events are triggered by a dark companion to the sun, traveling in a moderately eccentric orbit, which at its closest approach (perihelion) passes through the "Oort cloud" of comets which is believed to surround the sun.[3] During each passage this unseen solar companion perturbs the orbits of these comets, sending a large number of them (over 1 billion) into paths which reach the inner solar system. Several of these hit the earth, on the average, in the following million years. At present the unseen companion should be approximately at its maximum distance from the sun, about two light years, and it shall present no danger to the earth until approximately 15,000,000 A.D.

The possibility that the major evolutionary extinctions occurred in a periodic manner was suggested by A. Fischer and M. Arthur[4], who believed that the periodicity was driven by a terrestrial mechanism. But it is only with the detailed statistical analysis of D. Raup and J. Sepkoski[1] that many questions regarding systematic bias were eliminated. They weighted each of the 39 customary palentological boundaries according to the percentage of families in the preceding stage that were extinct in the following stage. A 26 million year 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 with large family extinctions they call "extinction events". Large excesses of iridium had been found at two of these boundaries by Alvarez et al.[2], who concluded that the events were associated with the impact of a asteroid or comet roughly 5 to 10 km in diameter.

While earth impacts by asteroids provide plausible explanations for the individual events in which many species are extinguished, it is difficult to find an explanation for the precise periodicity of such collisions. W. Napier and S. Clube[5] had proposed that periodic catastrophies could be triggered by the capture of planetesimals as the sun passed through the spiral arms of the Galaxy. However it is difficult to reconcile their model with the relatively sharp periodicity discovered by Raup and Sepkoski, in which the last four of the extinction events occured within two million years of the time predicted by an exact 26 million year cycle. In addition, as pointed out to us by the Alvarez group, 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 the one required, and one might try to hypothesize, for example, 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 and 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 about 6 km/sec. Since the last extinction event took place 11 million years ago, we are almost half-way in 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 million years, then we have difficulty in keeping the orbit stable. An object with this period has a large semi-major axis of about 10^5 AU, (where 1 AU or "astronomical unit" is the mean earth-sun separation of 1.5×10^{13} cm = 1.6×10^{-5} light-year). 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.

But 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[3] 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, since comets with smaller orbits are not significantly perturbed by most passing stars and therefore would usually not be observed on earth. J. Hills[6] has estimated the total number of comets to be closer to 10^{13}; even so, the total mass of these comets is 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 semimajor axis of 10^5 AU, the orbital eccentricity is $e = 0.7$ or greater. Such an orbit requires no "fine tuning"; in fact one expects the distribution of eccentricities in comet orbits to be flat in e^2, with the fraction of comet orbits with eccentricity greater than e given by[7]

$$N/N_0 = 1 - e^2 \qquad (1)$$

Thus the r.m.s. value of a random distribution of binary orbits has a mean value for the eccentricity[7] of $(0.5)^{1/2} = 0.7$, and this eccentricity is adequate for our orbit. Of course, the larger the eccentricity, the shorter is 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. An orbit with a semi-major axis of 10^5 AU will be significantly disrupted only on a time scale of 2 to 3 $\times 10^9$ years[7], comparable to the age of the solar system.

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[6] who was considering the effects of random (non-periodic) stars passing close to the sun. Normally the orbits of the comets are distributed isotropically within the cloud, with the exception of 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} solar mass) 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". This cone 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:

$$F = \left(\frac{27}{8}\right)\left(\frac{M^2}{M_O^2}\right)\left(\frac{a^4}{P^4}\right)\left(\frac{G M_O}{q\, v^2}\right) \qquad (2)$$

where M is the mass of the perturbing star, v is its velocity (assumed by Hills to be roughly 30 km/sec), and P is its distance of closest approach to the sun; M_O 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 "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 analyzed the particular case of a star passing within 3,000 AU of the sun, an event that should occur roughly every 500 million years. For this situation, each of the bracketed terms in equation (2) is of order unity, and the loss cone will be filled. A few hundred thousand years later (the free-fall time from 3000 AU to the sun) a "shower" of 10^9 comets will reach the inner solar system. Using estimates of Weissman[8] and

Everhart[9] for the probability of comets hitting the earth, Hills concluded that over the duration of the shower (10^5 to 10^6 years), 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 figure 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 semimajor axis a, the distance of closest approach q is given by

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

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

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

where we have neglected the term in $(q/a)^2$. Most of the $N_0 = 10^{13}$ comets in the Oort cloud will be between 10^3 and 10^4 AU. Taking $q = 1$ AU and $a = 10^4$ AU, we find that $N = 2 \times 10^9$ 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 the average, 4 trips to the inner solar system[6], and on each trip it has two opportunities to hit the earth. Putting these numbers together, we find that the total number of comets expected to hit the earth is $2 \times 10^9 \times 1.6 \times 10^{-9} \times 4 \times 2 = 25$.

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 about 0.2 km/sec, 150 times less than the velocity assumed by Hills. So 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, 10 to 200. If the mass of the companion is smaller (say $0.1\ M_{\odot}$) then the loss cone will not be completely filled, and only a few comets will hit.

Of course our estimates are rough, and we probably know the number of comets in the Oort cloud only within an order of magnitude or two. But the calculations do show that the model is plausible. Based on the geological record, we expect the true average number of impacts to be greater than one, since otherwise statistical fluctuations would cause too many of the 26 million year cycles to be missed to be consistent with the observed recurrences. Since a few of the cycles do seem to be lacking (or at least less pronounced) we also expect the true average number of collisions per shower, at least for large comets, to be less than four.

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.[10] 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 enable us to tell where in the sky to look for the yet unseen solar companion. Harrison[11] considered the possibility of an unseen solar companion affecting apparent pulsar frequencies but his analysis indicated a star too close to the sun to have the long period we require.[12] 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 gamma-ray source, Geminga, has been proposed as an object that may be very close to the sun, although the present limits simply put it at less than 1,000 light-years.[13] 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; if it is light (so the center of mass of the solar system is near the sun) it will have an annual parallax motion of about ± 1.4 arc second and a proper motion of 0.02 arc sec 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.[14] 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 give us 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 2 light year separation are rare in the Galaxy, and may occur on the average in only one out of 10^3 star systems or less.[15] It is possible that the conditions which drive evolution on the earth are rarer in the Galaxy than previously had been supposed.

The number of comets that arrive in a single shower is as much as one or two orders of magnitude greater than the number that arrive between showers. There are important implications for our understanding of solar system physics and other phenomena affected by comets and asteroids. Since the comets will be falling in from many regions of the Oort cloud, their arrival in the vicinity of the earth will be spread out over a considerable length 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. The discovery of iridium at two of the geologic boundaries suggests that at least some comets do have rocky cores. One should be able to find evidence in the geologic record, perhaps by looking for closely spaced iridium layers, by further studies of isotope ratios, or by looking for multiple layers of microtektites[16], that in the average extinction the earth was hit by more than one comet.

NOTE ADDED: After this work was complete, W. Alvarez and R. A. Muller[17] 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.

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10. 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. Alternative names are: KALI, "the black", after the Hindu goddess of death and destruction, who nonetheless is infinitely generous and kind to those she loves; INDRA, after the vedic god of storms and war, who uses a thunderbolt (comet?) to slay a serpent (dinosaur?), thereby releasing life-giving waters from the

mountains; and finally GEORGE, after the saint who slew the dragon. We worry that if the companion is not found, this paper will be our nemesis.

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