IS THERE EVIDENCE FOR A SOLAR COMPANION STAR?

SCOTT TREMAINE
Massachusetts Institute of Technology

This chapter contains a brief review of the major astronomical explanations for a possible 25 to 35 Myr period in the cratering and extinction records. The only viable theory is that the Sun has a distant companion star; however, the required orbit for this companion is an improbable one, since the companion will probably escape in a time short compared to its present age. The most likely resolution of this uncomfortable situation is that there is no periodicity: in both the cratering and extinction records, the statistical evidence for periodicity is very weak.

In this chapter I review, as requested, the evidence for the existence of an unseen solar companion, the so-called death star Nemesis, which may be responsible for periodic comet showers which are thought to have triggered many of the major extinction events of the last 200 Myr. There are three separate issues to be addressed: is there a periodicity in the cratering and/or extinction record; if it exists, can it be the result of comet showers induced by a companion of this sort; and, are there any other viable explanations of the periodicity. I will discuss these three issues in reverse order.

Explanations for a Periodicity

Several different explanations for the periodicity have been proposed. For example, Rampino and Stothers (1984*a,b;* see also their chapter) have suggested that the periodicity is associated with the interval between successive passages of the Sun through the galactic plane (the agreement between the times of the Sun's crossings of the galactic midplane and the boundaries of major geologic periods was pointed out by Innanen et al. [1978]), and arises because direct collisions and tidal encounters with interstellar clouds are more frequent when the Sun is in the plane. In these encounters, the gravitational field of the passing interstellar cloud perturbs the Sun's comet cloud, causing a shower of comets to rain into the planetary system and onto the Earth, with disastrous biological consequences. Assuming that the amplitude of the solar oscillation (around 70 pc) is small compared with the thickness of the dominant components of the disk, this interval is simply $P_g = 0.5(\pi/G\rho)^{1/2}$, where ρ is the local density. For a reasonable range in ρ, say 0.15 to 0.20 $M_\odot pc^{-3}$ (cf. Bahcall 1984*a*), P_g is between 29.5 and 34 Myr, tantalizingly close to the periods of 26 to 35 Myr which have been found in various biological and geological records.

The most incisive criticism of this possible source of periodicity is due to Thaddeus and Chanan (1985; see also chapter by Thaddeus). They show that the fractional variation in density of molecular clouds due to the Sun's vertical oscillation is simply too small to produce a significant period signal in the nine extinction events used by Rampino and Stothers. To save the Rampino-Stothers hypothesis, one would have to invent some unseen component of the disk with a thickness much smaller than that of molecular clouds (whose half-thickness at half-density $z_{1/2}$ = 85 pc is already the smallest of any known component of the Galaxy); this component would have to be either dissipative or young (so that it was not puffed up from encounters with molecular clouds), and dense enough to cause substantial perturbations to the comet cloud, yet not so dense as to be gravitationally unstable. Because of all these complications, I think that it is extremely unlikely that the periodicity arises from variations in the rate of encounters with interstellar clouds—or any other galactic objects—due to the Sun's motion perpendicular to the galactic plane. Other galactic environmental effects which might be modulated with the period P_g were discussed by Rampino and Stothers (1984*a*) and Schwartz and James (1984), but all of them seem to have similarly serious problems in explaining the observed periodicities.

The galactic tidal field also varies with the period P_g as the Sun oscillates through the plane. The tidal force is proportional to the local density, which is smaller when the Sun is at its maximum height. A. Toomre and I have wondered whether comets with periods close to P_g might be trapped into resonance with this oscillating force field. If a substantial population of comets were in this resonance, and if they had small libration amplitudes, so that they were always near aphelion when the tidal force was weakest, then periodic comet showers could occur when the Sun was passing through the plane. We have done a number of orbit integrations and have found resonant orbits of this type. However, it is our impression that these resonant orbits occupy a relatively small fraction of phase space, and, in addition, there is no obvious dissipative mechanism which could reduce the libration amplitudes to a point where well-defined showers occurred.

Thus, there is no promising mechanism which can connect the Sun's vertical oscillations to the cratering and extinction records, and I am forced to agree with Innanen et al. (1978) that the rough consistency of P_g with the apparent period in the terrestrial record is no more than "an interesting coincidence."

Another interesting possibility is that the periodicity might be due to some unrecognized oscillatory behavior in the known solar system. Important long-term periodicities are common, even though the orbital periods of the planets are comparatively short. For example, the Earth's eccentricity varies between 0.003 and 0.057 with a period of $\sim$ 0.1 Myr, and this variation is believed to be responsible for a substantial fraction of the climatic variation over the last 1 Myr (Hays et al. 1976; Berger 1977). The eccentricity of Pluto varies between 0.21 and 0.27 with a period of 4.0 Myr (Williams and Benson 1971). Are there still longer periodicities? The answer is that we do not know, because the integrations have not been done. The longest direct integration of the outer solar system was for 1.0 Myr and was done over a decade ago (Cohen et al. 1973). Fortunately, the construction of fast hard-wired integrators (Applegate et al. 1984) should lead to very accurate long-term integrations in the near future. Of course, even if a strong 25 to 35 Myr period is found, we would still need a mechanism to deliver bursts of comets or asteroids to the Earth. This will probably not be easy to arrange; so my best guess is that the answer does not lie in this direction either.

Comet Showers to Explain Periodicity

Whitemire and Matese (1985) have suggested that comet showers might be induced at regular intervals by a hypothetical planet X rather than by a distant companion like Nemesis. They argue that an unknown planet of mass M_X = 1 to 5 $M_\oplus$ at semimajor axis a_X = 100 AU would have a perihelion precession period of about 56 Myr, so that if its orbit were inclined, the intersections of its orbit with the ecliptic would oscillate in radius with a period of 28 Myr. Some theories of the origin of comets suggest that there is a disk of comets extending outward from around 40 AU, and Whitmire and Matese suggest that planet X clears out an annular gap in this disk between its perihelion and aphelion, with comet showers occurring when its perihelion lies in the ecliptic so that it passes close to the inner edge of the gap. One serious flaw in this proposal is that planet X is probably not able to clear out such a well-defined gap. The typical velocity impulse received by a comet in an encounter with impact parameter p and relative velocity v is $\Delta v = 2GM_X/pv$. This formula may overestimate the impulse in close encounters, but in any case the bound $\Delta v \leq 2v$ is imposed by energy conservation. If the encounter is to remove the comet from the disk, then we require $\Delta v \gtrsim v_c$, where $v_c = (GM_\odot/r)^{1/2}$ is the circular speed; thus we need $v \gtrsim v_c/2$ and $p \lesssim p_c = 4GM_X/v_c^2 = 4r(M_X/M_\odot)$. In time t planet X sweeps out a volume $\pi p_c^2 v_c t$, and if the comet disk has thickness h, then the fractional volume swept free of comets is

$$f = Q\frac{p_c^2 v_c t}{h(r_a^2 - r_p^2)} = \frac{4Q}{e}\left(\frac{M_X}{M_\odot}\right)^2 \frac{v_c t}{h}$$

where r_a and r_p are the aphelion and perihelion distances, e is the eccentricity of planet X, and Q is the fraction of time when the orbit of planet X lies in the disk. Taking parameters suggested by Whitmire and Matese (1985), $e = 0.3$, $h = 35$ AU (based on a typical comet inclination of 10° and a typical radius of 100 AU), $M_X = 5M_\oplus$, $v_c = 3$ km s^{-1}, and $Q = 0.1$ (since Q can be no larger than the ratio of the shower duration to the interval between showers), after $t = 4.5 \times 10^9$ yr, we find $f = 0.025$. Thus a much larger mass, at least 30 to 50 $M_\oplus$, would be needed to clear out a well-defined gap. A mass this large for planet X is quite unacceptable, both because the planet would be so bright that it would probably have been discovered, and because it would cause large systematic residuals in the positions of the outer planets (see, e.g., Seidelmann 1971; Reynolds et al. 1980).

More distant encounters, with $p \gtrsim p_c$, help to clear a gap by causing gradual diffusion of comet orbits out of the region $r_p < r < r_a$. The mean square velocity change due to encounters with $p \gtrsim p_c$ is of order $\Delta v^2 \approx f v_c^2 \ln \Lambda$, where $\Lambda = p_{max}/p_c$ and $p_{max} \approx 0.5\, r$. Thus, distant encounters with planet X could perhaps clear a gap with values of f as small as $(\ln \Lambda)^{-1} \approx 0.1$. However, the gap would not have sharp edges, since comets outside the gap are affected by distant encounters as well, and diffuse at a rate which is at least $\Delta v^2 \approx f v_c^2$. Thus, for $f \gtrsim 0.025$, $\Delta v/v_c \approx \Delta r/r \gtrsim 0.16$, so that the gap edges can be no sharper than $\Delta r \approx 11$ AU and brief showers cannot be produced (Whitmire and Matese [1985] estimate that $\Delta r \lesssim 0.3$ AU gives an acceptable shower duration). In other words, the requirements of a clean gap and sharp edges appear to be mutually contradictory. However, Whitmire and Matese have informed me that they now have a revised version of their theory which may avoid these problems.

This brings me to the final and most promising theory, namely that the periodicity might be caused by a distant unseen companion to the Sun (Nemesis), on an eccentric orbit with semimajor axis $\sim$ 90,000 AU and period $(90{,}000)^{3/2} = 27$ Myr (Whitmire and Jackson 1984; Davis et al. 1984). At its assumed perihelion distance of around 10,000 to 20,000 AU, Nemesis would pass close enough to the Sun to rattle the dense inner Oort cloud of comets, filling the loss cone which is normally swept clean by Jupiter and leading to a brief, intense shower of comets. In my view the only substantial objection to the Nemesis hypothesis is that the required orbit is an unlikely one for a solar companion, because the escape time from the present orbit is much less than the present age of the solar system. Monte Carlo calculations by Hut (1984) which include both the galactic tidal field and what Thaddeus calls "the pitter-patter of passing stars" yield a half-life of about 1000 Myr, starting from the present orbit. This half-life must be reduced somewhat to include the effects of molecular clouds; estimates for comets at $a = 25{,}000$ AU (Hut and Tremaine 1985) scaled to Nemesis at $a = 90{,}000$ AU yield a somewhat shorter half-life of about 400 Myr, but with large uncertainties. (Clube and Napier [1984*c*] estimate that the half-life is 50 Myr, but this is much too extreme.) Thus Nemesis would escape from the solar system at a future time which is only around 10% larger than its present age, and we are forced to the improbable conclusion that Nemesis, if it exists, has been discovered just as it is about to disappear.

In my opinion the solar companion star Nemesis remains, so far, the best hypothesis to explain the periodicity in the craters and extinctions. It has been exposed to intense examination over the last year and I am not aware that any fatal flaws have shown up. Nevertheless, the Nemesis explanation is entirely *ad hoc*. There is no evidence for Nemesis except the periodicities, and Nemesis would have to be in an unusual orbit capable of surviving from now onward for only a fraction of the age of the solar system.

Terrestrial Evidence for Periodicity

The absence of a compelling astronomical explanation for the periodicity leads us to ask whether the terrestrial evidence for the periodicity is itself very strong. A number of authors have claimed to find statistical evidence for periodicities of between 20 and 40 Myr in the biological and geological record; the literature in 1984 alone contains claims of significant periodicities at 20, 21, 22, 23, 26, 28, 30, 31, 32, 33, 34, 35, 36 and 38 Myr. Unfortunately, there has been a long and dismal history in astronomy of spurious periodicities which have been claimed in many types of data; Feller (1971, p. 76) writes that "hidden periodicities used to be discovered as easily as witches in medieval times, but even strong faith must be fortified by a statistical test." Thus I have attempted to fortify my faith by reanalyzing some of the papers in which evidence for periodicity is presented, in collaboration with J. Heisler. We concentrated on two investigations: Raup and Sepkoski's (1984) analysis of the extinction record, and Alvarez and Muller's (1984) analysis of the crater record.

The Raup-Sepkoski analysis is based primarily on 12 extinction peaks which occurred in the last 250 Myr. They test for periodicity by comparing the times of these peaks to a set of markers with a given period P and arbitrary phase, assigning each peak to the nearest marker, finding the mean difference between the peaks and the markers and then shifting the phase of the markers to reduce the mean deviation to zero. This shift may give one or more peaks an error exceeding half a period, in which case they reassign the peak to the nearest marker, recompute the mean difference, and shift the phase of the markers once again. They iterate this procedure to convergence, and then compute the standard deviation of the differences $\sigma(P)$. For randomly spaced events the root mean square (rms) value of $\sigma(P)/P$ is 0.268 independent of P (except for edge effects which arise because P does not divide evenly into 250 Myr; for $P \leq 60$ Myr, edge effects change the rms value of $\sigma(P)/P$ by $< 1\%$), and a value significantly below this is evidence that a periodicity is present. Raup and Sepkoski examine periods of 12,13,⋯,60 Myr and find a significant dip at 26 Myr, where $\sigma(P)/P = 0.148$. With 12 randomly spaced events, for a given P, $\sigma(P)/P$ would be larger than 0.148 in 99.74% of all samples. Raup and Sepkoski obtain significance levels of 99.55% to 99.99% using similar tests.

These estimates of significance are misleading, however, because the period of 26 Myr was not picked out in advance. Instead, it was chosen as giving the most significant result from many possible periods, i.e., from many possible statistical tests (Fisher 1929). In a time series of length T, Fourier components of frequencies $\nu = k/T$ are independent for $k = 0, 1, \cdots$. Therefore a search for periodicities between 12 Myr and 60 Myr in a time series of length 250 Myr involves frequencies with $k = 4,5,\cdots,21$, or 18 independent tests. Thus the significance level must be reduced from 0.9974 to $(0.9974)^{18} = 0.954$.

This effect was already recognized by Raup and Sepkoski and its importance was estimated by them, using Monte Carlo tests. However, the validity of their tests was severely limited by two restrictions. First, they looked only for periods < 30 Myr, a restriction for which there is no *a priori* justification (indeed, in principle one should probably look for all periods up to 250 Myr rather than just 60 Myr). Second, they required that the dip in $\sigma(P)/P$ be significant over a 3 Myr interval in P. The phase shift over an interval T caused by a period change ΔP is $2\pi T\Delta P/P^2$, and a dip will persist only as long as the phase shift is $\lesssim 2\pi$. To have a significant dip persist for $\Delta P = 3$ Myr requires $P \gtrsim \sqrt{T\Delta P} = 27$ Myr. Thus the Raup-Sepkoski tests were blind to all periods except those in the range $\sim$ 25 to 30 Myr.

To provide an independent estimate of the significance of the periodicity, Heisler and I have carried out our own Monte Carlo tests. We placed 12 extinction events randomly between 0 and 250 Myr and searched for values of $\sigma(P)/P$ below 0.148 in the interval 12 Myr $\leq P \leq$ 60 Myr. We used the Raup-Sepkoski algorithm except that we searched in frequency rather than in period and used a much finer mesh with step size $\Delta\nu << 1/T$. Out of 1000 simulations, we found that 115 had periods between 12 and 60 Myr for which $\sigma(P)/P$ was < 0.148. Therefore, according to this test, the significance level of the Raup-Sepkoski periodicity is $< 90\%$. We have carried out the same test with Sepkoski and Raup's (1986) revised list of eight extinction events, and find an even smaller significance level of only 50%. These results suggest that there is no strong evidence for periodicity in the extinction record.

The Alvarez-Muller analysis is based on 11 impact craters with ages between 5 and 250 Myr, with age uncertainties ≤ 20 Myr and diameters > 10 km. They describe a power-spectrum analysis which yields a period of 28.4

Myr, and ascribe a significance level of 97 to 99.5% to this periodicity. In the one test which they report in detail, they represent each crater by a Gaussian of unit area and rms width equal to the age uncertainty. They compute the power spectrum of the set of Gaussians, and then generate Monte Carlo simulations of 11 craters with random ages and the same set of age errors as in the real data. They then search for peaks as high as the peak seen in the real data at frequencies higher than 28.4 Myr^{-1}. They find higher peaks in fewer than 1% of the simulations and conclude that the peak is significant at the 99% level.

This significance level is misleading for the following reason. Convolution with a Gaussian is equivalent to multiplication of the power spectrum by a Gaussian. This process suppresses high-frequency peaks, and by searching only for peaks at frequencies higher than the observed frequency, Alvarez and Muller have looked only in the region where the peaks in the Monte Carlo simulations have been suppressed. Heisler and I have carried out an alternative analysis in which we calculated the power spectrum which results from representing the crater data by equally weighted delta functions rather than Gaussians. We then constructed simulations using 11 craters with random ages, and searched for peaks in the power spectra of the simulations with periods between 10 and 60 Myr. We found higher peaks in 4.3% of the simulations, implying that the periodicity in the crater data is significant at only about the 96% level, slightly lower than Alvarez and Muller's lower limit of 97%. Including periods longer than 60 Myr in the search would lower the significance level still further.

It might be argued that the significance of our result has been degraded because all craters are given equal weight, even if their age uncertainties are large. We therefore carried out an additional analysis in which each delta function was weighted by the inverse of the age uncertainty. This yielded a slightly lower significance level, 92.5%. To sum up, the evidence for a periodicity is stronger in the crater record than in the extinction record, but it is still rather weak.

It has sometimes been suggested that the evidence for the periodicity is stronger than these arguments suggest, because the extinction and crater records yield periodicities which agree in period and phase. However, this argument is misleading. The Alvarez group has accumulated very strong evidence that mass extinctions are associated with iridium layers and thus with impacts. With this strong correlation between extinctions and impact craters well established, if a spurious periodicity is found in one record, we should expect it also in the other.

One interesting point remains to be addressed. We have learned from W. Alvarez that there is now preliminary evidence that multiple iridium layers and multiple tektite layers are associated with at least some extinction events. This result suggests that major impacts are not random, i.e., that they tend to occur in bunches or showers of duration ~ 1 Myr, even though the showers may not be periodic. An additional advantage of a shower model is that some paleontologists claim that mass extinctions were not sudden but spread over 1 Myr or so, which is easier to reconcile with a shower than with a single major impact (Muller 1985). If impacts are bunched, then the statical analysis of the previous paragraphs should be modified. Rather than testing the null hypothesis that all craters occur at random times, we should test the hypothesis that they occur in random bunches. There are two clear bunches of craters in the Alvarez-Muller sample: two craters at 38 and 39 Myr and three at 95, 100 and 100 Myr. If we replace these bunches by single events at 38.5 Myr and 98 Myr, thus reducing the sample from 11 events to 8 events, the significance level drops from 96% to 75%, which is too low to provide any evidence of periodicity.

If there is no periodicity, and hence no evidence for Nemesis, then what caused the showers? Probably the answer is that they are comet showers which are set off by close stellar encounters, in precisely the manner envisaged by Hills (1981; see also his chapter). Hills showed that stellar encounters are frequent enough and strong enough to produce a steady flux of comets into the planetary system, but only for cometary semimajor axes $a > a_c = 2 \times 10^4$ AU. Comets with semimajor axes $< a_c$ enter the planetary system only in brief showers which occur when a passing star makes a close approach with impact parameter $p \lesssim a_c$. According to Hills, the mean interval between encounters with $p < a_c$ is about 10 Myr; for $p < 0.5\, a_c$ the interval is 40 Myr. Given the uncertainties, these intervals are consistent with the mean interval of 25 to 30 Myr between major impact showers. It would be very worthwhile to compare the statistics from a detailed Monte Carlo model of Hills' comet showers with the statistics of the cratering and extinction records.

Conclusions

To summarize, there is no very appealing astronomical model that would explain a 25 to 30 Myr periodicity in the cratering or extinction record, although the only argument against Nemesis is that the required orbit has a low *a priori* probability. However, the statistical evidence for a periodicity is weak, particularly if we accept the fact that extinctions are correlated with crater impacts and that the impacts occur in showers or bunches. Most likely, the extinctions are due to intense comet showers which occur at random times, as a result of occasional close encounters with passing field stars.

Thus the observational search for Nemesis is similar to the search for Pluto half a century ago, in at least two respects: first, it probably has no sound theoretical basis; and second, it is likely to yield extremely interesting results whether or not the theory is correct.

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