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EVIDENCE FOR NEMESIS: A SOLAR COMPANION STAR

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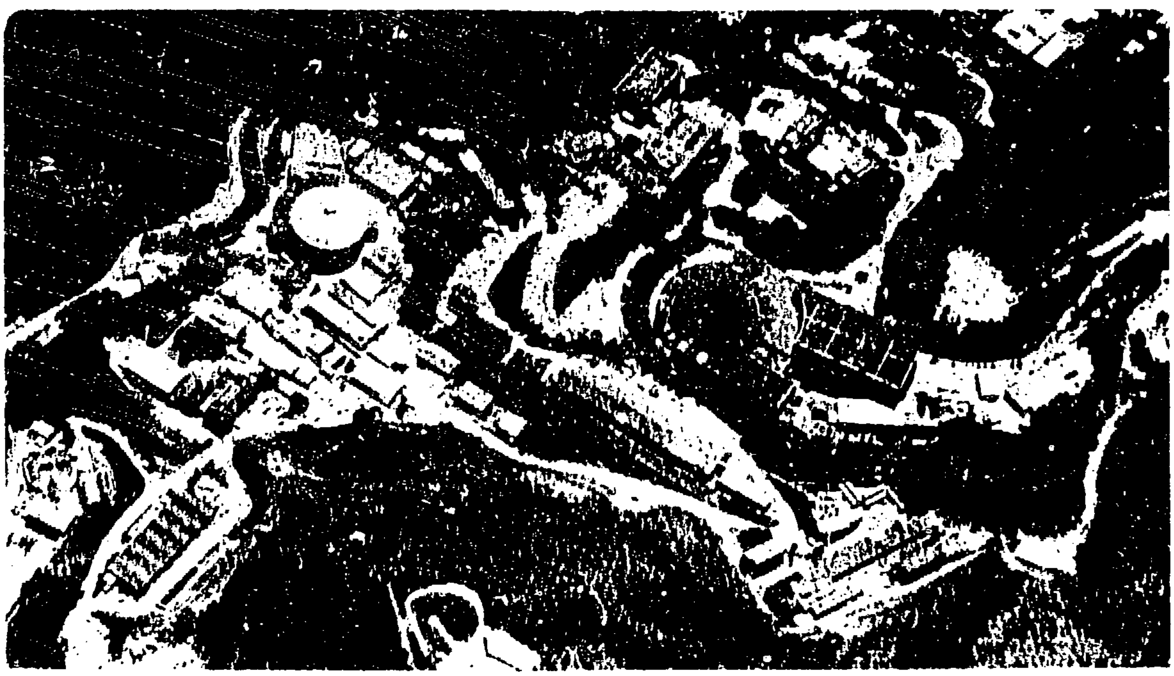

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a Solar Companion Star

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Evidence for Nemesis: a Solar Companion Star

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ABSTRACT

The evidence that the sun has a companion star "Nemesis" responsible for periodic mass extinctions is reviewed. A gaussian ideogram of the rates of family extinctions in the oceans shows periods of 26 and 30 Myr. Analysis of impact cratering on the earth shows a period of either 28.4 or 30 Myr, depending on the crater selection. Models which attempt to explain these periods with either oscillations through the galactic plane, or through the effects of a tenth planet, are seriously flawed. If the periods seen in the data are real (and not a spurious result of a statistical fluctuation) then the "Nemesis hypothesis" is the only suggested explanation that has survived close scrutiny. The Nemesis model predicts that the impacts took place during brief storms of several million years duration, perhaps accounting for the "extended" nature of the mass extinctions. A search for Nemesis is underway at Berkeley.

We have recently seen the status of the Alvarez et al.[1] claim, that an asteroid or comet hit the earth at the time of the cretaceous extinctions, have its status changed from that of a disputed hypothesis to that of the "standard dogma". Although there are still some who dispute that the impact caused the extinctions, there is virtually nobody left who disputes that an impact took place. But at the same time that the Alvarez model was becoming the standard picture, there have been two new and equally startling claims to keep the skeptics busy.

The first is the discovery by D. Raup and J. Sepkoski[2] that the mass extinctions were not isolated events, but that they have occured regularly with a period of 26 Myr. The original papers of Raup and Sepkoski show an alternative period of 30 Myr fits the data almost as well. In Figure 1, I have plotted the data of Raup and Sepkoski in a way somewhat different from that in their paper. The percentage of family extinctions at each of the geologic stages has been represented by a Gaussian curve, with area equal to the percentage, and half width equal to the uncertainty in the time of the extinctions. In this plot the regularity of the extinctions is somewhat more evident to the eye than in the original plot presented in their paper, but more importantly the curve in this plot represents an estimate of the extinction rate in the last 250 Myr. (We believe the statistical significance of the Raup and Sepkoski periodicity is more evident than in the logarithmic plot originally published by them; we suspect that much of the skepticism about the significance of their discovery arises because of the relatively unconvincing way that they plotted the data.) The Fourier power spectrum of this curve is shown in Figure 2. As in the original time series analysis of Raup and Sepkoski, the two dominant periods at 26 Myr and 30 Myr are evident. One should not assume that both of these periods are necessarily physical. One physical period can give rise to two apparant Fourier peaks if a few of the cycles are missing, as explained by Alvarez and Muller[3], who showed that a 28.4 Myr period could fit the extinction data of Raup and Sepkoski by slipping phase during the missing cycles. A single frequency with modulated amplitude is mathematically indistinguishable from the sum of two pure sine waves:

$$2 \cos[\Omega t] \cos[\omega t] = \cos[(\Omega+\omega)t] + \cos[(\Omega-\omega)t)]$$

We don't claim that the two peaks seen in the data must be interpreted in this way, but likewise it is premature to conclude either that there are two physical mechanisms responsible for the two peaks, or that at most only one of the two peaks in the Fourier transform is significant. The truth could lie in between.

The second startling discovery was the claim made independently by Alvarez and Muller[3] and by Rampino and Stothers[4] that a similar periodicity existed in the dates of impact craters on the earth. Both of these groups had read the Raup and Sepkoski paper, but they were inspired by different models: Alvarez and Muller by the "Nemesis hypothesis" of Davis, Hut and Muller[5], and Rampino and Stothers by their own theory of Galactic oscillations. (The model of Whitmire and Jackson[6], is equivalent in most respects to the Nemesis model, but requires an orbit of eccentricity 0.9; it is not clear whether such a high eccentricity is sufficiently stable to describe the extinction data.[7]) Alvarez and Muller found a dominant period of 28.4 Myr with an uncertainty of ± 1 Myr. Rampino and Stothers saw a broad peak in the Fourier transform at 31 Myr with a full-width at half maximum of 4 Myr, but did very little statistical analysis and did not offer an uncertainty limit. E. Shoemaker[8] made a reanalysis of the crater's periodicity, using the craters selected by Alvarez and Muller, supplemented with a few additional craters, and with his own selection of the best dates for each one based on a search of the original literature. (Shoemaker prefered dates obtained by fission-track dating, for example, over dates obtained from the potassium-argon method.) He concluded that there was a periodicity present, but it might not be statistically significant. If one was present, its dominant period was 30 ± 1 Myr. The Fourier transform of a Gaussian ideogram that we made from the Shoemaker crater list is shown in Figure 3.

These two discoveries, if real, significantly alter the original model of Alvarez et al. The most important change is the fact that the impacts must come during "showers" or "storms" when it is possible that there may be several impacts in a relatively short time. The idea of comet showers triggered by a passing star was originally due to Hills.[9] The Nemesis model[5] predicts the duration of these storms to be from 1 to several million years, depending on the eccentricity of the companion star orbit. Thus impacts are not expected to be isolated events, but should occur in short bursts. The significance of this change is that it offers the possibility of explaining the claim of some paleontologists that the extinctions were not abrupt, but took several million years. The "gradual mass extinction" would, upon closer scrutiny, be due to a series of impacts closely spaced in time.

NEW IRIDIUM DETECTOR

Frank Asaro and collaborators at Berkeley are making a careful search for the multiple iridium layers that are predicted in this model. A new detector invented by L. W. Alvarez is being constructed that will enable a complete scan of rock for the last 250 Myr. The instrument uses two germanium detectors to look for coincident gamma rays at 316 and 468 keV from the decay of activated Ir-192; a mineral oil scintillation counter surrounding the germanium gamma detectors will be used to reject cosmic ray events and background from Compton-scattered gammas. The system will be capable of detecting iridium levels as low as 50 parts per trillion in 7 minutes of counting using raw rock samples that have not been chemically purified.

NEMESIS AND THE SOLAR SYSTEM

The "Nemesis hypothesis" which offers a solar companion star as the possible trigger for the comet showers, has held up quite well after a year of close scrutiny. As stated in the original paper by Davis, Hut, and Muller, the orbit required for a 26 to 30 Myr period is unstable against perturbations from passing stars, with a lifetime of about 109 years. Thus it is extremely unlikely that the star has been in this orbit since the beginning of the solar system; it must have begun in a much more tightly bound orbit. Piet Hut has shown[7] that, on the average, the effects of passing stars will drive the binding energy of the Nemesis/Sun system linearly towards zero. Thus with a billion years remaining, we can extrapolate into the past, and conclude that Nemesis was probably 4.5 times as tightly bound at the time of the creation of the solar system. At this time Nemesis would have been 4.5 times closer, with a semi-major axis of 20,000 AU and a period of 3 Myr. The reader is referred to Hut's paper in this volume for details of the effect on the orginal solar system. One important note of caution: the average behavior is a very poor indicator of actual behavior, as Hut's Monte Carlo calculations have shown. Thus we cannot really conclude that we know anything about the past history of Nemesis in the case of interest. Nevertheless, it is still somewhat reassuring that the extrapolated separation of the Sun and Nemesis at the creation of the solar system is only 20,000 AU, a value at which other binary stars have been found.

As stated in the original paper[5], the orbit is sufficiently ustable that we do not expect a strict periodicity, but expect to see fluctuations of 10 to 15% over the past 250 Myr. It is possible that the fluctuations in the orbit, both in semi-major axis (affecting the intensity of the storms) and in period, give rise to the double peak structure seen in the Fourier analyses.

Soon after the original Nemesis hypothesis was published, objections were raised that passing molecular clouds would have a much bigger effect than passing stars in disrupting the orbit. Hut has shown that this is not true, by extrapolation from the relatively high abundance of double stars with semi-major axis of 10 to 20,000 AU. This indicated that the lifetime against breakup for this separation was comparable to the ages of the stars, and a simple extrapolation to the Sun/Nemesis system then indicates that the lifetime could not be much less than our calculated 10^9 years.

In summary, at the time of the time of this conference, we believe that there is no theoretical difficulty in postulating the existence of Nemesis with the orbit originally assigned to it.

OSCILLATIONS ABOUT THE GALACTIC PLANE?

Other theories to account for periodic comet showers have not fared so well. The model of Rampino and Stothers[4] had the showers caused by molecular clouds concentrated in the galactic plane. Their original paper claimed a 99% correlation between their calculated plane crossings for the sun, and the Raup and Sepkoski mass extinction times. Unfortunately this was in error; the correlation in the two data sets is easily shown to be zero, within statistics. Rampino and Stothers had made a simple mathematical mistake, as was pointed out by S. M. Stigler[10]: they had compared the correlation cofficient they had obtained to the correlations expected between unordered numbers, when in fact the numbers in their two lists were ordered. And finally, in a careful analysis done by P. Thaddeus and G. Channan at this conference[11], it was shown that the mechanism proposed by Rampino and Stothers, perturbations by molecular clouds, could not possibly account for the observed showers. In fact the Thaddeus and Channan method can be used to show that it is impossible to trigger the observed showers from any mass concentration in the galactic plane.

GEOLOGIC RHYTHMS?

M. R. Rampino and R. B. Stothers[12] have recently proposed that a period of 33 ± 3 Myr can be seen in many geological and biological upheavals. I do not think that their conclusion follows from their data. Most of the pheonomena they refer to have no statistically signficant periodicity. Of course one can always find a peak in the Fourier power spectrum of any data, and if the peaks from many data sets always fell at the same period then that would be of interest. But this is not the case. I have plotted a histogram of all the frequencies they found in Figure 4; in addition I added two periods from publications they refer to but don't mention explicitly (26 Myr from ref 2, and 28.4 Myr from ref 3). As can be seen in the figure, the distribution is relatively flat, as expected from the fact that most of the periods plotted (with the exception of those from references 2 and 3) are from data with no statistically significant periodicity. Rampino and Stothers incorrectly conclude that a period of 33 ± 3 Myr is present, and to do so they ingnore all periods in the range 11-14 Myr because they are third harmonics of 33; they ingnore the periods from 15 to 16 because they are approximately second h⁻monics of 33: they ignore the periods from 18 to 23 because they are 3/2 harmonics of 33, and as mentioned previously they ignore the periods of 26 and 28.4 with no reason given. Then they conclude that there is statisically significant clumping around 33 Myr. There is no valid justification for their procedure, particularly since in doing such work it is extremely important, as they say in their paper, "to avoid any possibility of subjective bias in selecting the data to be analyzed." In summary, the data they present in their paper does not justify their conclusion of statistically significant "geologic rhythms."

PLANET X?

Another clever trigger for comet showers was suggested by Whitmire and Matese,[13,14] who postulate the existence of a tenth planet, "Planet X", with mass of 1 to 5 times that of the earth, orbiting 70 to 100 AU from the sun. They must postulate that there is an inner part of the Oort comet cloud that has maintained a disk-like shape in the plane of the inner plants. Planet X periodically scrapes the edge of this disk, as its perihelion advances around its own orbit which is tilted at an angle of perhaps 45 degrees to the ecliptic. The major problem with this model is possibly the stability of the disk of comets near planet X, as was first pointed out by Don Morris[15]. Perturbations from planet X itself will cause these comets to leave the ecliptic and fill the postulated gap in a time comparable to the 26-30 Myr perhelion advance time. The comets would not then arrive in storms, but sprinkled out over the entire period.

MAGNET REVERSALS

David M. Raup[16] has recently made another discovery of potentially great significance: he has found a statisically significant periodicity in the rate of reversals of the earth's magnetic field. His conclusions are difficult to accept simply because the impact of a comet conveys little energy compared to that stored in the field of the earth. Don Morris and I have found a possible model[17] that can account for the correlation.

Briefly, we assume that an impact can trigger a climate change that persists for at least a few hundred years. As ice is deposited at polar latitudes, the sea level drops. (Sudden sea level drops of 10 meters or more are known to have occurred at least 41 times in the last 65 million years.) The redistribution of the mass of the water affects the moment of inertia of the crust and mantle to cause a sudden increase in its motion relative to the liquid and solid core. The resulting shear in the liquid core, $\geq 10^{-2}$ cm/sec, is sufficient to disrupt the dynamo. When the dynamo regenerates itself it has a 50% probability of creating a field opposite to the original one, thus causing a magnetic reversal. In the other 50% of the cases we predict a magnetic "excursion" or "aborted reversal."

Some paleontologists have noted the correlation between sudden sea level drops and mass extinctions, and concluded that the drops *caused* the extinctions. We see, however, that they may have both been caused by the same agent, a comet or asteroid impact. And we can't rule out that the sea level drop was important in killing some of the species that survived the more immediate effects of the impact.

TULIP ORBIT

While looking for alternative models for periodic perturbations, I found one that is particularly interesting and pretty. In the end the idea wasn't sufficient by itself to explain the periodic mass extinctions, but the physics of the problem is very relevant for understanding the stability of the Nemesis orbit, as well as that of comets.

Suppose we postulate an object orbiting the sun in a moderately eccentric orbit, with major axis initially perpendicular to the galactic plane. Let its orbital period be $t_N << t_g$, where tg is the period of oscillation of the sun up and down in the galactic plane. ($t_g \cong 66$ Myr.) Due to the nearly constant gravitational gradient in the galactic plane, the perihelion of the orbit will precess. As the major axis develops a component parallel to the galactic plane, the gradient will put a torque on the sun/object system, and remove angular momentum from it. Gradually the eccentricity will increase, and the object's distance of closest approach to the sun

r_{min} will decrease. When the instantaneous value of the orbit parameter r_{min} passes through zero (usually not when the object is near the sun) the angular momentum of the orbit will reverse sign, and the orbit will begin to precess in the opposite direction. The magnitude of the angular momentum will increase, until the major axis oscillates all the way to the other side of the normal to the galactic plane. A computer simulation of this orbit is shown in Figure 5; for obvious reasons I have come to call this orbit the "Tulip orbit".

The eccentricity of the Tulip orbit changes with a period t_T given roughly by

$$t_T = t_g^2/t_N$$

This formula was guessed at by me, checked using a Monte Carlo simulation (written by Jordin Kare) and proven analytically and independently by Marshall Rosenbluth (private communication). It implies that the eccentricity of the obit will change cyclically in a number of cycles n given by

$$n = t_T/t_N = (t_g/t_N)^2$$

Note that for Nemesis this value is $n = (66\ \text{Myr}/30\ \text{Myr})^2 = 5$ cycles. Thus we expect the distance of closest approach to vary with this period.

THE BERKELEY SEARCH FOR NEMESIS

There is no need to assume that Nemesis is an exotic object, such as a brown dwarf or black hole. If it were a red dwarf, the most common known star type in our galaxy, then it could have apparent magnitude between 8 and 12, dim enough to have been missed in full sky parallax surveys. If the last comet shower was 13 Myr ago, then Nemesis would be at its greatest distance, about 3 light-years; if the shower was 5 Myr ago, then Nemesis would be only half that distance. Its proper motion, due to its orbital velocity, would be less than 10 milliseconds of arc per year. Our group at Berkeley, including Carl Pennypacker, Jordin Kare, Frank Crawford, Saul Perlmutter and Roger Williams, are making a search for Nemesis. We are currently taking electronic images of 5000 red stars (M3 or later) in the Dearborn Catalog of the northern hemisphere, using a 512 x 320 element CCD (charge-coupled device). To save expense and tape, the images have been recorded on betamax videotape; pairs of images are analyzed with software we have developed for our PDP-11/44 computer. At 3 light-years, the expected 6 month peak-to-peak parallax of Nemesis is nearly 3 arc sec, and we are making a crude (±0.2 arc sec) measurement of the parallax of each star. Stars we identify as candidates will be studied with great care, and have their proper motion and radial velocity measured. If we fail to find Nemesis in the northern hemisphere, we hope to do a full-sky survey of the southern hemisphere using Schmidt plates measured on the Minnesota "Starcruncher", a technique suggested by Jordin Kare.

SUMMARY

We believe that the periodicity found by Raup and Sepkoski is made particularly evident when their data is plotted as a Gaussian ideogram. There are two strong periods present, at 26 and 30 Myr, although this made be due to a modulated single periodicity. Iridium layers have been found at a least two of the cycles (the Cretaceous/Tertiary and the Eocene/Oligocene), and there is unconfirmed evidence of iridium at a third (the Permian/Triassic), indicating the impact of a comet or asteroid. By making the natural assumption that all the cycles are due to impacts, we are drawn to the conclusion that the earth is periodically (or quasi-periodically) subjected to storms of comets or asteroids. Evidence of multiple iridium peaks within a few million years of the boundaries will confirm or deny this conclusion. The existence of multiple impacts during a storm could account for the "extended periods of extinctions" reported by some paleontologists.

The only model that has been proposed that is both self-consistent and compatible will all the known facts of astronomy and paleontology, is the Nemesis hypothesis which postulates a small star (mass from 0.3 to 0.05 solar masses) orbiting the sun in a moderately eccentric orbit ($0.7 < e < 0.9$) with a period of 26 to 30 million years. Despite early claims to the contrary, it has been shown that the orbit of Nemesis is not highly unusual, and it is sufficiently stable against perturbations by passing stars and molecular clouds to account for the observed periodic extinctions and periodic impacts.

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FIGURE CAPTIONS:

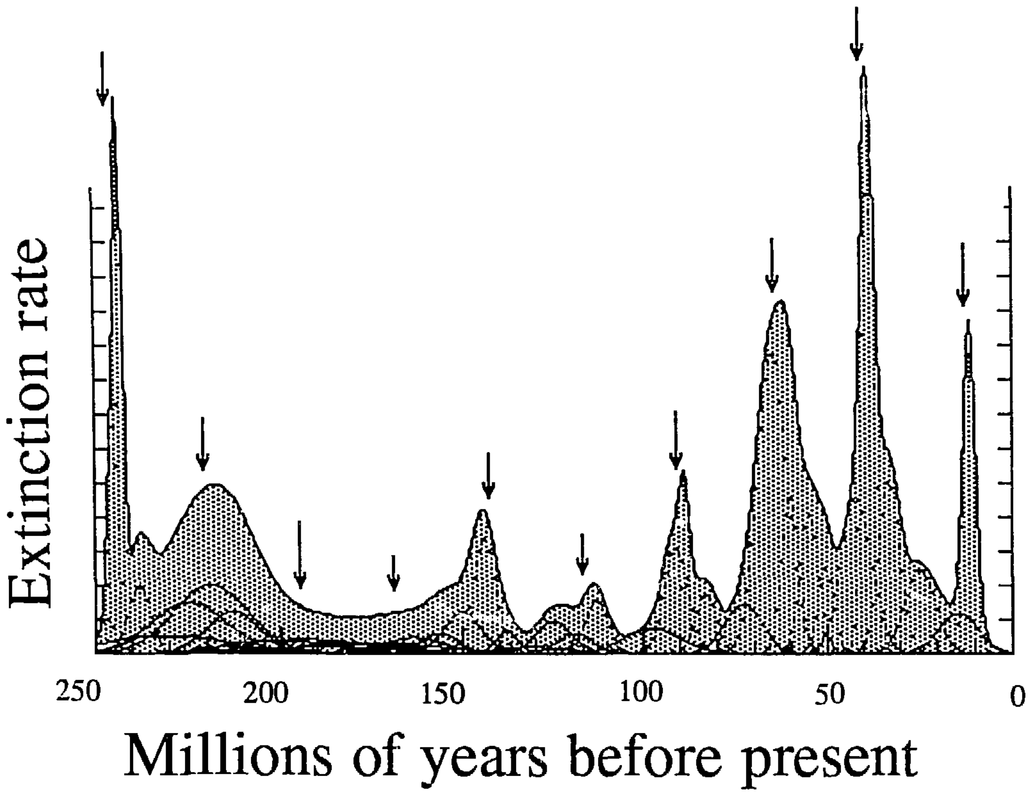
Fig. 1: Raup & Sepkoski data plotted as a Gaussian Ideogram. For each extinction, an error estimate ß was calculated from the uncertainty published in the Harland time scale (ref. 18), taken in quadrature with the duration of the preceding stage. Each point was turned into a Gaussian curve, with width equal to ß and area equal to the percentage of family extinctions published by Raup and Sepkoski (ref 2). The Gaussian curves for all the 39 stages were added to produce the figure. The arrows indicate the 26 Myr periodicity found by Raup and Sepkoski.

Fig. 2: Fourier transform of the curve shown in Figure 1. The existence of signficant periodicity at 26 or 30 Myr is indicated by the two peaks at these periods.

Fig 3: Fourier transform of Shoemaker crater ideogram, showing a single broad peak at a period of 30 Myr.

Fig 4: Histogram of periods found by M.R. Rampino and R. B. Stothers in ref. 12.

Fig 5: The "Tulip orbit", the path taken by a object in the presence of a both a central gravitational force F = 1/r2 and a uniform gravitational gradient F = k z.


Extinction rate
250
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150
100
50
0
Millions of years before present

Figure 1

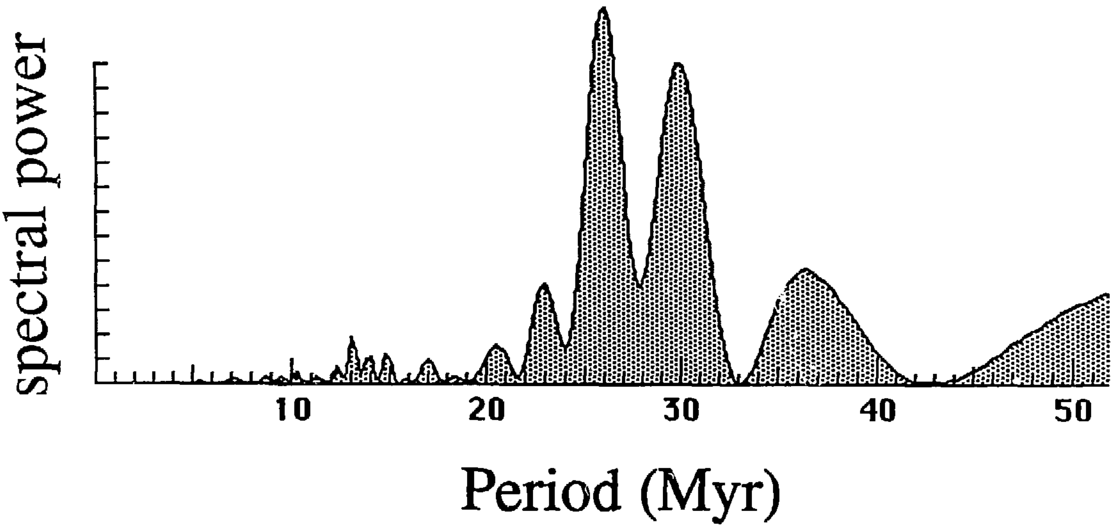


Figure 2

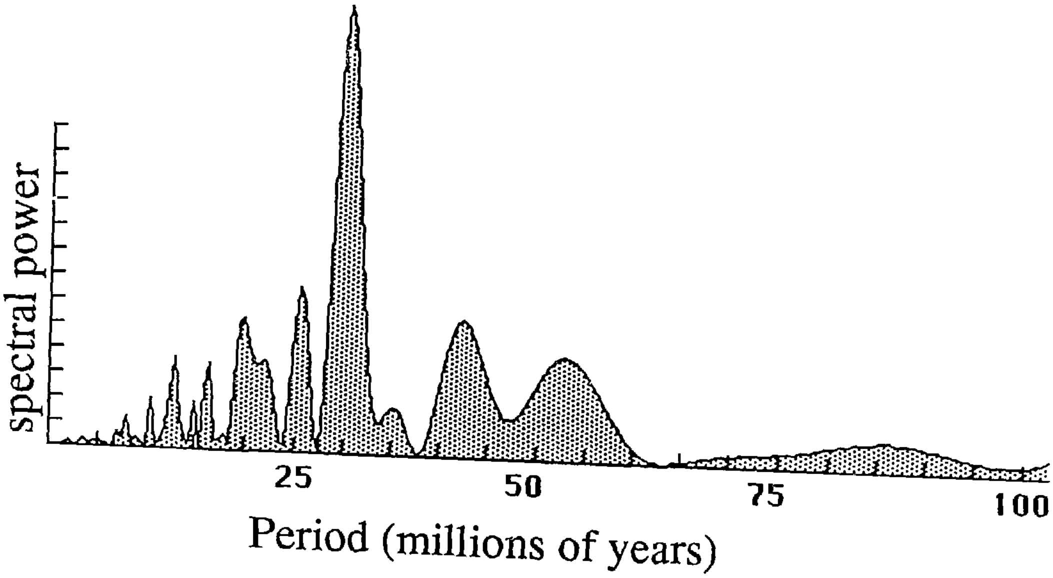
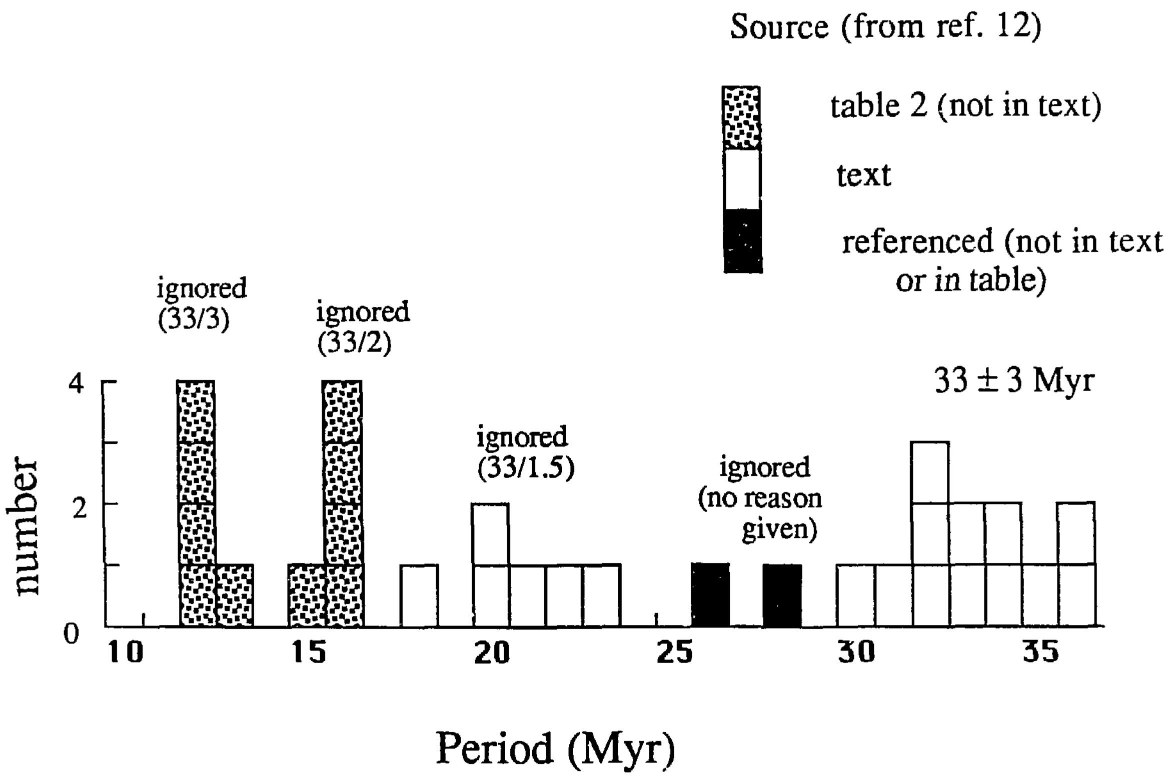


Figure 3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10
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20
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30
35
Period (Myr)

Figure 4

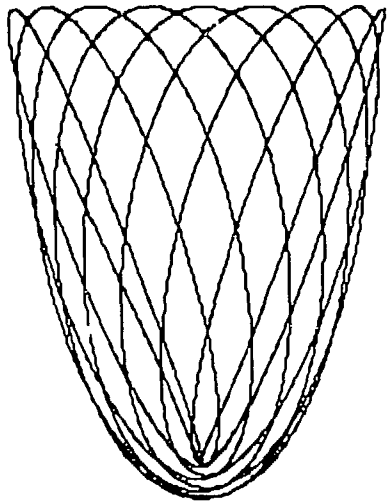

Figure 5