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Author(s): Charles W. Harper Jr.

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Might Occam's Canon Explode the Death Star?: A Moving-Average Model of Biotic Extinctions

CHARLES W. HARPER JR.
School of Geology & Geophysics
University of Oklahoma
Norman, OK 73019

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A controversial explanation for an apparent 26-million-year periodicity in extinctions over the last 250 million years is that the purported "pattern" merely reflects extinctions occurring at random. This explanation would be corroborated if it predicted that extinction maxima should occur on the average every 26 m.y. However, if extinctions are occurring at random, then maxima should occur on the average every 19 m.y. rather than every 26 m.y., so the argument loses its force. While a random model does not fit the observed data well, quasi-periodicity need not arise from extraterrestrial causes. An earth-based alternative is proposed in which the number of extinctions during a given time interval comprises a moving average sum of cohort components, one for the interval and for each previous time intervals (up to a threshold N). The magnitude of each such component simply reflects the number of species that originated in the time interval plus the time elapsed since the interval; the former is viewed as a random input and cohorts are considered to follow an exponential pattern of species loss by terminal extinction.

INTRODUCTION

Raup and Sepkoski (1984; 1986) propose that major extinctions over the last 250 million years exhibit a 26-million-year periodicity (Fig. 1A). They favor an extraterrestrial mechanism for cyclicity, labeling purely biological or earthbound cycles incredible (Raup and Sepkoski, 1984, p. 805). Extraterrestrial causes postulated to explain periodicity include oscillations of the solar

system back and forth across the galactic plane; an as yet unseen "Planet-X" with an excentric orbit; and a companion star to the sun (the "Death Star") (Angier, 1985; Benton, 1985; Maddox, 1984; Raup, 1986; Sepkoski and Raup, 1986a, p. 24–29).

Yet other alternatives exist: I shall first consider and reject the hypothesis that the 26-million-year quasi-periodicity in Raup and Sepkoski's data is due to extinctions occurring at random. Next, I propose an "Earth-based" model in which the number of species becoming extinct in a given time interval equals a moving average sum of cohort components, one for the interval and for N previous time intervals. The magnitude of each such component is determined by 1) the number of species that *originated* in the time interval, which is considered a random input, and 2) the time elapsed since the interval. Cohorts are considered to lose a fixed proportion of their remaining species (via terminal extinction) during each time interval.

THE RANDOM MODEL

Hoffman and Ghiold (1985) and Hoffman (1985) argue convincingly that an average span between extinction maxima of 26 million years is exactly what one would expect to find in the data as analyzed by Raup and Sepkoski given that extinctions are occurring at random: If extinctions are occurring at random, the probability of an increase or decrease in extinction rate from one stage (= time interval) to the next is 1/2. So the probability that a particular stage represents a local maximum is 1/4. Peaks should occur on the average every fourth stage; in other words, in the long run, the mean number of stage intervals between maxima should be four. The mean stage duration is 6.4 million years and estimates of the duration of the 38 stages studied mostly lie between 5 and 7 m.y., with about half estimated as 6 m.y. Thus, a 26 m.y. (= about 6.4×4) average span be-

tween local extinction maxima is expected if extinction maxima occur at random.

Hoffman and Ghiold erred in saying that the appearance of a 26-million-year periodicity is inevitable; they should have referred to an average or mean duration between peaks of 26 m.y. Gould (1985) and others (Sepkoski and Raup, 1986b; Gilinski, 1986) respond that the critical question at issue is whether or not extinction maxima occur with a periodicity of 26 million years. All Hoffman and Ghiold show is that maxima should occur on the average once every 26 million years given a random model. Nonetheless, if a 26-million-year average span between extinction maxima is a necessary, albeit not sufficient, condition for the random model, then the random model is strikingly corroborated by the actual observation of a 26 million year average. At the very least, if extinctions are not random than a surprising coincidence has occurred.

Yet Hoffman and Ghiold's argument is wrong. If mass extinctions occur at random, then local extinction maxima are to be expected, on the average, every *three* (not four) stages (Kendall, 1976, p. 21–24). Given a mean stage length of 6.4 million years, local maxima should occur, on the average, *every 19 million years*, not every 26. To see this, consider a plot of the number of extinctions as a function of time, such as one of Raup and Sepkoski's. Each data point except the first and last belongs to a triplet $\{i-1, i, i+1\}$ consisting of the previous point, the data point itself, and the next point. Exclude ties and let H,M,L represent the highest, middle and lowest of the 3 extinction values. A triplet will form a local maximum (= $\{L,H,M\}$ or $\{M,H,L\}$), a local minimum (= $\{M,L,H\}$ or $\{H,L,M\}$), or a monotonic sequence (= $\{H,M,L\}$ or $\{L,M,H\}$). If mass extinction counts occur in random sequence, the six sequences listed are equally likely. So the probability of a local maximum is 1/3.

Contrary to Raup and Crick (1981, p. 213), there is no need to assume that the values in the time series are drawn from a normal distribution. Also, the probability of a local maximum (= 1/3) equals the probability that the first two points in a triplet form a rise (= 1/2) times the probability that the last two in

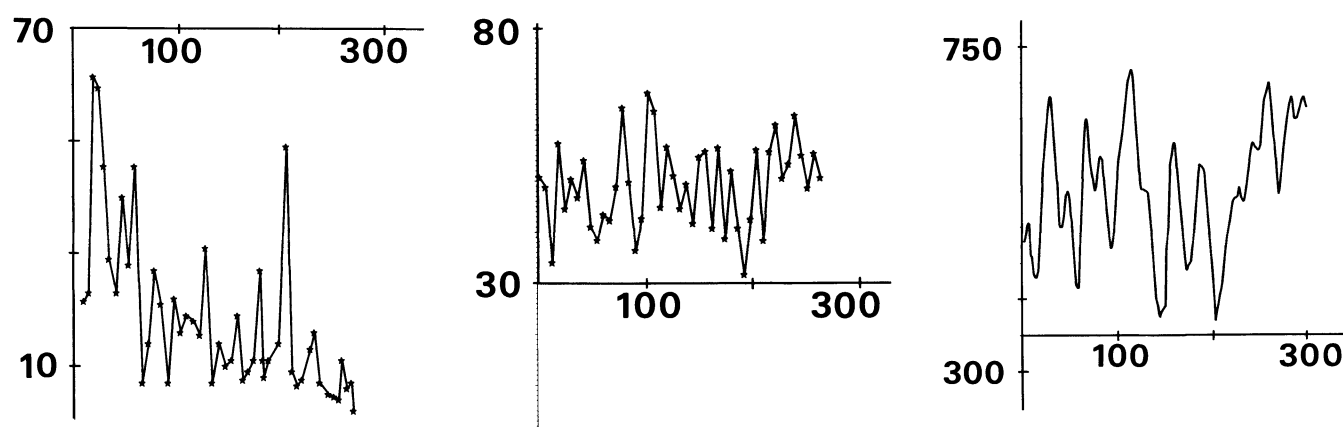


FIGURE 1—A) Percentage of genera becoming extinct in successive time intervals (ordinate) vs. age of end of time interval (abscissa), with 270 million years b.p. designated as 0 on abscissa. (From Raup and Sepkoski, 1986). **B**) Six-fold moving average of a computer-generated time-series. Latter with elements E_i as in Equation 2, with A_0, \dots, A_{29} equal to $.22, .22 \times (.78), .22 \times (.78)^2, \dots, .22(.78)^{29}$, and random inputs 0, varying from 0 to 100. **C**) Ten-fold moving average of a ten-fold moving average of random inputs which may take on values 0 to 9. Each moving average as in Equation 1 of text with A_0 to A_9 each equal to 1. After Slutsky (1937, fig. 2).

the triplet form a fall, given that the first two form a rise. Thus, the latter probability must be $2/3$ (not $1/2$ as Hoffman and others would say). Also, incidentally, the probability of a local maximum involving adjacent tied observations, given that such a tie has occurred, is still $1/3$. Each such pair of tied values belongs to a triplet consisting of the previous data point, the pair, considered as a unit, and the next data point. Thus, by analogy to the non-tie case, the probability of a local maximum is $1/3$.

Hoffman and Ghiold (1985) and Hoffman (1985) use a different model: the random walk. In such a model, the probability of a decrease, given that an increase has occurred, is $1/2$, not $2/3$. Implausibly, if the number of extinctions is markedly high (or low) in a given time interval, the probability is still $1/2$ that it will be even higher (or lower) in the next time interval. But, like many other phenomena, extinctions occurring at random should exhibit regression toward the mean (Tversky and Kahneman, 1974, p. 1126–1127; McKean, 1985, p. 24–25). McKean (1985, p. 25) notes: “In any series of random events clustering around an average or a mean, an extraordinary event . . . is . . . most likely to be followed, just by luck of the draw, by a rather more ordinary event.” So, the random-walk is an inappropriate model for extinctions occurring at random.

The number of turning points (= local maxima or minima) in Raup and Sepkoski’s family and generic data do not differ significantly from values expected under a random model. In a random sequence that mean and the variance of the number of turning points (= maxima or minima) in a series of N values are $2N/3$ and $(16N-29)/90$ [Kendall, 1976, p. 22]; or 29 and 7.3 for Raup and Sepkoski’s 1986 family data, and 31 and 7.8 for their generic data. So, the observed numbers, 21 (family) and 27 (genera) are not significantly different from the expected values. Raup and Sepkoski’s data may be tested for randomness against a cyclic alternative by comparing observed vs. expected numbers of intervals between turning points of length 1, 2, and 3 or greater. Their family data is significant at the .016 level but their generic data is consistent with a random model. (For family data, observed numbers of intervals between turning points of length 1, 2, 3 or greater are 8, 8, and 6; expected values of same are 16.67, 7.15 and 2.52; chi-square = 9.43 is significant at the .016 level. For generic data, observed numbers of intervals between turning points of length 1, 2, 3 or greater are 15, 7, and 5; expected values are 17.92, 7.7 and 2.717; chi-square = 2.46 is not significant. [Kendall, 1976, p. 25; Wallis & Moore, 1941].) Kitchell and Estabrook (1986) also tested the observed number of time intervals between local maxima.

However, their test is not applicable here since it is based on Hoffman and Ghiold’s random walk model (1985). Using a different approach, Raup and Sepkoski (1984; Sepkoski and Raup, 1986a, p. 16–22, 1986b) argue their data differ significantly from a random model.

A MOVING AVERAGE MODEL OF BIOTIC EXTINCTIONS

Introduction

Raup and Sepkoski’s family and genus level plots (e.g., Fig. 1A herein), do indeed appear to mimic a 26-million-year periodicity. But could this close periodicity be due to a summation of effects due to random causes? Using an example taken from Slutsky (1937), I shall first show how a nearly periodic pattern can result from a summation of effects due to random causes. Next I compare the pattern in Slutsky’s example to Raup and Sepkoski’s pattern. Thirdly I ask: if periodicity in biotic extinctions arises from a summation of effects due to random causes, what are these causes? One answer leads to the moving average model outlined in the final part of this section.

Effects of Random Causes and Close Periodicity

The plot shown in Figure 1C exhibits a notable 26-million-year periodicity if

each unit along the x-axis in the figure is taken as 1 m.y. But Figure 1C plots a tenfold moving average of a tenfold moving average of random inputs—of integers 0 to 9 obtained by the People's Commissariat of Finance in drawing numbers for a government lottery loan (Slutzky, 1937, Fig. 2). Figure 1C is taken from a paper by Slutzky entitled "The summation of random causes as a source of cyclic processes." Slutzky shows how moving averages of random input can produce highly cyclical phenomenon. He notes (1937, p. 108), "It seems probable that an especially prominent role is played in nature by the process of moving summation with weights of one kind or another; by this process a coherent series are obtained. . . . For example, let causes . . . x_{i-2} , x_{i-1} , x_i , . . . produce the consequences . . . y_{i-2} , y_{i-1} , y_i , . . . If the influence of causes in retrospective order is expressed by the weights A_0 , A_1 , . . . A_{n-1} , then:

$$y_i = A_0 x_i + A_1 x_{i-1} + \dots + A_{n-1} x_{i-(n-1)},$$

$$y_{i-1} = A_0 x_{i-1} + \dots + A_{n-2} x_{i-(n-1)} + A_{n-1} x_{i-n},$$

$$\dots$$

Slutzky observed that the summation of random causes, rather than producing a perfect cycle, generates a cyclical series which may be quasi-periodic for a number of cycles, than typically becomes disarrayed with a different periodicity taking over for a number of cycles. I have found such a pattern common in moving-average series generated by computer modeling. Kendall (1976, p. 43) gives an expression for the mean distance between peaks as a function of $A_0 - A_{n-1}$.

A reviewer asked for an explanation of why a moving average of a random series may exhibit quasi-periodicity. I can only point out that Kendall (1976, p. 40–41) shows that such a derived series possesses non-vanishing autocorrelations which can be quite high. So while it can be shown mathematically to occur, the periodicity effect is nevertheless surprising. Kendall (1976, p. 41) notes: "The realization that apparently systematic fluctuations can be generated merely as the average of random events came as something of a

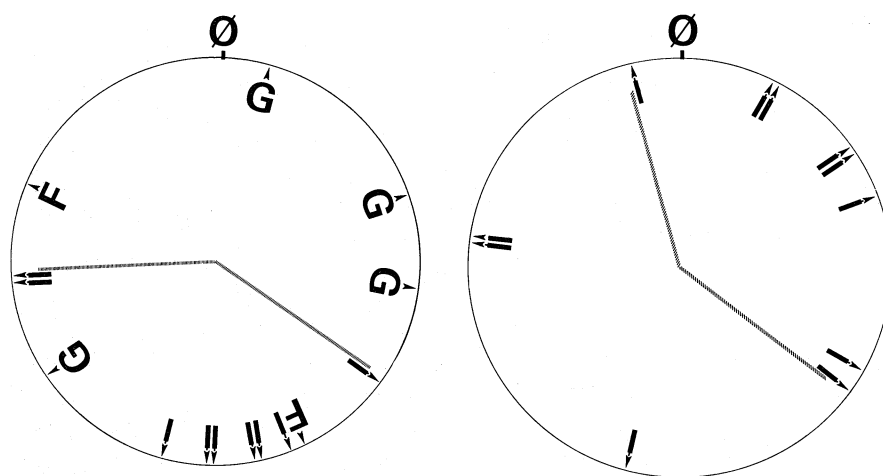


FIGURE 2—A Circular plot of extinction maxima for Raup and Sepkoski's generic data (Fig. 1A) and family data (Raup and Sepkoski, 1986). Extinction times t_i are converted into angles $(360/26) t_i \bmod (360)$, so that 360° of clockwise rotation corresponds to 26 million years. Solitary arrows indicate maxima for both generic and family data; arrows marked G for generic data only; arrows marked F for family data only. **B**) Equivalent plot of maxima for Slutzky's data shown in Figure 1C.

shock when Slutzky and Yule first called attention to the fact [in 1927], especially as Slutzky was able to mimic an actual trade "cycle" of the nineteenth century very closely by the process."

Comparison of Patterns

Lutz (1985) notes that a circular plot is useful in searching for periodicity. Suppose we wish to evaluate whether or not extinction maxima exhibit a periodicity of 26 million years. If times of extinction maxima are plotted on the circumference of a circle, with 360° of clockwise rotation representing 26 million years, then maxima should plot close together on the circumference (Batschelet, 1981, p. 3–30). Figure 2A shows such a plot of extinction peaks of Raup and Sepkoski's family and genus data, and Fig. 2B for Slutzky's data. 10 out of 13 generic peaks and 10 out of 11 family peaks fall within 140° of the arc marked on Figure 2A. Similarly, 8 out of 11 peaks in Slutzky's data fall within the 140° of arc marked on Figure 2B. (Raup and Sepkoski [1986] use a Poisson model to conjecture error bars for their data points on extinction plots, labeling maxima two standard errors or more above neighborhood minima as significant. Using this cutoff, 10 out of 12

"significant" generic peaks and 8 out of 9 family peaks fall within the 140° of arc on Figure 2A. If the same criterion [Sepkoski and Raup, 1986a, p. 9] is applied to Slutzky's data, 6 out of 8 peaks in Fig. 2B fall within 100° of arc.)

The close parallel between Figures 1A and 2A vs. 1C and 2B suggests that Raup and Sepkoski's pattern may result from additive effects of extinction totals behaving as moving averages—or more likely, moving averages of moving averages—of random causes. More precisely, their pattern may be due to moving averages of random causal inputs arising out of ordinary earthbound processes.

Random Causes of Periodicity in Biotic Extinctions

If a moving average sum of random causes brings about the periodicity observed by Raup and Sepkoski, what are these causes?

Family/Genus-Level Patterns: Using A Species-Level Model

Raup and Sepkoski base their conclusions on a summary of extinctions at the family and genus levels. Yet, as noted by Simberloff (1983): "a family is a mysterious unit" (he adds, perhaps unnecessarily, "to an ecologist"). Higher-

level taxa such as families are defined in subjective, various, and nonuniform ways by taxonomists. Indeed, fossil "species"—at least those without living representatives—are no better off. Those occurring in more than a single horizon at a single locality are defined in equally subjective and nonuniform ways. A compilation of extinctions of named fossil species would also count demises of non-equivalent entities. Still, it is possible that family genus-level extinctions closely mimic true biological species extinction patterns in geologic time.

Also, Raup and Sepkoski (1984; 1986) plot percent-extinctions (= total number of families [or genera] becoming extinct over a time interval/family [generic] diversity), rather than total extinctions. However, over the last 250 m.y. family (generic) diversity is largely monotonic showing modest increase in time (Raup and Sepkoski, 1982). So local maxima for the two types of plots should almost coincide and they do (Sepkoski and Raup, 1986A, p. 6–8, fig. 1; Hoffman and Ghiold 1985, table 1). For the purposes of discussion, let us assume that ups and downs on Raup and Sepkoski's family/genus-level plots accurately reflect total extinction patterns of biological species over time for the groups studied.

Extinction of a named fossil species can be terminal or phyletic. Phyletic extinction occurs when a single evolving species lineage changes to such an extent that it would be classified into two or more species by taxonomists. Let us assume further that Raup and Sepkoski's family/genus-level extinctions accurately mimic true terminal extinctions of biologic species. Thus our problem of explaining family/genus-level extinctions reduces to one of explaining species-level terminal extinctions.

The Proposed Model

Apart from the obvious extinctions at the end of the Paleozoic and Mesozoic, could terminal *species* extinctions at a million-year time interval t_i merely reflect number of species originations at time intervals t_{i-m} to t_i ? And could the number of species originations at any million-year time interval approximate a random input owing to multiple environmental causes (Vrba, 1985)? Consider a

cohort of new species originating at a time t_i ; might these merely become extinct in subsequent time intervals at a rate proportional to the number of cohort species remaining. If so, the number of extinction events at a time t_i ($= E_i$) would equal the sum over previous time intervals j of O_j , the number of originations in j , times a weighting factor A_j (A_j should become negligible after say n time intervals). Suppose for instance that, on the average, 10% of those species of a cohort remaining in a time interval become extinct in the interval: then, if O_{i-n} species originate at time t_{i-n} , about $.1 \times O_{i-n}$ of these will become extinct in t_{i-n} , $.1 \times (.9) \times O_{i-n}$ in t_{i-n+1} , $.1 \times (.9)^2 \times O_{i-n}$ in t_{i-n+2} , . . . $.1 \times (.9)^i \times O_{i-n}$ in t_i . Thus, as in equation 1:

$$\begin{aligned} E_i &= A_0 O_i + A_1 O_{i-1} + \dots \\ &\quad + A_{n-1} O_{i-(n-1)}, \\ E_{i-1} &= A_0 O_{i-1} + \dots + \\ &\quad A_{n-2} O_{i-(n-1)} + A_{n-1} O_{i-n}, \\ &\dots \end{aligned}$$

with weights A_0, A_1, \dots, A_{n-1} , equal to $.1, .1 \times (.9), \dots, (.1) \times (.9)^{n-1}$.

Raup and Sepkoski's data are for time intervals of about 6 m.y. If equation 2 above holds for time intervals notably less than 6 m.y., one m.y. intervals, say, then clearly Raup and Sepkoski's data represent moving average sums, over about 6 m.y., of moving average sums. A computer-generated stretch of one such sequence of six-fold moving averages of moving averages of random inputs O_j with weights $.22, .22 \times (.78), .22 \times (.78)^2, \dots, .22 \times (.78)^{29}$ is plotted in Figure 1B. On a plot as in Figure 2 but using a periodicity of 18 time units, 13 out of the 16 peaks in Figure 1B fall within 140° of arc.

J.A. Kitchell and D. Pena (1984) fit a very different stochastic time-series model to Raup & Sepkoski's 1984 data: a model involving autocorrelations rather than moving averages. An extinction value for a time period is "explained" as a linear combination of extinction values at the five previous periods, plus a random input. Their model also produces quasi-periodic cycles (Benton, 1985). They suggest that the logistic equation of species diversification can generate periodicity in extinction values. However, they do not make it clear how

logistic equation might lead to a fifth-order autocorrelation series.

While periodicities in extinction maxima can be explained as above, it does not follow that all extinction maxima reflect moving averages of cohort inputs. Additional information (e.g., peak magnitudes as well as peak positions, evidence of major environmental changes) might lead paleontologists to propose other mechanisms in some cases (for example, the end of the Paleozoic and end of Mesozoic extinctions). The point I wish to make is this: no catastrophic alternative is needed to explain apparent periodicity in peak positions.

CONCLUSIONS

A 26-million-year quasi-periodicity in extinctions over the last 250 m.y. very likely does not arise from extinctions occurring at random. The hypothesis of extinctions occurring at random would be supported if it predicted that extinction maxima should occur on the average every 26 m.y. However, if extinctions are occurring at random, then maxima should occur on the average every 19 million years rather than every 26.

A random extinction model does not fit the observed data well. Yet, quasi-periodicity may not arise from extraterrestrial causes. Perhaps family- and generic-level extinctions closely mimic patterns of terminal extinctions at the species level. Periodicity at the species level can be explained by an earth-based model: The number of species extinctions during a given time interval comprises a moving average sum of cohort components, one for the interval and for each previous time intervals (up to a threshold N). The magnitude of each such component merely reflects the number of species that originated in the time interval plus the time elapsed since the interval; the former may be treated as random input and cohorts follow an exponential pattern of species loss by terminal extinction. Quasi-periodicity arises from the fact that the number of species becoming extinct in successive time intervals approximate a moving average sum of random "causes," or causal components.

It could be so; it could be otherwise. Certainly contrary hypotheses of extra-terrestrial causes (e.g., a Death Star) may be entertained in the spirit of Popper (best hypotheses are highly improbable ones). Yet, to paraphrase Hallam (1984), perhaps we should look first at processes operating on our own planet.

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NOTE: In a recent paper (E. Noma and A.L. Glass, 1987, Mass extinction pattern: result of chance: *Geological Magazine*, v. 124, no. 4, p. 319–322), Noma and Glass independently 1) show that Hoffman's 1985 random walk model is inappropriate and that the average span between extinction maxima assuming extinctions are occurring at random is not $1/4$; 2) apply tests involving the number of turning points and run lengths (described in Kendall, 1976) to Raup and Sepkoski's 1984 family data. They conclude that the observed distribution of run lengths between turning points is consistent with a random model. However, when the same test applied to Raup and Sepkoski's 1986 data (see above) the random model is rejected at the .016 level.

In an important paper (S.M. Stigler and M.J. Wagner, 1987, A Substantial Bias in Nonparametric Tests for Periodicity of Geophysical Data: *Science*, v. 238, p. 940–945), Stigler and Wagner analyze Raup and Sepkoski's principal 1986 test for a 26 m.y. periodicity. They show the test to be significantly biased towards a 26 m.y. periodicity owing to different durations of the stages in the time scale used. They further show that a pseudo-periodicity of 26 m.y. appears, even assuming equal stage durations, when the test is applied to simulated extinction data using a simple two term *moving-average* model. They conclude that "since moving-average processes . . . could arise from measurement problems of the type known to occur with extinction data, this should be considered a likely explanation for the significant fit to an apparent cycle of 26 m.y."



Taffeta phrases, silken terms precise,
Three-piled hyperboles, spruce affectations,
Figures pedantical.

—Shakespeare