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The Relevance of the Background Impact Flux to Cyclic Impact/Mass Extinction Hypotheses

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The belief that mass extinctions of species on Earth have occurred on a ~26- to 33-my cycle is supported by some rather equivocal geological evidence. This has prompted a search for cosmic phenomena that could subject the Earth at regular intervals to bombardment by showers of comets, with resulting damage to the biosphere. A crucial assumption that an impact-driven mass extinction cycle would automatically show up in the geological record is questioned. Might the background flux of random impacts distort the cycle and render it unrecognizable? Computer simulation of the impact bombardment of the Earth over a 250-my period, in which the background impact flux is overlaid by a 26-my comet shower cycle, showed a periodicity in the mass extinction data between 24 and 33 my in ~40–60% of runs, dependent on the magnitude of the background flux chosen, and only ~20–40% indicated the "true" 26-my periodicity. Thus, background impact "noise" can be identified as an additional constraint on cyclic impact/mass extinction hypotheses.

1. INTRODUCTION

The geological record shows that the history of life has been punctuated by a number of discrete events during which a large number of species have become extinct. When of global extent, these biotic crises are known as mass extinctions. The causes most favored by paleontologists to account for mass extinctions are climatic change and alteration in sea level (Stanley 1987), both being mechanisms that might operate over millenia and yet still appear to be near instantaneous events in the geological record.

A challenge to this "gradualist" approach followed the discovery by Alvarez *et al.* (1980) of an anomalous iridium concentration in sediments at the Cretaceous–Palaeogene (K-Pg) boundary that is suggestive of an admixture of extraterrestrial material. The possibility that this excess resulted from the impact of a ~10-km-diameter asteroid which might have caused the K-Pg mass extinction has lead to the revival of the "catastrophist" approach to Earth evolution. Long relegated to the sidelines, catastrophism is once again being discussed seriously (Silver and Schultz 1982).

The debate was given greater impetus by Raup and Sepkoski (1984) who presented evidence that mass extinctions occurred periodically over ~26-my intervals. In another analysis of the extinction data Rampino and Stothers (1984a) identified a mass extinction periodicity of 30 ± 1 my, and a rough periodicity of geological upheavals as a whole of ~33 my (Rampino and Stothers 1984b). Since 1984, there has been much debate concerning the statistical significance of the extinction data, although more recent analyses continue to identify periods of ~26–33 my.

A number of alternative models have been proposed for astronomical mechanisms that might drive an impact/extinction cycle. All rely for lethal effect on the

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"comet shower," a huge influx of comets into the inner Solar System, precipitated by gravitational disturbance of the Sun's comet cloud. A shower of sufficient magnitude might cause several Earth impacts, initiating a global biotic crisis. Hypotheses fall into two classes dependent on the source of comet showers.

1.1. The Standard Oort Cloud

Clube and Napier have linked mass extinctions to the 60-my epicyclic motion of the Sun relative to the galactic plane. They propose a theory of "terrestrial catastrophism" (Napier and Clube 1979, Clube and Napier 1982, 1984a, 1984b) in which the Oort cloud is disturbed every 30-my half-period by encounters with molecular clouds as the Sun crosses the galactic plane. Comets in showers of ~6 my in duration cause mass extinction, either through direct impact with the Earth or by creating a dusty interplanetary environment. Apollo asteroids are seen as being the decayed remnants of a comet shower and thus the population density of these bodies would also exhibit a periodicity. Clube and Napier also point out that the Oort cloud is not likely to be stable, over the lifetime of the Solar System, from gravitational disruption by molecular cloud encounters. They overcome this problem by proposing that interstellar comets can form in molecular clouds (Clube and Napier 1985) and thus an encounter of the Sun with a molecular cloud results in both loss and replenishment of Oort cloud comets. It is this facet of the Clube/Napier hypothesis that causes many astronomers to reject it as too radical.

1.2. The Inner Comet Cloud

The galactic tidal field is of sufficient strength to perturb a continuous flux of "new" Oort cloud comets from $\sim 2.5 \times 10^4$ to 10^5 AU into the inner system. Hills (1981) believes the inner boundary of the Oort cloud therefore to be an observational artifact and has proposed the existence of a more massive inner comet cloud between $\sim 10^3$ and 2×10^4 AU. When disturbed, comets from this inner cloud would enter the planetary system in an intense shower of ~2 my duration causing a number of Earth impacts. The Oort cloud is replenished by the perturbation of a small fraction of these comets into more loosely bound orbits. The anatomy of comet showers originating from the inner cloud has been studied in more detail by Fernandez and Ip (1987) and Hut *et al.* (1987).

The existence of a massive inner comet cloud is still subject to speculation; however, the majority of cyclic extinction hypotheses assumes it to be present.

Davis *et al.* (1984) and Whitmire and Jackson (1984a) proposed the "death star" or "Nemesis" hypothesis, in which an undiscovered low-mass solar companion star follows a highly eccentric orbit with a period of 26 my. At perihelion Nemesis would come close enough to the inner comet cloud to precipitiate a comet shower.

Rampino and Stothers (1984a) link mass extinctions to disturbances of the inner comet cloud by encounters with molecular clouds. As in the Clube/Napier hypothesis, a cyclicity is imposed every ~30 my as the Sun passes through a concentration of molecular clouds in the galactic plane.

If the postulated inner comet cloud extends to the fringes of the planetary system then comet showers might be precipitated from this region. In the "planet X" hypothesis, proposed by Matese and Whitmire (1986), periodic comet showers are precipitated by the precession of the orbit of a hypothetical tenth planet through a primordial disk of comets they believe to lie beyond Neptune.

All of the above hypotheses have their distinct difficulties, although none have been so far totally disproved. For instance, it is not certain whether the orbit of Nemesis would be stable or that the star could act as a reliable "clock" (Clube and Napier 1984c, Torbett and Smoluchowski 1984, Hut 1984). Galactic regulation of comet showers may not appear if the concentration of molecular clouds close to the galactic plane is not sufficient to produce a strong periodicity (Thaddeus and Chanan 1985). The biological reality of the mass extinctions themselves has also come into question (Patterson and Smith 1987, Smith 1988); periodicity in fish and echinoderm family extinctions appears to be a taxonomic artifact produced by sampling errors. Recent papers detailing the competing arguments are found in Smoluchowski *et al.* (1986).

There is, however, another potential problem common to all cyclic impact/mass extinction hypotheses that has been largely neglected. This is the obscuring role of random impact "noise." Cyclical impact models proceed on the implicit assumption that the background flux of Earth impacts has been low enough for major irregularities in the periodicity of extinctions not to have occurred. This assumption may not be well founded, for if the background flux is significant, and cannot be linked to mass extinctions, then both the impact/mass extinction hypotheses and the validity of apparent periodicities in the geological record must be reexamined.

The following examination of the problem concentrates on those hypotheses which require the presence of an inner comet cloud.

2. THE BACKGROUND OR RANDOM IMPACT FLUX

The terrestrial cratering rate in the Phanerzoic Eon for craters of diameter >10 km has been estimated by Grieve and Dence (1979), from a study of craters on the North American and East European cratons, to be $\sim 1.4 \times 10^{-14}$ km^{-2} year^{-1}. For craters with $D > \sim 20$ km the cumulative abundance follows a power law $N\ (\geq D) \propto D^{-2}$ which is in good agreement with the size frequency distribution of lunar craters.

Converting the formula of Shoemaker *et al.* (1979) from kilotons of TNT equivalent to Joules, and taking into account crater collapse, the diameter in kilometers of an impact crater on the Earth scales with energy approximately as

$$D \simeq 1.96 \times 10^{-5}(E_K)^{1/3.4}, \qquad (1)$$

where E_K is the kinetic energy of impact in Joules. Taking a typical missile density of 2380 kg m^{-3} and impact velocity of 20 km sec^{-1}, then a missile of diameter $d = 1$ km will create a crater of $D = 19.4$ km. The infall rate for bodies of $d \geq 1$ km is therefore $\simeq 1.9$ my^{-1}.

Observations of Earth-crossing (Apollo and Aten) asteroids lead to higher estimates for impact and cratering rates. Shoemaker *et al.* (1979) estimate the impact flux for the current population of Earth-crossing asteroids to be $N(d \geq 1\text{ km}) \simeq 3.5$ my^{-1}, with a cratering rate of $N(D \geq 10\text{ km}) \simeq 2.3 \times 10^{-14}$ km^{-2} year^{-1}. Steel and Baggeley (1985) have obtained an impact rate of $N(d \geq 1\text{ km}) \simeq 6$ my^{-1}, although removing four Apollo asteroids from their sample that they believed might have introduced a bias into their results, reduces the estimate to $N(d \geq 1\text{ km}) \simeq 4$ my^{-1}. These higher impact rates do not necessarily conflict with the production of craters, as estimates for the terrestrial cratering rate from studies of surviving craters vary. There is good agreement between the cratering estimate derived from asteroid observations and the cratering rate of $N(D \geq 10\text{ km}) \simeq 2.2 \times 10^{-14}$ km^{-2} year^{-1} estimated by Shoemaker (1977) from impact structures in North America.

Steel and Baggeley (1985) also derived the mean lifetime for Earth-crossing asteroids against collision, with any of the terrestrial planets, to be $\sim 2.5 \times 10^7$ years for the Aten and $\sim 10^8$ years for the Apollo asteroids. However, since the number of Aten asteroids is thought to be considerably fewer than the number of Apollos, each class contributes about equally to the flux of asteroids impacting the Earth. Since these bodies have a finite lifetime, a continued replenishment mechanism must be invoked to explain their continued existence. The population may be maintained in a quasi-steady state by asteroids perturbed from the main belt and the decay of short period comets (see Shoemaker *et al.* 1979 for discussion), or it may be replenished at intervals by the remnants of a comet shower. The three Apollo asteroids discovered by IRAS all show characteristics that suggest they may be burnt out comet nuclei (Davies 1986).

The Earth is also subjected to bombardment by the steady-state flux of long-period comets perturbed from the Oort cloud by both the galactic tidal field and passing stars (Morris and Muller 1986, Heisler and Tremaine 1986, Heisler *et al.* 1987). However, Weissman (1982) has estimated that the rate of such impacts is only about one-tenth the asteroidal impact frequency. Thus, long-period comets are of little significance and can be disregarded for the purposes of this paper without committing serious error.

An impact rate of one asteroid hitting the Earth every 250,000 years seems high; however, this figure is for asteroids as small as ~1 km in diameter. The impact of a body of 10 km or greater, such as that envisaged by Alvarez *et al.* (1980) should occur much less frequently and would depend critically on the cumulative asteroidal diameter frequency distribution. Since $E_K \propto d^3$ and $D \propto E_K^{1/3.4}$ then $D \propto d^{0.882}$. Since the diameter frequency distribution for craters is $N(\geq D) \propto D^{-2}$ then the diameter frequency distribution for missiles $\simeq N(\geq d) \propto d^{-1.77}$. Thus from the approximate scaling just discussed, we might expect one impact producing a crater of D = 150 km every ~20–30 my and one crater of D = 200 km every ~34–55 my.

However, on the assumption that the inner comet cloud exists, the random impact flux is not expected to be just a combination of background fluxes of Earth-crossing asteroids and the occasional Oort cloud comet. It is possible for comet showers from the inner comet cloud to be precipitated on a random basis by close encounters with stars and interstellar gas clouds. Hills (1981) has studied the former of these two processes and calculates that a foreign star will pass within 10,000 AU of the Sun every ~4.4×10^7 years and with 3000 AU every ~4.9×10^8 years. He estimates that a 3000-AU close encounter will trigger an intense comet shower with a duration ~6.6×10^5 years, during which from 10 to 200 comets will strike the Earth, an infall rate ~4–76 times the background impact rate of Earth-crossing asteroids. Fernandez and Ip (1987) have also examined random comet showers produced by the perturbations of passing stars. Although their estimates for the efficiency of a number of processes differs, such as the rate of stellar encounters and the filling of the cometary loss cone, their combined model gives results that are not dissimilar to those of Hills.

Morris and Muller (1986) have examined the effectiveness of the tidal field of interstellar gas clouds at precipitating comet showers. On the assumption that an intense shower can be created by the perturbation of comets from orbits with semimajor axes of 10,000 AU, they conclude that clouds of relatively high density $>10^3$ atoms cm^{-3} are necessary. Encounters with these clouds are rare and would occur at intervals of ~4 $\times 10^8$ years. Over this time period about 10 stars would be expected to pass within 10,000 AU of the Sun; thus, in comparison with random stellar encounters, random gas cloud encounters would only precipitate about one-tenth the number of comet showers of a given intensity.

3. MODELING AN EARTH IMPACT CHRONOLOGY

To determine the effect of background impacts upon a cometary impact/mass extinction cycle, a simple Monte Carlo simulation of an Earth impact chronology has been written. The data analyzed by Raup and Sepkoski (1984) (hereafter R & S) extends over 250 my and so the model is capable of simulating at least this time span. All the major random impact processes that would occur, given the existence of an inner comet cloud, are included within this model of the background impact flux. These are (i) the impact flux of Earth-crossing asteroids; (ii) stellar-induced comet showers; (iii) molecular cloud-induced comet showers. The simulation has been run both with and without a superimposed comet shower cycle to look for quasi-periodicities in the background impact flux, to study random distortion of mass extinction periodicities and to compare cratering rates. A description of the program algorithm and embodied assumptions follows.

3.1. Impact Rates

3.1.1. Earth-crossing asteroids. Asteroidal background impact rates were discussed in Section 2., since uncertainty in the figures is still very great, two rates were chosen, a high figure of $N(d \geq 1\text{ km}) = 4\text{ my}^{-1}$ based on Earth-crossing asteroid data, and a lower figure of $N(d \geq 1\text{ km}) = 2\text{ my}^{-1}$ that is more in line with the estimated terrestrial cratering rate. Thus, to allow for an average of one impact per iteration the basic time step is taken as either $S = 0.25$ my or $S = 0.5$ my. During a comet shower when the impact rate is enhanced, the time step is reduced to maintain the same resolution of impact events. Between 0 and 5 impacts were allowed for each time step; probabilities are assumed to follow a binomial distribution. An interval of 20 my after the last comet shower is considered sufficient to deplete the population of Aten asteroids (Steel and Baggeley 1985) and the asteroidal background impact rate is halved. The next comet shower is assumed to replenish this population and the original impact rate is restored to its former value. Thus the asteroidal impact flux, as modeled here, is partially modulated by the occurrence of comet showers. Considering the magnitude of uncertainty, this is a justifiable compromise between the views that Earth-crossing asteroids originate from the main belt and are the remains of extinct comets.

3.1.2. Random comet showers. The Hills (1981) model of the inner comet cloud has been adopted, in which passing stars provide the primary random perturbing agency. The mean time T_s between encounters in which a star passes within a distance a_e of the Sun is given by

$$T_s = (\pi a_e^2 n_s V_s)^{-1}, \tag{2}$$

where n_s is the number of stars per unit volume in the solar neighborhood and V_s is the average velocity of passing stars. Here, $n_s = 0.1\text{ pc}^{-3}$ and $V_s = 30\text{ km sec}^{-1}$. Thus, for $a_e = 10{,}000$ AU, $T_s = 44$ my.

During a comet shower caused by a passing star, the fraction of comets with perihelia less than q is

$$N/N_0 \simeq \frac{2q}{a}\left(1 - \frac{q}{2a}\right), \tag{3}$$

where N_0 is the number of comets in the inner cloud and a is the semimajor axis of the innermost comets affected in AU (for stellar passages, encounter times are short so $a \equiv a_e$). The population of comets within the inner cloud is very uncertain since there is no way to "directly" observe this region like there is for the Oort cloud; here we take $N_0 \sim 10^{13}$. For comets intersecting the orbit of the Earth, $q = 1$ AU and Eq. (3) simplifies to $N_{\oplus}/N_0 \simeq 2q/a$. This equation should not be viewed as precise, since it is dependent on the unknown distribution of comets within the inner cloud. It does, however, probably represent a reasonable estimate to within a factor of order unity.

Hills (1981) estimated the duration of a comet shower to be approximately equal to four cometary orbital periods. Thus the duration of maximum shower intensity T_ι in years is

$$T_\iota = 4a^{1.5}. \tag{4}$$

Hut *et al.* (1987) have estimated that a typical comet would make an average of ~8.6 returns to the planetary region, having an average lifetime of 0.48 my before being destroyed or ejected on a hyperbolic orbit: a further illustration of the uncertainties inherent in an analysis of this type.

The number of comets expected to hit the Earth has been estimated by Davis *et al.* (1984). The probability that a 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}. If each comet makes an average of four trips to the inner Solar System, then there are a total of eight opportunities to hit the Earth. The approximate number of impacts resulting from a comet shower is, therefore,

$$N_{\text{hits}} \simeq 1.28 \times 10^{-8} N_{\oplus}. \qquad (5)$$

This estimate for the number of Earth impacts lies between previous upper and lower estimates. For instance, where a_e = 3000 AU, Eq. (5) gives 85 impacts, which compares favorably with the range of 10 to 200 impacts obtained by Hills (1981). Since T_ι, for the range of cometary semimajor axes of interest, is always ≪6 my, the average age of a stratigraphic stage, the assumption was made that showering comets were distributed evenly over T_ι. This is a reasonable simplification, for although it is possible to simulate the detailed microstructure of a comet shower, it would not be possible to date any extinction caused by the shower with a similar degree of precision.

Numerical data for comet showers are summarized in Table I. Since the impact rate for a shower where a =10,000 AU is estimated as only 60% greater than that of the asteroidal impact rate, it was decided to make this value of a the upper limit for comet showers and Earth-crossing asteroid replenishment.

Comet showers precipitated by randomly encountered interstellar clouds are also included, even though they are likely to be less common than stellar-induced showers. Talbot and Newman (1977) have found that encounters between the Sun and interstellar clouds can be approximated by a broken power law:

$$N_e(\geq D) = 10(D/10^3)^{-\alpha}, \qquad (6)$$

where the function N_e ($\geq D$) is the number of encounters between the Sun and clouds of number density $\geq D$, D is the number density in atoms cm^{-3}, and the exponent α has the value 0.9 for $D < 10^3$ cm^{-3} and the value 2.3 for $D > 10^3$ cm^{-3}.

Morris and Muller (1986) have shown that for perturbations by interstellar clouds, the lowest value of a in AU for showering comets is dependent on cloud density:

$$a \simeq 6 \times 10^5 R^{-1/2} D^{-1/2}, \qquad (7)$$

where R is the cloud radius, here represented by an average value of 5 pc.

3.2. Missile Parameters

The mass and velocity distribution of impacting missiles are critical parameters as an impact would have to produce adverse ecological effects worldwide to initiate a mass extinction.

A simple way to represent missile diameter frequency distribution is by a power

TABLE I

NUMERICAL DATA

a_e	T_s (10^6 years)	N_{hits}	T_ι (10^6 years)	Step size (10^6 years)	Impact rate (my^{-1})	Ratio of shower rate to asteroid rate
2,000	1100	128	0.36	2.8	358	89
3,000	490	85	0.66	7.7	129	32
4,000	280	64	1.0	16	63	15
5,000	180	51	1.4	28	36	9
6,000	120	43	1.9	43	23	5.8
7,000	90	37	2.3	63	16	3.9
8,000	69	32	2.9	89	11	2.8
9,000	54	28	3.4	122	8	2.0
10,000	44	26	4.0	154	6.5	1.6

law. However, for asteroids and comets this function can only be estimated between wide limits of uncertainty as observational data is scant. Thus, the missile diameter frequency index $N(\geq d) \propto d^{-1.77}$, estimated in Section 2, was chosen.

Following Shoemaker *et al.* (1979), Earth-crossing asteroids are assumed to be 50% S-type, with a material density of 3500 kg m^{-3}, and 50% C-type, with a material density of 2500 kg m^{-3}. Correcting for about 32% combined internal and external void space gives overall densities of 2380 and 1700 kg m^{-3}, respectively. If comet P/Halley is typical, then the density of comets in general probably lies between 100 and 400 kg m^{-3} (Mendis 1986). A value of 300 kg m^{-3} is used here based upon an estimate of Halley's density derived from the comet's rotational angular momentum (Ferrin 1988).

Impact velocities were assumed to be 18 km sec^{-1} for Earth-crossing asteroids and 40 km sec^{-1} for the 50% of comets in direct orbits (Hartmann 1977). Impact velocities can be very high, however, if there is a head-on collision with a comet in a retrograde orbit. Therefore, 50% of comets were assumed to impact at 68 km sec^{-1}.

3.3. Mass Extinctions

The kinetic energy of impacts is chosen as the determining parameter of mass extinction events.

Alvarez *et al.* (1980) have estimated that the K-Pg extinction was caused by the impact of a body 10 ± 4 km across. A 10-km-diameter C-type asteroid with a density of 1700 kg m^{-3} and striking at 18 km sec^{-1} liberates an impact energy $E_K = 1.44 \times 10^{23}$ J or $\sim 3 \times 10^7$ Mt. A number of smaller impacts, occurring over a relatively short space of time, and distributed widely over the Earth's surface, might combine in their adverse environmental effects to cause a stepwise global mass extinction which would appear nearly instantaneous in the geological record (Hut *et al.* 1987). However, whether the precipitating event is a single impact or a number of impacts, the minimum necessary total impact energy is unknown. Thus, it was decided to take the energy of the proposed K-Pg impact, released over a maximum of 1 my as the minimum threshold value to cause a global mass extinction. This assumption of an energy threshold for mass extinctions is roughly in line with similar discussions in Berger *et al.* (1985).

The dating of extinction events is fraught with uncertainty. The finest division of the geological column is into stratigraphic stages which, for the Mezozoic through Cenozoic interval, have a mean duration of ~6 my. Although this is a relatively short space of time, R & S have pointed out that is impossible to adequately resolve extinction events less than ~12 my apart. This is because extinctions are dated, by convention, at the end of the stage in which they occur, and at least one stage must lie between events for them to be recognized as separate. A number of arbitrary methods of resolving mass extinctions to within 12 my were tested during the development of the model. None of them, however, was entirely satisfactory, as it was found that the detection of a statistically significant cycle from a simulated extinction sequence was to some degree dependent on the method of resolution. Possibly the best way to simulate the resolution of mass extinctions is to use the geologic time scale itself. This can of course be criticized by pointing out that the mass extinctions came first and the geologic column was "invented" later, rather than vice versa. However, of the 39 stages considered by R & S, only 12 end in mass extinctions and so the structure of the time scale is not strongly influenced by them.

A time scale of 46 stages from Harland *et al.* (1982) is used here. After an extinction sequence has been generated, mass extinctions are dated at the end of the stages in which they occur, in line with geological convention. When two extinction events occur in successive stages, one mass extinction is resolved at the end of the second stage. (This is similar to the situation in the late Permian where a mass extinction is dated at the end of the Tatarian stage, but probably started in the preceding Kazanian stage.) When three extinction events occur in successive stages, mass extinctions are resolved at the terminal dates of the first and third. The minimum separation of extinction events within the simulation is, therefore, two stage lengths, between ~3 and 22 my, averaging at ~12 my.

3.4. *Statistical Testing of the Extinction Series*

Running the simulation produces a series of resolved extinction events. Manual inspection of such data is often not sufficient to reveal the presence of a periodicity, or its statistical significance. The nonparametric testing method of R & S has thus been used to analyze the data. A perfectly periodic impulse function of a given cycle length is superimposed over the extinction series in the best-fit position. The discrepancy between each extinction event and the nearest predicted peak from the impulse function is recorded as an error. The standard deviation of these errors, the SDE, can be used as a gauge of goodness of fit. An SDE of zero thus represents a perfect match of "real" and predicted impulses.

To obtain an SDE value for a given cycle at which their extinction data was considered to exhibit a periodicity, R & S performed 500 Monte Carlo simulations in which 12 extinction impulses were randomly scattered over a 250-my time scale. If the SDE calculated for the geological extinction data was less than 99% of the SDE computed from the random data, a statistically significant periodicity was assumed. The simulation presented here only investigates cycles between 24 and 33 my, but since it produces its own extinction series, with a varying number of impulses, a greater random data base is needed for comparison. For each of 4–18 extinction impulses, 1000 Monte Carlo simulations were run and the <99% SDE threshold values for a given cycle were calculated.

4. RESULTS

4.1. *Simulation of the Background Impact Flux*

Study of the background impact flux as an isolated process is important before investigating its effect on a periodic comet shower cycle. It is essential to determine whether it is likely that this flux may deviate from a purely random process and exhibit a tendency toward periodic behavior. The behavior of the background impact component of the model has, therefore, been investigated by analysis of data from two sets of 1000 runs each for timesteps of 0.5 and 0.25 my.

The results of the simulations are displayed in Table II. Salient characteristics of a sample run where $S = 0.5$ my are shown in Fig. 1. Ten "lethal events" occurred over 250 my, with seven mass extinction events being resolved. Even though two peaks are missing, calculations of SDE for cycles between 24 and 33 my demonstrate a particularly good fit of a 30-my cycle to the simulated extinction data, with a SDE of 4.31 that is lower than the <99% threshold value. The extinction data for this run can

TABLE II

RANDOM IMPACTS ONLY

Mean numerical value	S 0.5 my	S 0.25 my
Total impacts	581.4	914.9
Comet impacts	247.0	245.8
Asteroid impacts	334.4	669.1
Lethal events	11.0	17.7
Resolved mass extinctions	7.43	10.5
Resolution fraction	0.67	0.59
Total comet showers	5.91	5.92
Lethal showers	2.82	2.96
Shower lethality fraction	0.48	0.50
No. of quasi-periodic runs	102	94
Total No. of quasi-periods	148	148

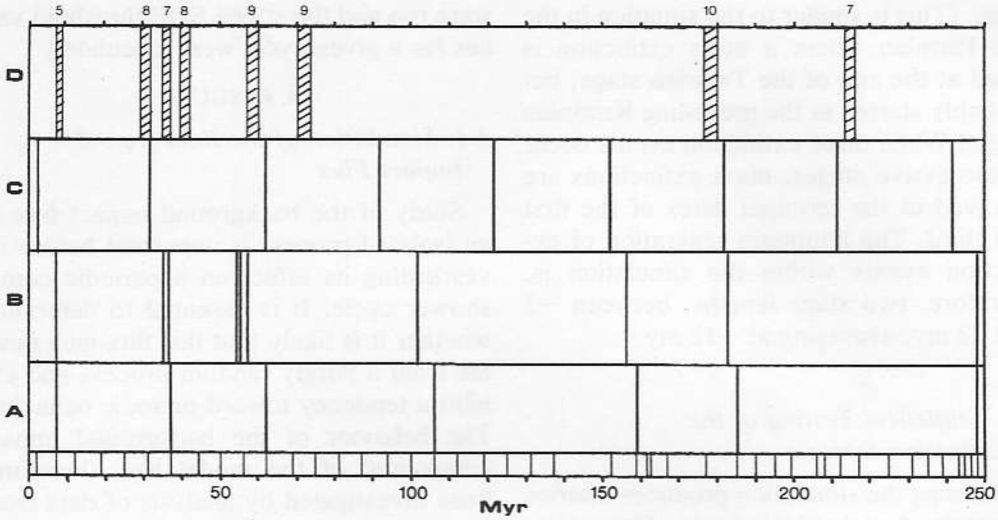

FIG. 1. Salient characteristics of a sample run where $S = 0.5$ my. Elapsed time, in million years from the start of the simulation (250 my B.P.), and the divisions of the geologic time scale are on the horizontal axis. Row A displays the resolved mass extinction events, row B shows the total number of lethal events, and the impulses for a best fit 30-my cycle are shown in row C. The occurrence of comet showers is displayed in row D along with specific values of a in units of 1000 AU.

therefore be stated to possess a quasi-periodicity at 30 my.

Table II shows that ~100 quasi-periodic runs are produced from each run set; this is what would be expected, testing 10 cycles between 24 and 33 my 100 times, if the model background flux is behaving randomly. A slightly higher number of significant quasi-periods were detected as some extinction sequences could be well fitted by a pair or triplet of successive cycles. The total number of quasi-periods per cycle, for both run sets, are displayed in Table III; none of the numbers shown deviate significantly from the approximate expectation of ~10–20 quasi-periods per cycle. No abnormal tendency to produce quasi-periodicities between 24 and 33 my is observed.

It is interesting to compare simulated background flux impact rates with the terrestrial cratering rate. The $S = 0.5$ my run set produces an average impact rate by missiles of $d \geq 1$ km of 4.55×10^{-15} km^{-2} year^{-1}. The $S = 0.25$ my run set gives an average impact rate of 7.16×10^{-15} km^{-2} year^{-1}. Converting these figures to the production rate of craters of $D \geq 10$ km, gives rates of $\sim 1.7 \times 10^{-14}$ and $\sim 2.7 \times 10^{-14}$ km^{-2} year^{-1} which are similar to the cratering rates calculated by Grieve and Dence (1979) and Shoemaker (1977), respectively. Thus, although the production of impact craters can be explained entirely by the cur-

TABLE III

RANDOM IMPACTS ONLY

Cycle	No. of quasi-periods	
	S = 0.5 my	S = 0.25 my
24	10	8
25	16	16
26	17	19
27	18	16
28	21	15
29	18	18
30	19	21
31	9	18
32	12	9
33	8	8

rent asteroidal impact flux, it can also be accounted for by a model which includes random comet showers. This model of the background impact flux, therefore, appears a reasonable one over which to superimpose a comet shower cycle.

4.2. *Simulation of a Comet Shower Cycle*

A 26-my perfectly periodic comet shower cycle has been chosen for detailed study, for reasons of comparison with the data of R & S and the Nemesis hypothesis of Davis *et al.* (1984). If a mass extinction cycle is to be driven by comet showers, then each shower must have a high probability of being "lethal" and leaving its mark in the geological record. As can be seen from Table II, only about half of the modeled random comet showers cause a mass extinction event. This is because the majority of showers are minor, the loss cone being filled for comets of $a > 7000$ AU. A more substantial disturbance of the inner Oort cloud is required. Since Nemesis would be moving more slowly than a passing star, relative to the comet cloud, it would disturb comets to a distance of less than its pericenter. Hills (1984) has estimated that it is necessary to disturb comets with $a \sim 4000$ AU in order to cause a shower of sufficient intensity to cause mass extinctions. He estimates that the loss cone could be filled to this distance by a Nemesis of 0.05 $M_{\odot}$, pericenter $<1.04 \times 10^4$ AU, and orbital eccentricity 0.88.

A 26-my cycle of comet showers of $a =$ 4000 AU has, therefore, been simulated. To accord with the best fit postion of the cycle found by R & S to their extinction data, the first shower was initiated 2 my after the start of each simulation. Two run sets were chosen, with differing intensities of background impact flux: 1000 runs at $S = 0.5$ my and $S = 0.25$ my were performed and the relevant data are presented in Tables IV and V.

Characteristics of a sample run where $S = 0.5$ my are shown in Fig. 2. Thirteen extinction peaks were resolved from a total of 17 lethal events. The extinction data were found to exhibit a periodicity, at 26 my with an SDE of 4.88, so the comet shower cycle is showing through as a mass extinction cycle at the 99% significance level. The effects of background impact noise are apparent, however, as the best-fit 26-my cycle has been displaced 7 my from the shower cycle. Row B of Fig. 2 makes it apparent that if the resolution of lethal events was better, the 26-my periodicity would not have been recorded for this run at all.

TABLE IV

26-my Comet Shower Cycle

Mean numerical value	S	
	0.5 my	0.25 my
Total impacts	1286.9	1703.6
Comet impacts	863.9	854.7
Asteroid impacts	422.9	848.9
Lethal events	22.3	30.3
Resolved mass extinctions	13.6	15.6
Resolution fraction	0.61	0.51
Total Comet showers	15.2	15.1
Lethal showers	12.0	12.1
Shower lethality fraction	0.79	0.80
No. of periodic runs	557	375
Total No. of periods	994	568

Another run, with $S = 0.5$, is shown in Fig. 3. Here, 19 lethal events have occurred, 12 of them being resolved as mass extinctions. Row C shows the best fit for a 26-my cycle which has an SDE of 6.15. In this case, therefore, background impact noise, and the fact that the 184- my and 210-my comet showers were not lethal, have combined to obscure the shower cycle entirely.

If the effect of the background flux is to totally obscure the 26-my cycle and to randomize extinction peaks produced, then only about 100 periodic runs would be expected. If no obscuration occurs then extinction data from every run would be expected to show a strong 26-my periodicity.

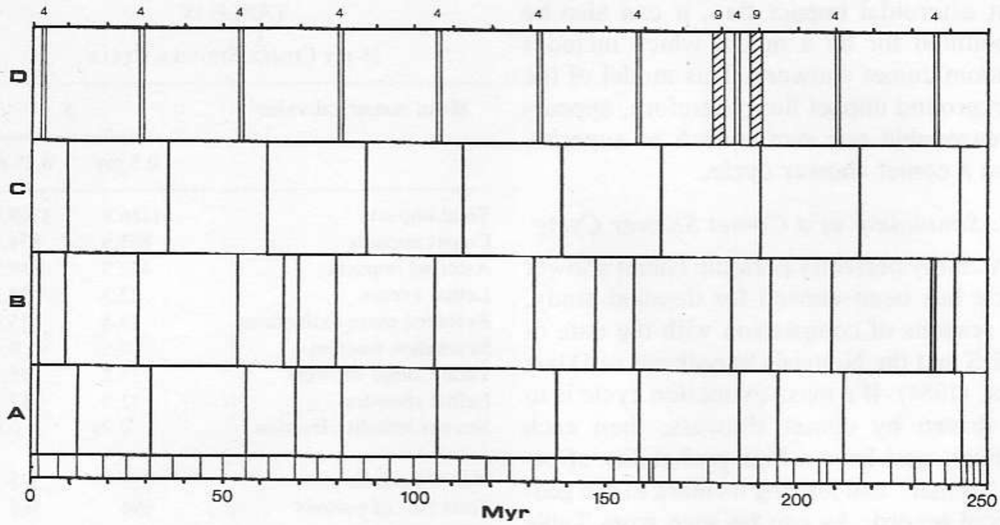

FIG. 2. Salient characteristics of a sample run where $S = 0.5$ my and $a = 4000$ AU. A 26-my comet shower cycle, starting at 2 my, is imposed. In row D, comet showers without diagonal hatching represent those belonging to the cycle. The best-fit impulse function in row C is that of a 26-my cycle.

The results in Tables IV and V show that the situation, as modeled, lies somewhere in between. Sufficient periodicities were found to demonstrate that obscuration of the shower cycle is not certain in every case. As expected, the $S = 0.5$ my runs, where the asteroidal background flux is set at a low value, allowed the detection of the largest number of cycles. Even so, only 56% of runs produced an extinction sequence with a significant periodicity betwen 24 and 33 my; 38% of runs showed the true 26-my cycle. For the higher background impact rate, 38% of runs produced a periodic extinction sequence, the 26-my cycle being detectable in only 19% of runs. It is clear that the background impact flux is not totally randomizing all extinction sequences. However, there is nonetheless a high probability (~60–80%) of random impacts introducing sufficient noise into a cyclic extinction sequence to either obscure it completely or to shift the cycle detected by −1 to +2 my. A similar series of runs, incorporating a 30-my comet shower cycle, gave nearly identical results, demonstrating that background impact noise is also relevant to the Rampino and Stothers (1984a, 1984b) hypothesis where comet showers are regulated by the Sun's motion through the galaxy.

TABLE V

26-my COMET SHOWER CYCLE

Cycle	No. of periods $S = 0.5$ my	No. of periods $S = 0.25$ my
24	5	9
25	145	53
26	376	194
27	370	229
28	62	55
29	3	4
30	8	9
31	13	8
32	6	4
33	6	3

The cycles investigated above were assumed to be perfectly periodic. However, Hut (1984) has shown that, for the past 250 my, the period of revolution of a putative Nemesis would have varied by ~10–20%

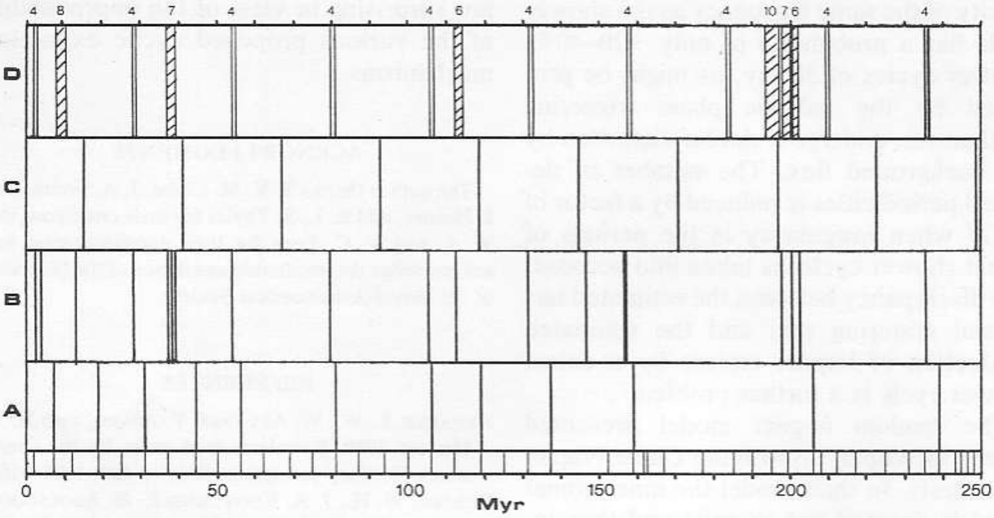

FIG. 3. Salient characteristics of a sample run where $S = 0.5$ my and $a = 4000$ AU. A 26-my comet shower cycle, starting at 2 my, is imposed. No cycle between 24 and 33 my fits the extinction data well; the best fit of a 26-my cycle is shown in row C.

because of perturbations by passing stars and the galactic tidal field. To investigate the consequences of this effect on the number of detected mass extinction cycles, two comet shower cycles were simulated: 26 and 30 my. The date of each impulse was randomized uniformly between ± 2 and ± 4 my, respectively, superimposed over an $S = 0.5$-my background impact flux. The results of 200 runs of the 26 ± 2 my set were that 45% of runs show a periodic extinction sequence and 28% of runs revealed the average 26-my cycle. Only 41% of the 200 runs of the 30 ± 4 my set showed a periodicity, the 30-my cycle being significant in 25% of runs. These results are possibly more realistic than those obtained from runs in which the imposed cycle was perfectly periodic, although they differ by only a factor of ~ 1.25.

Mean crater production rates for $D \geq 10$ km are $\sim 3.8 \times 10^{-14}$ km^{-2} year^{-1} for the $S = 0.5$ my run sets and $\sim 5 \times 10^{-14}$ km^{-2} year^{-1} for $S = 0.25$ my. These rates range from ~ 1.7 to 3.6 times more than the estimates of the terrestrial cratering rate already mentioned. The density of impact craters discovered on the Earth does not seem sufficient to account for the number of cometary impacts expected in this cyclic comet shower scenario.

5. CONCLUSIONS

All the proposed cyclical extinction mechanisms have their difficulties but none has yet been totally rejected (Smoluchowski *et al.* 1986). A model of background impact "noise" has been applied here to the class of cyclic impact/mass extinction hypotheses that require the existence of an inner comet cloud. The computation of simulated Earth impact chronologies identifies significant further constraints on such theories and renders them more improbable, but does not rule them out completely. Distortion of the extinction record by background impacts is a significant factor that has been hitherto largely disregarded (see the replies by Muller *et al.* (1984) and Whitmire and Jackson (1984b) to Weissman (1984)). The probability of a simulated 250-my impact history showing a mass extinction periodicity within a few million years of an imposed perfectly periodic 26-my comet shower cycle is ~ 40–60%. The occurrence of a periodicity of the same frequency as the shower cycle has a probability of only ~20–40%. Shower cycles of 30 my, as might be produced by the galactic plane triggering mechanism, undergo a similar distortion by the background flux. The number of detected periodicities is reduced by a factor of ~1.25 when irregularity in the periods of comet shower cycles is taken into account. The discrepancy between the estimated terrestrial cratering rate and the estimated production of impact craters by a comet shower cycle is a further problem.

The random impact model presented here is incompatible with the Clube/Napier hypothesis. In their model the inner comet cloud is deemed not to exist and thus intense, random, stellar-induced comet showers would not occur. Moreover, the flux of Earth-crossing asteroids is expected to exhibit a strong periodicity in step with the comet shower cycle. Thus, it would seem that an impact cycle generated by the Clube/Napier mechanism would be less vulnerable to random impact distortion, although by no means completely so.

Study of the Earth impact probabilities of Earth-crossing asteroids shows that it is likely that there have been several encounters of large bodies with the Earth over the last 250 my, with inevitable deleterious consequences to the biosphere. The case for impacts playing a part in the K-Pg mass extinction remains strong. A cyclic impact/extinction scenario, however, requires acceptance of a number of improbable processes and the current state of the debate renders it impossible to draw any definite conclusions. This has not prevented many scientists from expressing opinions. It is the opinion of the present author that, on the basis of the available evidence, mass extinctions are not linked by an externally driven cycle. Mass extinctions are difficult to identify and resolve, and correlation depends on which geological time scale is used. Dating of most of these events is still not precise enough to be confident that a periodicity actually exists. This is perhaps not surprising in view of the improbability of the various proposed cyclic extinction mechanisms.

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