THE “SHIVA HYPOTHESIS”: IMPACTS, MASS EXTINCTIONS, AND THE GALAXY

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Abstract. The “Shiva Hypothesis”, in which recurrent, cyclical mass extinctions of life on Earth result from impacts of comets or asteroids, provides a possible unification of important processes in astrophysics, planetary geology, and the history of life. Collisions with Earth-crossing asteroids and comets $\geq$ a few km in diameter are calculated to produce widespread environmental disasters (dust clouds, wildfires), and occur with the proper frequency to account for the record of five major mass extinctions (from $\geq 10^8$ Mt TNT impacts) and $\sim$ 20 minor mass extinctions (from 10^7-10^8 Mt impacts) recorded in the past 540 million years. Recent studies of a number of extinctions show evidence of severe environmental disturbances and mass mortality consistent with the expected after-effects (dust clouds, wildfires) of catastrophic impacts. At least six cases of features generally considered diagnostic of large impacts (e.g., large impact craters, layers with high platinum-group elements, shock-related minerals, and/or microtektites) are known at or close to extinction-event boundaries. Six additional cases of elevated iridium levels at or near extinction boundaries are of the amplitude that might be expected from collision of relatively low-Ir objects such as comets.

The records of cratering and mass extinction show a correlation, and might be explained by a combination of periodic and stochastic impactors. The mass extinction record shows evidence for a periodic component of about 26 to 30 Myr, and an $\sim$ 30 Myr periodic component has been detected in impact craters by some workers, with recent pulses of impacts in the last 2-3 million years, and at $\sim$ 35, 65, and 95 million years ago. A cyclical astronomical pacemaker for such pulses of impacts may involve the motions of the Earth through the Milky Way Galaxy. As the Solar System revolves around the galactic center, it also oscillates up and down through the plane of the disk-shaped galaxy with a half-cycle $\sim 30\pm3$ Myr. This cycle should lead to quasi-periodic encounters with interstellar clouds, and periodic variations in the galactic tidal force with maxima at times of plane crossing. This “galactic carrousel” effect may provide a viable perturber of the Oort Cloud comets, producing periodic showers of comets in the inner Solar System. These impact pulses, along with stochastic impactors, may represent the major punctuations in earth history.

1. Introduction

Mass extinctions are geologically brief episodes when large numbers of existing species ($\sim$ 25% to > 90%) disappeared (Raup and Sepkoski, 1984). Paleontologists recognize five major mass extinctions of marine organisms, and about 20 other identifiable peaks of extinction above the background during the Phanerozoic Eon, the past $\sim$ 540 Myr (Sepkoski, 1982, 1992, 1994) (Fig. 1). These extinctions of marine life coincide with extinctions of non-marine organisms (e.g., vertebrates, insects, land plants) (e.g., Rampino,

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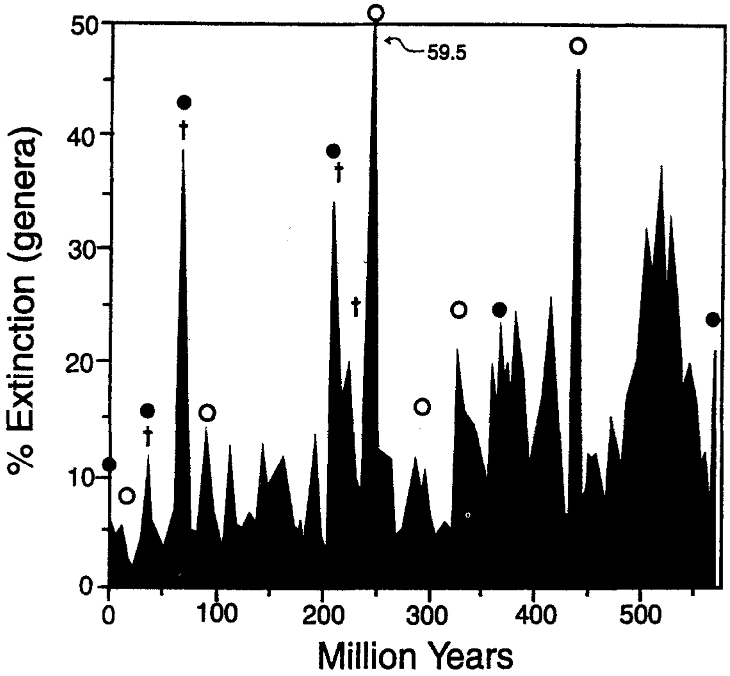

Fig. 1. Percent extinction of marine genera per geologic stage (or substage) during the Phanerozoic (data from Sepkoski, 1992, 1994, and pers. comm.). The following local maxima are recognizable in Sepkoski's data (end of stage, as defined, may not be exactly coincident with the extinctions) age in Myr (approx.), as dated by most recent geologic time scales, : 1. Pliocene (1.6), 2. Mid-Miocene (14), 3. Upper Eocene (35.4), 4. Maastrichtian (65.0), 5. Cenomanian (92), 6. Aptian (112), 7. Tithonian (144), 8. Callovian (163), 9. Pliensbachian (193), 10. Norian (205), 11. Carnian (225), 12. Tatarian (245), 13. Guadelupian (253), 14. Stephanian (286), 15. Serpukhovian (320), 16. Famennian (362), 17. Frasnian (367), 18. Eifelian (381), 19. Ludlovian (411), 20. Ashgillian (438), 20a. Caradocian? (448), 21. lower Llanvirnian (478), 22. Trempeleauan (505*), 23. Dresbachian (515*), 24. Botomian (520*), 25. Proterozoic/Cambrian? (540*). Data were culled by removing rare genera known from single localities of exceptional preservation. Note that Cambrian extinction peaks may be anomalously high as a result of the relatively poor record of diversity, and have recently been redated (*). Diagnostic stratigraphic evidence of impact (solid dots), possible stratigraphic evidence of impacts (open circles), and large, dated impact craters (crosses) (see text and Tables).

1988; LaBandiera and Sepkoski, 1993; Benton, 1995), suggesting global environmental perturbations as a cause.

The possible causes of mass extinctions of life remains a subject of intense debate. With the discovery of considerable evidence for the impact of a comet or asteroid precisely at the Cretaceous/Tertiary (K/T) mass extinction boundary (65 Myr) by L.W. Alvarez et al. (1980; for a recent review, see Glen, 1994), much attention has focused on large-body impacts as an agent of mass extinctions. A periodic component of 26 to 30 Myr in the record of mass extinctions was detected (Raup and Sepkoski, 1984, 1986), and a similar periodic component was soon reported in terrestrial impact craters (Rampino and Stothers, 1984a,b; Alvarez and Muller, 1984). Although controversial (see Weissman, 1986), these results led to several astrophysical hypotheses involving generation of periodic comet showers from the Oort comet cloud (Rampino and Stothers, 1984a; Whitmire and Jackson, 1984; Davis et al., 1984; Whitmire and Matese, 1985).

The name "Shiva (or Siva) Hypothesis", after the Hindu deity of destruction and renewal, has been suggested for this hypothesis relating recurrent mass extinctions to cyclical astrophysical causes (Gould, 1984; Goldsmith, 1986; Rampino, 1990). The name seems particularly apt. Shiva is perhaps the most ancient deity worshipped in the world today (Campbell, 1987), and in his role as a cosmic dancer, as Gould (1984) writes, "he holds in one hand the flame of destruction, in another (he has four in all) the *damaru*, a drum that regulates the rhythm of the dance and symbolizes creation. He moves within a ring of fire – the cosmic cycle – maintained by an interaction of destruction and creation, beating out a rhythm as regular as any clockwork of cometary collisions."

The idea that mass extinctions on the Earth might be paced by astrophysical cycles is far-reaching, and Raup (1989) suggested that "the subject involves so many separate scientific disciplines – from paleontology to astrophysics – that no one individual is competent to judge the merits of all the arguments and counterarguments." However, a general theory of mass extinction by impact catastrophe would represent a powerful predictive generalization in the geological and paleobiological sciences (Alvarez, 1986), and links to astrophysical dynamics make for a intuitively pleasing scientific paradigm. We believe that enough information now exists to develop a coherent and, most importantly, a testable hypothesis.

2. Impacts and Environmental Catastrophes

Most studies have come to the conclusion that the impact of an asteroid or comet $\geq$10 km in diameter (releasing $\geq 10^{24}$ J, 10^8 Mt TNT) would cause a global catastrophe of enormous proportions (e.g., Chapman and Morrison, 1994; Toon et al., 1994), and the severe end-Cretaceous crisis seems to have involved an $\sim$ 10 km diameter impactor (Alvarez et al., 1980). In looking at a general connection between impacts and extinctions, it is important to determine the threshold impactor size predicted to cause a global environmental crisis that could result in an identifiable peak in extinction of life.

Chapman and Morrison (1994) suggested that a $>$ 5 km object ($> 10^7$ Mt) would cause a global disaster, and calculations by Raup (1990) support the idea that the impact of a ~ 5 km diameter asteroid would be sufficient to cause extinction pulses clearly recognizable above the background rate. Large impacts of these magnitudes are predicted to result in major global environmental disasters primarily related to production of dense clouds of fine ejecta, and surface fires from intense heating caused by re-entry of ejecta into the earth's atmosphere (see Morrison, 1992; Chapman and Morrison, 1994).

In a more detailed analysis, Toon et al. (1994) recently calculated that an impact releasing between 10^7 and 10^8 Mt would be sufficient to produce a dust cloud of very large optical depth covering the entire planet. A global cloud of fine debris could reduce global atmospheric transmission below the limit of photosynthesis for several months (Gerstl and Zardecki 1982). Model calculations predict that land-surface temperatures could decrease by ~ 15°C in less than a week under such conditions (Toon et al., 1982; Pollack et al., 1983; Covey et al., 1990).

Toon et al. (1994) also find that the threshold impact energy required to cause global-scale wildfires through intense heating from ballistic ejecta reentering the atmosphere was $\geq 10^8$ Mt. The heat emitted globally by such ejecta is capable of igniting combustible material (Melosh et al., 1990), and large amounts of soot have been discovered at the K/T boundary suggesting combustion of a significant fraction of the terrestrial biomass (Anders et al. 1986, Wolbach et al., 1988).

Other disastrous environmental effects of large impacts that have been proposed include enhanced greenhouse effect from water vapor injected into the atmosphere by an oceanic impact (Croft, 1982; O'Keefe and Ahrens, 1982), or from CO_2 released by impact into a carbonate-rich terrane (O'Keefe and Ahrens, 1989), and the possible creation of large amounts of H_2SO_4 aerosols, and thus a marked cooling, from sulfur in the impactor, and if the target rocks contained deposits of $CaSO_4$ (Sigurdsson et al., 1992). Atmospheric shock waves from a large impact are calculated to create large amounts of NO, possibly producing nitric acid rain with a pH of ~ 1, and NO_x in the stratosphere that could rapidly remove the ozone layer.

Astronomical observations of earth-crossing asteroids and comets, and the cratering records of the inner planets, are consistent with a waiting time of $\geq 10^8$ yr for asteroids and comet impacts of 10^8 Mt, and perhaps 2 to 3×10^7 yr for objects producing explosions releasing a few times 10^7 Mt of energy (Fig. 2) (e.g., Shoemaker et al., 1990; Chapman and Morrison, 1994). The observations would thus predict 5 or 6 major mass extinctions (related to $\geq 10^8$ Mt impacts), and about 20 to 30 less severe events (related to $\sim 10^7 - 10^8$ Mt events) during the Phanerozoic Eon (the last 540 Myr), as simulated by Raup (1990). This agrees with the Phanerozoic record of extinctions that can be interpreted as showing 5 major and ~ 20 minor extinction pulses (Fig. 1). The results suggest that the record of extinction events could be explained by

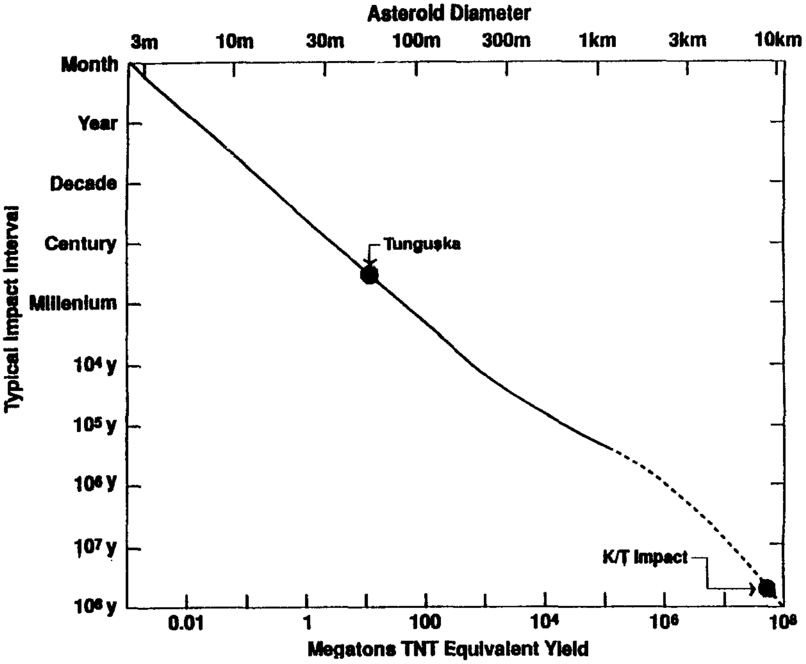

Fig. 2. Estimated frequency curve for impacts on the earth, from astronomical data. The line is a best estimate for the average interval between impacts $\geq$ the indicated energy yield. Equivalent asteroid diameters are shown (assuming an impact speed of 20 km s^{-1} and density of 3 g cm^{-3}) (after Chapman and Morrison, 1994).

comet and asteroid impacts, as has been suggested by several workers (e.g., Urey, 1973; Alvarez et al., 1980; McLaren and Goodfellow, 1990; Raup, 1990, 1991b; Rampino and Haggerty, 1994). This working hypothesis is testable, in principle, by examining the stratigraphic evidence for impacts at, or near, geologic boundaries that involved mass extinction.

3. Geologic Evidence of Large Impacts

The discovery of the K/T impact layer prompted the search for impact signatures at other geological boundaries (Kyte, 1988; Orth, 1989; Orth et al., 1990). Among the materials considered most diagnostic of impact are shocked mineral grains from the target area (including shocked quartz, stishovite, zircons, etc.), impact glass (microtektites/tektites), microspherules with structures indicating high-temperature origin, and Ni-rich spinels (see Glen, 1994 for a review). These materials have been reported in stratigraphic horizons, ranging from regionally to globally, at, or near, six recorded extinction events in Figure 1, as shown in Table I.

TABLE I
Direct Evidence for Impacts at/or near Extinction Boundaries

Age	Evidence	References
Pliocene (2.3 Myr)	Microcrystites, microtektites?	Kyte, 1988; Margolis et al., 1991
Miocene (~ 15 Myr)	Glass spherules (volcanic? impact?)	Vallier et al., 1978
Late Eocene (~ 36 Myr)	Microtektites, tektites, microspherules, shocked quartz	Montanari et al., 1993
Cretaceous/Tertiary (65 Myr)	Microtektites, tektites, shocked minerals, stishovite, Ni-rich spinels	see Glen, 1994
Triassic/Jurassic (~ 205 Myr)	Shocked quartz	Bice et al., 1992
Frasnian/Famennian (~ 367 Myr)	Microtektites	Wang, 1992; Claeys et al., 1992, 1994

The initial report of evidence of impact was the discovery of enrichments of iridium and other trace metals at the K/T boundary (Alvarez et al., 1980). An iridium anomaly in the parts per billion to tens of parts per billion range is globally well documented at the K/T boundary, and in the search for impact-related iridium anomalies, the K/T boundary has been used as the standard of reference. Criteria for impact signature have thus consisted of high (ppb) levels of iridium, and chondritic or near-chondritic element ratios. Kyte (1988), however, has argued that the relatively high Ir concentrations at the K/T boundary anomaly should not be considered typical of stratigraphic iridium anomalies expected from impacts of comets and asteroids.

The search for iridium has resulted in reports of elevated iridium levels (commonly $\geq$10 times background values) at or close to a number of geologic boundaries associated with mass extinctions (Table II). However, the Ir levels are generally significantly weaker (100s of ppt) than the typical K/T iridium anomaly, and the anomalies are commonly associated with non-chondritic element abundance patterns (Kyte, 1988; Orth et al., 1990; Wang et al., 1991; Wang et al., 1993a,b). This has led to the general conclusion that the Ir peaks are probably unrelated to impact processes (Orth et al., 1990), although Kyte (1988) listed six such sedimentary horizons as "possible" impact horizons (Cenomanian/Turonian [~ 92 Myr], Callovian/Oxfordian [~163 Myr], Early/Middle Jurassic [~ 190 Myr], Permian/Triassic [~ 250 Myr], Frasnian/Famennian [~ 367 Myr], and Proterozoic/Cambrian [~ 540 Myr], see Figure 1).

The meaning of these Ir enrichments is still a subject of debate. Although a number of workers have proposed ways in which Ir could be concentrated at stratigraphic layers by various biological and abiological processes (e.g., Rampino, 1982; Colodner et al., 1992), geological studies suggest that elevated iridium levels may be uncommon in the rock record away from recognized boundaries (Kyte and Wasson, 1986; Alvarez et al., 1990). It should also be noted that times of increased input of extraterrestrial Ir to the oceans (vaporized or dissolved meteoritic material) might also lead to enhanced secondary precipitation in sediments (Kyte, 1988).

If the elevated, but sub-ppb, Ir levels are related to impacts, then other impact debris should be present at the same stratigraphic levels. In this context, it is significant that some biostratigraphic boundaries and transitions marked by relatively small Ir anomalies are now known to be associated with impact-related material – the Late Eocene interval (~ 36 – 34 Myr, microtektites, microspherules, shocked quartz), Triassic/Jurassic (~ 205 Myr, shocked quartz), and Late Devonian (~ 367 Myr, microtektites). Furthermore, some microtektite layers have no detectable iridium and vice versa, and the widespread Australasian microtektites (0.76 Myr), clearly of impact origin, coincide with an iridium anomaly of only ~ 160 ppt (Koeberl, 1993).

Moreover, there are several reasons why impact-related Ir anomalies in the geologic record might show lower values than seen at the K/T boundary, and/or non-chondritic element abundance patterns. For one, meteorites differ in iridium content from $> 10^3$ ppb (some irons) to $\sim 10^{-2}$ ppb (eucrites and achondrites), and terrestrial impact melts range from > 30 ppb to background (0.01 ppb), thus impacts of different kinds of extraterrestrial material may produce distributed iridium anomalies of various concentrations (Palme, 1982).

Impacts of comets should produce significantly lower amounts of iridium than asteroid impacts. Because of the rms collision velocity of comets is almost 3 times greater than that of asteroids (~ 60 km s^{-1} versus ~ 20 km s^{-1}), the amount of iridium produced per Joule of impact energy (or for a crater of a given size), for a comet would be only ~ 1/9 that of an asteroid. Taking an extreme range, the velocity of a head-on collision with a long-period comet is ~ 6.6 times that of collision with the slowest asteroids, thus the iridium yield per J of such a comet could be ~ 1/50 that of an asteroid.

TABLE II

Elevated Iridium Reported at Extinction Boundaries (questionable results marked by ?)

Locality	Ir (ppt)	References
	Pliocene (~ 2.3 Myr)	
Core EL13-3, southeast Pacific	~ 5,000	Kyte, 1988
	Lower/Middle Miocene (~ 11 – 15 Myr)	
DSDP Site 588B, South Pacific	152	Orth, 1989
	Late Eocene (~ 36 Myr)	
Many localities	Up to ~ 4,000	Montanari et al., 1993
	Cretaceous/Tertiary (65 Myr)	
Worldwide	1,000s ppt	see Alvarez et al., 1980; Glen, 1994
	Cenomanian/Turonian (~ 91 Myr)	
Western US, Colombia, S.A., Western Europe	≤560	Orth 1989; Orth et al., 1993
	Jurassic/Cretaceous? (~ 140 Myr)	
Central Siberia	ave. 7,800	Zhakarov et al., 1993
	Callovian/Oxfordian (~ 163 Myr)	
Spain and Poland	1,000-2,400?	Orth, 1989
	Early/Middle Jurassic (~ 190 Myr)	
Italy	~ 3,000?	Rocchia et al., 1986
	Triassic/Jurassic (~ 205 Myr)	
Europe	≤400	McLaren & Goodfellow, 1990
	Permian/Triassic (~ 250 Myr)	
Changxing, China	8,000?	Orth, 1989
Meishan, China	600±400?	Xu et al., 1989
Meishan, China	2,000?	Xu & Yan, 1993
Guangyuan, China	2,480?	Orth 1989; Xu et al., 1989
Nammal, Pakistan	366	Xu et al., 1989
Bolzano, Italy	230	Xu et al., 1989
San Antonio, Italy	3,000?	Brandner, 1988
Tesero, Italy	135	Oddone & Vannucci, 1988
Casera Federata, Italy	100-145	–
Butterloch, Austria	90-95	–
Carnic Alps, Austria	165	Holser et al., 1991
	230	–
Lalung, India	73	Bhandari et al., 1992
	114	–
	Devonian/Carboniferous (~ 360 Myr)	
Texas	380	Orth, 1989; Wang et al. 1993a
	Frasnian/Famennian (~ 367 Myr)	
China	230	Wang et al., 1991
Australia	300	Orth, 1989
Europe	75-160	Orth, 1989
	Ordovician/Silurian (~ 438 Myr)	
Anticosti Island, Canada	58	Orth, 1989
Scotland	≤250	Orth, 1989
China	≤230	Wang et al., 1992, 1993b,c
	Proterozoic/Cambrian (~ 540 Myr)	
China	2,900	Orth, 1989, Xu et al., 1989

Furthermore, the ice-rich composition of comets (≥50% ice?) also means that their Ir content is probably much less than that of asteroids, and could lead to actual comet yields of Ir per J less than 1/100 that of asteroids (Van

Den Bergh, 1994). As an added factor, Vickery and Melosh (1990) calculated that a very energetic impact might send most of its iridium-enriched ejecta into space.

4. Geologic Evidence of Biological Catastrophes

As there is now considerable evidence for an impact at the K/T boundary, McLaren and Goodfellow (1990) argued that other impact-related extinction boundaries might be expected to show a number of geologic features in common with the K/T. These include: (1) a globally synchronous marked negative shift in $\delta^{13}C$ in marine carbonate sediments, indicating a biomass loss and drop in productivity (the Strangelove ocean), coupled with a die-off of marine plankton and proliferation of opportunistic species, followed by recovery and radiation of surviving biota, (2) a marked negative shift in $\delta^{18}O$ in marine sediments, suggesting a brief global warming (e.g., induced by increased greenhouse gases), (3) a positive shift in $\delta^{34}S$ in sediments, suggesting ocean waters with a low dissolved oxygen content, and (4) a reduction in marine biogenic $CaCO_3$ (e.g., Smit, 1990).

Published studies suggest such a common sequence at extinction horizons in the Late Triassic ($\sim$ 205 Myr), Late Permian ($\sim$ 250 Myr), Frasnian/Famennian ($\sim$ 367 Myr), Late Ordovician ($\sim$ 438 Myr), and possibly Proterozoic/Cambrian ($\sim$ 540 Myr) events (see reviews in Magaritz, 1989; McLaren and Goodfellow, 1990; Rampino and Haggerty, 1994). A number of events show evidence for a sequence of ecological destruction and subsequent recovery that suggests an abrupt and severe ecological disaster (see Rampino and Haggerty, 1994).

5. Extinctions and Evidence of Impacts: Correlations

Of the 24 Phanerozoic extinction peaks in the genus-level data of Sepkoski (1992), six seem to be associated with significant stratigraphic evidence of impacts (large (>ppb) Ir anomalies, shocked quartz, and/or microtektites) and/or large craters (Table I) (Rampino and Haggerty, 1994). At least six more are associated with "possible" evidence of impact consisting of lower (sub-ppb) concentrations of Ir, but still anomalous with respect to background values (Table II). Several other stratigraphic boundaries and faunal transitions (e.g., the Jurassic/Cretaceous [$\sim$ 140 Myr], Callovian/Oxfordian [$\sim$ 163 Myr] , Devonian/Carboniferous [$\sim$ 360 Myr]) may show significant iridium enrichment, but data are scarce (Table II).

Non-productive searches for iridium anomalies and shocked minerals in the geologic record away from boundaries suggest that these features may be uncommon in the geologic record (Kyte and Wasson, 1986; Alvarez et al., 1990; Schmitz et al., 1994). If this is the case, then a simple test of the significance of this correlation might be to consider the chances of hitting a target time series consisting of the 24 extinction events (age error bars taken as the difference in ages given by two recent geological time scales; Palmer, 1983; Harland et al., 1990) with a time series consisting of the six times of diagnostic evidence of impacts. The chance of such a correlation calculated in this way is very low ($\sim 10^{-7}$). The accidental correlation of all 12 "diagnostic" and "possible" indicators of impact with the 24 mass extinctions is of even lower probability. Thus, given the assumption that the two time series are related, the correlation of mass-extinction events and evidence of large impacts is extremely unlikely to be an accidental occurrence.

6. Impact Size and Severity of Extinctions

Natural phenomena (e.g., earthquakes, volcanic eruptions, floods) commonly show a variation in intensity and frequency in which lower intensity events are more common than high intensity events. One can represent this variation by noting the average time interval between events of a given magnitude. Extinctions of life may be viewed this way, and Raup (1990, 1991a,b) constructed a "species kill curve" using extinction data for the last 600 Myr by determining the mean waiting times between extinctions of various severity. If the impact of a large asteroid or comet can produce extinctions, then a relationship should exist between the impactor size and the number of species killed. Raup combined the extinction data with information on the waiting times of terrestrial impact craters of various sizes to construct a possible theoretical relationship between mass extinctions and impact cratering (Fig. 3).

Using the known rate of impacts, and the hypothesized relationship between impacts and mass extinctions, Raup (1990) performed Monte Carlo simulations to determine the appearance of the extinction record supposing that impacts are sufficient to explain the entire record of the past 250 Myr. The results of these simulations compared well with the actual extinction record based on several criteria, including the severity of extinction events, and the general level of background extinction.

Although we realize that severity of mass extinctions is probably related to a number of variables (e.g. ambient climate conditions, susceptibility of fauna and flora, site of impact, etc.), size of impactor may be a first-order cause. The theoretical curve of Raup can be compared with data representing specific large (> 80 km) known impact craters with relatively well-defined ages (Grieve, 1991) that overlap the ages of mass-extinction boundaries (when full dating uncertainties in both are taken into consideration)

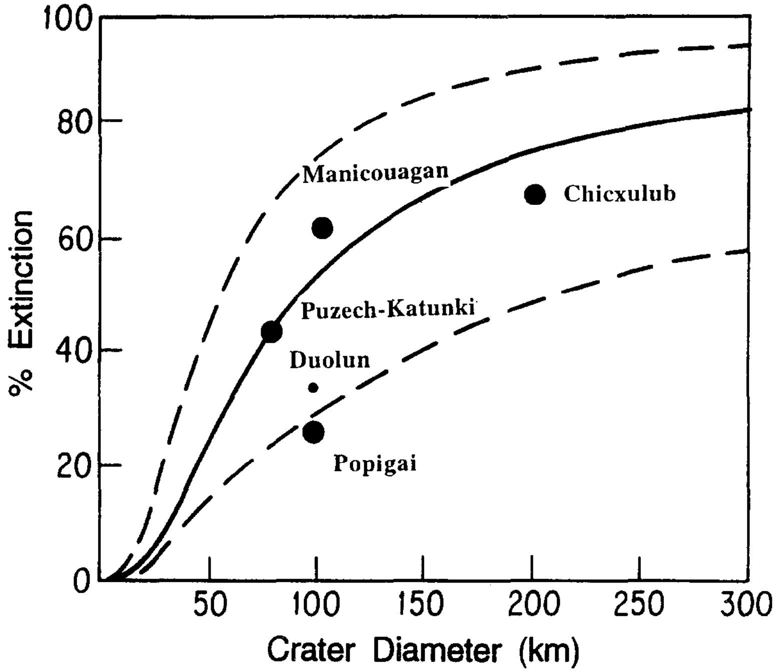

Fig. 3. Kill curve for Phanerozoic marine species (with estimated reasonable error envelope) determined from waiting times of large impacts and extinction events (see text and Raup, 1990, 1991a,b). We have plotted the sizes of the largest individual craters with dates overlapping mass extinctions (Table III) against the species kill magnitude of those extinctions (based on culled data). Data points suggest that the "true" kill curve has a step at impacts producing craters $\geq$100 km diameter ($\sim$ 107 Mt events) (see text).

(Table III). No other large, well-dated Phanerozoic craters are known to exist. The Duolun structure in North China is a possible impact structure $\sim$ 100 km in diameter, with an estimated age of $\sim$ 136 Myr (Wu, 1987), which may have occurred near the Jurassic/Cretaceous boundary ($\sim$ 140 Myr) ($\sim$ 33% extinction of marine species). The observed points agree with the predicted curve within the broad envelope of error permitted by the geologic data, supporting at least a first-order relationship.

The points could be interpreted, however, as indicating a possible step-up in the kill curve at crater sizes of $\geq$100 km diameter (about 10^7 Mt of energy release), suggesting some kind of a threshold effect. This agrees with the calculations of Toon et al. (1994) showing that the approximate thresholds of dense global dust clouds, and the effect of global-scale surface incineration by heat from re-entering ejecta, occur in the 10^7 to 10^8 Mt range.

The shape of the species kill curves predicts that for craters smaller than $\sim$ 60 – 80 km in diameter there will be no associated extinction pulse that

TABLE III

Large Impact Craters (Grieve, 1991) and Possible Correlative Extinctions (culled data of Sepkoski, 1992, 1994)

Name (Age in Myr)	~Diam. (km)	Extinction (Age)	% Genera	% Species
Puzech-Katunki (220±10)	80	Ladin.-Carn. (~ 230)	20.1	43
Popigai (35±5)*	100	Late Eocene (~ 36)	11.4	26
Manicouagan (212±2)	100	Late Triassic (~ 205)	34.1	62
Chicxulub (65.2±0.4)	200?	K/T (65)	38.5	67
Duolun (~ 136?)	100	Jur./Cret. (~ 140)	12.5	33

* Latest work indicates date of 36 ± 1 Myr (J. Garvin, pers. comm., 1993)

stands above the ~ 20–25% background level of % species extinction (Raup, 1990; see also Jansa et al., 1990), and indeed there are well-dated craters in this size range (e.g., Kara (~ 73 Myr), ~ 65 km; Montagnais (~ 51 Myr), ~ 45 km) that apparently do not correlate with significant increases in extinction over background levels.

7. Periodic Component in Mass Extinctions and Impacts?

The ~ 24 pulses of extinction at the genus level (using the metric of % extinction) that have occurred during the Phanerozoic (approximately the last 540 Myr) give a mean occurrence rate of one every ~ 23 Myr (Figure 1). Raup and Sepkoski (1984) originally identified 12 extinction events at the family level by geologic stages over the last 250 Myr, and reported a statistically significant 26 Myr periodicity in the extinction time series. Later studies found a similar periodicity in extinctions at the genus level (Raup and Sepkoski, 1986). Rampino and Stothers (1986) reported a 29±1 Myr periodic component in the record of vertebrate extinctions. Periods of ~ 26 to 31 Myr have been derived using various subsets of extinction events (family and genus levels), different geologic time scales, and various methods of time-series analysis (e.g., Quinn, 1987; Connor, 1986; Stothers, 1989; Sepkoski, 1989).

The regularity, statistical significance, and reality of the dominant underlying periodicity have been subjects of intense debate (e.g., Stigler and Wagner, 1987, and reply by Raup and Sepkoski, 1988). It is important to note that the detection of a periodic component in the record of marine mass extinctions does not imply either that the record contains a strict periodicity, or that every extinction event follow a 26-Myr timescale. The extinction record might be a mixture of periodic and random events.

Part of the problem in acceptance of periodicity as a real manifestation of the geologic record has been the shortness of the record, and the reported

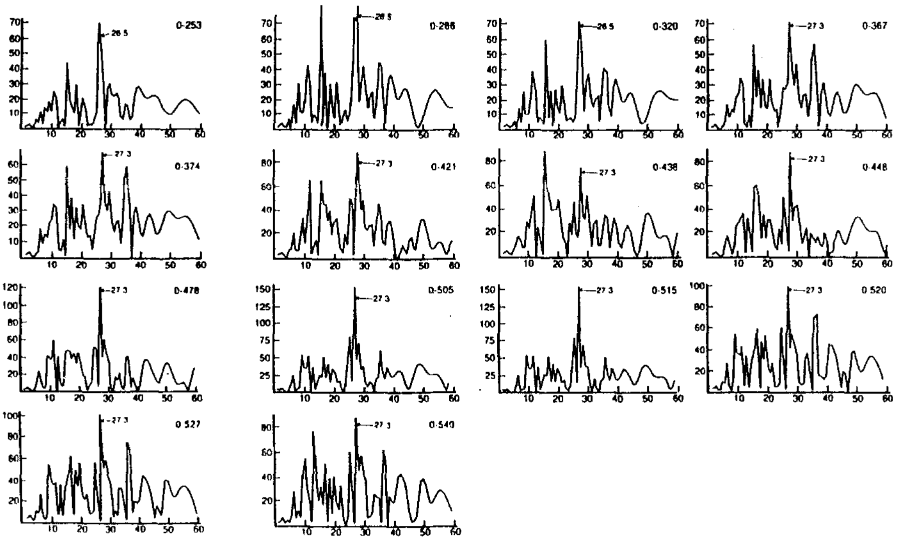

Fig. 4. Fourier power spectrum for extinction events from Fig. 1 (0-540 Myr), computed as described in Rampino and Caldeira (1992, 1993). X-axis = period in Myr, y-axis = spectral power. The time series were truncated, one extinction event at a time, from 540 Myr to 253 Myr. The highest peak remained in the range 26.5 to 27.3 Myr in all but one of the truncations, where the 27.3 Myr peak was the second highest. The results for the 0-253 Myr sequence gives 26.5 Myr period, similar to that obtained in previous studies (Raup and Sepkoski, 1984, 1986; Rampino and Caldeira, 1992, 1993).

apparent lack of evidence of a statistically significant periodicity in extinction events prior to 250 Myr ago. We performed Fourier analysis (using methods described in Rampino and Caldeira, 1993) on the extended record of 22 extinctions going back ~ 540 Myr, more than doubling the length of the series (culled genera-level data from Sepkoski, 1992, and pers, comm., dated using Palmer, 1983 time scale). For the entire record, we find that the highest peak in the Fourier spectrum is at 27.3 Myr (Fig. 4).

As a test of the significance of the 27.3 Myr peak, we used the 0 to 515 Myr record, and generated 1,000 pseudo-data sets, each containing the same number of randomly dated pseudo-events over the same time interval. Based on this analysis, for example, the probability of generating higher spectral power at 27.3 Myr in the data set is ~ 2%, but the probability of generating higher spectral power at any period between 10 and 65 Myr falls below the 95% confidence level (Rampino and Haggerty, 1994).

As another measure of significance, however, we tested the robustness of the ~ 27 Myr peak, by performing Fourier analysis on the series of truncated extinction time series starting from 0 to 540 Myr, and subtracting one extinction at a time back to 250 Myr (Fig. 4). The robustness of the ~ 27 Myr periodicity in the extinction time series is attested to by the fact that a stable peak between 26.5 and 27.3 Myr remains the dominant feature of the Fourier spectrum in the truncated extinction data sets.

Time-series analyses of terrestrial impact craters have provided some evidence of a possible 28 to 32 million year periodicity in impacts (Rampino and Stothers, 1984a,b; Alvarez and Muller, 1984, Rampino and Stothers, 1986; Shoemaker and Wolfe, 1986; Yabushita 1991, 1992, but see Grieve and Pesonen, 1995). In some studies, an ~ 36 Myr periodic component of variable significance was detected (Durrheim and Reimold, 1987; Grieve, 1991). The record may be characterized as a mixture of periodic and random events (Stothers, 1988; Trefil and Raup, 1987; Yabushita, 1992). These studies are still plagued by small number statistics and poorly dated craters, however, and other workers have found no significant periodicity in even the best-dated craters (e.g., Grieve et al., 1986; Grieve, 1991; Grieve and Shoemaker, 1994; Grieve and Pesonen, 1995).

In the most recent studies, a revised data set of 32 craters from the last 250 Myr (with diameters $\geq$5 km and dating uncertainties $\leq$20 Myr) have been used in time series analysis (see Grieve and Pesonen, 1995). Using a linear time-series analysis technique, Grieve and Shoemaker (1994) found the most significant peak in their time-series analysis of these data at 30 Myr, but the peak failed to meet their rather stringent criterion (3 standard deviations from the mean) by a small margin, and its significance was questioned. We were impressed, however, that the highest peak in the spectrum was again close to 30 Myr, and we performed a standard Fourier analysis on the newest list of craters. Our results also show the highest peak at 30 Myr, but again the significance level is marginal; clearly more and better crater data are required.

On the other hand, a simple plot of crater frequency with time suggests showers of objects at ~ 0, 35, 65, and 95 Myr ago (Hut et al., 1987), and Stothers (1993) found a significant correlation between impact crater ages and geologic boundaries. The fact that many of the correlative craters seem to be too small (according to the kill curves discussed above) to have produced the associated faunal turnover events is at least consistent with the idea that impacts come in clusters of large and small objects, with many crater still undiscovered (Stothers, 1993).

8. How Well Can the Periodicity in Extinctions and Impact Craters be Determined?

Several investigators have argued that the differences in the periodic components detected in mass extinctions and impact craters may preclude a direct relationship (e.g., Yabushita, 1992, 1994). However, in comparing the periodicities obtained for mass extinctions and impact cratering (and other geological events such as geomagnetic reversals, tectonism, etc., see Rampino and Stothers, 1986; Rampino and Caldeira, 1992, 1993), it is necessary to determine the range of values expected from the data sets in question. This depends on uncertainties in the magnitude of extinction events, completeness of the record of events, uncertainties in radiometric and other dating techniques, differences in geological timescales used, and the ratio of periodic to non-periodic components in the data sets analyzed (Trefil, 1986 unpublished; Trefil and Raup, 1987; Fogg, 1989; Stothers, 1988, 1989; Heisler and Tremaine, 1989).

It is important to note that several studies have demonstrated that the 26 to 33 Myr periods detected in these data sets are not significantly different, and that the range can be readily explained by a combination of dating errors and biases, and signal-to-noise problems. Working with the mass extinction data for the last ~ 250 Myr, Trefil (1986, unpublished) found that uncertainties in extinction rates introduce an error of ±2 Myr (2σ), and uncertainties in the geologic timescale lead to errors of ±2.5 Myr (2σ) in the detected periodicity. He concluded that there was no significant difference between the 26 Myr period detected in extinctions and 29 to 30 Myr periodic component in impact cratering. Stothers (1989) found that the use of three recently published geological time scales (with differences in ages of extinctions of ±1% to ±5% in the last 250 Myr) gave extinction periods ranging from 25 to 27 Myr, 25 to 30 Myr, and 24 to 33 Myr.

Using numerical simulations, Raup and Trefil (1987) concluded that the observed cratering record was most likely a combination of an ~ 29 Myr periodic component and random background impacts comprising ~ 50 to 66% of the total. The range of periods expected from variations in the ratio of cyclic to background impacts was tested by Fogg (1989), who used a computer simulation of impact bombardment of the earth in which the background flux was overlain by a 26 Myr comet-shower cycle. His time-series analysis of impact-related mass extinctions showed periodicities ranging from 24 to 33 Myr in most runs, with the observed period dependent upon the magnitude of the background flux of impactors; < 40% of the runs showed the "true" introduced 26 Myr periodicity. Thus, the impact record might be consistent with a mixture of a random component and an ~30 Myr periodic component.

9. Periodic Comet Showers and the Galaxy

If the periodic component of ~ 26 to 30 Myr in the mass extinction and impact cratering pulses is real, then it may be related to the carrousel-like movement of the Solar System through the Milky Way Galaxy. Increased flux of comets (comet showers) might come gravitational perturbations of

Oort comet cloud during the periodic passage of the Solar System through the central plane of the Galaxy (the half-cycle of the oscillation is estimated to be ~ 26 to 36 Myr depending on galactic models) (Rampino and Stothers, 1984a; Clube and Napier, 1984), although this scenario has been criticised on various grounds (see Weissman, 1986).

Recent calculations by Matese et al. (1994) suggest that time modulation of the flux of new Jupiter-dominated Oort cloud comets could come from gravitational perturbations of the comet cloud by adiabatically varying galactic tides during the in-and-out of plane oscillation. They find that in a galactic model in which half of the disk matter is compact, the peak-to-trough comet flux variation should be ~ 5 to 1, with a full width of 9 Myr. According to their model, the phase of the nearest cycle peak is 0.6 Myr in the future. For the parameters chosen, Matese et al. (1994) found that the most recent times of peak comet flux were ~ 30.7, 64.7, and 98.1 Myr ago, and that the cycle interval varied from 29.5 to 34.2 Myr over a 350 Myr run of the model.

In this case, major events in the history of life (and possibly geophysical changes) on Earth may be tied to the dynamics of the Galaxy (Napier and Clube, 1979; Rampino and Stothers, 1986; Rampino and Caldeira, 1992, 1993). Alternative periodic astrophysical models for the Shiva Hypothesis, involving a companion star to the sun (Whitmire and Jackson, 1984; Davis et al., 1984), or a tenth planet (Whitmire and Matese, 1985), seem less likely (e.g., Weissman, 1986; Vandervoort and Sather, 1993).

10. Conclusions

The observed orbital elements and size-frequency distributions of earth-crossing asteroids and comets predict that impactors greater than a few km in diameter ($> 10^7$ Mt events) should collide with the earth on average every few tens of millions of years, with larger ($\sim 10^8$ Mt) events occurring about once every hundred million years. Calculations suggest that the threshold impact size required to cause a detectable mass extinction lies at a few times 10^7 Mt event (with global distribution of fine dust), whereas major mass extinctions seem to require impacts of $\sim 10^8$ Mt (sufficient to cause global scale wildfires). The predicted post-impact environmental effects are expected to lead to mass mortality and subsequent extinction of a large fraction of extant species. Such large climatic perturbations might also destabilize the climatic system, leading to longer term changes in the environment.

A number of extinction events seem to show a generally common pattern in the geologic record, with sharp negative shifts in carbon isotopes in marine sediments suggesting abrupt mass mortality, sudden crash of ocean plankton communities, destruction of terrestrial plant communities, impoverished post-extinction ecosystems, and proliferation of opportunistic survivor species, all suggestive of severe ecological disturbances, mass mortality, and delayed recovery.

Six of the ~ 24 pulses of marine extinction in the last 540 Myr seem to be associated (although not always precisely correlated) with large impact craters and/or stratigraphic evidence of impacts – layers containing high siderophile trace-element anomalies (especially iridium), and/or shocked minerals, tektites and microtektites. An additional six extinction levels are associated with known layers of elevated iridium (and other trace-metal) concentrations above background that might be related to impacts of Ir-depleted objects, possibly comets or non-chondrite-composition asteroids. Alternatively, sediment mixing and trace-metal fractionation may be affecting impact signatures. We believe that although elements of uncertainty remain in many aspects of the problem, and much more work needs to be done, the principle of parsimony suggests that a general relationship between large impacts and mass extinctions is a reasonable working hypothesis.

A periodic component of ~ 26 to 31 Myr has been reported in mass extinction time series for the past 250 Myr, and we report here a robust period of ~ 26.5 to 28 Myr in the record of extinctions of marine organisms going back 540 Myr. A similar period of ~ 28 to 32 Myr has been reported in some sets of dated impact craters, and tests suggests that, if such a periodic component exists in cratering, and considering the uncertainties in dating of geologic events, the periods detected in extinctions and craters are identical within reasonable error. A "Galactic Carrousel" model in which periodic passages of the solar system through the plane of the Milky Way Galaxy lead to gravitational perturbations of the Oort Comet cloud and resulting comet showers might explain the periodic component in cratering and mass extinctions. If supported by further studies, this could provide a connection between critical events here on Earth and the dynamics of the Milky Way Galaxy.

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