

Periodic impact cratering and extinction events over the last 260 million years

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ABSTRACT

The claims of periodicity in impact cratering and biological extinction events are controversial. A newly revised record of dated impact craters has been analyzed for periodicity, and compared with the record of extinctions over the past 260 Myr. A digital circular spectral analysis of 37 crater ages (ranging in age from 15 to 254 Myr ago) yielded evidence for a significant 25.8 ± 0.6 Myr cycle. Using the same method, we found a significant 27.0 ± 0.7 Myr cycle in the dates of the eight recognized marine extinction events over the same period. The cycles detected in impacts and extinctions have a similar phase. The impact crater dataset shows 11 apparent peaks in the last 260 Myr, at least 5 of which correlate closely with significant extinction peaks. These results suggest that the hypothesis of periodic impacts and extinction events is still viable.

Key words: comets: general – Earth – meteorites, meteors, meteoroids – planets and satellites: surfaces.

1 INTRODUCTION

A number of studies going back 30 years have reported that impact craters on the Earth formed in the last 260 Myr occur periodically with an underlying cycle time ranging from about 26 to 36 Myr, (e.g. Alvarez & Muller 1984; Rampino & Stothers 1984a,b; 1986; Shoemaker & Wolfe 1986; Fox 1987; Fogg 1989; Yabushita 1992a,b, 1996a,b, 1998; Clube & Napier 1996; Chang & Moon 2005; Wickramasinghe & Napier 2008). The range of periods (and phases) detected in the various studies may be the result of the methods of time-series analysis, inaccurate and imprecise age determinations, and selection of various sets and subsets of craters for the analysis (e.g. Yabushita 1996a,b; Chang & Moon 2005).

By contrast, other spectral analysis studies report little or no evidence of statistically significant cycles in crater ages over the same period (e.g. Bailey & Stagg 1988; Heisler & Tremaine 1989; Montanari, Campo-Bagatin & Farinella 1998; Jetsu & Pelt 2000; Lyytinen et al. 2009; Bailer-Jones 2011), so the question of periodicity is still open. Some of the problems in detecting significant cycles involve the suitability of the various methods of spectral analysis for the impact-cratering record, and come about because the record is short, incomplete, and may be a mixture of periodic and non-periodic components (e.g. Trefil & Raup 1987; Chang & Moon 2005; Lyytinen et al. 2009).

We utilized an updated impact-crater data set (Earth Impact Database 2015) with some crater ages different than in previous crater compilations used in previous studies (e.g. Alvarez and Muller 1984; Rampino and Stothers 1984a; Yabushita 1992a,b 1996a,b, 1998, 2002; Matsumoto & Kubotani 1996; Chang & Moon 2005; Napier 2006; Wickramasinghe & Napier 2008). For example, the 16 crater ages listed in Alvarez and Muller (1984) all now have revised ages differing by as much as 60 Myr from the original ages. In the present study, only craters with 1σ error bars of less than or equal to ± 10 Myr were used, and we omitted the many young craters with ages of ≤ 5 Myr to prevent any bias created by the relatively large number of recent craters. Our list has 37 crater ages over the last 260 Myr (Table 1).

2 SPECTRAL ANALYSIS OF CRATER AGES

For our study, we chose a circular method of spectral analysis (Lutz 1985; Stothers 1991; Yabushita 1996a) to evaluate the revised impact-crater record. This method works well for time-series like the craters, which lacks amplitude information, is most likely missing data, may be a mixture of periodic and non-periodic events, and consists of unevenly spaced data (Lutz 1985; Stothers 1991).

For circular spectral analysis, a timeline can be ‘wrapped’ around a circle, the circumference of which represents a trial period. For each occurrence, we calculate a unit vector from the origin. A series that is not periodic will tend to plot randomly around the circle, regardless of trial period selected. A periodic series, however, will

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Table 1. Ages with 1σ errors of the 37 impact craters used in the analyses (Impact Data Base 2015). Only ages >5 Myr ago and with errors of less than or equal to ± 10 Myr were used and are listed here.

Impact crater	Age (Myr ago with 1σ errors)
Steinheim	15.1 ± 1
Ries	15.1 ± 0.1
Chesapeake Bay	35.3 ± 0.1
Popigai	35.7 ± 0.2
Mistastin	36.4 ± 4
Wanapitei	37.2 ± 1.2
Logoist	42.3 ± 1.1
Shunak	45 ± 10
Ragozinka	46 ± 3
Chiyli	46 ± 7
Kamensk	49.0 ± 0.2
Gusev	49.0 ± 0.2
Montagnais	50.5 ± 0.76
Marquez	58 ± 2
Chicxulub	64.98 ± 0.05
Boltysh	65.17 ± 0.64
Kara	70.3 ± 2.2
Manson	74.1 ± 0.1
Lappajarvi	76.2 ± 0.29
Wetumpka	81 ± 1.5
Dellen	89 ± 2.7
Steen River	91 ± 7
Deep Bay	99 ± 4
Carswell	115 ± 10
Rotmistrovka	120 ± 10
Mien	121 ± 2.3
Vargeao Dome	123 ± 1.4
Tookoonoka	128 ± 5
Mjolnir	142 ± 2.6
Gosses Bluff	142.5 ± 0.8
Morokweng	145 ± 0.8
Zapadnaya	165 ± 5
Puchezh-Katunki	167 ± 3
Obolon	169 ± 7
Rochechouart	201 ± 2
Manicouagan	214 ± 1
Araguainha	254.7 ± 2.5

tend to form a cluster at one point on the circumference when the correct trial period P is selected. The angular location of the cluster relative to 0° (the present) gives the phase (t_0). The event times t_i are mapped onto a circle by conversion to angles a_i and b_i :

$$\begin{aligned}
 a_i &= \sin 2\pi / P(t_i) \\
 b_i &= \cos 2\pi / P(t_i) \\
 S &= 1/N \sum_{i=1}^N (a_i) \\
 C &= 1/N \sum_{i=1}^N (b_i) \\
 R &= (S^2 + C^2)^{1/2},
 \end{aligned} \tag{1}$$

where i ranges from 1 to N (the number of events), and P is the trial period. S and C are the summations, $S = (\sum \sin a_i) / N$ and $C = (\sum \cos b_i) / N$.

Application of circular statistics leads to a mean vector magnitude, $R = (S^2 + C^2)^{1/2}$ (a normalized measure of goodness of fit). The direction of the vector that minimizes the dispersion at the trial period P indicates the phase, which can be computed: $t_0 =$

$(P/2\pi) \tan^{-1} (S/C)$, if $C > 0$, or as $t_0 = (P/2) + (P/2\pi) \tan^{-1} (S/C)$, if $C < 0$.

If R is plotted against P , then maximal values of R would correspond to periods in the series, t_1, t_2, \dots, t_N . If, however, t_1, t_2, \dots, t_N are randomly distributed, then (a_i, b_i) would define a random walk, and the sum R will be small.

The two highest R peaks in the spectrum of impact-crater ages fall at 25.8 and 18.4 Myr (Fig. 1a). Following the statistical approach of Lutz (1985), we tested the significance level of the resulting spectral peaks by evaluating the probability that a random series with similar statistical properties would have more power at that frequency. In particular, all of our random series had 37 crater ages between 5 and 260 Myr ago, and similar long-term trends in impact-crater frequency.

In order to take into account the fall-off in number of crater ages going back in time, (Fig. 2) we first established, for a crater of any specific age, an estimate for the expected time until the next older crater. This was done for 10 000 representations of the actual crater record, with the uncertainties in the crater ages representing 1σ Gaussian errors. We then fit a straight line to each of these 10 000 time series on a log-linear plot (crater age versus log of time to next earlier crater), where a straight line represents exponential decay. The e-folding time-scale for the fall-off of craters with increasing age resulting from this process is 79.2 Myr.

Then, following Lutz (1985), we assumed that the times to the next crater followed a gamma distribution function with a shape factor of 2. We then adjusted the constant for the argument to the gamma distribution function to a value most likely to give 37 craters between 5 and 260 Myr ago. For the estimate of the time to the next crater, the gamma distribution we used was

$$\Delta T = (1.02 \text{ Myr})^* \text{Exp}(t/(79.2 \text{ Myr})). \tag{2}$$

Thus, we created random pseudo-crater data sets with the same number of craters (37), and the same long-term trend in crater frequency as the real data set. The 95 percent confidence line in Fig. 1a represents the 95th percentile result of 10 000 pseudo-crater data sets.

3 SIGNIFICANCE OF CRATERING PERIODICITY

The R peaks at 18.4 and 25.8 Myr both rise above the calculated 95 percent significance level (Fig. 1a). The 25.8 ± 0.6 Myr peak agrees with previous spectral analyses of various impact-crater data that gave significant peaks ranging from 26 to 36 Myr (Alvarez & Muller 1984; Rampino & Stothers 1984a,b; Yabushita 1992a, 2002; Chang & Moon 2005; Wickramasinghe & Napier 2008). The error bars for the peak periods are found by computing the standard deviation of the location of the peaks closest to the peak period in 10 000 Monte Carlo simulations of pseudo-crater data.

The phase (t_0) for the 25.8 Myr cycle is at 16 ± 1.3 Myr ago. The phase error represents the standard deviation of the phase at a particular period.

The peak in our analysis at 18.4 Myr also rises above the 95 percent confidence level. Similar peaks between ~ 15 and 20 Myr, which appeared in some previous studies of impact-crater periodicity, were mostly interpreted either as noise or harmonics of the ~ 30 Myr cycle (Alvarez & Muller 1984; Rampino & Stothers 1986; Yabushita 1992a, 1996a, 1998, 2002; Napier 1998;), although some workers have maintained that there might be a real ~ 15 Myr cycle in the data (e.g. Napier 1989; Yabushita 1998).

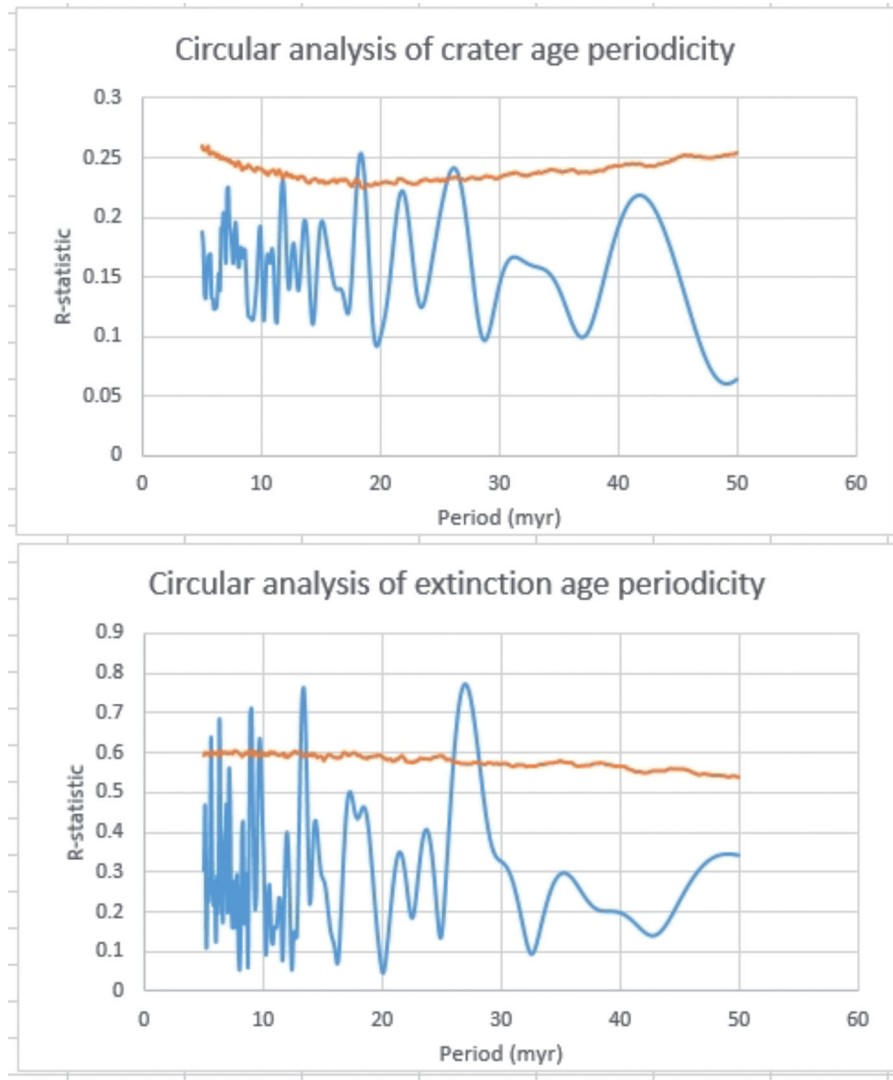


Figure 1. (a) Results of circular spectral analysis of 37 impact-crater ages for the last 260 Myr. The red line is the 95 percent confidence level. (b) Results of circular spectral analysis of eight mass-extinction ages for the last 260 Myr. The red line is the 95 percent confidence level (for discussion, see text).

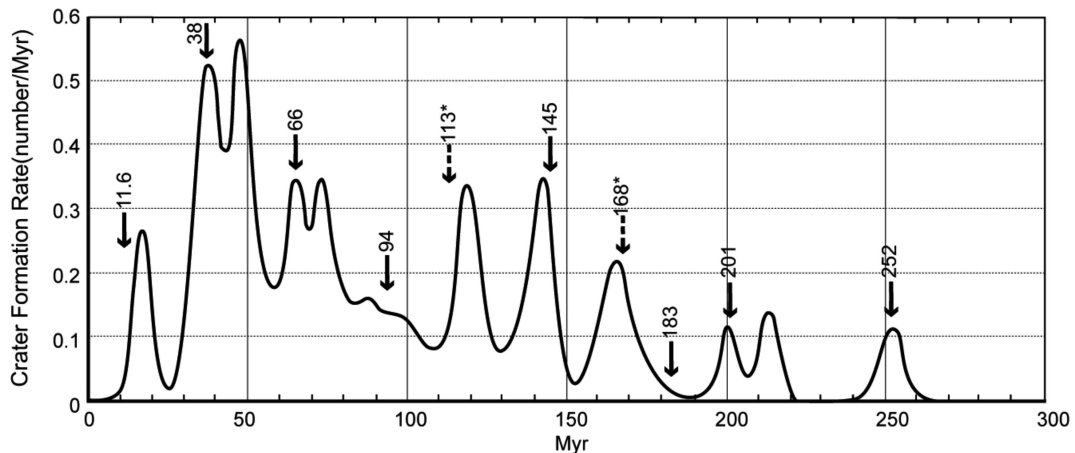


Figure 2. Probability distribution of crater-formation rate for the last 260 Myr. The probability distribution of 37 crater ages (with their 1σ errors) has been smoothed by a Gaussian window function of 3 Myr. Solid arrows indicate times of eight significant extinction events after Raup & Sepkoski (1986). Broken arrows with asterisks indicate two additional potential extinction events at 113 Myr ago and 168 Myr ago. The impact crater ages show 11 peaks over the last 260 Myr, at least 5 of which correlate with significant extinctions events (6, if the potential extinction events in Table 2 are included).

Table 2. Times of significant mass extinctions of marine genera for the last 260 Myr (after Raup & Sepkoski 1986, dates from Gradstein et al. 2012). Two potential extinction events are included.

Extinction	Age (Myr)
Middle Miocene	11.6
Mid-Late Eocene	37.8
End Cretaceous	66
Cenomanian/Turonian	93.9
Aptian/Albian ^a	113 ^a
Jurassic/Cretaceous	145
Bajocian/Bathonian ^a	168.3 ^a
Pliensbachian/Toarcian	182.7
Triassic/Jurassic	201.3
End-Permian	252.2

Note. ^apotential extinction event

For various periodic-analysis methods, the spurious periods are in most cases less significant than the real periods. Hence, the 18.4 Myr period could be the real cycle and the 25.8 Myr cycle could be spurious. Napier (2006), however, observed that if a periodicity is weak, harmonics of the underlying signal will commonly dominate over the basic periodicity. Bearing on this question, Yabushita (1992a), using the linear spectral analysis technique of Stothers (1991) on a previous compilation of crater ages, detected significant cycles of about 30–32 Myr in impact cratering, with a second peak at 16.5 Myr, ($\sim P/2$) this peak appearing especially when young craters are removed from the study. Similarly, Alvarez & Muller (1984), using Fourier analysis on only 13 crater ages, found a 28.4 Myr peak, and also reported the presence of a significant 21 Myr peak that was not stable. We suggest that the spectral peak at 18.4 Myr in our cratering study is a false peak, and might be interpreted as the multiple period $2P/3$ of the 25.8 Myr cycle (Rampino and Stothers 1984b). Shorter periods are below the Nyquist limit for these data.

4 SPECTRAL ANALYSIS OF EXTINCTION EVENTS

A similar ~ 26 Myr periodicity has been reported in the dates of occurrences of extinction events during the past 250 Myr (e.g. Rampino & Stothers 1984a; Raup & Sepkoski 1984, 1986; Connor 1986; Gilinsky 1986; Fox 1987; Trefil & Raup 1987; Fogg 1989; Prokoph, Fowler & Patterson 2001; Lieberman and Melott 2012). Further studies have extended a significant, stable ~ 27 Myr cycle in the record of extinctions back to 540 Myr ago (Rampino, Haggerty & Pagano 1997; Melott & Bambach 2010, 2013). Some workers, however, argue that there are no statistically significant periods in the extinction data (e.g. Noma & Glass 1987; Quinn 1987; Stigler & Wagner 1987; Heisler & Tremaine 1989; Bailer-Jones 2011; Feng & Bailer-Jones 2013).

Using the same methods of circular statistical analysis described above (Lutz 1985; Stothers 1991), we analyzed the record of the eight times of significant extinction of marine genera of the last 260 Myr reported by Raup & Sepkoski (1986; see also Bambach 2006, who finds seven significant extinctions in the same time interval), redated with the most recent geologic time-scale (Gradstein et al. 2012) (Table 2).

We found a significant R peak at 27.0 ± 0.7 Myr for the times of extinction (Fig. 1b). We calculated the 1σ error bars of the highest

peak in a similar manner as that for cratering. The phase (t_0) of the this cycle is 11.8 ± 1.0 Myr ago, predicting the most recent maxima for a perfectly periodic series at 11.8, 38.8 and 65.8 Myr ago. The 95 per cent confidence line in Fig. 1b represents the 95th percentile result of 10 000 pseudo-extinction data sets. The spectral peak at 13.4 Myr, which also is above the 95th percentile, is likely the first harmonic of the 27 Myr cycle. Shorter period peaks are below the Nyquist limit.

5 COMPARISON OF CRATER AND EXTINCTION RESULTS

Impact crater ages for the last 260 Myr, when plotted with their Gaussian errors, may be directly compared to the extinction record of Raup & Sepkoski 1986 (Fig. 2). The probability distributions of impact-crater ages show 11 apparent peaks over the last 260 Myr, 5 of which correlate with times of significant extinctions (out of a total of 8). The impact-crater record is certainly incomplete, and many more craters wait to be discovered and dated. It should be noted, however, that the exact number of impact peaks, and their ages are partly dependent on the Gaussian smoothing factor (3 Myr) used in this study (Fig. 2). The 3 Myr smoothing factor seems to be optimal for the crater-age data. Also, because of the pull of the recent, we have omitted from our analyses all craters whose age is given at less than or equal to 5 Myr (37 craters, mostly small), and a potential extinction peak in the Late Pliocene, which might affect the phase calculations. Moreover, if we consider those occurrences, then it may be that we are in a period of increased impact now (Shoemaker & Wolfe 1986).

Two additional potential extinction events at 113 and 168.3 Myr ago were also discussed by Raup & Sepkoski (1986) (Table 2). If we include the two potential extinctions, then impact peaks correlate with 6 out of a total of 10 extinction events. Furthermore, one poorly dated crater (Carswell) is dated at 115 ± 10 Myr ago, overlapping the Aptian/Albian boundary at 113 Myr ago. With better dating, this could define another impact/extinction episode. The apparent clustering of impact-crater ages suggests that some portion of the impactors may be coming in pulses, perhaps as comet showers (Alvarez & Muller 1984; Rampino & Stothers 1984a; Rampino 2015), or asteroid showers (although those would most likely be non-periodic; Schmitz et al. 2015). The correlation of these pulses with times of extinction suggests that these episodes might include some large impacts that have not yet been discovered or are dated incorrectly.

As seen from the R -statistics in Fig. 1a and b, the periodic component explains a greater fraction of the variability in the extinction record than in the cratering record. (If the periodicity were perfect, the R -value would be 1.) If impacts and extinctions are always correlated, we would predict impact peaks at about 94 Myr ago (Cenomanian/Turonian) and 183 Myr ago (Pliensbachian/Toarcian) boundaries (Raup & Sepkoski 1986; Bambach 2006). Several poorly dated impacts have ages which overlap ~ 94 Myr ago (Dellen, Steen River and Deep Bay). Previous impact-crater compilations had impacts dated at ~ 183 Myr ago (e.g., Rochechouart, Puchezh-Katunki), but these craters are now listed with different revised ages.

6 DISCUSSION OF RESULTS

For the crater data, our analysis revealed a strong period at 25.8 ± 0.6 Myr, with the most recent maximum at 16.0 ± 1.3 Myr ago. For the extinction data, our analysis found the strongest period is 27.0 ± 0.7 Myr, with the most recent maximum occurring

11.8 \pm 1 Myr ago. If, however, we examine the phasing of the extinction data assuming the 25.8 Myr period estimated from the crater data, the optimal phasing for extinctions has the most recent maximum at 14.7 Myr ago, just 1.3 Myr later than was estimated from the crater data. Similarly, if we examine the phasing of the extinction data assuming a 27.0 Myr periodicity as estimated from the extinction data, the optimal phasing has the most recent maximum at 13.0 Myr ago, just 1.2 Myr earlier than was estimated from the extinction data. The similarity of both period and phasing in these two disparate data sets is suggestive of a potential causal relationship.

It might be thought that this similarity of period and phasing is unduly influenced by the end-Cretaceous extinction (66 Myr ago), which is clearly associated with the Chicxulub crater (Schulte et al. 2010). However, if we remove the end-Cretaceous extinction from the extinction record, the estimated extinction period remains at 27.0 Myr, and the timing of the most recent extinction maximum remains at 11.8 Myr ago. Note that this would produce an expectation of an extinction event at 65.8 Myr ago in a perfectly periodic series ($=11.8 + 2 \times 27.0$), close to the actual end-Cretaceous extinction (66 Myr ago) removed from this record.

Similarly, if we remove Chicxulub from the crater record, the estimated crater period remains at 25.8 Myr, with the time of the most recent maximum at 16.2 Myr ago. Thus, the Chicxulub/end-Cretaceous extinction relationship contributes to the similarity of periods and phasing observed in the extinction and crater records, but this similarity does not rest on those events.

Further testing of the relationship between impacts and extinctions will depend upon more and better ages for impact craters, and consideration of a longer timescale (e.g., at present, only 11 craters with stated 1σ errors less than or equal to 10 Myr are known from the entire record of impact prior to 260 Myr ago). Our work, and the recent work of others (e.g. Chang & Moon 2005; Lieberman & Melott 2007, 2012; Melott & Bambach 2010, 2013), support the idea that impacts and extinction events are periodic, with a period of ~ 26 –27 Myr, and that the hypothesis of periodic extraterrestrial impacts as a contributing cause of periodic extinctions of life, while controversial, is still viable (Randall & Reece 2014; Rampino 2015).

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