MASS EXTINCTIONS, COMET IMPACTS, AND THE GALAXY

MICHAEL R. RAMPINO
NASA, Goddard Institute for Space Studies, New York, New York, 10025 USA, and Earth & Environmental Science Program, New York University, New York, New York, 10003 USA

AND

RICHARD B. STOTHERS
NASA, Goddard Institute for Space Studies, New York, New York, 10025 USA

Abstract. The hypothesis relating mass extinctions of life on Earth to impacts of comets whose flux is partly modulated by the dynamics of the Milky Way Galaxy contains a number of postulates that can be tested by geologic evidence and statistical analyses. In an increasing number of cases, geologic evidence for impact (widespread impact debris and/or large impact craters) is found at times of mass extinction events, and the record of dated impact craters has been found to show a significant correlation with mass extinctions. Statistical analyses suggest that mass extinction events exhibit a periodic component of about 26 to 30 Myr, and periodicities of 30 ± 0.5 Myr and 35 ± 2 Myr have been extracted from sets of well-dated impact craters. The evidence is consistent with periodic or quasi-periodic showers of impactors, probably Oort Cloud comets, with an approximately 30-Myr cycle. The best explanation for these proposed quasi-periodic comet showers involves the Sun's vertical oscillation through the galactic disk, which may have a similar cycle time between crossings of the galactic plane.

1. INTRODUCTION: IMPACTS AND MASS EXTINCTIONS

Numerous studies have now established that the mass extinction of life at the end of the Cretaceous Period (65 Myr ago), the so-called Cretaceous/Tertiary (K/T) boundary, was the result of the impact of an asteroid or comet ~ 10 km in diameter which created the ≥ 200 km diameter Chicxulub impact structure in the present Yucatán region of Mexico (Alvarez, 1986; Hildebrand *et al.*, 1995). Such an impact (releasing $> 10^{24}$ J or 10^8 Mt TNT equivalent) is calculated to cause a global catastrophe of enormous proportions, primarily related to dense clouds of fine ejecta, production of nitric oxides and acid rain, and smoke clouds from fires triggered by atmospheric re-entry of ejecta (Toon *et al.*, 1994). Other "target-sensitive" effects include enhanced greenhouse effect from atmospheric water vapor in an ocean impact, CO_2 released by impact into carbonate rocks, and cooling and acid rain from large amounts of sulfuric acid aerosols derived from calcium sulfate target rocks (Pope *et al.*, 1994; Toon *et al.*, 1994). If flood basalt eruptions are impact triggered (Rampino and Stothers, 1988), then volcanic perturbations of climate might also be expected.

Astronomical observations of Earth-crossing asteroids and comets and the cratering record of the inner planets allow estimates of the expected mean times between collisions of objects of various sizes with the planet (Shoemaker *et al.*, 1990). On the large-diameter end of the size spectrum, these data predict that in an ~ 100 Myr period, the Earth should be hit by several asteroids and comets larger than a few km in diameter (these release $\sim 10^{23}$ J or 10^7 Mt) and perhaps one ~ 10-km diameter ($\sim 10^{24}$ J, 10^8 Mt) object (most likely cometary) (Shoemaker *et al.*, 1990).

The likelihood that a 10^8 Mt event would have considerably greater global environmental impact than a 10^7 Mt event (Melosh *et al.*, 1990; Toon *et al.*, 1994), leads to the prediction of ~ 5 major mass extinctions, and about 25 ± 5 less severe pulses of extinction during the Phanerozoic Eon (the

J. Andersen (ed.), Highlights of Astronomy, Volume 11A, 246–251.

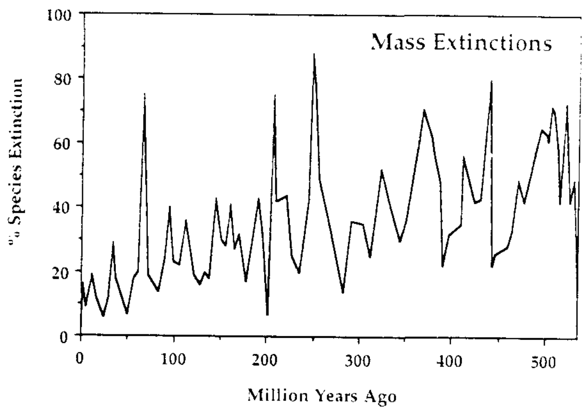

Figure 1. Percent extinction of marine species per geologic stage (or substage) during the Phanerozoic (data from Sepkoski, 1995).

TABLE 1. Large Dated Impact Craters (Grieve and Pesonen, 1996) with updates and Associated Extinctions (Sepkoski, 1995)

Name	Diameter (km)	Age (Myr)	Extinction	% Species
Popigai	100	35.7 ± 0.8	Late Eocene	30
Chesapeake	90	35.2 ± 0.3	Late Eocene	–
Chicxulub	200?	65.2 ± 0.4	K/T	76
Morokweng	100	145 ± 3	J/K	42
Manicouagan	100	214 ± 1	Late Triassic	76
Puchezh-Katunki	80	220 ± 10	Carnian	42

last 540 Myr). This agrees surprisingly well with the record of extinctions for that interval, which clearly shows 5 major mass extinctions and $\sim$ 20 less severe extinction pulses (Fig. 1).

Although the severity of impact-induced mass extinctions would probably depend on a number of variables (e.g. ambient climate conditions, susceptibility of fauna and flora, site of impact, etc.), the size and energy of the impactor is likely to be the most important factor. A theoretical "kill curve" relating mass extinctions and impacts (Fig. 2) has been proposed (Raup, 1992), and this curve can be compared with data representing specific large (> 80 km diameter) known impact craters with well-defined ages that overlap the ages of mass-extinction boundaries (when the full dating uncertainties in both are taken into consideration) (Table 1). We note that no other large, well-dated Phanerozoic craters are known. The observed points in Fig. 2 agree with the predicted curve within the envelope of error permitted by the geologic data, supporting at least a first-order relationship between large impacts and mass extinctions.

2. IS THERE A CORRELATION BETWEEN IMPACTS AND MASS EXTINCTION EVENTS?

The discovery of the K/T impact layer prompted the search for impact signatures at other geological boundaries. Among the materials considered diagnostic of impact are shocked minerals (including shocked quartz, stishovite, shocked zircons, etc.), impact glass (microtektites/tektites), microspherules with structures indicating high-temperature origin, and Ni-rich spinels. Shocked minerals and tektite glass are quite rare in the geologic record, and yet these materials have been reported in stratigraphic horizons close to the times of six recorded extinction pulses (Table 2) (Rampino *et al.*, 1997; Grieve, 1997). A recent preliminary report of shocked quartz from the Permian/Triassic boundary ($\sim$ 248 Myr) in Antarctica and Australia (Retallack *et al.*, 1996) is still

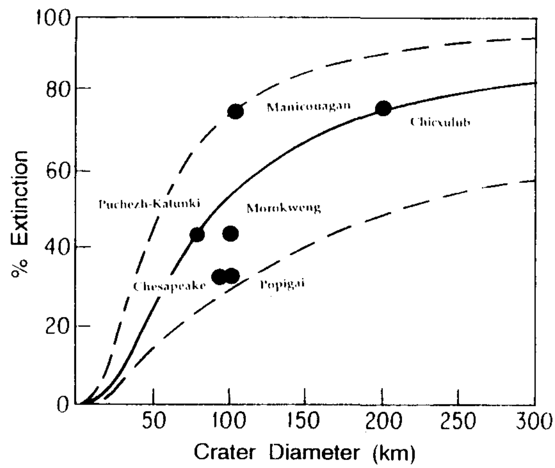

Figure 2. Kill curve for Phanerozoic marine species, with estimated error bars, plotted against estimated size of impact craters associated with extinctions of various magnitudes (assuming that the two are related) (Raup, 1992). Largest well-dated impact craters with ages overlapping mass extinction times are plotted for comparison (Table 1).

unconfirmed.

Seven of the ~ 25 extinction peaks in Fig. 1 [Pliocene (2.3 Myr), Late Eocene (36 Myr), Cretaceous/Tertiary (65 Myr), Jurassic/Cretaceous (144 Myr), Late Triassic (210 Myr), Late Devonian (365 Myr), and possibly the Proterozoic/Cambrian (540 Myr) boundary] are associated with large impact craters and/or some form of stratigraphic evidence of impacts (Tables 1 and 2). Several other extinction events are associated with "possible" evidence of impact consisting of iridium concentrations somewhat elevated with respect to background values; see tables in (Rampino *et al.*, 1997; Grieve, 1997).

The chances of accidentally matching a time series consisting of 24 extinction events (with the age error bars in this case taken as the difference in ages given by recent published time scales), with a time series consisting of the seven times of diagnostic stratigraphic evidence of impacts is $< 10^{-7}$. Studies thus far indicate that iridium anomalies above background and shocked quartz are rare in the geologic record, also suggesting that correlation of mass-extinction events and evidence of large impacts is very unlikely to be accidental.

Recently, Matsumoto and Kubotani (1996) showed a statistically significant correlation between the record of impact cratering of the last 250 Myr and the record of mass extinctions. Stothers (1993) had earlier found a significant correlation between impact crater ages and stratigraphic stage boundaries that are defined by faunal changes during the Cenozoic Era (the last 65 Myr). These studies support a general correlation between impacts and extinctions of various magnitudes from significant mass extinctions ($\geq 10^8$ to 10^7 Mt impacts) to the less severe faunal turnover events that mark stratigraphic stage boundaries ($\sim 10^6$ to 10^7 Mt impacts).

TABLE 2. Stratigraphic Evidence of Impacts at or near Extinction Boundaries (for references see text)

Age	Evidence
Pliocene (2.3 Myr)	Microkrystites, microtektites?
Late Eocene (36 Myr)	Microtektites (multiple), tektites, microspherules, shocked quartz
Cretaceous/Tertiary (65 Myr)	Microtektites, tektites, shocked minerals, stishovite, Ni-rich spinels, iridium
Jurassic/Cretaceous (142 Myr)	Shocked quartz
Late Triassic (210 Myr)	Shocked quartz (multiple?)
Late Devonian (368-365 Myr)	Microtektites (multiple)

3. ARE MASS EXTINCTIONS AND IMPACTS PERIODIC?

The mean occurrence rate of the 24 extinction pulses shown in Fig. 1 is one every ~ 23 Myr. Raup and Sepkoski (1984, 1986) reported a statistically significant 26.4 Myr periodicity in extinction time series for the last 250 Myr, and a secondary periodicity of 30 Myr. 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, and Rampino and Stothers (1986) reported detection of an ~ 29 Myr component in the record of extinctions of non-marine vertebrates. The interpretation of these results has been a subject of considerable debate (e.g., Rampino and Haggerty, 1996). The detection of a periodic component in extinctions does not imply either that the record contains a strict periodicity, or that all extinction events follow a 26-Myr timescale; the extinction record might be a mixture of periodic and random events.

Fourier analysis of an extended record of 21 extinctions going back to about 515 Myr, more than doubling the length of the original time series, resulted in a spectrum with the highest peak at 27.3 Myr (Rampino and Haggerty, 1996). Fourier analyses on a series of truncated extinction time series starting from 0 to 540 Myr, and subtracting one extinction at a time back to 253 Myr produced a stable peak between 26.5 and 27.3 Myr which remained the dominant feature in the spectra (Rampino and Haggerty, 1996).

The impact-crater record has been interpreted as showing pulses at about 1, 35, 65, and 95 Myr ago (Shoemaker and Wolfe, 1986; Hut *et al.*, 1987). 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, 1984b, 1986; Alvarez and Muller, 1984; Shoemaker and Wolfe, 1986; Yabushita, 1991, 1992, 1996a, 1996b), and have been interpreted as suggesting that the impact record may be a mixture of periodic and random events (Trefil and Raup, 1987; Heisler and Tremaine, 1989; Fogg, 1989). Several studies have concluded that, considering the problems in dating, the observed differences in the formal periodicity detected in impact craters and mass extinctions are to be expected (Stothers, 1988, 1989; Fogg, 1989). Critics have argued, however, that the number of well-dated craters is still too small to extract a consistent statistically significant periodicity (Grieve and Shoemaker, 1994; Grieve and Pesonen, 1996).

4. A GALACTIC FORCING FOR PERIODIC IMPACTS AND EXTINCTIONS?

In the galactic models, the flux of long-period comets (comet showers) is modulated by the periodic passage of the solar system through the central plane of the Milky Way Galaxy (Rampino and Stothers, 1984a; Matese *et al.*, 1995). The original model (Rampino and Stothers, 1984a) proposed that the probability of encounters with molecular clouds that would perturb the Oort comet cloud causing comet showers would be modulated by the Sun's oscillation about the galactic disk. The rather flat distribution of clouds around the galactic plane suggests that an encounter would be more likely as the Sun passed through the plane region, and hence the encounters would be quasi-periodic, with a period equal to the time between plane crossings (Rampino and Stothers, 1986). Extensive numerical simulations have shown that this effect should be detectable in the terrestrial record of impact cratering with at least a 50% a priori probability (Stothers, 1985).

Matese *et al.* (1995) suggested that time modulation of the flux of new Jupiter-dominated Oort cloud comets could come from gravitational perturbations of the comet cloud by the adiabatically varying galactic tides during the in-and-out of plane oscillation; see also (Scalo and Smoluchowski, 1984). One remaining uncertainty is the most likely cycle time. The cycle time and modulation depend critically on the mass distribution in the galactic disk, particularly the distribution of dark matter in the disk. As Matese *et al.* (1995) have shown: (1) If there is no dark matter in the disk, then the mean plane crossing period is ~ 44 Myr, and the peak-to-trough ratio in the comet flux is about 2.5 to 1. (2) If the current best estimate of local disk density is used, then the mean plane crossing period is ~ 33 Myr, and the peak-to-trough flux ratio is about 4 to 1. (3) If the estimated errors of the various recent estimates in the disk matter density are considered, then the period could be as short as about 28 Myr, with a comet flux ratio of 4 to 1. The issue of dark disk matter is still unsettled (Gould *et al.*, 1996), and if there is substantial dark matter, the most likely remaining source may be very cold molecular clouds (Stothers, 1984; Lequeux *et al.*, 1993).

Using the current best estimate of disk mass density, Matese *et al.* (1995) found that the most recent times of peak comet flux were ~ 1 Myr in the future, and also about 31, 65, and 98 Myr

TABLE 3. Results of Spectral Analyses of Impact Crater Ages

Smallest Diameter	N	Phase	Highest Peak (Myr)	Second highest Peak (Myr)
5 km	31	Free	30	35
		Fixed	30	35
35 km	11	Free	35	None
		Fixed	35	None
90 km	5	Free	36	29
		Fixed	36	30

ago, and that the cycle interval varied from 29.5 to 34.2 Myr over a 350 Myr run of their galactic model. Peak flux times lag the times of galactic plane crossing by about 1 Myr. Shoemaker *et al.* (1990) maintained that the largest impactors should be comets, and hence the largest craters should preferentially show the galactic modulation. Such pulses of increased comet flux would explain the stepped nature of some extinction events, clusters of similar-age craters, and multiple impact layers seen in the geologic record. Both galactic models must assume that shower comets come from the Oort cloud, in numbers moderately greater than background comets and asteroids (especially comets from the Kuiper belt).

In order to test the consistency of the latest cratering and extinction data with the galactic models, we performed a series of new linear spectral analyses on these data. Using the 11 mass extinctions over the last 250 Myr, we have performed the time-series analyses either allowing the phase to be a free parameter, or with fixed phasing, in which case we only used trial starting epochs in the range ± 1 Myr (the time of most recent galactic plane crossing). When the phase is allowed to vary, only one high spectral peak at 27 Myr is apparent. When the phase is fixed at the present time, the highest peak shifts to 28 Myr, but two somewhat smaller peaks at 32 and 35 Myr become considerably more prominent. These results suggest that although the average time interval between these mass extinctions is 25 Myr, the spacing is actually somewhat irregular, and so one need not accept 27 Myr as the "correct" period.

To test the crater record, we performed linear time-series analyses on sets of various size craters using the impact crater list of (Grieve and Pesonen, 1996) containing 32 craters, to which we added the Chesapeake crater (90 km, 35.2 ± 0.3 Myr), the Mjölnir crater (40 km, 142 ± 2.6 Myr), the Morokweng crater (> 100 km, 145 ± 3 Myr), and a correction for the ages of the Rochechouart (214 ± 8 Myr) and Popigai (35.7 ± 0.8 Myr) craters (Grieve, 1996, 1997; Rampino *et al.*, 1997). In all cases, the upper age limit was taken to be 250 Myr, and only those ages with errors of less than ± 10 Myr were used. Table 3 shows the results for the best-fitting periods obtained.

As Table 3 shows, we detected two peaks, a narrow peak at 30 ± 0.5 Myr and a broader peak at 35 ± 2 Myr. In a study designed to test the effects of the errors in the ages of the craters on the periods detected, Stothers (1988) showed that the errors alone were capable of shifting the dominant period between 30 and 35 Myr. We note, however, that the periods detected in the mass extinction and cratering records are statistically significant (at the 5% level) only when they are treated as periods known a priori.

Our studies show that the geologic data on mass extinctions and evidence of large impacts are consistent with a quasi-periodic modulation of the flux of Oort cloud comets with a mean period of about 30 to 36 Myr, as predicted by current galactic models. Further astronomical and geological studies should help to refine both the astronomical cycle time and the periodicity detectable in the geologic record.

References

Alvarez, W. 1986. Toward a Theory of Impact Crises. *Eos, Transactions of the American Geophysical Union* **67**, 649-658.

Alvarez, W. and R.A. Muller 1984. Evidence From Crater Ages for Periodic Impacts on the Earth. *Nature* **308**, 718-720.

Fogg, M.J. 1989. The Relevance of the Background Impact Flux to Cyclic Impact/Mass Extinction Hypotheses. *Icarus* **79**, 382-395.

Gould, A., Bahcall, J.N. and C. Flynn 1996. Disk M Dwarf Luminosity Function from Hubble Space Telescope Star Counts. *Astrophys. J.* **465**, 759-768.

Grieve, R.A.F. 1996. Chesapeake Bay and Other Terminal Eocene Impacts. *Meteoritics and Planetary Science* **31**, 166-167.

Grieve, R.A.F. 1997. Extraterrestrial Impact Events: The Record in the Rocks and the Stratigraphic Column. *Palaeoclimatology, Palaeogeography, Palaeoecology* **132**, 5-23.

Grieve, R.A.F. and L.J. Pesonen 1996. Terrestrial Impact Craters: Their Spatial and Temporal Distribution and Impacting Bodies. *Earth, Moon and Planets* **72**, 357-376.

Grieve, R.A.F. and E.M. Shoemaker 1994. The Record of Past Impacts on Earth. *Hazards Due to Comets & Asteroids* (T. Gehrels, Ed.), 417-462. Univ. of Arizona Press, Tucson.

Heisler, J. and S. Tremaine 1989. How Dating Uncertainties Affect the Detection of Periodicity in Extinctions and Craters. *Icarus* **77**, 213-219.

Hildebrand, A.R., Pilkington, M., Connors, M., Ortiz-Aleman, C. and R.E. Chavez 1995. Size and Structure of the Chicxulub Crater Revealed by Horizontal Gravity Gradients and Cenotes. *Nature* **376**, 415-417.

Hut, P., Alvarez, W., Elder, W.P., Hansen, T., Kauffman, E.G., Keller, G., Shoemaker, E.M. and P.R. Weissman 1987. Comet Showers as a Cause of Mass Extinctions. *Nature* **329**, 118-126.

Lequeux, J., Allen, R.J. and S. Guilloteau 1993. CO Absorption in the Outer Galaxy, Abundant Cold Molecular Gas. *Astronomy and Astrophysics* **280**, L23-L26.

Matese, J.J., Whitman, P.G., Innanen, K.A. and M.J. Valtonen 1995. Periodic Modulation of the Oort Cloud Comet Flux by the Adiabatically Changing Galactic Tide. *Icarus* **116**, 255-268.

Matsumoto, M. and H. Kubotani 1996. A Statistical Test for Correlation Between Crater Formation Rate and Mass Extinctions. *MNRAS* **282**, 1407-1412.

Melosh, H.J., Schneider, N.M., Zahnle, K.J. and D. Latham 1990. Ignition of Global Wildfires at the Cretaceous/Tertiary Boundary. *Nature* **343**, 251-254.

Pope, K. O., Baines, K.H., Ocampo, A.C. and B.A. Ivanov 1994. Impact Winter and the Cretaceous/Tertiary Extinctions: Results of a Chicxulub Asteroid Impact Model. *Earth and Planetary Science Letters* **128**, 719-725.

Rampino, M.R. and B.M. Haggerty 1996. The "Shiva Hypothesis": Impacts, Mass Extinctions, and the Galaxy. *Earth, Moon and Planets* **72**, 441-460.

Rampino, M.R., Haggerty, B.M. and T.C. Pagano 1997. A Unified Theory of Impact Crises and Mass Extinctions: Quantitative Tests. *Annals of the New York Academy of Sciences* **822**, 403-431.

Rampino, M.R. and R.B. Stothers 1984a. Terrestrial Mass Extinctions, Cometary Impacts and the Sun's Motion Perpendicular to the Galactic Plane. *Nature* **308**, 709-712.

Rampino, M.R. and R.B. Stothers 1984b. Geological Rhythms and Cometary Impacts. *Science* **226**, 1427-1431.

Rampino, M.R. and R.B. Stothers 1986. Geologic Periodicities and the Galaxy. *The Galaxy and the Solar System* (R. Smoluchowski, J. N. Bahcall and M. S. Matthews, Eds.), 241-259. Univ. of Arizona Press, Tucson.

Rampino, M.R. and R.B. Stothers 1988. Flood Basalt Volcanism During the Past 250 Million Years. *Science* **241**, 663-668.

Raup, D.M. 1992. Large-Body Impact and Extinction in the Phanerozoic. *Paleobiology* **18**, 80-88.

Raup, D.M. and J.J. Sepkoski, Jr. 1984. Periodicity of Extinctions in the Geologic Past. *Proceedings of the National Academy of Sciences USA* **81**, 801-805.

Raup, D.M. and J.J. Sepkoski, Jr. 1986. Periodic Extinctions of Families and Genera. *Science* **231**, 833-836.

Retallack, G.J., Seyedolali, A., Holser, W.T., Krinsley, D. and E.S. Krull 1996. Shocked Quartz at the Permian-Triassic Boundary in Australia and Antarctica. *Geological Society of America Abstracts with Programs* **28**, A-368.

Scalo, J.M. and R. Smoluchowski 1984. Galactic Gravitational Shock and the Extinction of Species. *Bulletin of the American Astronomical Society* **16**, 493-494.

Sepkoski, J.J., Jr. 1995. Patterns of Phanerozoic Extinction: A perspective From Global Data Bases. *Global Events and Event Stratigraphy in the Phanerozoic* (O.H. Walliser, Ed.), 35-51. Springer, Berlin.

Shoemaker, E.M. and R.F. Wolfe 1986. Mass Extinctions, Crater Ages, and Comet Showers. *The Galaxy and the Solar System* (R. Smoluchowski, J.N. Bahcall and M.S. Matthews, Eds.), 338-386. Univ. of Arizona Press, Tucson.

Shoemaker, E.M., Wolfe, R.F. and C.S. Shoemaker 1990. Asteroid and Comet Flux in the Neighborhood of Earth. *Geological Society of America Special Paper* **247**, 155-170.

Stothers, R.B. 1984. Mass Extinctions and Missing Matter. *Nature* **311**, 17.

Stothers, R.B. 1985. Terrestrial Record of the Solar System's Oscillation About the Galactic Plane. *Nature* **317**, 338-341.

Stothers, R.B. 1988. Structure of Oort's Comet Cloud Inferred From Terrestrial Impact Craters. *Observatory* **108**, 1-9.

Stothers, R.B. 1989. Structure and Dating Errors in the Geologic Time Scale and Periodicity in Mass Extinctions. *Geophysical Research Letters* **16**, 119-122.

Stothers, R.B. 1993. Impact Cratering at Geologic Stage Boundaries. *Geophysical Research Letters* **20**, 887-890.

Toon, O.B., Zahnle, K., Turco, R.P. and C. Covey 1994. Environmental Perturbations Caused by Asteroid Impacts. *Hazards due to Asteroids and Comets* (T. Gehrels, Ed.), 791-826. Univ. of Arizona Press, Tucson.

Trefil, J.S. and D.M. Raup 1987. Numerical Simulations and the Problem of Periodicity in the Cratering Record. *Earth and Planetary Science Letters* **82**, 159-164.

Yabushita, S. 1991. A Statistical Test for Periodicity Hypothesis in the Crater Formation Rate. *MNRAS* **250**, 481-485.

Yabushita, S. 1992. Periodicity in the Crater Formation Rate and Implications for Astronomical Modeling. *Dynamics and Evolution of Minor Bodies with Galactic and Geological Implications* (S.V.M. Clube, S. Yabushita and J. Henrard, Eds.), 161-178. Kluwer, Dordrecht.

Yabushita, S. 1996a. Are Cratering and Probably Related Geological Records Periodic? *Earth, Moon, and Planets* **72**, 343-356.

Yabushita, S. 1996b. Statistical Tests of a Periodicity Hypothesis For Crater Formation Rate-II. *MNRAS* **279**, 727-732.