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Disc dark matter in the Galaxy and potential cycles of extraterrestrial impacts, mass extinctions and geological events

Michael R. Rampino[1,2,3★]

[1]*Department of Biology, New York University, New York, NY 10003, USA*
[2]*Department of Environmental Studies, New York University, New York, NY 10003, USA*
[3]*NASA, Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA*

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ABSTRACT

A cycle in the range of 26–30 Myr has been reported in mass extinctions, and terrestrial impact cratering may exhibit a similar cycle of 31 ± 5 Myr. These cycles have been attributed to the Sun's vertical oscillations through the Galactic disc, estimated to take from ∼30 to 42 Myr between Galactic plane crossings. Near the Galactic mid-plane, the Solar system's Oort Cloud comets could be perturbed by Galactic tidal forces, and possibly a thin dark matter (DM) disc, which might produce periodic comet showers and extinctions on the Earth. Passage of the Earth through especially dense clumps of DM, composed of Weakly Interacting Massive Particles (WIMPs) in the Galactic plane, could also lead to heating in the core of the planet through capture and subsequent annihilation of DM particles. This new source of periodic heating in the Earth's interior might explain a similar ∼30 Myr periodicity observed in terrestrial geologic activity, which may also be involved in extinctions. These results suggest that cycles of geological and biological evolution on the Earth may be partly controlled by the rhythms of Galactic dynamics.

Key words: comets: general – Earth – Galaxy: disc.

1 INTRODUCTION

The connection between a large body impact on the Earth and the mass extinction of life that marked the end of the Cretaceous Period, 66 Myr ago is now well established (Schulte et al. 2010). A number of other mass extinctions over the last 540 Myr were recognized (Raup & Sepkoski 1982), and Raup and Sepkoski (1984) reported that these extinctions showed a period of about 26 Myr, at least over the last 250 Myr (the best dated part of the record). More recently, and with better dating, an ∼27 Myr mass-extinction cycle has been extended to the entire 540 Myr interval (Rampino et al. 1997; Melott & Bambach 2010, 2013). Several other studies have reported an ∼26–30 Myr cycle in mass extinctions (e.g. Raup & Sepkoski 1986; Fox 1987; Trefil & Raup 1987; Stothers 1989; Lieberman & Melott 2012). Connor (1986) found a period of ∼30 Myr in the Raup/Sepkoski data set, but emphasized that from these data, the extinction period could only be determined with an error of ±3 Myr.

Following the suggestion of periodic extinctions, a search for cycles in the impact cratering record initially turned up evidence for a similar cycle of 28–31 Myr over the same 250 Myr period (Alvarez & Muller 1984; Rampino & Stothers 1984b). Some subsequent studies confirmed the presence of a 30–35 Myr cycle in impact cratering in various sets of crater ages (Yabushita 1992, 1996a,b, 1998; Shoemaker 1998; Stothers 1998; Napier 2006; Wickramasinghe & Napier 2008). Using an updated crater list, and treating impact cratering as an oscillator in the time domain, Chang and Moon (2005) reported an ∼26 Myr period in the impact crater data.

It should be noted, however, that a number of other researchers find no evidence of significant periods of ∼30 Myr in either extinctions (e.g. Noma & Glass 1987; Quinn 1987; Stigler & Wagner 1987; Heisler & Tremaine 1989; Bailer-Jones 2011), or large-body impacts (e.g. Bailey & Stagg 1988; Grieve et al. 1988; Heisler & Tremaine 1989; Grieve 1991; Grieve & Shoemaker 1994; Jetsu & Pelt 2000; Lyytinen et al. 2009; Yabushita 2002; and full Bayesian analysis by Bailer-Jones 2009). The periodic nature of these events, and the significance of the periods detected by various methods of spectral analysis, continue to be controversial subjects.

Bailer-Jones (2011) and Lyytinen et al. (2009), however, specifically note the difficulty in detecting significant cycles in data sets that are composed of a mixture of periodic and non-periodic events, such as might be the case for mass extinctions and impacts. It has also been demonstrated that such a mixture of periodic and non-periodic events can alter the length and significance of any cycles detected (Trefil & Raup 1987; Bailer-Jones 2011). In the case of impact craters, for example, dating errors and grouping by size are capable of shifting the dominant period from ∼30 to ∼37 Myr

★ E-mail: mrr1@nyu.edu

(Stothers 1998, 2006; Rampino 2001; Yabushita 2002). Here, we investigate the possible connections between geological cycles and the Galaxy, particularly the possible role of dark matter (DM) in affecting periodicity in terrestrial events.

2 MECHANISMS TO PRODUCE CYCLIC IMPACTS AND MASS EXTINCTIONS

Several astrophysical mechanisms were proposed to explain cyclic impacts and extinctions (see Smoluchowski, Bahcall & Matthews 1986). One proposal (Rampino & Stothers 1984a) involves the Sun's oscillation through the Galactic mid-plane, which is estimated to be in the range of 33 ± 3 Myr (Bahcall & Bahcall 1985) to as great as 42 Myr (Holmberg & Flynn 2000) between plane crossings (Fig. 1), depending in part on the abundance and distribution of disc DM. It has been proposed that during the crossing of the Galactic plane, the Solar system's Oort comet cloud would be gravitationally perturbed by Galactic tidal forces of visible matter (Matese et al. 1995, 2001; Nurmi, Valtonen & Zheng 2001), and possibly by a thin disc of DM most likely made up of Weakly Interacting Massive Particles (WIMPs) concentrated in the Galaxy's mid-plane (Randall & Reece 2014). These perturbations could lead to periodic comet showers in the inner Solar system, and hence comet impacts and associated mass extinctions on the Earth.

This idea can be tested by studying terrestrial impact craters to determine whether they were formed by comets or asteroids (Grieve 1991). Shoemaker (1998) held the opinion that most large craters on the Earth were produced by comet impacts. Another method of testing involves the occurrence in sediments of excess He-3 from comet-derived dust in the inner Solar system at times of showers (e.g. Farley et al. 1998). Results, thus far, are mixed (Farley 2002),

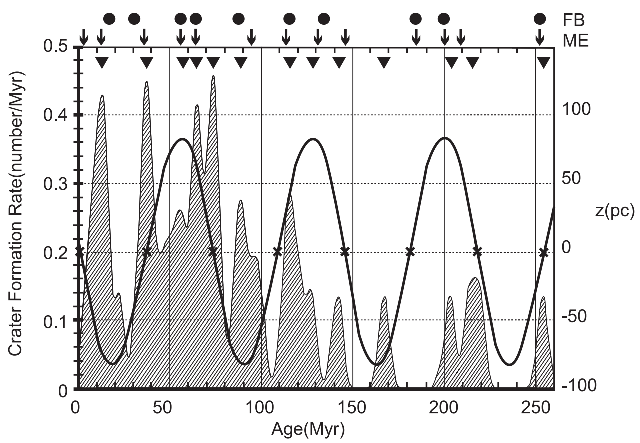

Figure 1. Comparison of ages of impact craters, mass extinctions and flood-basalt eruptions, and relation to estimated times of Galactic plane crossings. Probability distribution of crater-formation rate (hatched) (number of impacts per Myr), for the last 260 Myr. Crater-age data from Matsumoto & Kubotami 1996, with updates, excluding data from the last 5 Myr. The probability distribution has been smoothed by a Gaussian window function with a 3 Myr dispersion. Peaks in the cratering record are indicated by dark inverted triangles (see Table 1 – after Matsumoto & Kubotami 1996); times of mass extinctions (ME, arrows, from Raup & Sepkoski 1986, with revised ages from Gradstein et al. 2012); times of continental flood basalts (FB, dots, from Rampino & Self 2000 and Courtillot & Renne 2003), all plotted against the Sun's estimated height above and below the Galactic plane (Z, in parsec), with a half cycle of ~35 Myr (from Randall & Reece 2014). Estimated times of Galactic plane crossings of the Solar system are marked by X's.

with possible showers at 36–37 Myr ago and during the last 2 Myr, but apparently the lack of evidence of shower 66 Myr ago, at the time of the end-Cretaceous mass extinction (Mukhopadhyay 2001).

Simulations of the effects of Galactic tidal forces on Oort Cloud comets as the Solar system weaves its way through the Galaxy (Matese et al. 1995, 2001; Nurmi, Valtonen & Zheng 2001) produce periodic variations of new comets from the Oort Cloud that enter the inner Solar system. The flux depends upon the surface mass density of the Galactic disc; the best fitting model assumes a value of 60 solar masses pc^{-2}. Furthermore, radial Galactic tidal effects arising from the eccentricity of the Galactic orbit, with a period of around 180 Myr, should modulate the ~30 Myr cycle (Shuter & Klatt 1986; Gardner et al. 2010), and could produce a detectable perturbation of the Oort Cloud (Matese et al. 1995, 2001; Nurmi, Valtonen & Zheng 2001). It may be significant that the time between the most severe mass extinctions, the end-Permian extinction (252 Myr ago) and the end-Cretaceous extinction (66 Myr ago) is estimated to be ~186 Myr, and the time between the end-Permian event (252 Myr ago) and the end-Ordovician extinction (444 Myr ago) is ~192 Myr, suggesting modulation by the longer cycle.

According to Randall & Reece (2014), the thin dark-disc surface density may be ~10 solar masses pc^{-2}, with a scaleheight of only ~10 pc. They estimate that the time required to cross this DM disc is of the order of 1 Myr. Since the Sun gets as much as ~80 pc away from the Galactic plane, this density distribution should be capable of producing a detectable periodicity in terrestrial impact cratering (Randall & Reece 2014). The total local Galactic surface density has been estimated to range between 47 and 84 solar masses pc^{-2}. Visible matter shows only about 40 solar masses pc^{-2}, so some DM seems to be indicated (Stothers 1998). The existence of such a DM disc will be tested directly soon through the *GAIA* satellite's measurements of stellar kinematics (Bailer-Jones 2009).

3 POSSIBLE CYCLICAL NATURE OF GEOLOGIC EVENTS

Applying spectral analysis to the records of various terrestrial geologic events, including global tectonism, flood-basalt volcanism and sea level, Rampino & Stothers (1984b, 1988) reported a similar cycle of about 30 Myr in the timing of these events. This is supported by independent correlation of times of mass extinctions with impact episodes (Table 1; Matsumoto & Kubotani 1996; Yabushita 1998), and correlation between mass extinctions, impact craters and massive flood-basalt eruptions (Rampino & Stothers 1988; Stothers 1993; Yabushita 1998), which have been proposed as a possible independent cause of mass extinctions (Rampino & Stothers 1988; Courtillot & Renne 2003); see Fig. 1.

From Fig. 1 and Table 1, it can be seen that, over the last 260 Myr, 9 of the 13 proposed impact pulses correlate closely with times of mass extinction (including the Late Paleocene warming event), 7 impact pulses correlate with flood-basalt eruptions, 7 flood basalts correlate with mass extinctions and 6 impact pulses can be correlated with estimated times of the Solar system crossing the Galactic plane in the last 260 Myr, specifically in the model used by Randall & Reece (2014). From these data, we would predict an impact episode near 183 Myr ago, at a time of Galactic plane crossing. Because of possible bias in recent cratering data, the most recent mid-plane crossing in the last 2–3 Myr was not considered by Matsumoto & Kubotani (1996) and is not considered here, although it does correlate with the time of several recent impact craters, microtektite layers and a minor extinction in the Pliocene. Thus, we could be in a comet shower at the present time (Yabushita 1992;

Table 1. Mass extinctions, continental flood basalts and impact pulses (ages in Myr). Mass extinctions after Raup & Sepkoski (1986), ages after Gradstein, Ogg & Schmitz (2012); flood-basalt ages after Courtillot & Renne (2003) and Rampino & Self (2000); impact pulses (except for the last 5 Myr) after Matsumoto & Kubotani (1996) with updates, with uncertainties being in most cases peak half-width at half maximum.

Mass extinction		Flood basalt		Impact pulses
Pliocene	2.6	No flood basalt		NA
Middle Miocene	11.6	Columbia River	16 ± 0.5	12 ± 1
Late Eocene	37.8 ± 0.1	Ethiopian	30 ± 1	38 ± 2
Late Paleocene[a]	56 ± 0.2	North Atlantic	56 ± 1	57 ± 1
K-Pg boundary	66 ± 0.3	Deccan	66 ± 0.5	65 ± 1
				73 ± 1
Cenoman,-Turon.	94 ± 0.8	Madagascar	88 ± 2	89 ± 2
Aptian-Albian	113 ± 1	Rajmahal	116 ± 2	115 ± 2
Hauteriv-Barrem.[b]	131 ± 0.5	S. Geral/Etendeka	133 ± 1	128 ± 2
End Jurassic	145 ± 2	No flood basalt		143 ± 2
				167 ± 2
Pliensbach-Toarc.	183 ± 1.5	Karoo	183 ± 1	
End-Triassic	201 ± 1	Camp	201 ± 1	202 ± 2
Norian-Rhaetian	210 ± 2	No flood basalt		215 ± 3
End-Permian	252 ± 0.7	Siberian	251 ± 1	254 ± 2

Notes. [a]Not a true mass extinction, but a sudden global climatic warming.
[b]Possible mass extinction.

Shoemaker 1998). Statistical analyses suggest that these are unlikely to be chance correlations (Stothers 1993; Matsumoto & Kubotani 1996; Yabushita 1998), and the record seems to be made up of a combination of periodic and non-periodic impact/extinction/flood-basalt events.

Similarities in the cycle length and timing led to the idea that the comet or asteroid impacts were somehow affecting global tectonism, although a mechanism for this is not established (Clube & Napier 1982; Rampino & Stothers 1984b; Pal & Creer 1986; Rampino 1987; Muller 2002). Rampino & Caldeira (1992, 1993) extended the study to include the timing of 77 major terrestrial geologic events of various kinds during the past 250 Myr (continental flood basalts, tectonic episodes, extinctions, changes in sea-floor spreading, sea level and oceanic anoxic events) and reported a persistent cycle of ∼26–27 Myr in the occurrence of these events (see also Napier et al. 1998). Several studies also reported an ∼30 Myr period in the frequency of geomagnetic reversals over the last 250 Myr (Negi & Tiwari 1983; Raup 1985; Stothers 1986; Pal & Creer 1986), although these results have been challenged (Lutz 1985). Liritzis (1993) took a different track, and detected an ∼30 Myr cycle in the frequency of occurrence of radiometric dates over the past 600 Myr. Shaviv et al. (2014) recently reported both a 32 Myr and a 175 Myr cycle in oxygen-isotope analyses indicating climatic changes over the past 540 Myr.

4 ENCOUNTERS OF THE SOLAR SYSTEM WITH DM

The key to the problem may be the recognition that encounters of the Solar system with DM (composed of WIMPs) as it moves through the Galaxy's disc might cause capture of some of this matter within the Earth (Krauss, Srednicki & Wilczek 1986; Abbas & Abbas 1998). Incoming DM particles would scatter off nucleons, lose energy and become gravitationally captured when below the Earth's escape velocity. The gravitationally captured DM is expected to drift to the bottom of the potential well in the Earth's core (Gould 1987; Abbas & Abbas 1998). This leads to number densities high enough for mutual annihilation, with potential release of large amounts of energy.

All annihilation processes that directly or indirectly create photons, and where energy is delivered to the Earth's core through inelastic collisions, would lead to generation of heat within the planet. Depending on the nature of DM particles, various annihilation channels are possible (Abbas & Abbas 1998). Capture can be enhanced by resonant interactions when the WIMP mass is approximately equal to the nuclear mass of elements (e.g. Fe, Ni, S) abundant in the Earth's core (Gould 1987).

For the Earth, the capture rate of DM WIMP particles is given by Krauss, Srednicki & Wilczek (1986) as

$$N_{\rm E} = (4.7 \times 10^{17}\ {\rm s}^{-1})\,(3ab)\,(\rho_{0.3}\ v_{300}^{-3}\sigma_{N,32})\ \left(1 + m_X^2/m_N^2\right)^{-1}, \quad (1)$$

where m_X is the mass of the DM particle, m_N is the mass of a typical nucleus off which the particle elastically scatters with cross-section σ_N; ρ_X is the mean mass density of DM particles in the Solar system; v = the rms velocity of DM particles in the Solar system; $\rho_{0.3} = \rho_X/0.3\ {\rm GeV\ cm}^{-3}$; $\sigma_{N,\ 32} = \sigma_N/10^{-32}\ {\rm cm}^2$; $v_{300} = v/300\ {\rm km\ s}^{-1}$; and a and b are numerical factors of order unity, which depend upon the density profile of the Earth (Abbas & Abbas 1998).

In this case, heat generation in the Earth's core (Q_E) would be given by $Q_E = eN_{\rm E}m_X$, where e is the fraction of annihilations that leads to the production of heat within the Earth's core; e may be as large as 1.0 for the ideal case, where the WIMPs annihilate predominantly through photons only.

In equation (1), [following Abbas & Abbas (1998)] taking $ab = \sim 0.34$, $\rho 0.3 = 1$, $V_{300} = 1$, $m_X = 15$–100 GeV and the cross-section of iron to be $\sigma_N = 10^{-32}$ cm^2, it may be estimated that capture of DM and its annihilation in the Earth could lead to the generation of an amount of internal heat, Q_E up to 10^{10} W for encounters with normal DM density (Abbas & Abbas 1998). This is quite small in relation to the present terrestrial heat flow of $\sim 4 \times 10^{13}$ W (Mack, Beacom & Bertone 2007).

5 ENCOUNTERS WITH DENSE CLUMPS OF DM

For encounters with dense clumps of DM, however, with core DM densities up to 10^9 times the average (Silk & Stebbins 1993), Abbas (1999) found that up to 10^{19} W of internal heating is possible during clump crossing, with clumps encountered every ∼30–100 Myr (Collar 1996). Since disc DM is expected to be concentrated strongly in the plane of the Galaxy (Stothers 1984; Randall & Reece 2014), encounters with dense clumps of DM should preferentially occur when the Solar system is crossing the Galaxy's mid-plane, and hence would give those encounters an underlying periodicity of ∼30 Myr. Collar (1996) further suggested that in passing through a dense clump of DM, increased doses of radiation, such as alpha particles, fast neutrons and heavy ions could also contribute directly to extinctions.

For heating of the entire core of the Earth, if the mass of the Earth's core is 1.95×10^{24} kg and its specific heat is 800 J K^{-1} kg^{-1}, then it would take 1.56×10^{27} J to raise the temperature of the entire core by 1 K (although partial heating of the core is also possible). Using a heating rate of 10^{19} W, it would take about 5 years of heating to get a 1 K temperature rise within the entire core. So for the case of 10^{19} W heating, the accretion and annihilation of DM in dense clumps for a few thousand years could raise the Earth's core temperatures by hundreds of degree K.

Episodic heating of the Earth's core might affect the workings of the geodynamo and thus frequency of geomagnetic reversals, as the power requirement of the geodynamo is only 2–5 × 10^{11} W (Christensen & Tilgner 2004). Excess heat near the core-mantle boundary could trigger upwelling plumes of mantle material. These plumes could rise to the surface in possibly as short as a few million years, depending on mantle viscosity (Larson & Olson 1991). The plumes would create volcanic hotspots, rift apart continents and perturb mantle convection, possibly leading to pulses of tectonic unrest, changes in direction and rate of sea-floor spreading, and associated changes in volcanism, sea level and climate. Thus, periodic encounters of the Earth with dense clumps of DM particles may partially explain the episodic nature of terrestrial volcanism, geomagnetism and plate tectonics. Geologic events that have been thought of as independent occurrences might have common roots, and might be partly related to extraterrestrial forces.

Since the maximal heating rate due to DM in a planet scales with surface area (Mack, Beacom & Bertone 2007), the other terrestrial planets and the moons of the Jovian planets may be too small to experience much internal heating, except for Venus, which should also capture significant DM. Annihilation of planet-bound DM has been proposed to explain aspects of the heat flow of the Jovian planets (Kawasaki, Hitoshi & Yanagada 1992; Mack, Beacom & Bertone 2007; Adler 2009).

If this model of DM interactions with the Earth as it cycles through the Galaxy is correct, then it could explain much about the history of impacts on the Earth and other planets and moons, the geological and biological evolution of the Earth and of earth-like exoplanets, and tell us something about the nature and distribution of DM in the Galaxy and Solar system.

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REFERENCES

Abbas A., 1999, preprint (astro-ph/9910265)
Abbas S., Abbas A., 1998, Astropart. Phys., 8, 317
Adler S. L., 2009, Phys. Rev. Lett., 671, 203
Alvarez W. A., Muller R. A., 1984, Nature, 308, 718
Bahcall J. N., Bahcall S., 1985, Nature, 316, 706
Bailer-Jones C. A. L., 2009, Int. J. Astrobiol., 8, 239
Bailer-Jones C. A. L., 2011, MNRAS, 416, 1163
Bailey M. E., Stagg C. R., 1988, MNRAS, 235, 1
Chang H-Y., Moon H-K., 2005, PASJ, 57, 487
Christensen U. R., Tilgner A., 2004, Nature, 429, 169
Clube S. V. M., Napier W. M., 1982, Earth Planet. Sci. Lett, 57, 251
Collar J. J., 1996, Phys. Lett. B, 368, 26
Connor E. F., 1986, in Raup D. M., Jablonski D., eds, Patterns and Processes in the History of Life. Springer-Verlag, Berlin, p. 119
Courtillot V. E., Renne P. R., 2003, C. R. Geosci., 335, 113
Farley K., Montanari A., Shoemaker E. M., Shoemaker C. S., 1998, Science, 280, 1250
Farley K., 2002, Nature, 376, 153
Fox W. T., 1987, Paleobiology, 13, 257
Gardner E., Nurmi P., Flynn C., Mikkola S., 2010, MNRAS, 411, 947
Gould A., 1987, ApJ, 321, 571
Gradstein F. M., Ogg J. G., Schmitz M., Ogg G., 2012, The Geologic Time Scale. Elsevier, Boston
Grieve R. A. F., 1991, Meteoritics, 26, 175
Grieve R. A. F, Sharpton V. L., Rupert J. D., Goodacre A. K, 1988, Proc. 18th Lunar & Planet. Sci. Conf., Detecting a Periodic Signal in the Terrestrial Cratering Record. Cambridge Univ. Press, Cambridge, p. 375
Grieve R. A. F, Shoemaker E. M., 1994, in Gehrels T. ed., Hazards due to Asteroids and Comets. Univ. Arizona Press, Tucson, AZ, p. 417
Heisler J., Tremaine S., 1989, Icarus, 77, 213
Holmberg J., Flynn C., 2000, MNRAS, 313, 209
Jetsu L., Pelt J., 2000, A&A, 353, 409
Kawasaki M., Hitoshi H., Yanagida T., 1992, Prog. Theor. Phys., 87, 685
Krauss L. M., Srednicki M., Wilczek F., 1986, Phys. Rev. D, 33, 2079
Larson R. L., Olson P., 1991, Earth Planet Sci. Lett., 107, 437
Lieberman B. S., Melott A. L. 2012, in Talent J. A., ed., Earth and Life. Springer, Berlin, p. 37
Liritzis I., 1993, QJRAS, 34, 251
Lutz T. M., 1985, Nature, 317, 404
Lyytinen J., Jetsu I., Kajatkari P., Porceddu S., 2009, A&A, 499, 601
Mack G. D., Beacom J. F., Bertone G., 2007, Phys. Rev. D, 76, 043523
Matese J. J., Whitman P. J., Innanen K. A, Valtonen M. J., 1995, Icarus, 116, 255
Matese J. J, Innanen K. A., Valtonen M. J., 2001, in Marov M. Ya., Rickman H. eds, Collisional Processes in the Solar System. Kluwer, Dordrecht, p. 91
Matsumoto M., Kubotami H., 1996, MNRAS, 282, 1407
Melott A., Bambach R. K., 2010, MNRAS, 407, L99
Melott A., Bambach R. K., 2013, ApJ, 773, 6
Mukhopadhyay S., Farley K. A., Montanari A., 2001, Science, 291, 1952
Muller R. A., 2002, Geophys. Res. Lett., 29, 41
Napier W. M., 1998, Geol. Soc. London Spec. Publ., 140, 19
Napier W. M., 2006, MNRAS, 366, 977
Negi J. G., Tiwari R. K., 1983, Geophys. Res. Lett., 16, 713
Noma E., Glass A. L., 1987, Geol. Mag., 124, 319
Nurmi P., Valtonen M., Zheng J. Q., 2001, MNRAS, 327, 1357
Pal P. C., Creer K. M., 1986, Nature, 320, 148
Quinn J. F., 1987, Paleobiology, 13, 465
Rampino M. R., 1987, Nature, 327, 468
Rampino M. R., 2001, in Marov M. Ya., Rickman H. eds, Collisional Processes in the Solar System. Kluwer, Dordrecht, p. 103
Rampino M. R., Caldeira K., 1992, Celest. Mech. Dyn. Astron., 54, 143
Rampino M. R., Caldeira K., 1993, Earth Planet. Sci. Lett., 114, 215
Rampino M. R., Haggerty B. M., Pagano T. C., 1997, Ann. New York Acad. Sci., 822, 403

Rampino M. R, Self S., 2000, in Sigurdsson H. et al., , eds, Encyclopedia of Volcanoes. Academic Press, San Diego, p. 1083
Rampino M. R., Stothers R. B., 1984a, Nature, 308, 709
Rampino M. R., Stothers R. B., 1984b, Science, 226, 142
Rampino M. R., Stothers R. B., 1988, Science, 241, 663
Randall L., Reece M., 2014, Phys. Rev. Lett., 112, 161301
Raup D. M., 1985, Nature, 314, 341
Raup D. M., Sepkoski J. J., Jr, 1982, Science, 215, 1501
Raup D. M., Sepkoski J. J., Jr, 1984, Proc. Natl. Acad. Sci. USA, 81, 801
Raup D. M., Sepkoski J. J., Jr, 1986, Science, 231, 833
Schulte P. et al., 2010, Science, 327, 1214
Shaviv N., Prokoph A., Veizer J., 2014, Nat. Sci. Rep., 4, 6150
Shoemaker E. M., 1998, J. R. Astron. Soc. Can., 92, 397
Shuter W. L. H., Klatt C., 1986, ApJ., 301, 471
Silk J., Stebbins A., 1993, ApJ., 411, 439
Smoluchowski S., Bahcall J. N., Matthews M. S., eds, 1986, The Galaxy and the Solar System. Univ. Arizona Press, Tucson, AZ
Stigler S. M., Wagner M. L., 1987, Science, 238, 940
Stothers R. B., 1984, Nature, 311, 17
Stothers R. B., 1986, Nature, 322, 444
Stothers R. B., 1989, Geophys. Res. Lett., 16, 119
Stothers R. B., 1993, Geophys. Res. Lett., 20, 1399
Stothers R. B., 1998, MNRAS, 300, 1098
Stothers R. B., 2006, MNRAS, 365, 178
Trefil J. S., Raup D. M., 1987, Earth Planet. Sci. Lett., 82, 59
Wickramasinghe J. T., Napier W. M., 2008, MNRAS, 387, 153
Yabushita S., 1992, Earth Moon Planets, 58, 57
Yabushita S., 1996a, Earth Moon Planets, 72, 343
Yabushita S., 1996b, MNRAS, 279, 727
Yabushita S., 1998, Celest Mech. Dyn. Astron., 69, 31
Yabushita S., 2002, MNRAS, 334, 369

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