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Evidence for cometary bombardment episodes

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ABSTRACT

Evidence is found that large terrestrial impacts tend to cluster in discrete episodes, with characteristic separations 25–30 Myr and durations of about 1–2 Myr. The largest impactors are strongly concentrated within such events, and the Cretaceous–Tertiary extinctions occurred within one of them. The evidence also indicates the presence of a weak periodicity, which might be ∼24, ∼35 or ∼42 Myr depending on which peaks are taken as harmonics. The periodicity is most easily explained as a result of the action of the Galactic tide on the Oort comet cloud. The two longer period solutions are consistent with Galactic density estimates and with the current passage of the Solar system through the plane of the Galaxy. Other episodes may be a result of sporadic encounters with spiral arms, nebulae or stars.

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

1 INTRODUCTION

Impact cratering on the Earth is now well established as a catastrophic geological process. That there might be a pattern of episodicity, or even periodicity, in the rate of arrival of large impactors has been suggested from time to time. Napier & Clube (1979) proposed that Galactic disturbances of the Oort Cloud might generate bombardment episodes, which in turn could generate mass extinctions of life and geological disturbances. Periodicity of such episodes might be expected by virtue of spiral arm penetrations (ibid.; Leitch & Vasisht 1998) and the variation of the Galactic tides which perturb the orbits of long-period comets (Napier 1987; Matese et al. 1995; Nurmi, Valtonen & Zheng 2001), but several other phenomena could yield sporadic bombardment episodes: the breakup of a very large comet (Clube & Napier 1984; Bailey et al. 1994); the passage of a star through a dense inner Oort Cloud (Hills 1984; Hut et al. 1987); or a close encounter with a massive nebula (Napier & Staniucha 1982; Clube & Napier 1982).

About 170 confirmed impact structures were known by the end of 2004, 40 of which have been dated with precision $\sigma \leqslant 10$ Myr, are less than 250 Myr old and have diameters $\geqslant$3 km (Earth Impact Database 2005). 35 of these 40 have ages with formal $\sigma \leqslant 5$ Myr, 18 with $\sigma \leqslant 1$ Myr. The data base of well-dated craters has about tripled in the last 20 yr and has now reached the stage where strong episodicity and periodicity, as predicted by the above hypotheses, might now be detected with some degree of statistical confidence. In this paper I describe the results of such an analysis. I find that there is evidence that large impacts do not occur at random but, rather, are concentrated into strong discrete episodes of bombardment. Both random and periodic components seem to be present, the latter consistent with a solar oscillation about the Galactic plane. The random surges interfere with the analysis and do not allow the periodicity to be specified unambiguously: it may be one of ∼(24, 35, 42) Myr. It also appears that we are immersed in a bombardment episode now.

Episodicity or periodicity in the rate of impacts, if present, has a bearing on the likely source of impactors and the mechanisms which might be responsible for terrestrial phenomena such as mass extinctions. A one-off stray asteroid yields a 'sudden death' set of expectations; an episode of cometary bombardment will involve both prolonged multiple impacts and atmospheric dusting and so yield another. Further, given the existence of surges, assessments of the current celestial hazard based on Poissonian assumptions about cratering on old surfaces may not reflect current circumstances.

2 LARGE BOLIDES

Table 1 lists the 40 terrestrial impact craters known to epoch 2004 November, satisfying the following criteria:

(i) diameter $\geqslant$3 km;
(ii) age $\leqslant$250 Myr;
(iii) ages quoted to precision $\sigma \leqslant 10$ Myr. These have been culled from the Earth Impact Database (2005).

Six of these 40 craters are less than 5 Myr old. One, Kara-Kul in Tajikistan, has an age given only as an upper limit of <5 Myr, which I have replaced by 2.5 ± 2.5 Myr. All but five have $\sigma < 5$ Myr. Their age distribution is plotted in Fig. 1, along with a cubic spline fit. The fit clearly shows a decline in the known craters with increasing age, presumably because of loss with time through erosion and sedimentation.

3 CLUSTERING

Assuming the true cratering rate has not changed secularly over the last 250 Myr, it is clear from the steep decline in Fig. 1 that discovery of impact craters is highly incomplete, even amongst the largest

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Table 1. Impact craters used in this paper.

N	Crater	D (km)	Age (Myr)	σ (Myr)
01	Gusev	3	49.0	0.2
02	Zapadnaya	3	165.0	5.0
03	Steinheim	4	15.0	1.0
04	Chiyli	6	46.0	7.0
05	Wetumpka	7	81.0	5.0
06	Wanapetei	8	37.2	1.2
07	Bigach	8	5.0	3.0
08	Mien	9	121.0	2.3
09	Ragozinka	9	46.0	3.0
10	Karla	10	5.0	1.0
11	Bosumtwi	10	1.1	0.0
12	Marquez	13	58.0	2.0
13	Deep Bay	13	99.0	4.0
14	Zhamanshin	14	0.9	0.1
15	Logoisk	15	42.3	1.1
16	El'gygytyn	18	3.5	0.5
17	Dellen	19	89.0	2.7
18	Gosses Bluff	22	142.5	0.8
19	Rochechouart	23	214.0	8.0
20	Lappajarvi	23	73.3	5.3
21	Ries	24	15.1	0.1
22	Boltysh	24	65.17	0.64
23	Haughton	24	23.0	1.0
24	Kamensk	25	49.0	0.2
25	Steen River	25	91.0	7.0
26	Mistastin	28	36.4	4.0
27	Manson	35	73.8	0.3
28	Carswell	39	115.0	10.0
29	Mjolnir	40	142.0	2.6
30	Araghuaina	40	244.40	3.25
31	Montagnais	45	50.50	0.76
32	Kara-Kul	52	2.5	2.5
33	Tookoonooka	55	128.0	5.0
34	Kara	65	70.3	2.2
35	Morokweng	70	145.0	0.8
36	Puch.-Kat.	80	167.0	3.0
37	Chesapeake	90	35.5	0.3
38	Manicougan	100	214.0	1.0
39	Popigai	100	35.7	0.2
40	Chicxulub	170	64.98	0.05

ones. If all recent craters $\gtrsim$3 km across have been discovered – an unlikely assumption – completeness has declined to ~40 per cent within 100 Myr and ~10 per cent within 200 Myr (much higher survival rates have been claimed by Hughes 2000). Thus, to be detected at all in the geological record, a comet shower would have to be relatively strong; and it might now be represented, if at all, by only two or three surviving impact structures of similar age, scattered over the Earth. A periodic modulation of amplitude say 2:1 to 5 : 1 in the cratering rate as a result of variable Galactic tides might reasonably be expected (Matese et al. 1995; Clube & Napier 1996; Nurmi et al. 2001), although over the 250-Myr record discussed here there is a reasonable probability of a phase shift as a result of spiral arm or nebula encounters.

Examining Fig. 1, there is a suggestion that some craters do tend to bunch together at discrete epochs. This can be seen more clearly in Fig. 2, in which the age distribution has been smoothed by application of a rectangular window 8 Myr wide. Peaks appear in the distribution, some distinctive, some less so. Eight putative impact

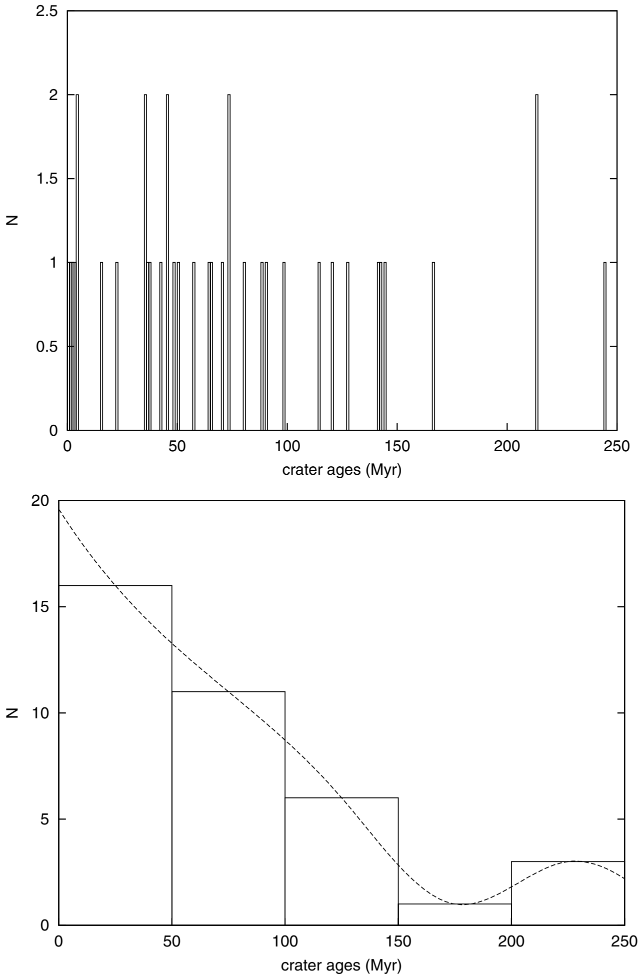

Figure 1. Top: age distribution of impact craters listed in Table 1 with ages $t \leqslant 250$ Myr and $\sigma \leqslant 5$ Myr. Bottom: the data represented as a histogram and a cubic spline fit.

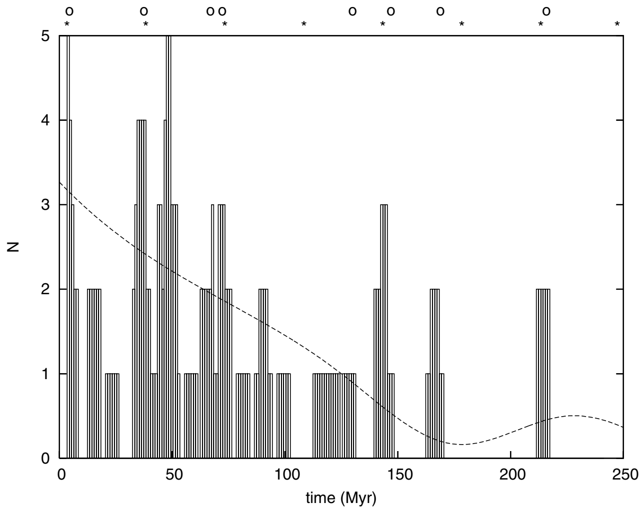

Figure 2. Possible epochs of enhanced bombardment. The age distribution has been smoothed by a rectangular window of width 8 Myr, in steps of 1 Myr. Distinct peaks appear and the craters within them are listed in Table 2. The circles represent the formation dates of all craters >40 km across. The asterisks mark out a best-fitting periodicity of 36 Myr.

Table 2. Possible impact episodes.

Episode	Craters	Age (Myr)	Diameter (km)
1	Zhamanshin	0.9 ± 0.1	14
	Bosumptwi	1.1 ± 0.0	10
	Kara-Kul	2.5 ± 2.5	52
	El'gygytyn	3.5 ± 0.5	18
	Bigach	5.0 ± 3.0	8
	Karla	5.0 ± 1.0	10
2	Chesapeake	35.5 ± 0.3	90
	Popigai	35.7 ± 0.2	100
	Mistastin	36 ± 4	28
	Wanapetei	37.2 ± 1.2	8
3	Ragozinka	46 ± 3	9
	Gusev	49.0 ± 0.2	3
	Kamensk	49.0 ± 0.2	25
	Montagnais	50.5 ± 0.76	45
4	Chicxulub	64.98 ± 0.05	170
	Boltysh	65.17 ± 0.64	24
5	Ust-Kara, Kara	70.3 ± 2.2	25,65
	Lappajarvi	73.3 ± 5.3	23
	Manson	73.8 ± 0.3	35
6	Mjolnir	142.0 ± 2.6	40
	Gosses Bluff	142.5 ± 0.8	22
	Morokweng	145.0 ± 0.8	70
7	Zapadnaya	165 ± 5	3
	Puchezh-Katunki	167 ± 3	80
8	Manicougan	214 ± 1	100
	Rochechouart	214 ± 8	23

episodes are listed in Table 2; their selection was subjective and so their reality has to be tested. The discovery selection effect may be involved to some extent in the most recent episode, but the concentration towards the recent past seems too strong for this to be a full explanation: seven of the nine impact craters formed within the last 15 Myr were created within the last 5 Myr; no craters in the list appear in the range 5–10 Myr, and only two in the range 10–25 Myr. The question is then: are these apparent groupings real, or would such arise in any random distribution of impacts?

To test this, synthetic data sets consisting of 'craters' randomly distributed in time were constructed, and a 'nearest-neighbour' count was carried out for each data set – 'nearest' in this context being in time rather than space. Dates were extracted randomly from the spline curve shown in Fig. 1 so that the overall distribution of 'impact times' simulated that of the real data set. For each such artificial data set, the numbers of crater pairs separated by less than a prescribed interval of time Δt were counted. Fig. 3 shows the outcome of these trials as compared with the real data; the error bars shown are crude Poissonian estimates: if eight crater pairs are found with separations $\lesssim 0.4$ Myr, say, then the uncertainty in this is taken as $\sqrt{8} \sim 2.8$. Fig. 4 shows the probability distribution of the pair counts in which a 'pair' of craters was defined by $\Delta t \leqslant 0.5$ Myr. The real data set has 10 such pairs, a number attained or exceeded by 15 in a thousand trials with synthetic data sets. On this evidence, therefore, at least some of the apparent bombardment episodes are likely to be real, at confidence level ~99 per cent. Table 2 could of course contain 'false positives'. This estimate is likely to be a lower limit because the procedure takes no account of the errors associated with the age determinations; the effect of declining accuracy would be to progressively obscure any real episodicity.

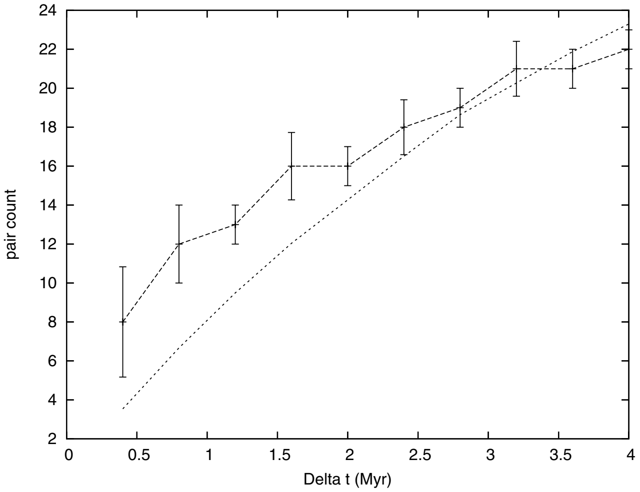

Figure 3. Excess of crater pairs as a function of counting threshold Δt. Upper curve: the 40 craters of Table 1. Lower curve: mean counts of 1000 synthetic data sets obtained by random extraction from the spline curve of Fig. 1.

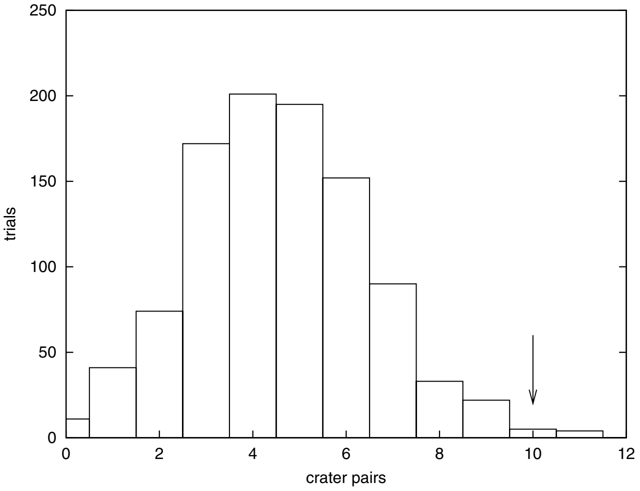

Figure 4. Count of impact crater pairs from synthetic data sets, the pairs defined by $\Delta t \leqslant 0.5$ Myr. There are 1000 trials. The vertical arrow shows the numbers of pairs for the real data set.

The effect of dating errors was examined in two ways. First, the distribution function of the crater ages was computed, taking account of their uncertainties, which were assumed to have a Gaussian distribution (Fig. 5). The distributions are sharply peaked, with four episodes standing out clearly. One of these (at 15 Myr) is the Ries and Steinheim pair, probably representing a single impact event. The Cretaceous–Tertiary pair (Chicxulub and Boltysh) form an outstandingly strong peak, because of their closeness in age and the smallness of the associated error bars. The probability of attaining the three peaks by chance was assessed as before, constructing synthetic probability distributions, with the age uncertainties assigned to the synthetic craters by randomly shuffling the given error distribution. Out of a thousand such trials, 12 had three or more peaks with strengths in excess of those observed. That is, taking full account

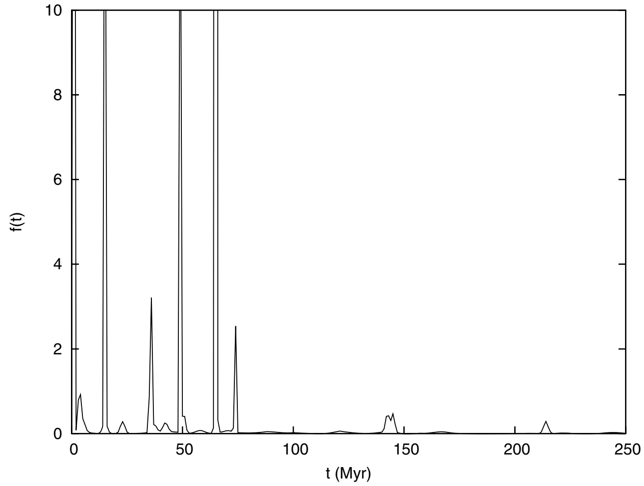

Figure 5. Distribution function $f(t)$ of crater ages determined using the (assumed Gaussian) error bars associated with individual measurements. The highest peaks are off the graph and occur at the present epoch (height 32.4), 15 Myr BP (17.4), 49 Myr BP (14.2) and 65 Myr BP (104.8).

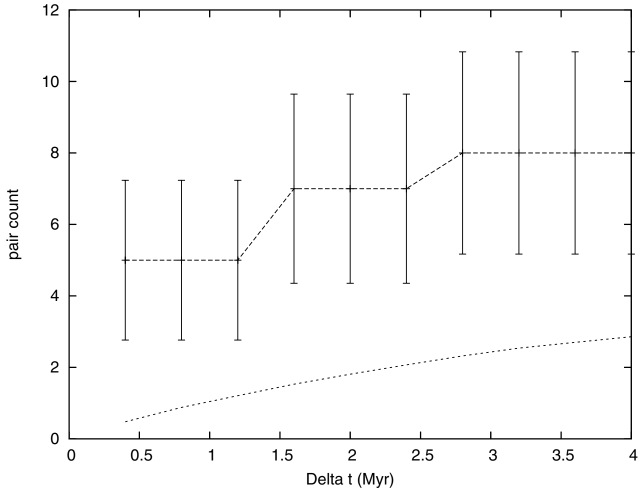

Figure 6. As Fig. 3, but applied to 20 craters with rms age determinations $\Sigma < 1.5$ Myr, and adopting $\Delta t \leqslant 4$ Myr.

of the distribution of age uncertainties, the three major episodes (1, 3, 4) at (0, 49, 65) Myr BP at least appear to be real, at a confidence level ~99 per cent.

The second approach was simply to conduct trials using a reduced data set of 20 extremely well-dated craters. In the limit when $\sigma \ll T$, where T is the duration of a bombardment episode, dating inaccuracies will not strongly degrade any underlying structure. A crater pair was defined through having ages with quoted precision $\Sigma \leqslant 1.5$ Myr (Σ is the rms sum), and age differences $\Delta t \leqslant 4$ Myr. This procedure has the advantage that weaker episodes are given due weight rather than being overwhelmed by the statistically strongest episodes. The outcome of 1000 trials is illustrated in Fig. 6. There are eight crater pairs so defined, as against an expectation of 2.3 from the random data, a result which has probability $p \sim 1.9 \times 10^{-3}$ of arising by chance. The probability declines as Δt is reduced until, for $\Delta t \leqslant 0.4$ Myr, five pairs are found as against an expectation of 0.34, and $p \sim 2.7 \times 10^{-5}$. Thus, the effect of using high precision data is to strengthen the conclusion that the apparent bombardment episodes are real.

Table 3. Peak power I for craters of diameter $> D_{\rm min}$ km. N represents the number of craters, and P and ϕ are the best-fitting periodicity and phase, respectively.

$D_{\rm min}$	N	P	ϕ	I
5	37	34.7	4.2	8.6
20	23	24.5	19.9	7.1
40	12	34.9	0.5	7.0
60	7	35.5	34.1	7.7
80	5	25.6	11.3	8.0

Amongst the younger craters, say <100 Myr old, saturation effects will tend to disguise any tendency to clustering. There are 29 craters <100 Myr old, with a mean separation ~3.4 Myr (hence the merging of 'real' and 'synthetic' curves beyond ~3 Myr in Fig. 3). The Δt criterion employed above is therefore necessarily stringent, and excludes episodes 6, 7 and 8 of Table 3. However, these older craters are more sparsely scattered in time and an independent check with a more relaxed criterion is possible. Seven of the eight craters over 130 Myr old, scattered over a 120-Myr interval, seem to belong to three age groupings, within their age measurement errors. What is the probability that this is due to chance? Take episodes (6, 7, 8) as boxes (5, 10, 16) Myr wide respectively, corresponding to 2σ for Mjolnir, Zapadnaya and Rochechouart, respectively. Then the boxes occupy 31/120 or 0.25 of the 120-Myr time-span under consideration, and each of the remaining five craters thus has a probability $p \sim 0.25$ of falling into a box by chance. Four of the five do, an event which has chance expectancy ~0.015.

There is a strong tendency for the larger craters to belong to the bombardment episodes identified in Table 2. Thus, the mean diameter of the 20 craters belonging to the bombardment episodes is ~47 km; that of those outside is ~20 km. In fact, every large crater found so far was formed inside such an event. Nothing in the analysis would generate this correlation spuriously, and so this further supports the hypothesis that the bombardment episodes are real rather than statistical artefacts.

4 PERIODICITY: A BOOTSTRAP ANALYSIS

Seyfert & Sirkin (1979) claimed that impact craters occurred in discrete epochs of bombardment, recurring with a ~26-Myr cycle. Their data set, however, was an inhomogeneous mix with no estimates of accuracy and they did not attempt to quantify their claim. Rampino & Stothers (1984), with a data set of 41 craters which excluded very recent events, found evidence for a periodicity 30 ± 1 Myr in crater ages over the past 250 Myr. Alvarez & Muller (1984) found a moderately strong 28.4-Myr periodicity in 11 craters whose ages were known to relatively high precision. The existence of periodicity in the record has since been disputed by a number of authors (e.g. Grieve & Pesonen 1996) on the grounds of uncertainties in age estimates, biases in the record and the like. Others (e.g. Yabushita 2002, 2004) have continued to claim that a significant periodic signal is present, and to associate peaks with geological events (Stothers & Rampino 1990; Rampino & Haggerty 1996; Napier 1998).

Solutions that have appeared in the literature have generally clustered around two discrete values $P \sim 25$ Myr or ~35 Myr: for the former, see for example Napier (1998) and Chang & Moon (2005); for the latter, see Stothers (1998) and Yabushita (2002, 2004). Peaks at 13.5 or 18 Myr have sometimes predominated and been interpreted as harmonics (half-periods) of the basic periodicity. Although these solutions are weak, they have persisted as the data set has grown. This behaviour is illustrated in Table 3, which tabulates the outcome of power spectrum analysis (PSA) for subsets of increasingly large craters. Depending on the vagaries of data choice, periodicities of ~25 or ~35 Myr emerge, none of them of very high statistical significance [power I is here defined conventionally such that $\langle I \rangle = 2$ for white noise, the single-trial probability of a random signal exceeding I by chance declining as $\exp(-I/2)$].

The crater age distribution is a representation of the underlying stochastic process, but it is only a single sample from a universe of possible random samples, dictated by the vagaries of impact history. In a bootstrap analysis we repeatedly sample from this given age distribution to simulate the full range of possible impact histories consistent with the data (e.g. Manley 1997). Thus, we extract 40 crater ages at random from Table 1 – with replenishment, so that some craters may be chosen two or three times, others not at all – apply a PSA, record the peak power anywhere in the range 20–60 Myr, and repeat the process. The outcome is shown in Fig. 7 for 1000 such trials. Fig. 7 also gives the outcome of a bootstrap analysis of synthetic data sets, created by randomly extracting 40 'craters' at a time from the spline curve of Fig. 1. The solutions in the two cases are quite different in character and confirm that the impact crater data set is not consistent with random sampling from a smooth, secularly declining distribution.

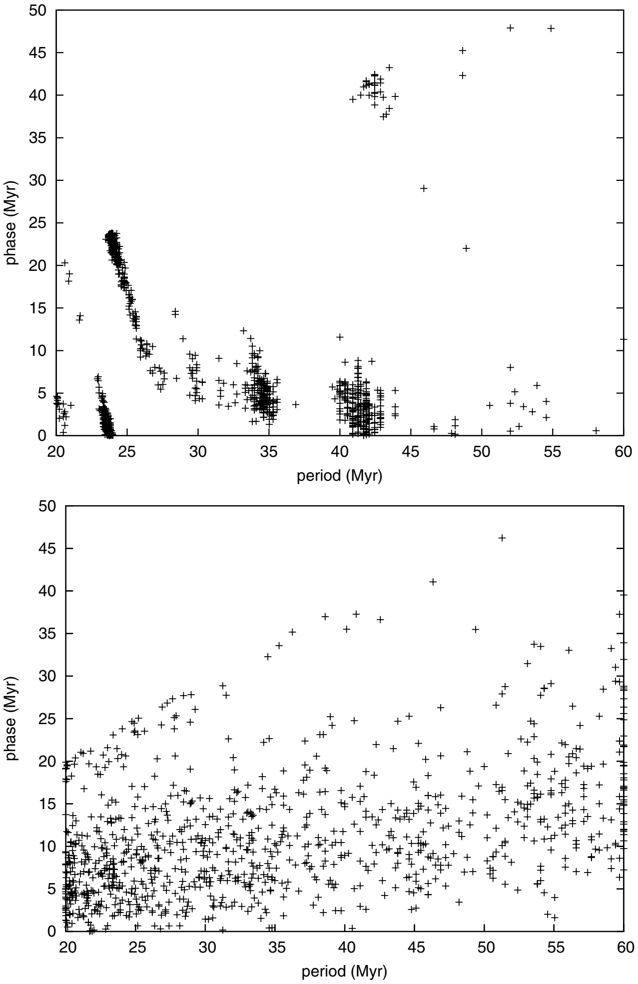

Figure 7. Upper: 1000 periodicity solutions for the impact craters listed in Table 1, obtained from a bootstrap analysis. The phase is the time elapsed since the most recent peak. Lower: solutions obtained from synthetic data sets created by random extraction from the spline fit of Fig. 1

As to the nature of this structure, we note that periodic solutions close to two predominant solutions in the literature emerge from this procedure, one around $(P, \phi) \sim (25, 10)$ Myr and the other around $(P, \phi) \sim (35, 3)$ Myr. The figure also reveals a new class of solution, with periodicity around 42 Myr and phase ~2 Myr, and a weak signal at ~30 Myr. The solutions (24, 30, 36, 42) Myr are in the ratio (4 :: 5 :: 6 :: 7). In essence, if a periodicity is weak, harmonics of the underlying signal will often dominate over the basic periodicity, small changes in the data set causing sometimes one solution to dominate, sometimes another. As to which solution is 'real' and which are harmonics, no secure preference emerges for one over the others in the present case.

As described in Section 1, it is expected that the Oort Cloud is subjected to Galactic disturbances which are both periodic and sporadic. Periodicities of (25, 30, 36, 42) Myr correspond to mid-plane densities (0.30, 0.20, 0.14, 0.10) $\mathrm{M_\odot\ pc^{-3}}$, respectively. The *Hipparcos* data give 0.10 $\mathrm{M_\odot\ pc^{-3}}$ to within 10 per cent for the Galactic mid-plane density (Holmberg & Flynn 2000), although Stothers (1998) has argued for a density 0.15 $\mathrm{M_\odot\ pc^{-3}}$ from a variety of astronomical data (see the discussion by Yabushita 2004). Thus, the solutions around 25 and 30 Myr seem definitely inconsistent with the Galactic hypothesis, but either of the long-period solutions (36, 42) Myr is consistent with published estimates of the Galactic mid-plane density. The Sun passed through the plane of the Galaxy 2–3 Myr BP, when the tidal stress on the Oort Cloud was at its peak. Because the infall time of a long-period comet is ~2–3 Myr, it is likely that we are in a bombardment episode now. This is again consistent with either of the two long-period solutions but not the 25-Myr set, which peaks around 10–12 Myr BP.

A real periodicity immersed in noisy data will emerge with increasing strength as the data set grows. The number of precisely dated craters has more than trebled since the early studies by Alvarez & Muller (1984) and Rampino & Stothers (1984), and if the periodic signal found by them were real, one might expect it to be much stronger in the modern impact cratering data, all else being equal. Conversely, a spurious signal would have died away. Neither of these has happened.

The explanation may lie in the randomly placed bombardment episodes. In the presence of systematic structure of comparable size, a weak periodicity will remain weak no matter how much the data set grows, because the contributions of periodic and discrete episodes will increase pro rata. The impact cratering data set seems to be of this character: the same solutions have continued to emerge as the sample of well-dated craters has tripled in size. Thus, the structure of the cratering record has remained robust, and seems to show a weak periodicity in combination with discrete bombardment epiodes.

5 DISCUSSION AND CONCLUSIONS

The present study has revealed evidence for structure on a number of characteristic time-scales in the impact cratering record of the past 250 Myr. These are, first, a secular trend, which is most easily understood as caused by the progressive effects of erosion and sedimentation. Secondly, there is 'fine structure' in the form of bombardment episodes of duration $\lesssim$1–2 Myr, in which bolides $\gtrsim$1 km across enter the atmosphere as part of a swarm. Thirdly, these episodes show evidence of periodicity whose period and phase are easily matched with those expected from Galactic perturbations of the Oort Cloud.

The relative contributions of comets and asteroids to the impact rate on Earth remain uncertain over almost the entire impact energy spectrum. The main asteroid belt may provide bodies of km or subkm dimensions through fast dynamical routes, although whether it can replenish larger bodies at a sufficient rate is doubtful. It is also doubtful whether asteroid breakup can supply the bombardment episodes:

The discovery of large craters is very incomplete and so two or three known craters $\gtrsim$20 km across within a bombardment episode probably represent the tip of a much larger iceberg. Only about 1–4 per cent of asteroids perturbed into Earth-crossing orbits actually hit the Earth, most falling into the Sun or being ejected from the Solar system, and of those which do, two-thirds will land in the oceans and go unrecorded. These factors combined with incompleteness of discovery on land imply that, in order to reproduce the observed pairs and triplets, probably hundreds of large bolides would have to be injected into near-Earth orbits. If they derived from the collisional breakup of a parent body in the main asteroid belt, the parent body would have had to be say 20–30 km across. However, the collisional lifetimes of 20-km main-belt asteroids are of the order of a Gyr, inadequate to generate surges at characteristic intervals ∼25–30 Myr. Further, the spread of arrival times is typically tens of Myr, smoothing out any surges. Thus, the strong bombardment episodes found here are difficult to reconcile with an asteroid belt provenance.

The sharpness of the bombardment episodes (1–2 Myr) relative to their characteristic separation (∼25–30 Myr) implies that the surges are substantial, perhaps an order of magnitude. If the periodic component is a result of tidal perturbations of the Oort Cloud, then the current position of the Sun in its Galactic orbit implies that we should be undergoing a peak of bombardment now (Napier 1987, 1998). Thus, the apparent concentration of very young crater ages in Table 1 is likely to be largely real rather than a discovery artefact.

The resolving power of other Solar system surfaces (e.g. Europa whose surface has age ∼10 Myr; Zahnle, Dones & Levison 2003) is inadequate to check independently whether a bombardment episode is currently underway, while the near-Earth object surveys may be missing many low-albedo, dormant comets (Napier, Wickramasinghe & Wickramasinghe 2004; Asher et al. 2005). The terrestrial atmosphere will progressively winnow out more fragile bodies at smaller sizes, yielding a preponderance of stony or rocky missiles below some threshold. Hughes (2002) finds that the atmosphere has a negligible effect on the formation of craters $\gtrsim 21.0 \pm 1.5$ km. Ground data are thus not available to say how far down the scale of impactor dimensions these amplitude fluctuations hold.

Two main terrestrial consequences flow from the conclusion that the Earth is subject to strong bombardment episodes. First, crater counting on ancient terrains such as the lunar surface may not provide an accurate guide to the current impact hazard. Arguments have indeed recently been given to suggest that the current small-body impact rate is about an order of magnitude higher than that inferred from the long-term lunar cratering record (Asher et al. 2005). Secondly, cometary impact episodes involving large bodies, significant quantities of dust and prolonged trauma seem to provide a more plausible astronomical framework for mass extinctions than the popular but over-simplistic one-off asteroid scenario.

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