Impact cratering and the Oort Cloud

J. T. Wickramasinghe* and W. M. Napier*
Cardiff Centre for Astrobiology, Cardiff University, 2 North Road, Cardiff CF10 3DY

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ABSTRACT
We calculate the expected flux profile of comets into the planetary system from the Oort Cloud arising from Galactic tides and encounters with molecular clouds. We find that both periodic and sporadic bombardment episodes, with amplitudes an order of magnitude above background, occur on characteristic time-scales \( \sim 25-35 \) Myr. Bombardment episodes occurring preferentially during spiral arm crossings may be responsible both for mass extinctions of life and the transfer of viable microorganisms from the bombarded Earth into the disturbing nebulae. Good agreement is found between the theoretical expectations and the age distribution of large, well-dated terrestrial impact craters of the past 250 Myr. A weak periodicity of \( \sim 36 \) Myr in the cratering record is consistent with the Sun’s recent passage through the Galactic plane, and implies a central plane density \( \sim 0.15 \, M_\odot \, \text{pc}^{-3} \). This leaves little room for a significant dark matter component in the disc.

Key words: astrobiology – Oort Cloud.

1 INTRODUCTION
It has been proposed that disturbances of the Oort Cloud due to encounters with spiral arms and molecular clouds would lead to episodes of bombardment of comets on to the Earth, and that these episodes would cause geological disturbances and mass extinctions of life such as the Cretaceous–Tertiary event of 65 Myr BP (Napier & Clube 1979). More recently, it has been pointed out that such episodes may also provide a mechanism for interstellar panspermia (Napier 2004, 2007; Wickramasinghe 2007). Microorganisms thrown from the surface of the Earth by large impacts may be ejected by radiation pressure into star-forming regions within the passing nebula, and so seed protoplanetary nebulae within them. The transfer of microorganisms from Earth to protoplanetary nebulae is comfortably less than the time expected for cosmic rays to sterilize them (e.g. Mileikowsky et al. 2000; Horneck et al. 2002; Bidle et al. 2007).

A key feature of both the extinction and panspermia processes is the enhanced terrestrial impact rate occurring during the encounter with the nebula. In the present paper we examine this quantitatively. We find that order of magnitude increases in the impact rate of comets on to the Earth occur during encounters with molecular clouds of \( \gtrsim 5 \times 10^4 \, M_\odot \) and that such encounters take place quite frequently on geological time-scales (Napier 2007). If, within a giant molecular cloud, there are at least 1,1 exosystems with a receptive planet and an impact environment permitting the escape of microbiota, life may propagate throughout the habitable zone of the Galaxy within the lifetime of the Galactic disc (Napier 2007). In addition to these sporadic episodes, periodic impact surges are also expected to occur due to the variable stress exerted on the Oort Cloud by the vertical Galactic tide. The impact cratering record is thus predicted to be dominated by surges showing a weak periodicity. In the present paper we show that the record of well-dated impact craters of the last 250 Myr does indeed have this character. Thus the major impactors on Earth are probably for the most part comets, coming in as ‘showers’.

2 COMPUTATIONAL AND ANALYTIC CONSIDERATIONS
The adopted initial configuration of the Oort Cloud, being dictated by its mode of origin, is model dependent and uncertain, and the cloud will evolve from this initial state under the influence of various perturbers. The strongest perturbers acting on the Oort Cloud as a whole are the vertical Galactic tide (Byl 1986) and passing molecular clouds (Napier & Staniucha 1982). An orbit influenced by this tide conserves its semimajor axis but the initial eccentricities and inclinations vary cyclically; thus an initial ensemble will relax towards some statistical equilibrium of eccentricity and inclination.

The evolution of Oort Cloud comets under the influence of the vertical Galactic tide was first computed, in order to find this equilibrium distribution. For a differential semimajor axis distribution \( n(a) \propto a^{-\gamma} \), initial values of \( \gamma \) in the range \( 2 \leq \gamma \leq 4 \) were adopted for the outer Oort Cloud (Bailey 1983; Fernandez & Ip 1987), although probably no single power-law fits the entire range (Emel’yanenko, Asher & Bailey 2007). As a measure of the relaxation time, the flux of comets entering spheres of various radii was computed. Three independent approaches were used.

(i) Straightforward numerical integration (fourth-order Runge–Kutta with error control using the Fehlberg procedure; see e.g. Gerald & Wheatley 1994).

*E-mail: janakitara@hotmail.com (JTW); napierwm@cardiff.ac.uk (WMN)
interstellar material in the disc was taken to decline exponentially with scaleheight 60 pc (Joshi 2007), and the vertical motion of the Sun was then given by solving

\[ z = -4\pi G \rho(z) z \] (1)

The period and amplitude of the solar orbit may then be found, for a prescribed vertical velocity \( v_0 \) at \( z = 0 \) pc. The run of density against time may then be combined with the local tidal force \( T \) acting on an Oort Cloud comet:

\[ T = 4\pi G \rho(z) z_c \] (2)

where \( z_c \) represents the vertical height of the comet above or below the Sun.

The **Hipparcos** data have been used to yield a local in-plane density \( \rho_0 = 0.105 \, \text{M}_\odot \, \text{pc}^{-3} \) (Holmberg & Flynn 2004), but this appears to be an underestimate by \( \sim 50 \) per cent due to incompleteness of discovery of low-luminosity stars (Garcia-Sanchez et al. 2001). Stothers (1998) has argued for a local value \( \sim 0.15 \pm 0.01 \, \text{M}_\odot \, \text{pc}^{-3} \), while Svensmark (2007) has argued for a mean in-plane density \( \sim 0.145 \pm 0.01 \, \text{M}_\odot \, \text{pc}^{-3} \) averaged over the Sun’s traversal of the Galaxy over the last 200 Myr. Adopting the latter value and assuming \( v_0 = 9 \, \text{km s}^{-1} \), the variation of flux of long-period comets into the Solar system is derived as shown in Fig. 3. The tidal cycle has amplitude 2:1, and the peaks are quite sharp. In Section 5 we argue that this is detectable in the record of impact cratering on Earth. Depending on the uncertain scaleheight of the low-luminosity stars, amplitude ratios of around 2:1 to 5:1 are obtained in these models.

4 FLUX MODULATION DUE TO ENCOUNTERS WITH NEBULAE

In addition to the cyclic component of the long-period comet flux, sporadic surges are expected due to close encounters with stars and nebulae. The former have been studied by a number of authors. The Oort Cloud is known to be unstable in the Galactic environment due to the disruptive effect of encounters with massive nebulae. The half-life due to such encounters is \( \sim 1.9 \) Gyr (Bailey, Clube &
Earth. If the density of molecular clouds has halved over the lifetime of ten such encounters over the period in which life has existed on V where $\sigma$ represents the asymptotic encounter velocity and $(V_e/V)^2$ is significant for a close encounter with a massive nebula. For example, a giant molecular cloud (GMC) of mass $M = 5 \times 10^5 M_\odot$ and radius 20 pc has a surface escape velocity $V_e \sim 15$ km s$^{-1}$, and so for an asymptotic approach speed $15$ km s$^{-1}$ the mean interval between grazing encounters is halved from 800 to 400 Myr, implying about ten such encounters over the period in which life has existed on Earth. If the density of molecular clouds has halved over the lifetime of the Solar system (Talbot & Newman 1977), then the expected number of encounters should be increased by about 25 per cent over this period. The differential mass distribution of molecular clouds is found to be a power law over at least eight decades of mass, with index $\alpha = 1.6 \pm 0.2$ (Mundy 1994). From this, the intervals between encounters with nebulae of various masses can be found; these are illustrated in Fig. 4 for impact parameter 20 pc. It can be seen that, over the Phanerzoic period (to 600 Myr BP), there has probably been at least one grazing encounter with a giant molecular cloud, and three or four encounters with nebulae of mass at least $1.5-2 \times 10^5 M_\odot$.

Such encounters enhance the comet flux into the planetary system by filling the loss cones which the Galactic tide cannot reach. In the present study penetrating encounters were neglected (see Mazeeva 2004 for an analysis of their disruptive effects). Two independent approaches were again used: direct numerical integration, and analytic formulæ.

For the latter, the trajectory of the molecular cloud was split into a series of short segments of length $\Delta x$ and the change in orbital elements arising from the mini-impulse from each segment was computed. For the latter, formulæ given by Roy (1978) were used, in which $\Delta a$, $\Delta e$, $\Delta i$ etc. are given in terms of a velocity impulse $\Delta v = (\Delta v_S, \Delta v_T, \Delta v_W)$, where $(\Delta v_S, \Delta v_T)$ are the components of the impulse in the orbital plane in the radial and transverse directions, and $\Delta v_W$ is the component normal to the orbit. The instantaneous acceleration of the comet relative to the Sun, due to each mini-impulse, is given by

$$GM/R^3(R + r) - GM/R^3r,$$

where $R$ represents the instantaneous distance between Sun and molecular cloud, and $r$ is the position vector of the comet relative to the Sun. Therefore the instantaneous acceleration of the comet relative to the Sun is $GM/R^3r$ and from an element of trajectory $\Delta x$ along the velocity vector $V$ of the molecular cloud, the impulsive velocity delivered to the comet is

$$(\Delta x/V)(GM/R^3r).$$
which is simply the vector $\Delta v_y$ in the direction of the radial coordinate of the comet in its orbit around the Sun. The two remaining orthogonal velocity components, $\Delta v_r$ and $\Delta v_\theta$, conveniently vanish, simplifying the application of the impulse equations. The evolution of each orbit was computed by the addition of 40 such mini-impulses. A comparison between this approach and direct numerical integration yielded essentially identical results, but the semi-analytic method was orders of magnitude faster.

Fig. 5 shows the flux of comets entering the planetary system due to a grazing encounter with a giant molecular cloud of mass $5 \times 10^5 M_\odot$. The comets in this 90,000-particle simulation initially had a random, isotropic distribution of orbits such that $n(r) \propto r^{-4}$ in the range $10,000 \leq r \leq 60,000$ au. Their evolution was followed by numerical integration. The model imposed a survival probability of 0.5 on a comet entering the planetary system during each return, due not only to physical destruction but also to the risk of ejection into interstellar space through encounters with the giant planets. The figure illustrates the flux of comets entering the planetary system, represented by a sphere of heliocentric radius 40 au. We see a distinct bombardment episode, declining with a half width $\sim 3$ Myr. A key feature which emerges is that the bombardment rate is enhanced while the nebula is still in the neighbourhood of the Solar system, and indeed increases for several million years while the nebula is approaching.

The amplitude of such episodes, relative to the mean background, depends on the unknown radial structure of the Oort Cloud and is enhanced somewhat for Oort Cloud models with greater central condensation: for example, when $y = -3$, a close encounter with a GMC yields a bombardment episode with amplitude $A \sim 30$. Fig. 6 shows the effect of a close encounter (10 pc) with a 50,000 $M_\odot$ nebula, this time computed with the semi-analytic approach. Again, a strong bombardment episode is seen, but its duration is shorter. It appears that the cometary component of the impact cratering record should be quite ‘bumpy’, characterized by a periodic component due to the variable Galactic tide, on which are superimposed discrete surges due to passing nebulae, an order of magnitude above background.

5 THE IMPACT RECORD

The record of large impact craters on the Earth appears to show evidence of a $\sim 36$–$38$ Myr periodicity (Yabushita 2004; Napier 2006; Stothers 2006) and a tendency towards bunching, or occurrence in impact episodes (Napier 2006). The latter is particularly conspicuous for impact craters greater than 40 km in diameter. Break-up of main belt asteroids is inadequate to reproduce this pattern (Napier 2006), and the question arises whether these characteristics are quantitatively compatible with Galactic perturbations of the Oort Cloud, yielding impacts either directly through long-period comet impacts or the intermediary of the Halley-type comet population.

To examine this further, theoretical cratering flux distributions were derived from numerical models of the Sun’s vertical motion in the Galactic disc. The impact cratering flux was taken to vary pro rata with the ambient density (cf. Matese et al. 1995), and the apparent decline of cratering with time (an artefact of the discovery process) was included. Synthetic data sets were obtained from this theoretical flux distribution by extracting ‘craters’ from it at random, in batches of 40 to match the real sample of high-precision craters (Napier 2006). For the model illustrated in Fig. 3, $v_\parallel = 9$ km s$^{-1}$ and the Sun traverses the Galactic plane every $\sim 39$ Myr. In this case the flux varies with amplitude $\sim 2$.

Bootstrap analysis (1000 trials) was then applied to both real and synthetic data sets. The procedure was to extract data (in sets of 40) at random from the data – real or artificial – apply a power spectrum analysis to each set of 40, and record the peak of the spectrum wherever it occurred in the range 20–60 Myr. Fig. 7(a) illustrates the outcome of one such 1000-trial analysis. It can be seen that the inbuilt periodicity $\sim 39$ Myr in this model – is quite well retrieved, but that some solutions, depending on the vagaries of data selection, yield harmonics. It thus seems that the tidal model is broadly able to reproduce the observed periodicity in the impact cratering record (Fig. 7b), although which signal is the underlying periodicity and which are harmonics is open to discussion. These trials indicate that the larger impactors (say > 2 km in diameter) are more likely to be comets than the main belt asteroids, and that the observed bombardment episodes are most likely of Galactic provenance.

Both our position relative to the Galactic plane (Joshi 2007 and references therein) and the impact cratering record indicate that we are presently in, or very close to, the peak of an impact episode.
6 DISCUSSION AND CONCLUSIONS

From this numerical study the following points can be concluded.

(i) The ebb and flow of the vertical Galactic tide may explain the quasi-periodic bombardment episodes observed in the record of impact craters (ages $t < 250$ Myr and dating errors $\lesssim 5$ Myr), obtained by bootstrap analysis as described in the text. Bottom: the same for a synthetic data set, obtained from a model of the Sun’s vertical motion in the Galaxy coupled with systematic tidal disturbance of the Oort Cloud.

(ii) To the extent that such episodes generate ecological and geological disturbances, then the Galactic environment is exerting control over terrestrial phenomena (Napier & Clube 1979).

(iii) Order of magnitude enhancements in the comet impact rate occur during close encounters with massive nebulae and so provide a crucial link in the chain between ejection of microbiota from the Earth and their insertion into passing star-forming regions (Napier 2006).

Giant molecular clouds are concentrated within the spiral arms of the Galaxy. Leitch & Vasisht (1998) identify two great mass extinctions, the Cretaceous–Tertiary (65 Myr BP) and end Permian (225 Myr BP) with Sagittarius–Carina and Scutum–Crux arm crossings respectively. Gies & Heisel (2005), on the other hand, find the mid-points of recent spiral arm crossings at 80 and 156 Myr BP. Svensmark (2006) has modelled the motion of the Sun in relation to the spiral arm pattern using a model-dependent hypothesis which has the Earth’s past temperature as a proxy for encounters with spiral arms. With this model, the Solar system passed through the Sagittarius–Carina arm $\sim 34$ Myr BP and the Scutum–Crux arm $\sim 142$ Myr BP. Both these dates coincide with exceptionally strong bombardment episodes (Napier 2006). It seems that, at present, uncertainties in both the modelling of spiral arm kinematics and the strong incompleteness of the impact crater record preclude a secure identification of impact episodes or mass extinctions with specific spiral arm crossings.

Both the impact cratering record and the Sun’s position near the Galactic plane imply that we are in a bombardment episode now.

REFERENCES

Bailey M. E., 1983, MNRAS, 204, 603
Bailey M. E., Clube S. V. M., Napier W. M., 1990, The Origin of Comets. Pergamon, Oxford
Bidle K. D. et al., 2007, Proc. Natl. Acad. Sci., 104, 13455
Byll J., 1986, Earth Moon Planets, 36, 263
Clube S. V. M., Napier W. M., 1996, QJRAS, 37, 617
Emel’yanenko V. V., Asher D. J., Bailey M. E., 2007, MNRAS, 381, 779
Fernandez J. A., Ip W.-H., 1987, Icarus, 54, 377
Fouchard M., 2004, MNRAS, 349, 347
Garcia-Sanchez J., Weissman P. R., Preston R. A., Jones D. L., Lebreton J.-F., Latham D. W., Stefanik R. P., Paredes J. M., 2001, A&A, 379, 634
Gerald C. F., Wheatley P. O., 1994, Applied Numerical Analysis. Addison-Wesley, Menlo Park, CA
Gies D. R., Heisel J. W., 2005, MNRAS, 626, 844
Holemb J., Flynn C., 2004, MNRAS, 352, 440
Horneck G., Mileikowsky C., Melosh H. et al., 2002, in Horneck G., Baumstark-Khan C., eds, Astrobiology, The Quest for the Conditions of Life. Springer-Verlag, Dordrecht, p. 57
Joshi Y. C., 2007, MNRAS, 378, 768
Klacka J., Gajdosik M., 2001, in Pretka-Ziomek H., Wnuk E., Seidelmann P. K., Richardson D., eds, Dynamics of Natural and Artificial Celestial Bodies. p. 347
Leitch E. M., Vasisht G., 1998, New Astron., 3, 51
Matese J. J., Whitman P. G., Innanen K. A., Valtonen M. J., 1995, Icarus, 116, 255
Mazeeva O. A., 2004, Sol. Syst. Res., 38, 325
Mileikowsky C. et al., 2000, Icarus, 145, 391
Mundy L. G., 1994, in Clemens D. P., Barvainis R., eds, ASP Conf. Ser. Vol. 65, Clouds, Cores and Low Mass Stars. Astron. Soc. Pac., San Francisco, p. 35
Napier W. M., 2004, MNRAS, 348, 46
Napier W. M., 2006, MNRAS, 366, 977
Napier W. M., 2007, Int. J. Astrobiol., 6, 223
Napier W. M., Clube S. V. M., 1979, Nat, 282, 455
Napier W. M., Staniucha M., 1982, MNRAS, 198, 723
Roy A. E., 1978, Orbital Motion. Adam-Hilger, Bristol, p. 309
Stothers R. B., 1998, MNRAS, 300, 1098
Stothers R. B., 2006, MNRAS, 365, 178
Svensmark H., 2006, Astron. Nachr., 327, 866
Svensmark H., 2007, AdG, 48, 18
Talbot R. J., Newman M. J., 1977, ApJS, 34, 295
Wickramasinghe J. T., 2007, PhD thesis, Cardiff Univ.
Yabushita S., 2004, MNRAS, 355, 51

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