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Impact cratering and the Oort cloud

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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 timescales ∼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 million years. A weak periodicity of ∼36 Myr in the cratering record is consistent with the Sun's recent passage through the Galactic plane, and implies a central plane density $\sim 0.15\ M_\odot\,pc^{-3}$. This leaves little room for a significant dark matter component in the disc.

Key words: Oort cloud - nebulae - astrobiology

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 onto 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 time of microorganisms from Earth to protoplanetary nebula is comfortably less than the time expected for cosmic rays to sterilise them (e.g. Horneck et al. 2002, Mileikowsky et al. 2004, 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 timescales (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 (*loc. cit.*). 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 semi-major 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 γ in the range $2 \leq \gamma \leq 4$ were adopted for the outer Oort cloud

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Figure 1. Flux evolution for 1000 Myr under the influence of the vertical Galactic tide, computed by numerical integration of formulae due to Klacka & Gajdosik (1994). The flux is into a heliocentric sphere of radius 2000 AU, and is computed for 50,000 Oort cloud comets with $n(a) \propto a^{-2}$, perihelia >10,0000 AU and aphelia <50,000 AU. Equilibrium is reached on a timescale of order 300 Myr.

Figure 2. Flux evolution for 500 Myr into heliocentric spheres of radii 16 AU (upper curve) and 8 AU (lower curve) under the influence of the vertical Galactic tide. 25,000 Oort cloud comets with $n(a)$ as before and a flat initial eccentricity distribution. Computed from formulae by Fouchard (2004). Equilibrium is again reached on a timescale of order 300 Myr.

(Bailey 1983; Fernandez & Ip 1987), although probably no single power law fits the entire range (Emel'yanenko et al. 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 (4th order Runge-Kutta with error control using the Fehlberg procedure: see for example Gerald & Wheatley 1994).

(ii) Equations given by Klacka & Gajdosik (1994) were integrated. These were derived by averaging the tidal force over an orbit, and reduce the evolution in eccentricity e and argument of perihelion ω to two first-order differential equations. In this case an initially isotropic Oort cloud was adopted, and 50,000 comets were taken with initial semi-major axis distribution $\gamma = 2$, with perihelia constrained to have $q > 10,000$ AU and aphelia $Q < 50,000$ AU . The lower limit was set by the consideration that the Galactic tide is negligible for distances less than this, and the upper by the fact that comets with such large semimajor axes have very short dynamical lifetimes. A starting eccentricity distribution $n(e) \propto e$ was adopted. The flux of comets entering a heliocentric sphere of radius 2,000 astronomical units was computed. Fig. 1 shows the resulting evolution of flux with time: equilibrium is attained on a timescale of order 300 Myr.

(iii) Analytic formulae due to Fouchard (2004) yield the discrete change in orbital elements over a single orbit due to the vertical tide. These were applied to 25,000 comets, and the flux entering within heliocentric spheres of radii 16 and 8 AU measured. In this case the initial eccentricity distribution $n(e)$ was taken to be uniform. Fig. 2 shows the results: essentially the same relaxation time as before – 300 Myr – was found, even although very different heliocentric spheres and starting $n(e)$ had been adopted.

The semi-analytical and first-order integrations were some orders of magnitude faster than the direct numerical integrations. They involve some approximations, but comparison with the numerical integrations revealed no significant difference in the results obtained. Synthetic Oort clouds with these relaxed properties were taken as the starting points for discussing perturbations by a variable Galactic tide and passing nebulae.

3 FLUX MODULATION DUE TO THE SUN'S VERTICAL GALACTIC MOTION

Because of the Sun's vertical motion through the Galactic disc, the vertical Galactic tide experienced by Oort cloud comets varies cyclically. The vertical density distribution $\rho(z)$ of ambient stellar and interstellar material in the disc was taken to decline exponentially with scale height 60 pc (Joshi 2007), and the vertical motion of the sun was then given by solving

$$\ddot{z} = -4\pi G\rho(z)z \qquad (1)$$

The period and amplitude of the solar orbit may then be found, for a prescribed vertical velocity v_o 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:

$$T = 4\pi G\rho(z)z_c \qquad (2)$$

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 $\rho_0 = 0.105\ M_\odot\,\mathrm{pc}^{-3}$ (Holmberg & Flynn 2004), but this appears to be an underestimate by ~50% due to incompleteness of discovery of low-luminosity stars (Garcia-Sánchez et al. 2001). Stothers (1998) has argued for a local value $\sim 0.15 \pm 0.01\ M_\odot\,\mathrm{pc}^{-3}$, while Svensmark (2007) has argued for a mean in-plane density $\sim 0.145 \pm 0.1\ M_\odot\,\mathrm{pc}^{-3}$ averaged over the Sun's traversal of the Galaxy over the last 200 Myr. Adopting the latter value and assuming $v_0 = 9\ \mathrm{km\,s^{-1}}$, 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 scale height of the low-luminosity stars, amplitude ratios of around 2:1 to 5:1 are obtained in these models.

Figure 3. Top panel: vertical motion of sun in Galactic plane with local plane density 0.15 $M_\odot\,pc^{-3}$, scale height taken from the Hipparcos data and solar velocity crossing the plane $v_0 = 9\ km\,s^{-1}$. Bottom panel: the corresponding variation in flux of long-period comets into the solar system.

Figure 4. Mean interval between encounters with nebulae for various asymptotic approach speeds, for impact parameter 20 pc, illustrating the effect of gravitational focusing.

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 ∼1.9 Gyr (Bailey et al. 1990) and it is generally assumed, although it is not proven, that a dense inner cloud of comets is available to replenish the loss of long-period comets.

Close encounters with, or penetrations of, cold dense nebulae have occurred quite frequently over geological timescales. Neglecting gravitational focusing, the solar system passes within d pc of dark cloud complexes at intervals Δt Myr given by

$$\Delta t \sim 800(M/5\times10^5)^{0.75}(d/20)^{-2} \qquad (3)$$

With gravitational focusing, the effective interval is reduced by a factor

$$\sigma = 1 + (V_e/V)^2 \qquad (4)$$

Figure 5. Flux of comets entering the planetary system, taken as a sphere of radius 40 AU, due to a grazing encounter with a GMC. The flux is computed by direct numerical integration of the cometary orbits. The GMC has $M = 5\times10^5\ M_\odot$, p=20 pc, $V = 15\ km\,s^{-1}$, perihelion occurring at 20 Myr. The initial Oort Cloud in this simulation comprises 90,000 comets distributed as γ=-2 over the range 10,000≤ r ≤60,000 AU.

where V represents the asymptotic encounter velocity and V_e is the escape velocity at the point of closest approach. σ is significant for a close encounter with a massive nebula. For example, a GMC of mass $M = 5\times10^5\,M_\odot$ 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 Myr 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% 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 Phanerozoic 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×$10^5\ M_\odot$.

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 formulae.

For the latter, the trajectory of the molecular cloud was split into a series of short segments of length Δx and the change in orbital elements arising from the mini-impulse from each segment was computed. For the latter, formulae 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 Δv_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

$$GM/R^3(\mathbf{R}+\mathbf{r}) - GM/R^3\mathbf{R} \quad (5)$$

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

$$GM/R^3\mathbf{r} \quad (6)$$

and from an element of trajectory Δx along the velocity vector V of the molecular cloud, the impulsive velocity delivered to the comet is

$$(\Delta x/V)(GM/R^3)\mathbf{r} \quad (7)$$

which is simply the vector Δv_S in the direction of the radial coordinate of the comet in its orbit around the Sun. The two remaining orthogonal velocity components, Δv_T and Δv_W, 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 into the planetary system due to a grazing encounter with a giant molecular cloud of mass 5×10^5 $M_\odot$. 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 ∼3 Myr. A key feature which emerges is that the bombardment rate is enhanced while the nebula is still in the neighborhood 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 $\gamma = -3$, a close encounter with a GMC yields a bombardment episode with amplitude A ∼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', characterised 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 ∼36–38 Myr periodicity (Yabushita 2004; Stothers 2006; Napier 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. Breakup of main belt asteroids is inadequate to reproduce this pattern (loc. cit.), 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

Figure 6. Enhanced comet flux due to an encounter with a 50,000 $M_\odot$ nebula at 10 pc; computation is by semi-analytic formulae as discussed in the text.

Figure 7. Top: period/phase distribution of well-dated impact craters (ages $t \leq$250 Myr and dating errors $\leq$ 5 Myr), obtained by bootstrap analysis as described in the text. Below: the same for a synthetic dataset, obtained from a model of the Sun's vertical motion in the Galaxy coupled with systematic tidal disturbance of the Oort cloud.

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, $v_0 = 9\ \mathrm{km\,s^{-1}}$ 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 datasets. 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. 7a 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

It appears from this numerical study that:

(i) The ebb and flow of the vertical Galactic tide may explain the quasi-periodic bombardment episodes observed in the record of impact craters $\gtrsim$40 km in diameter (Napier 2004). There is no known mechanism capable of yielding similar periodic disturbances of the asteroid belt. Thus on this model the major impactors largely arrive in relatively short-lived periodic surges from 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.

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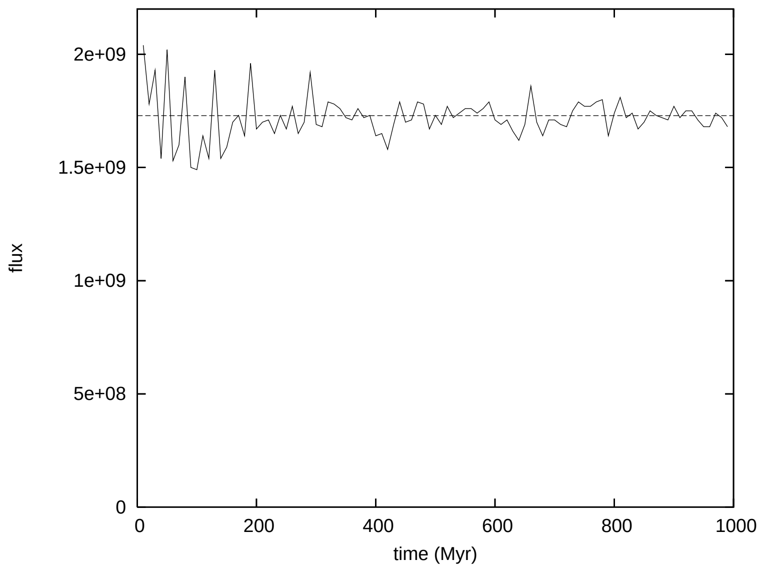

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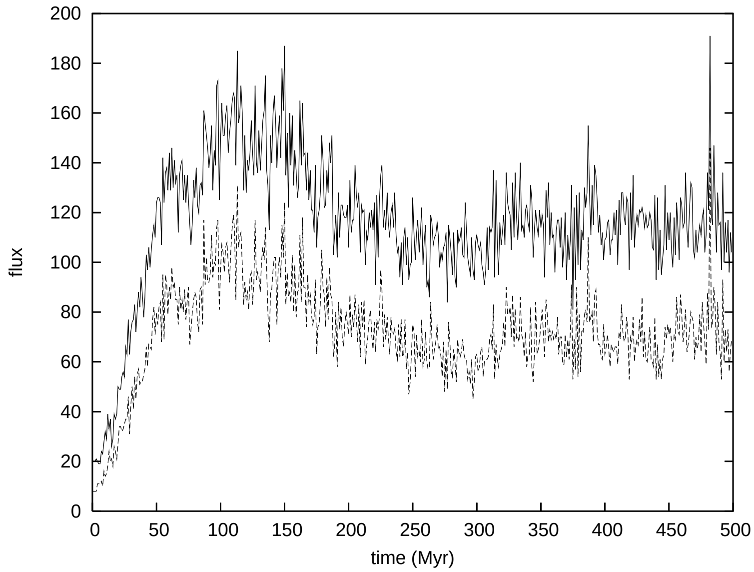

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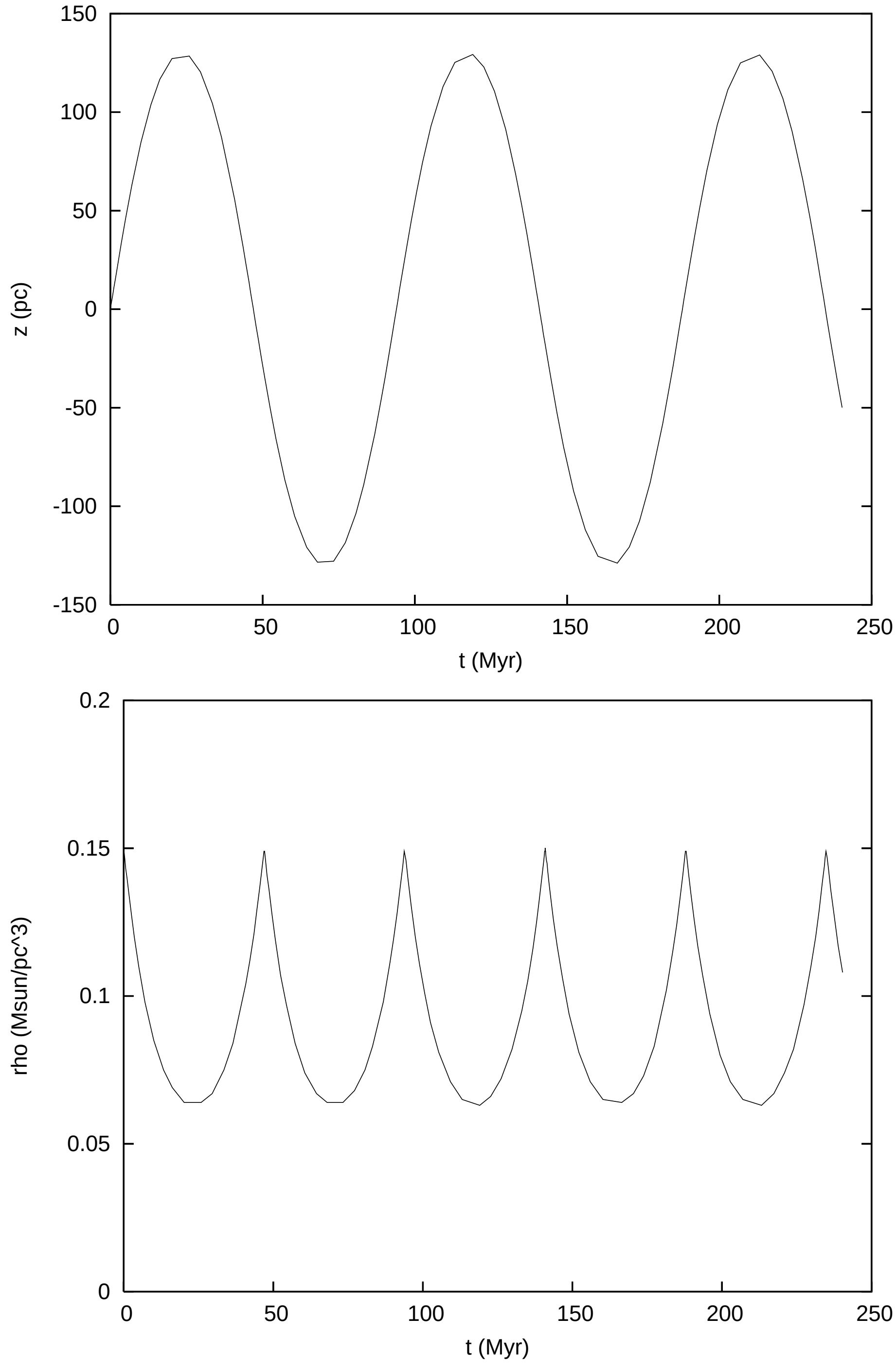

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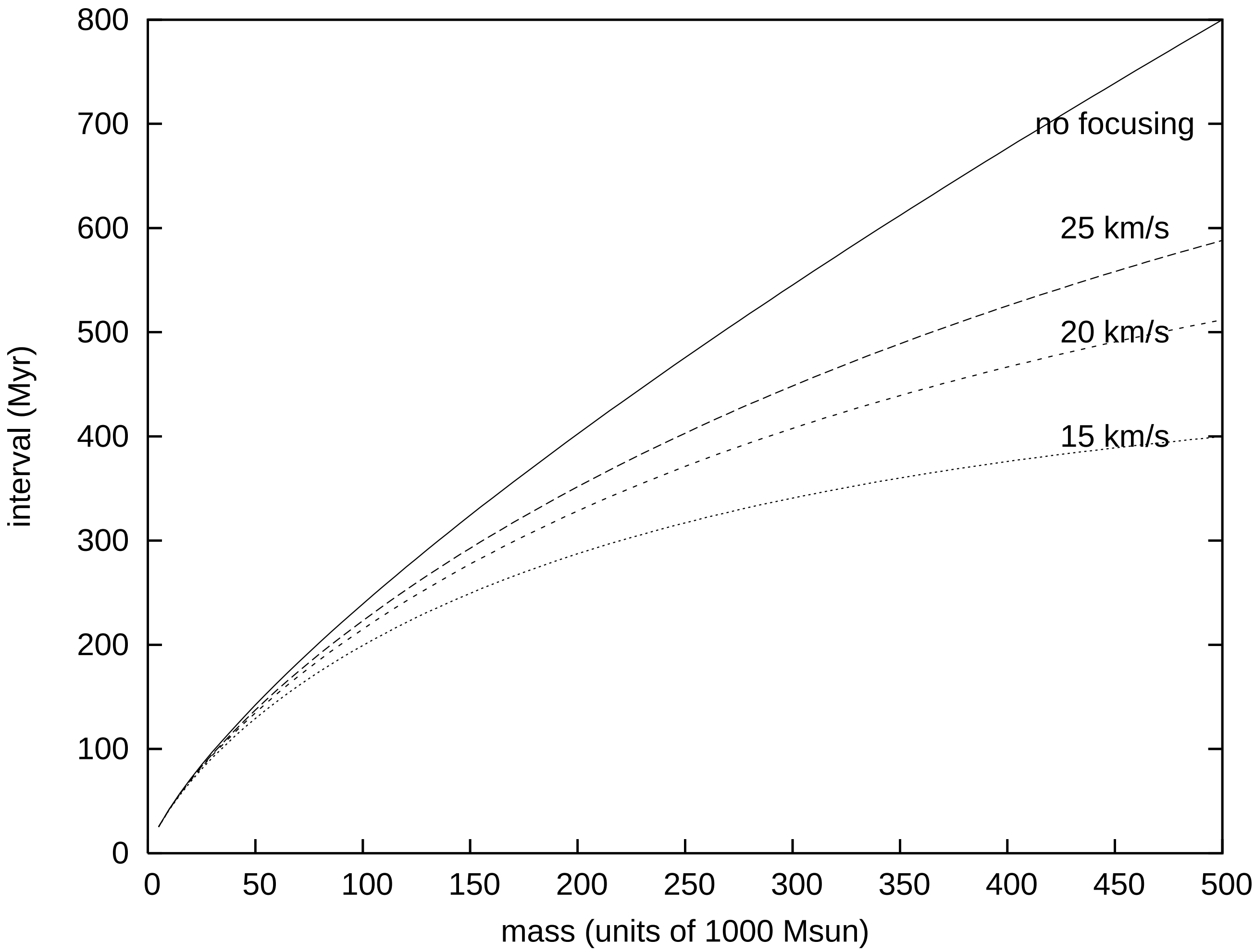

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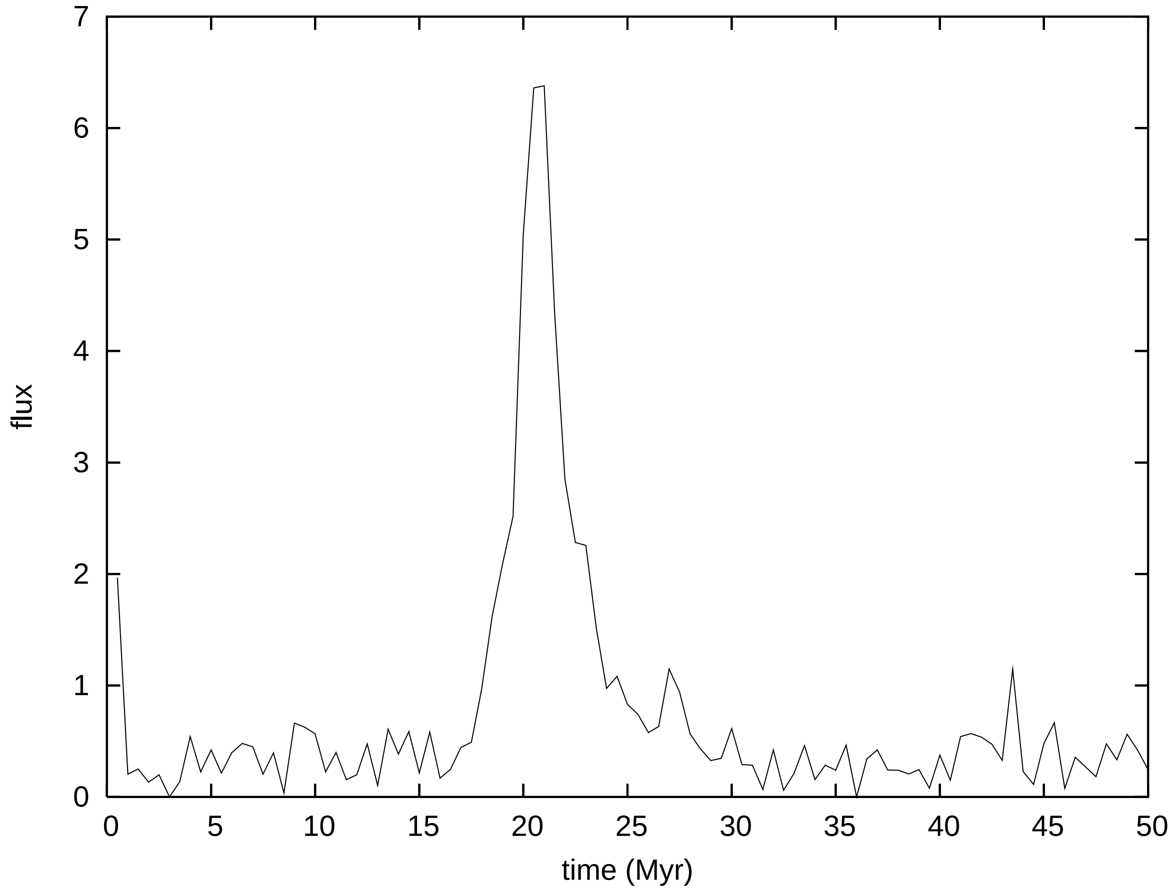

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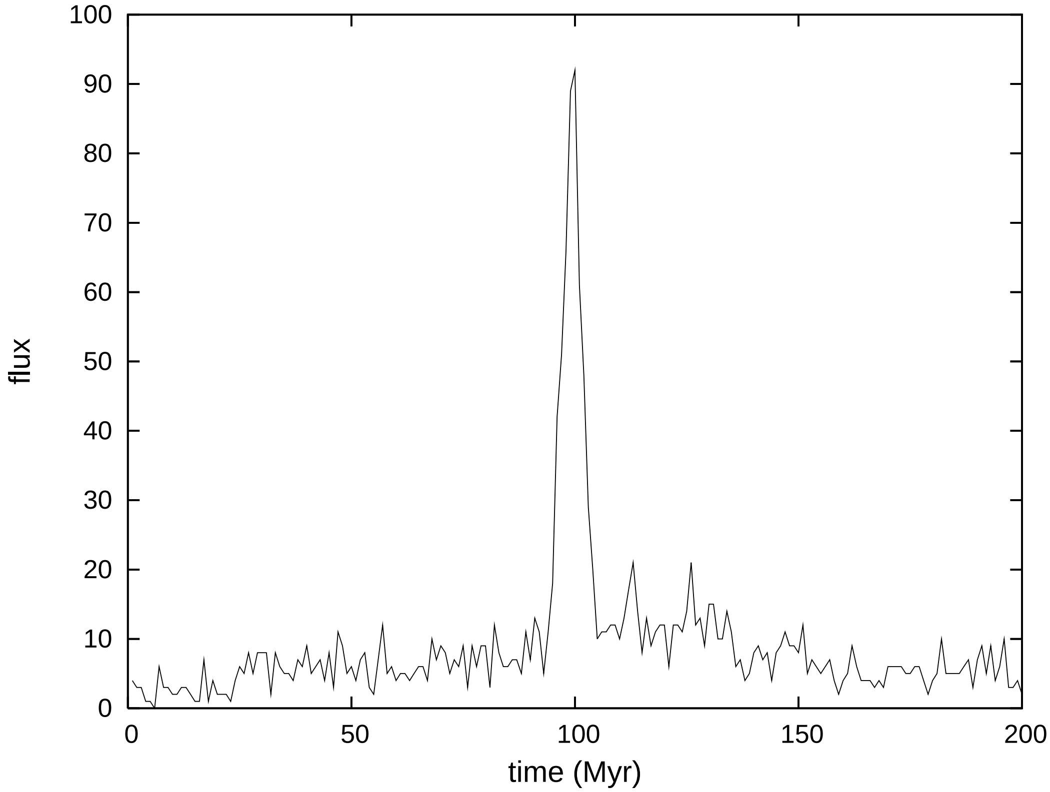

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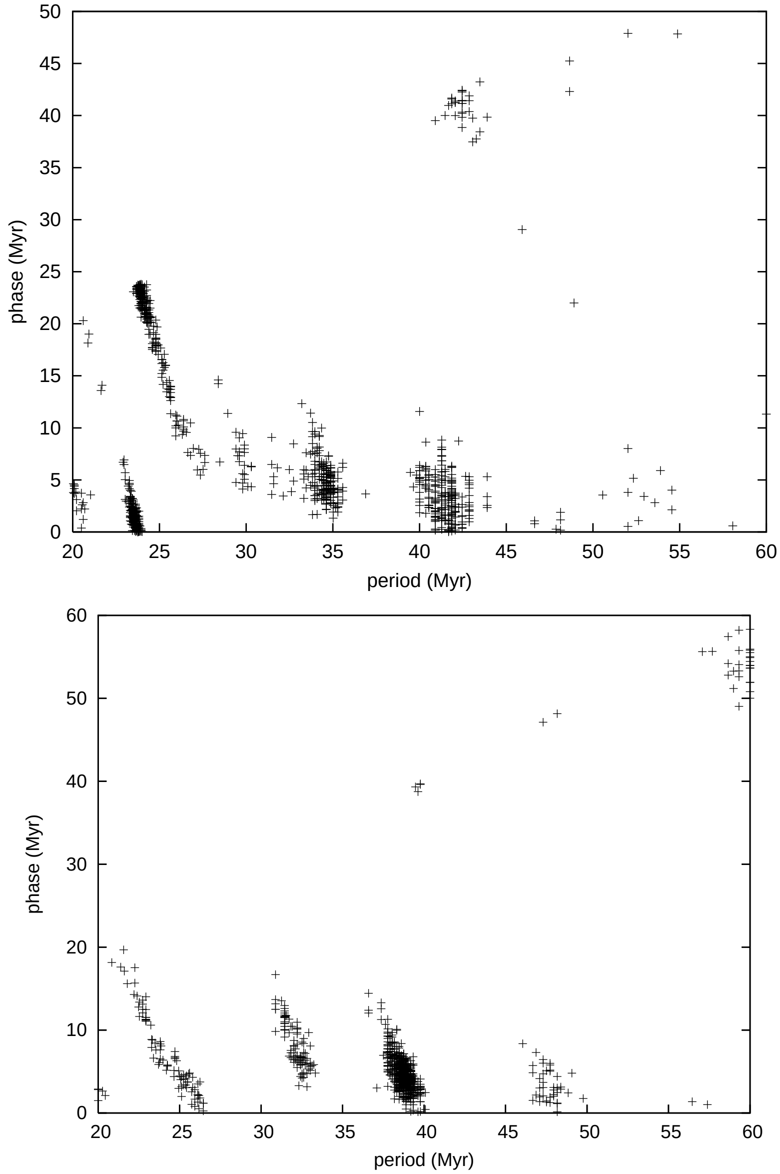

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