THE MAIN BELT AS A SOURCE OF NEAR–EARTH ASTEROIDS

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Abstract. We investigate the flux of main–belt asteroid fragments into resonant orbits converting them into near–Earth asteroids (NEAs), and the variability of this flux due to chance interasteroidal collisions. A numerical model is used, based on collisional physics consistent with the results of laboratory impact experiments. The assumed main–belt asteroid size distribution is derived from that of known asteroids extrapolated down to sizes of ≈ 40 cm, modified in such a way to yield a quasi–stationary fragment production rate over times ≈ 100 Myr. The results show that the asteroid belt can supply a few hundred km–sized NEAs per year, well enough to sustain the current population of such bodies. On the other hand, if our collisional physics is correct, the number of existing 10–km objects implies that these objects either have very long–lived orbits, or must come from a different source (i.e., comets). Our model predicts that the fragments supplied from the asteroid belt have initially a power–law size distribution somewhat steeper than the observed one, suggesting preferential removal of small objects. The component of the NEA population with dynamical lifetimes shorter than or of the order of 1 Myr can vary by a factor reaching up to a few tens, due to single large–scale collisions in the main belt; these fluctuations are enhanced for smaller bodies and faster evolutionary time scales. As a consequence, the Earth's cratering rate can also change by about an order of magnitude over the 0.1 to 1 Myr time scales. Despite these sporadic spikes, when averaged over times of 10 Myr or longer the fluctuations are unlikely to exceed a factor two.

Key words: Asteroids, Near–Earth asteroids, Cratering record

1. Introduction

It is well known that the population of interplanetary bodies which can collide with the Earth — near–Earth asteroids (NEAs), comets, meteoroids — is characterized by dynamical and collisional lifetimes much shorter than the age of the solar system, i.e. ranging from $\approx 10^5$ to 10^8 yr. Thus, in order to maintain a quasi–stationary abundance of bodies on such orbits, sources are needed to balance the loss rate due to hyperbolic ejections out of the solar system and to disruptive impacts with the planets, the Sun and other interplanetary objects. As a matter of fact, a significant, probably major fraction of the near–Earth population appears to be supplied from the "storage region" in the main asteroid belt, where fragments are continuously produced by interasteroidal collisions and sometimes injected into resonant, chaotic orbits undergoing large variations of eccentricity and

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therefore amenable to planetary encounters. Although this transport mechanism is known since a long time as a matter of principle, only recently quantitative models of it have become available, thanks to a better understanding of both asteroidal collisions and resonant dynamics (Farinella et al. 1993a,b, 1994a,b; Morbidelli et al. 1994; Michel et al. 1994).

In particular, Farinella et al. (1993a) have estimated that the fraction of main–belt asteroid fragments ending up into either the 3/1 mean motion resonance with Jupiter or the ν_6 secular resonance (the two most effective dynamical *routes* from the main belt to the inner planet zone) range from about 1% to 4%, depending on the detailed assumptions adopted on the collisional physics — in particular, the ejection velocity distribution of fragments from hypervelocity impacts. With standard assumptions about the collisional lifetimes of main–belt asteroids — which approach the age of the solar system for bodies 100 km in diameter, and for smaller asteroids are roughly proportional to the square root of size (see Farinella et al. 1992a) — this model predicts a yield of the order of 100 fragments larger than 1 km in diameter per Myr into the resonances. This appears to be of the same order as the loss rate quoted above, even taking into account the recent findings about the frequency of NEAs reaching extreme orbital eccentricities and thus hitting the Sun (Farinella et al. 1994b).

The purpose of this paper is to refine this order–of–magnitude estimate of the NEA flux from the main belt by performing *ad hoc* simulations of the collisional evolution of main–belt asteroids through a suitable numerical model (Campo Bagatin et al. 1993, 1994a,b). The corresponding algorithm takes into account a variety of possible collisional outcomes (cratering, break–up, partial reaccumulation of ejecta), in agreement with the available experimental evidence on hypervelocity impacts (e.g., Giblin et al. 1994), and has been modified to give as an output the number of new fragments of any given size generated by chance asteroidal collisions over time. These simulations can be used both to estimate the average flux of new fragments injected into the resonant *routes* — by applying the injection efficiency factor of 0.01 to 0.04, derived as explained in Farinella et al. (1993a) — and to provide the first quantitative estimate of the time variability of this flux on different time scales. These estimates are important for many applications, e.g. studies of the equilibrium population of NEAs of different sizes, of the cratering rates on the terrestrial planets, of meteorite fall rates and exposure ages, and of possible "transient" processes related to a temporarily enhanced impact flux against the Earth.

The remainder of this paper is organized as follows. In Sec. 2 we describe our numerical collisional evolution code and the corresponding assumptions we have made to address the problems mentioned above. In Sec. 3 we will present and discuss some quantitative results of the numerical simulations carried out with the code. Sec. 4 will be devoted to a summary of some general conclusions on the significance of these results for the "demography" of NEAs and their impact rates against the inner planets.

2. The collisional evolution model

An improved version of the numerical model developed by Campo Bagatin (1993) and described in details in Campo Bagatin et al. (1994a,b), has been used to estimate the creation rate of new fragments in the main asteroid belt and its variability. The original purpose of this model was that of studying the evolution of a population of colliding bodies, such as the asteroids, taking into account both cratering and catastrophic disruption events. Like in previous codes of this type (Davis et al. 1985, 1989; Farinella et al. 1992b), the bodies making up the overall evolving population are divided into a number of discrete size bins, which at every time step interact due to mutual collisions; as a consequence, the number of objects residing in all the bins is suitably updated. Collision rates are estimated in agreement with the average intrinsic collision probability for the real asteroid population calculated from Wetherill's (1967) formulae by Farinella and Davis (1992).

The novel feature of Campo Bagatin's code is the *a priori* derivation of a "collision matrix" which includes all the assumptions on the collisional physics, and whose elements C_{ijk} give the number of bodies in the k–th size bin generated (or lost) after a typical collision involving a projectile in the i–th bin and a target in the j–th bin. These numbers are derived from a semiempirical collisional model, as described in Davis et al. (1989) and Petit and Farinella (1993). By multiplying the collision matrix times the number of events involving, during every time step, objects belonging to the corresponding pair of bins, the variations of the bin populations over time are readily obtained.

We have now modified this program by devoting a specific attention to the problem of "rare" impact events: they are defined as those events whose probability is low enough that they are expected to happen a small number of times (< 1, or a few) *within one time step*, and for which using just average collision rates cannot account for the intrinsic random fluctuations of the collisional process. For instance, in the previous version of the code, when 0.1 events involving a given pair of target/projectile bins were expected, the number of fragments predicted for one such event by the collision matrix was just divided by 10 — neglecting the fact that collisions are in fact discrete events, which in a given interval either do not occur at all or occur an integer number of times. Note that these "rare" events must be distinguished from the "improbable" ones, those which might not take place even in the whole lifetime of the Solar System, and which typically involve pairs of sizeable asteroids both in the target and in the projectile role: these latter events represent of course an unavoidable source of uncertainty in our reconstructions of the past evolution of the asteroid belt. On the other hand, since in the current context we are interested just in relatively recent times (say, the last 10^8 yr), these "improbable" events have a very small probability of having taken place, and therefore can be safely neglected.

The "rare" events are not so critical for the overall history of the asteroid belt (however, we plan to devote a future study to analyzing their possible systematic effects on the results of the numerical simulations). On the other hand, they are extremely important for assessing what happens on a shorter time scale, represented in the code as a single time step or a small number of them. In particular, for what concerns the production of small and intermediate–sized fragments, which could be transformed into NEAs or meteoroids, the rare events can cause strong fluctuations in time. As previously done by Farinella et al. (1992b), the problem of rare events has been dealt with in this way: when, in a time step, a collision involving two given (i–th and j–th) bins is expected to happen a (real) number $x_{ij} < 5$ of times, a random number generator is called, which gives back an integer number n_{ij} (≥ 0), chosen according to a Poisson probability distribution having x_{ij} as the mean value. In this way we have always an integer number of "rare" collisions in a discrete time step (of course, when the expected number x_{ij} is > 5, the difference between x_{ij} and n_{ij} is not important). In the following we will make some comparisons between this procedure and the simpler, deterministic one using always real numbers of events and thus deriving a kind of "mean evolution".

In addition to introducing this probabilistic feature in the evolution code, in this work we adopted the following assumptions:

(i) The evolution is started basically at the present time, 4.5 Byr after the origin of the solar system (and of the asteroid belt). Consistent with this, the initial population is an approximation to the current one, derived from observations for large asteroids and extrapolated to smaller ones with a constant power–law exponent, as explained by Davis et al. (1994) and Campo Bagatin et al. (1994a,b). As pointed out by Cellino et al. (1991) and Farinella and Davis (1994), the observed population can be considered complete only for diameters larger than ≈ 40 km, and an increasing uncertainty affects the extrapolated size distribution at smaller sizes. At diameters of a few km, the smallest ones relevant for the results in the present context, the uncertainty in the size distribution can be estimated to be of about plus or minus a factor two.

(ii) The collisional physics parameters used to generate the matrix C_{ijk} are those corresponding to the "standard case" defined by Campo Bagatin et al. (1994a,b). Significant uncertainties affect many of these parameters, in particular because they have to be scaled from sizes typical of laboratory experiments up to asteroidal ones. However, on the basis of a number of tests, we believe that these uncertainties cannot change the derived fragment supply by orders of magnitude, and probably they affect even less its inferred time variability (which basically comes from the random character of the collisional process).

(iii) The numerical calculations are made by using 32 logarithmic size bins, spanning each a factor 4 in mass (1.587 in size), with central values ranging from 53 cm to 890 km in diameter. The largest bin contains only (1) Ceres, whereas the smallest one extends down to about 42 cm. The effects of this small-size cutoff on the shape of the evolving size distribution are discussed in details by Campo Bagatin et al. (1994b). Again, the corresponding uncertainty cannot change our results by more than a factor of a few.

We analyzed the collisional evolution predicted by the code for our assumed current population over some time, monitoring in particular the production of small and intermediate-sized fragments. We soon discovered that the assumed initial population is rather far from an equilibrium one in which at every size the collisional losses are approximately balanced by the input of new fragments and the shape of the size distribution keeps unchanged with time (see Dohnanyi 1969; Campo Bagatin et al. 1994b; Paolicchi 1994). Instead, we had a transient phase in which the production of fragments varied in a significant way in the different bins before stabilizing at quasi-stationary values, after a time of the order of several tens of Myr. Comparing the transient phase to the quasi-stationary regime, we found that in the former phase the fragment production rate was larger by factors of about 4 and 2 for fragments 100 m and 1 km in diameter, respectively, while it was smaller by about 8% at 10 km. Since the real asteroid size distribution has already had 4.5 Byr to reach a quasi-stationary regime, this is clearly an artifact of our collisional model and/or initial conditions, both of which are only rough approximations to the reality.

This problem compounds with the uncertainties described earlier (although it is in fact a consequence of them). We have chosen to estimate the fragment production rate after the initial population has relaxed to the quasi-stationary regime, so we evolved it for 100 Myr and then used the final population as a basis for our computations (it is interesting to note that this final population differs little from the initial one for sizes larger than a few tens of km, where the real asteroid size distribution is known in a reliable way). Since, as mentioned earlier, up to about 10 km in diameter the transient fragment production rates are higher than the quasi-stationary ones, this choice is likely to provide a lower bound to the actual fragment yield. At the current state of knowledge, however, we think that an overall uncertainty of a factor 2 to 4 cannot be avoided.

TABLE I

Results from the "mean evolution" simulations described in the text: fragment production rates, resonance yields, and equilibrium abundances in the "fast-track" and "slow-track" NEA populations.

Size bin (km)	Production rate (Myr^{-1})	Resonance yield (Myr^{-1})	Fast-track eq. pop.	Slow-track eq. pop.
0.07-0.11	1.25×10^7	2.5×10^5	2.1×10^5	1.1×10^6
0.69-1.10	1.85×10^4	370	300	1700
6.96-11.05	2.3	0.05	0.04	0.2

3. Numerical experiments and results

With the assumptions described above, we carried out numerical simulations of the collisional evolution process spanning 100 Myr and obtained the production rate of collisional fragments in the three size bins centered at 86 m, 0.87 km, and 8.8 km. The average fragment production rates obtained from the "mean evolution" algorithm defined in Sec. 2 (no Poisson–distributed random numbers in deriving how many impacts take place in a time step) are listed in the second column of Table I. The third column of the Table gives the corresponding "mean" fragment yields to the resonances, assuming a size–independent delivery efficiency of 2% (Farinella et al. 1993a; note that in reality this efficiency is likely to be somewhat higher for smaller fragments, characterized by higher average ejection speeds from their parent bodies). It is interesting to note that Farinella's et al. (1993a) value of $\approx$ 100 fragments larger than 1 km per Myr injected into the resonances, derived from approximate estimates of asteroid collisional lifetimes, appears to be confirmed in order of magnitude by the current results of the numerical simulations. We shall discuss the last two columns of the Table, giving the steady–state abundances of NEAs corresponding to the supply flux derived from the "mean evolution", in Sec. 4.

As far as the time variability of the fragment yield is concerned, we were interested in time scales ranging from about 0.1 to 10 Myr, corresponding to different dynamical/collisional time scales for the evolution of the fragments into Earth–crossing orbits and their final loss by impact into the Sun or the planets, or hyperbolic ejection. Actually, the 10^5 yr time scale is probably relevant for bodies in comet–like orbits undergoing close approaches to Jupiter (this appears to be the most likely fate for fragments injected in the resonances located in the outer part of the belt, such as the 5/2 and 2/1 mean motion resonances with Jupiter; see e.g. Hahn et al. 1991); the 1–Myr time scale applies to "fast–track" NEAs hitting the Sun or ejected on hyperbolic orbits after their eccentricity has been drastically pumped up by the 3/1 or ν_6 resonances (Farinella et al. 1994b, Valsecchi et al. 1994); and the 10^7 yr time scale is more typical of "slow–track" non–resonant NEAs evolving mainly under the influence of close encounters with the inner planets (Milani et al. 1989; Michel et al. 1994). Thus we chose a time step of 0.1 Myr in computing the fragment production rates, and in order to estimate the fluctuations over the longer time scales, we simply averaged over 10 or 100 such steps run with the same initial conditions (the quasi–stationary population described earlier). Of course this procedure neglects the long–term variations of the asteroid size distribution, but these have been certainly minor over the last 100 Myr ($\approx 2\%$ of the age of the solar system). Our plots have the abscissae ranging from 4.5 to 4.6 Byr after the origin of the solar system and labelled "fictitious time", to remind of the way the fragment production rates have been computed.

Another important point concerning the random fluctuations of the fragment supply has to do with the way the corresponding yield to the resonance zones should be evaluated. In the "mean evolution" approach whose results were discussed above, it is sufficient to multiply the fragment production rates (given in the first column of Table I) times the 0.02 delivery efficiency factor. But the situation is different when the random fluctuations about the "mean yields" are considered. Using also for them the 0.02 efficiency factor would clearly be too conservative: when a rare event (as defined in Sec. 2) occurs near a resonance, a fraction of the created fragments much larger than 2%, and possibly not much smaller than unity, would be injected into the chaotic zone (see e.g. the fragment delivery efficiencies of several real asteroids close to resonances computed by Farinella et al. 1993a, and Morbidelli et al. 1994). On the other hand, the full fluctuations obtained by the probabilistic collision evolution codes refer to the total fragment production rate in the main belt, including parent bodies far from the resonances and therefore inefficient as NEA deliverers. To solve this dilemma, we decided to proceed in the following way: the (real) number x_{ij} of collisional events expected in each time step for every bin pair was multiplied times the 0.02 factor (roughly giving the effective number of events occurring near the resonances), and only afterwards the corresponding random integer number (to be multiplied times C_{ijk}) was computed by the Poisson probability routine, from a distribution having $0.02\, x_{ij}$ as a mean value. The figures discussed below show how the fluctuations derived in this way (referred to as "fluctuations of resonant fragments") compare with the more conservative estimates ("normalized fluctuations") which are obtained simply by multiplying the overall fragment production rates times 0.02, as explained in Sec. 2. In all cases the fluctuations are referred to the "mean evolution" values discussed earlier, which correspond to the zeros of the vertical axes.

Figs. 1 and 2 show the results on the fluctuations in the production of fragments in the 100 m bin (for the exact bin limits, see Table I). Parts (a), (b) and (c) refer to the 0.1, 1 and 10 Myr time scales, respectively. The largest fluctuations showing up in the 100 Myr time span of the simulations (some 10^6 fragments about 100 m across produced by three discrete, "rare" collisional events) are only partially smoothed out over the longest time scales. Note that, by coincidence, the number of fragments supplied to resonances in the largest fluctuations is about the same as the overall number of fragments created in the main belt over 0.1 Myr, on the average (i.e., in the "mean evolution" scenario; see Table I). Therefore, chance collisional events can increase the abundance of 100–m NEAs with lifetimes of the order of 0.1 Myr by a factor of the order of 50. This is reduced to a factor ≈ 5 and to a $\approx 50\%$ increase when 1-Myr and 10-Myr evolution time scales are considered, respectively. The corresponding "normalized fluctuations" are shown in Figs. 2: as expected, a much larger number of discrete events is recorded, but each of them gives rise to a smaller fluctuation in the fragment supply. The reduction factor with respect to the previous scenario is about 20, that is somewhat smaller than 50, since the largest "rare" event in the whole belt creates more fragments than the largest one in the reduced sample of "resonance–bordering" asteroids.

Figs. 3 and 4 refer to 1–km sized bodies, Figs. 5 to 10–km bodies. The same qualitative features as in Figs. 1 and 2 are apparent again, but the absolute numbers of fragments are reduced by factors of about 10^3 and 10^6, respectively. Note that these factors correspond to having the same total mass in the three size bins, so we can conclude that the fragments injected into to NEA orbits have approximately a power–law size distribution with the number of bodies in any interval $[D, D + \delta D]$ proportional to D^{-4} (and the number of bodies larger than D proportional to D^{-3}). These distributions are somewhat steeper than those inferred from the observed NEA population or from the lunar and terrestrial cratering record; this may be due either to problems with our collisional physics, or to preferential collisional elimination of smaller NEAs during their dynamical lifetimes. The latter explanation would be consistent with the results of Bottke et al. (1994) on the (fairly strong) size dependence of the collisional lifetime of NEAs.

The largest "rare" random events create about 700 1–km fragments, with the corresponding fluctuations surviving over the 1–Myr time scale; comparing these values with those listed in Table I, fluctuations by factors ≈ 20, 2 and 1.2 apply to the 0.1, 1 and 10 Myr time scales, respectively. Note that for 1–km fragments, the reduction in passing to the more conservative "normalized fluctuations" does not exceed a factor ≈ 6.

As regards the 10–km fragments, Figs. 5 show that over the 100–Myr time span only two "rare" events create one of these bodies each. For these large fragments, the effects of the "rare" events persist over 1 Myr, and

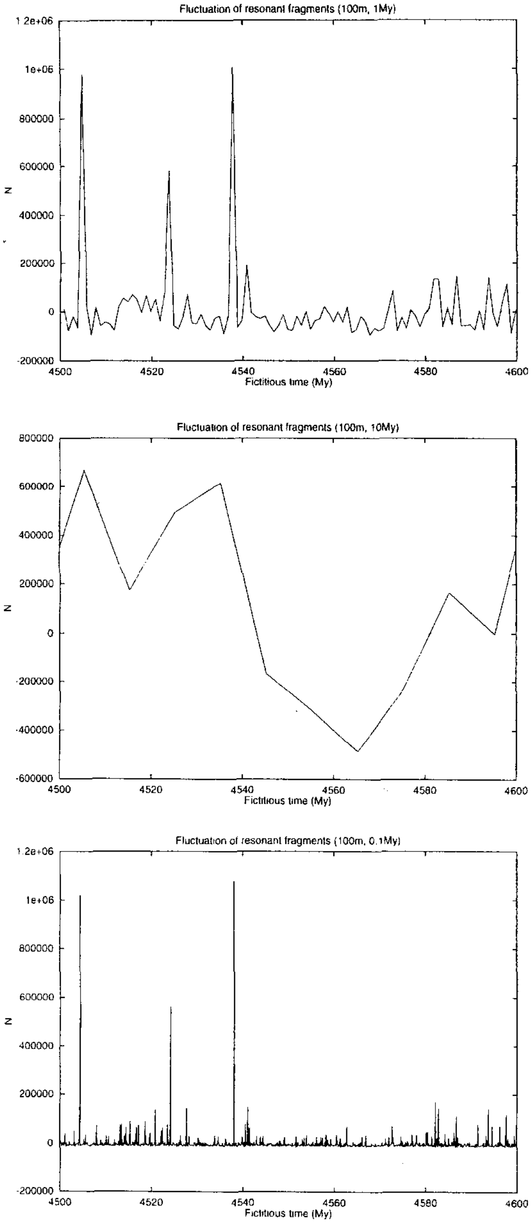

Fig. 1. The fluctuations in the number of fragments formed close to the resonances, referred to the mean evolution" case described in the text (dashed line at $N = 0$). Here fragments about 100 m in diameter are considered. The abscissae mark the "fictitious time", obtained from a sequence of 1000 equal time steps of 0.1 Myr starting from the same quasi-stationary main-belt population (see text). Since this population is close to the real one of the current asteroid belt, "fictitious times" between 4.5 and 4.6 Byr after the origin of the solar system have been used along the horizontal axis. In Fig. 1a fluctuations appearing in the original 0.1 Myr time steps have been plotted; Figs. 1b and 1c show the same simulation, but with fluctuations referred to longer time steps of 1 and 10 Myr, and obtained simply by averaging over 10 or 100 consecutive 0.1 Myr steps.

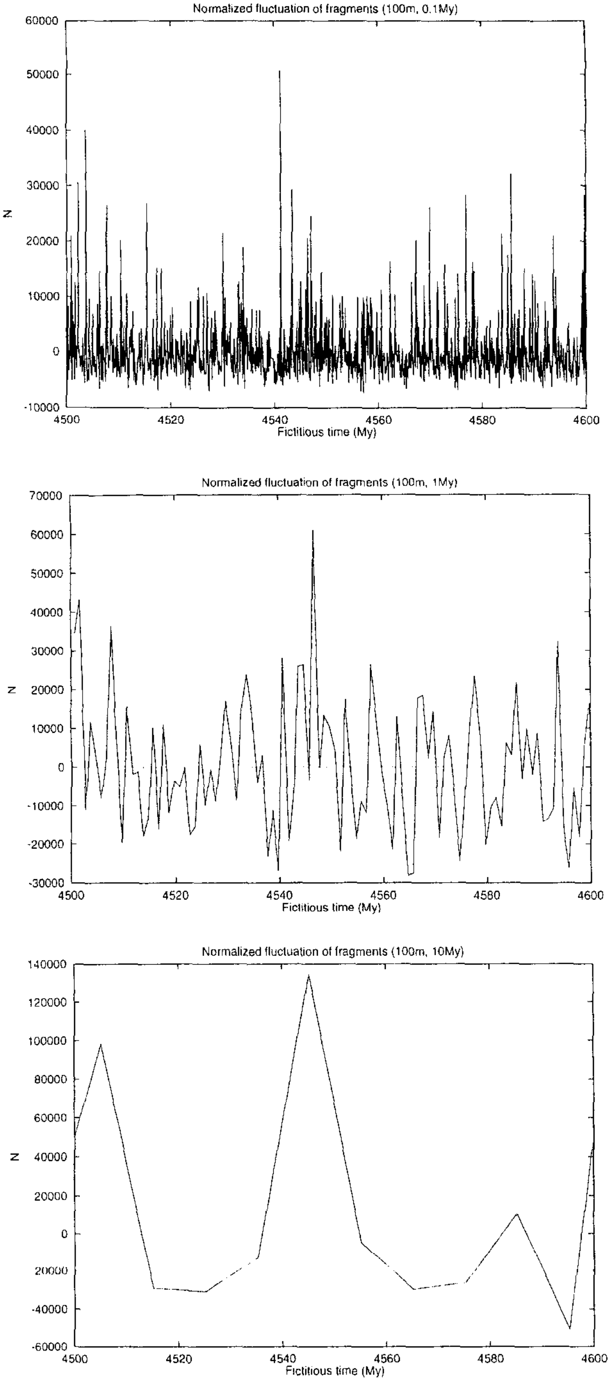

Fig. 2. The "normalized fluctuations" in the number of fragments created in the whole belt, multiplied times the delivery–efficiency factor 0.02 (see text). As in Fig. 1, the 100–m size bin and three different time scales (0.1, 1 and 10 Myr in Figs. 2a, 2b and 2c, respectively) are considered.

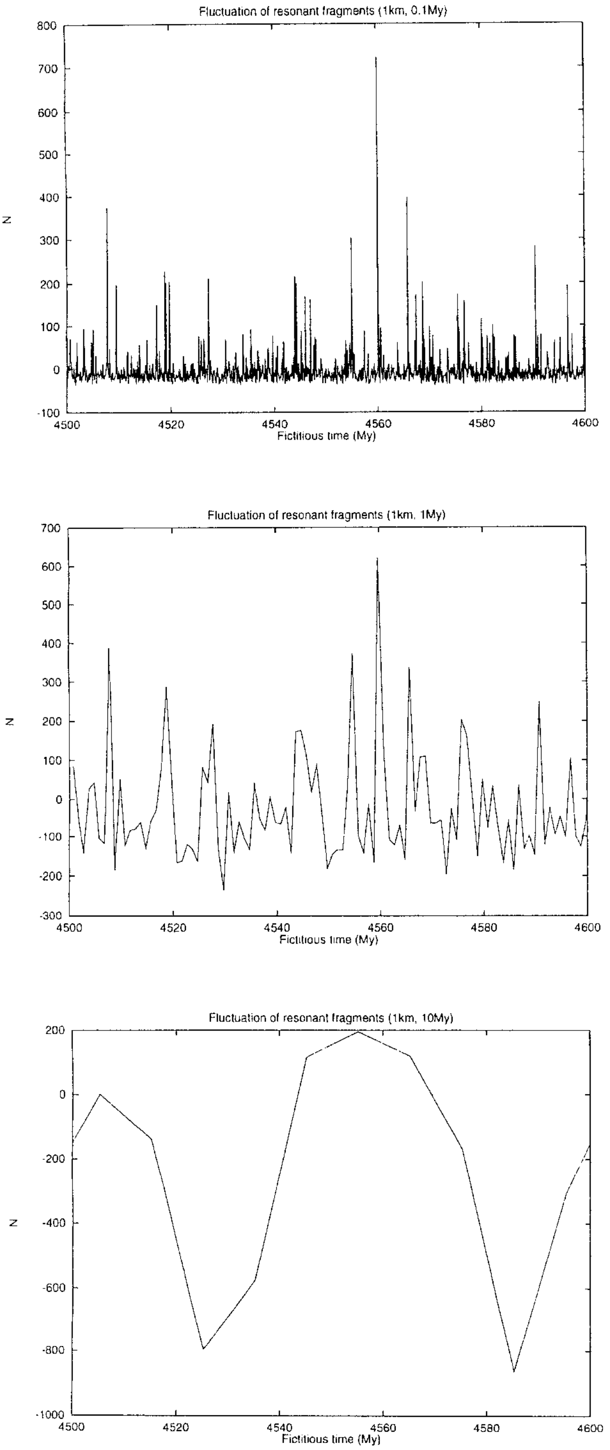

Fig. 3. The same as Fig. 1 but for fragments in the 1–km size bin.

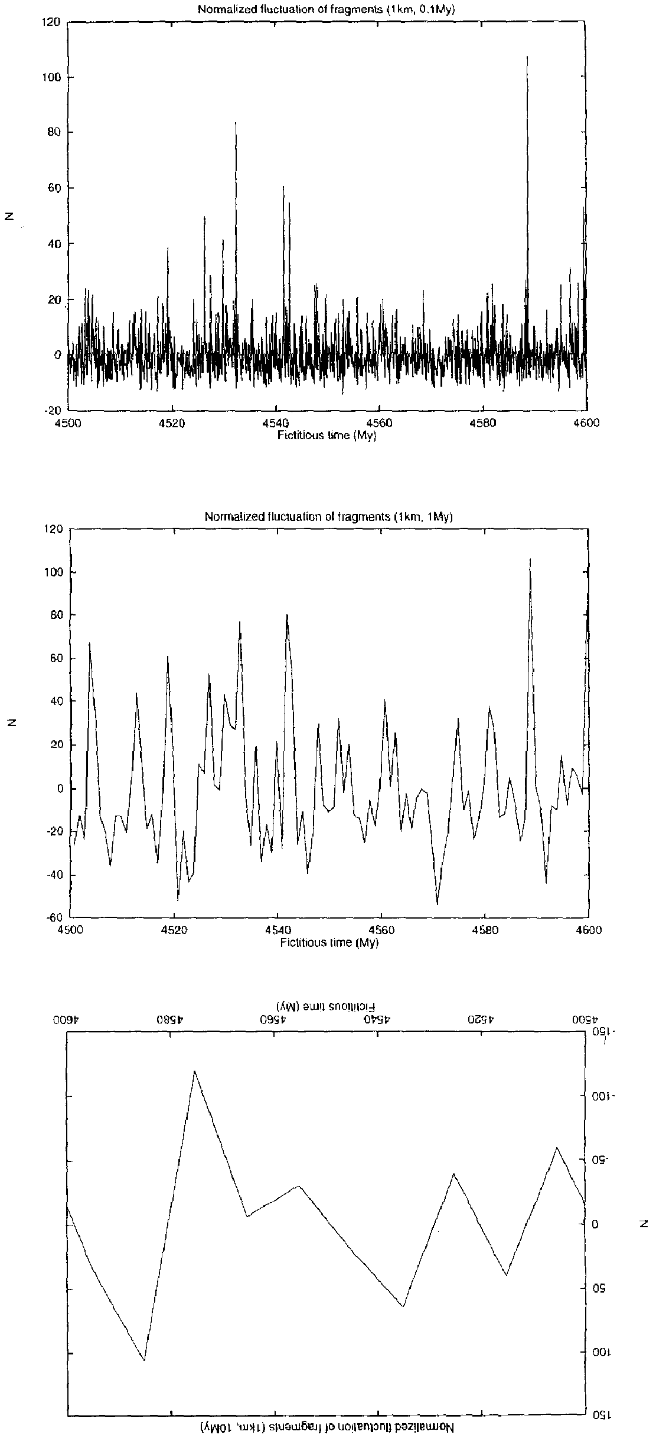

Fig. 4. The same as Fig. 2 but for fragments in the 1-km size bin.

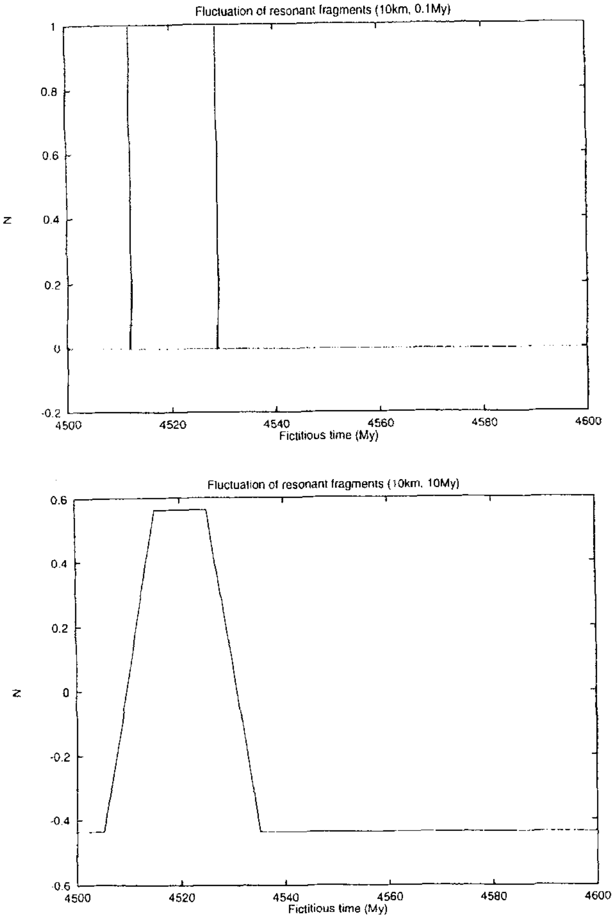

Fig. 5. The same as Fig. 1 but for fragments in the 10-km size bin. Only the 0.1 and 10 Myr time scales have been represented in Figs. 5a and 5b, respectively. The 1-Myr plot provides no new information with respect to Fig. 5a, therefore it has been omitted.

are partially smoothed out only over 10 Myr (Fig. 5b). The "normalized fluctuations" are not meaningful, as they correspond always to values much smaller than unity. It is interesting to note that in the real NEA population several sizeable bodies exist: (1036) Ganymed, with a diameter exceeding 35 km; (433) Eros and (3552) Don Quixote, in the 20 km class; (1580) Betulia, (1627) Ivar, (1866) Sisyphus and (3200) Phaethon, all 7 to 8 km across (see data in McFadden et al. 1989). If our collisional physics is correct, we have to expect that either these NEAs are located in very long-lived, "slow-track" orbits, or they must come from a different source (i.e., comets). The latter explanation appears certainly plausible for (3552) Don Quixote, a D-type NEA with a Jupiter-crossing orbit similar to those of short-period comets, whose dynamical lifetime is only of the order of 10^5 yr (Milani et al. 1989).

Our model indicates that it is very unlikely that such a big and young object has been recently supplied from the asteroid belt, and its taxonomic type confirms that this is a very good candidate for a dormant/extinct cometary nucleus. This appears also to be the case for (3200) Phaethon, an F–type object which has been identified as the likely parent body of a prominent meteor stream (the Geminids). The situation is different for objects such as the two largest Amors, (1036) Ganymed and (433) Eros, which are likely to be "old" fragments from very rare disruption events in the main belt, as their orbits currently do not approach the Earth and evolve very slowly owing to encounters with Mars only; to the same category probably belongs also (1866) Sisyphus, which is "protected" from Earth encounters by the so–called Kozai mechanism (or e–ω coupling, see Milani et al. 1989). More rapid is probably the orbital evolution of (1580) Betulia and (1627) Ivar, which are not currently Earth–crossers, but become so within $\approx 10^5$ yr; however, neither of these objects is on a resonant, "fast–track" orbital *route*, so their dynamical lifetime is probably much longer than 1 Myr.

4. Conclusions

A first interesting conclusion of this work, derived from our "mean evolution" simulations, is that collisional evolution in the main asteroid belt, modelled in a way consistent with the evidence from laboratory experiments, is capable of supplying to NEA orbits a few hundreds km–sized fragments per Myr, enough to sustain the loss rates from planetary/solar collisions and hyperbolic ejection. This can be seen from the following simple argument. Let us we assume that: (i) the NEA population is characterized by two typical lifetimes, $\approx$ 1 Myr ("fast–track" objects) and $\approx$ 30 Myr ("slow–track objects"), as indicated by numerical integrations; (ii) some 20% and 80% of the current NEA population are accounted by fast–track and slow–track objects, respectively, again in agreement with recent dynamical work (Farinella et al. 1994b, Froeschlé et al. 1995); (iii) the steady–state abundance of both fast– and slow–track NEAs is simply given by their supply rate times their lifetime. Then, from the current proportions of NEAs of the two types, we can infer that about 15% of the fragments initially supplied to resonances end up "parked" into slow–track orbits, whereas the remaining 85% stays on short–lived fast–track orbits. Using the resonance yields given in the third column of Table I, the steady–state populations listed in the fourth and fifth columns can be derived. We obtain an overall population of about 2000 km–sized objects and more than one million of 100–m sized bodies. The former number is in excellent agreement with the observations, although we stress that uncertainties in both observations and our model imply that this may be at least in part coincidental.

Big NEAs, $\approx$ 10 or more km in diameter, appear to be overabundant in the real Apollo–Amor population with respect to the predictions of our model. Although this may be due to problems with our collisional physics and/or to random fluctuations coupled with small-number statistics, the dynamical properties of the observed sizeable NEAs rather suggest that these bodies either have a different (i.e., cometary) source, or have settled onto comparatively long-lived orbits.

Our simulations have allowed us to address for the first time in a quantitative way the important issue of the time variability of the fragment supply from the main belt to the near-Earth environment. The fast-track component of the NEA population is variable up to tens of times its average abundance, and such fluctuations are strongly enhanced for smaller bodies and faster evolutionary time scales. Although at most times (including the present one) the short-lifetime objects probably account only for a minority of the existing population, our results suggest that from time to time they may become dominant, with an important fraction of them generated from a single chance collision occurred in the main belt close to a resonance. This may be tested by physical observations of NEAs, in particular those on fast-track orbits. Relevant insight in this context may be also provided by evidence from meteorite types, thermal histories, Argon–Argon and cosmic-rays exposure ages, as well as from comparisons between the Antarctic and non-Antarctic collections (which record different average fall times). For instance, Benoit and Sears (1993) have recently found indications that the flux of H-chondrites has significantly changed in the last several hundred thousand years. As for the cratering fluxes onto the Earth, the other inner planets and the Moon, our results indicate that significant (up to an order of magnitude) peaks over the 0.1 to 1 Myr time scales are possible from time to time. Even with these sporadic spikes, however, when averaged over time scales of $\approx$ 10 Myr and longer, the overall population of NEAs down to bodies in the 100 m size range, as well as the corresponding cratering rates, are unlikely to vary by more than a factor two.

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