

Dynamical evolution of cometary asteroids

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Accepted 1998 February 23. Received 1998 February 18; in original form 1997 March 12

ABSTRACT

We present results from long-term numerical integrations of hypothetical Jupiter-family comets (JFCs) over time-scales in excess of the estimated cometary active lifetime. During inactive periods these bodies could be considered as ‘cometary’ near-Earth objects (NEOs) or ‘cometary asteroids’. The contribution of cometary asteroids to the NEO population has important implications not only for understanding the origin of inner Solar system bodies but also for a correct assessment of the impact hazard presented to the Earth by small bodies throughout the Solar system. We investigate the transfer probabilities on to ‘decoupled’ subJovian orbits by both gravitational and non-gravitational mechanisms, and estimate the overall inactive cometary contribution to the NEO population. Considering gravitational mechanisms alone, more than 90 per cent of decoupled NEOs are likely to have their origin in the main asteroid belt. When non-gravitational forces are included, in a simple model, the rate of production of decoupled NEOs from JFC orbits becomes comparable to the estimated injection rate of fragments from the main belt. The Jupiter-family (non-decoupled) cometary asteroid population is estimated to be of the order of a few hundred to a few thousand bodies, depending on the assumed cometary active lifetime and the adopted source region.

Key words: celestial mechanics, stellar dynamics – comets: general – minor planets, asteroids.

1 INTRODUCTION

We focus here on the question of the inactive Jupiter-family comet (JFC) (i.e., ‘cometary asteroid’) contribution to the near-Earth object (NEO) population, which we define to include all bodies of asteroidal appearance which have perihelion distances $q < 1.4$ au and orbital periods $P < 20$ yr. The limit on the orbital period is introduced for consistency with the conventional definition of JFCs and to exclude Halley-type asteroids such as (5335) Damocles (Asher et al. 1994). Following Harris & Bailey (1996), we separate orbits according to their aphelion distances into two broad classes: the longer period Class 1 orbits have aphelia $Q > 4.2$ au, allowing these objects possibly to have close approaches to Jupiter or even to cross Jupiter’s orbit, whereas Class 2 orbits have $Q < 4.2$ au. The latter comprise the majority (about 90 per cent) of the known NEO population and are dynamically ‘decoupled’ from having close Jovian encounters. Approximately 400 NEOs are currently known, the number growing at an ever-increasing rate due to the introduction of new and effective survey techniques (e.g. Scotti 1994) and because of growing interest amongst astronomers generally in the number and origin of the objects which in principle may crater the Earth. The distribution of these and other inner Solar system bodies in the (q, Q) -plane is shown in Fig. 1, based on data from the Catalogue of Cometary Orbits (Marsden & Williams 1996), the asteroid orbit data base compiled by Bowell, Muinonen &

Wasserman (1994), and a list of NEOs compiled and kindly provided by Steel (1996, personal communication).

A recent theoretical estimate of the NEO population, based on the assumption that NEOs are fragments arising from collisions between asteroids in the main belt, which have subsequently evolved through chaotic routes associated with various secular and mean-motion resonances in the inner Solar system, suggests that around 370 km-sized fragments and 2.5×10^5 0.1-km-sized fragments could be injected from the main asteroid belt per million years (Menichella, Paolicchi & Farinella 1996). Taking into account the mean dynamical lifetime of these objects, the results indicate that the steady-state NEO population derived from this source alone may contain about 2000 km-sized bodies, and more than 10^6 bodies larger than 0.1 km in diameter (cf. Morrison 1992; Rabinowitz et al. 1994). On this basis, the main asteroid belt is a plausible, fluctuating source of NEOs with the potential to explain something close to the observed population of km-sized NEOs.

The sublimation of cometary surface layers during successive perihelion passages could leave behind a non-volatile organic and dusty residue that superficially resembles an asteroidal regolith. Some NEOs may therefore be devolatilized, inactive or ‘dormant’ cometary nuclei. In fact, there are examples of ‘asteroidal’ objects in the inner Solar system that are likely to have had histories as active comets, either by reason of previously observed low-level activity or on the basis of associated meteoroid streams [e.g.,

(4105) = 107P/Wilson-Harrington and (3200) Phaethon]. Mantling, or devolatilization of the surface of a cometary nucleus, is a gradual process that is thought to occur over a time-scale of the order of 10 kyr, or around 1000 perihelion passages (revolutions) for a typical JFC (e.g. Rickman 1992). This time-scale thus provides a rough upper limit to the physically active lifetime of a short-period cometary nucleus circulating in an orbit of small perihelion distance. However, although depletion of cometary surface ices might lead to deactivation of the central nucleus, it is unknown how long such a ‘dormant’ nucleus might continue to exist without reactivation. In particular, meteoroidal bombardment or a reduction of orbital perihelion distance may cause disruption or fracture of the insulating mantle and allow fragments of the surface to break off, while a sufficiently large impact, close encounter with a planet or Sun-grazing event might cause splitting or fragmentation of the whole nucleus. A possible example of this type of evolution, in which a presumably inert main-belt asteroid has developed transient ‘cometary’ characteristics, is provided by P/1996 N2 Elst-Pizarro. This object appears to be a member of the Themis family, and certainly has an extremely stable main-belt asteroidal orbit (Ipatov & Hahn 1997); yet it also displays a dust tail suggestive of recent cometary outgassing. ‘Comet’ Elst-Pizarro thus demonstrates that a minor fraction of the observed JFC population may also originate from the population of outer main-belt asteroids (Marzari et al. 1995, 1997).

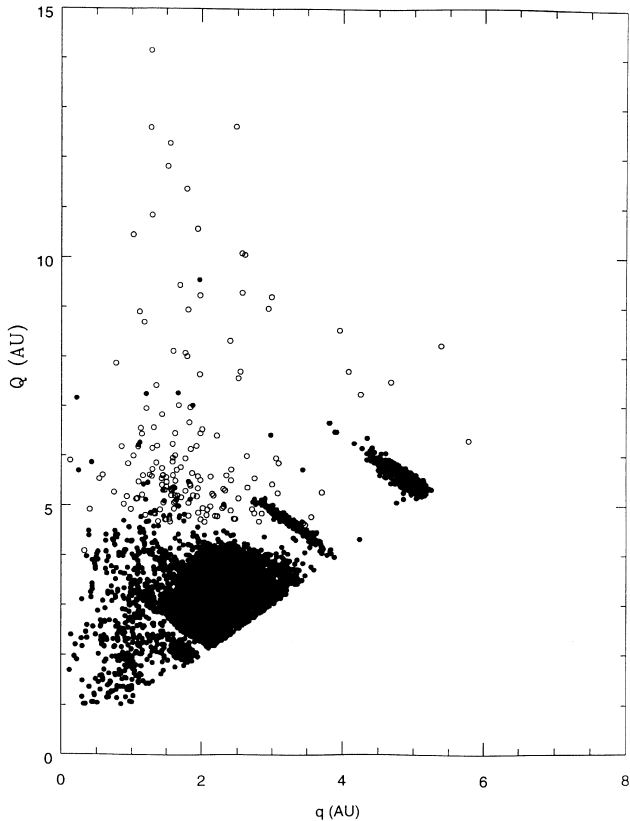


Figure 1. The distribution of observed short-period ($P < 20$ yr) minor bodies in the (q, Q) -plane. The open and filled circles correspond respectively to active JFCs and inactive asteroidal bodies comprising NEOs and main-belt asteroids. Notice the presence of NEOs and other ‘asteroidal’ bodies in the region largely occupied by JFCs, and a single active comet (2P/Encke) in the Class 2 NEO region.

2 NUMERICAL EXPERIMENTS

2.1 The model

In order to assess the probability of JFCs to evolve on to orbits similar to those of NEOs, we have performed long-term numerical integrations of hypothetical JFCs using the RADAU integrator RA15 (Everhart 1985), in a model Solar system including the seven planets Venus to Neptune and with tolerance parameter set to 10^{-8} . The initial orbits were chosen to have orbital periods $P < 20$ yr (i.e., semimajor axes $a < 7.37$ au), perihelion distances close to 1 au and aphelia close to 5.2 au, allowing initial close encounters to both Jupiter and the Earth. The motivation for this choice of initial conditions was to generate an ensemble of typical JFCs from which to calculate the transfer probability to Class 2 orbits (i.e., to $q < 1.4$ au and $Q < 4.2$ au) via terrestrial planet encounters, and to determine the proportion of cometary bodies which might survive for longer than the active cometary lifetime on Class 1 orbits, presumably in the form of inactive ‘cometary asteroids’.

We first integrated a sample of 360 bodies, denoted Ensemble 1, with identical initial orbits ($q = 1$ au, $Q = 5.2$ au, $i = 0^\circ$) except for the longitudes of perihelion which were distributed uniformly in the range $0^\circ < \varpi < 360^\circ$. The initial Tisserand parameter with respect to Jupiter was $T_J = 2.81$. This ensemble was integrated for approximately 0.785 Myr including only gravitational forces. The originally similar orbits were rapidly dispersed (within less than 100 revolutions; see Harris & Bailey 1996, fig. 2), and the values of T_J evolved to lie within the approximate range 2.5–3.0, typical of most observed JFCs. There were no long-term transitions to Class 2 orbits over the time-scale of the integration (see Section 2.3).

Since these initial orbits started with perihelia deep inside the Class 1 zone ($q < 1.4$ au), it is possible that results from this ensemble might over-estimate the number of objects circulating on Class 1 orbits for significant periods of time. In order to investigate this effect, a second sample of hypothetical JFCs was integrated, denoted Ensemble 2, containing 51 objects which had been captured into short-period orbits ($P < 20$ yr) from the inner core of the Oort Cloud during a previous numerical integration (Emel’yanenko & Bailey 1998). These objects had evolved from ‘original’ orbits with $i < 30^\circ$, $2500 < a < 3500$ au and $12.5 < q < 31$ au. It is notable that the objects in Ensemble 2 exhibit similar dynamical characteristics to objects captured into Jupiter-family orbits from the Edgeworth–Kuiper belt source region. At the start of this second integration the bodies had $P < 20$ yr, $i < 40^\circ$ and $q > 3$ au, and their Tisserand parameters covered approximately the same range as the evolved Ensemble 1. The evolution of Ensemble 2 was followed for 1 Myr using the same model Solar system and RADAU parameters as before.

Fig. 2 shows the evolution of Ensemble 2 in the (q, Q) -plane for the entire span of the integration. The degree of concentration of dots in the plot represents the probability for objects to be found in a particular region of (q, Q) space. This diagram may be compared with the observed populations shown in Fig. 1. It is obvious that the observed distribution of JFCs is highly incomplete for perihelion distances $q > 2$ au. As with the previous group, no objects were transferred on to Class 2 orbits (see Section 2.3).

A typical example of the orbital evolution of an object from Ensemble 2 is shown in Fig. 3. The evolution follows a line of nearly constant Tisserand parameter with respect to Jupiter, indicating that the evolution is dominated by this giant planet. Initially the particle describes a low-eccentricity orbit with perihelion just inside

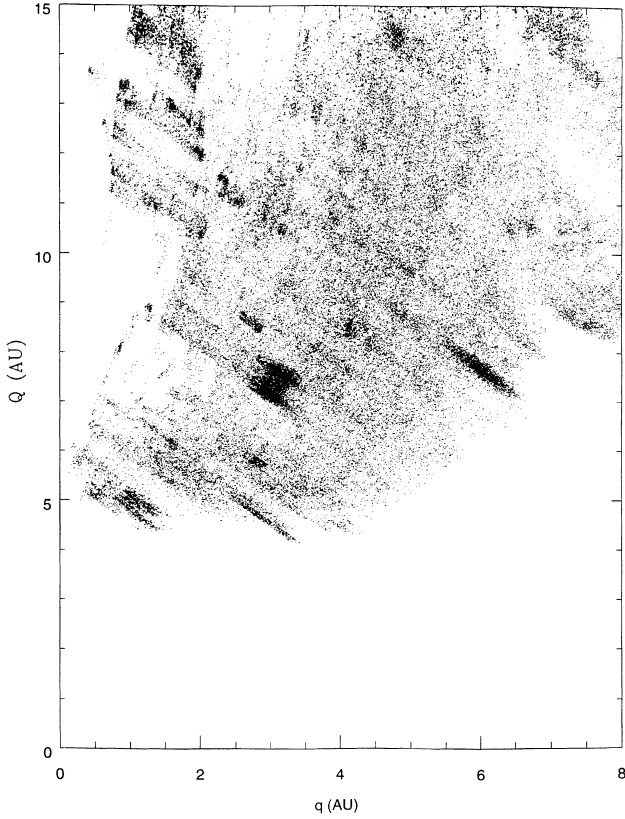


Figure 2. The evolution of 51 hypothetical JFCs (Ensemble 2) in the (q, Q) -plane for the entire duration of the numerical integration (1 Myr). Diagonal lines from top-left to bottom-right signify evolution inside mean-motion resonances where the semimajor axis librates about the resonant value. Note that the probability of orbital evolution into the region occupied by Class 2 NEOs ($q < 1.4$ au, $Q \leq 4.2$ au) is low.

Jupiter's orbit. The object makes two visits to the terrestrial planet region on a Class 1 JFC orbit, and the total time spent in this region is around 4 kyr. Notice that these visits correspond to periods of low ($< 30^\circ$) orbital inclination due to the Kozai $e-i$ coupling mechanism. This mechanism was first described by Kozai (1962); more recent discussions may be found in Milani et al. (1989) and Bailey, Chambers & Hahn (1992). When the object first became short-period ($P < 20$ yr), the inclination was around 35° . Therefore the orbital inclination distribution of the *observed* JFCs is not necessarily indicative of the orbital inclination distribution of the source region. After around 43 kyr on a Jupiter-family short-period orbit the particle is ejected from the terrestrial planet region by Jupiter, and after a further 200 kyr it is ejected from the Solar system.

2.2 Dynamical evolution: Class 1 orbits

We found that roughly 71 per cent of Ensemble 2 evolved to JFC orbits with perihelia $q < 3.0$ au, and around 35 per cent evolved to Class 1 orbits ($q < 1.4$ au, $Q > 4.2$ au, $P < 20$ yr). (These figures correspond to 36 and 18 of the 51 bodies respectively.) The relevant results for Ensemble 2 are summarized in Tables 1 and 2. Table 1 shows the mean lifetime and injection rate of active JFCs and the steady-state number of cometary asteroids as a function of the assumed active cometary lifetime for two different ranges of perihelion distance. The figures in this table may be illustrated by considering, for example, a restricted cometary active lifetime of 1000 revolutions within a perihelion distance of $q < 1.4$ au (top row,

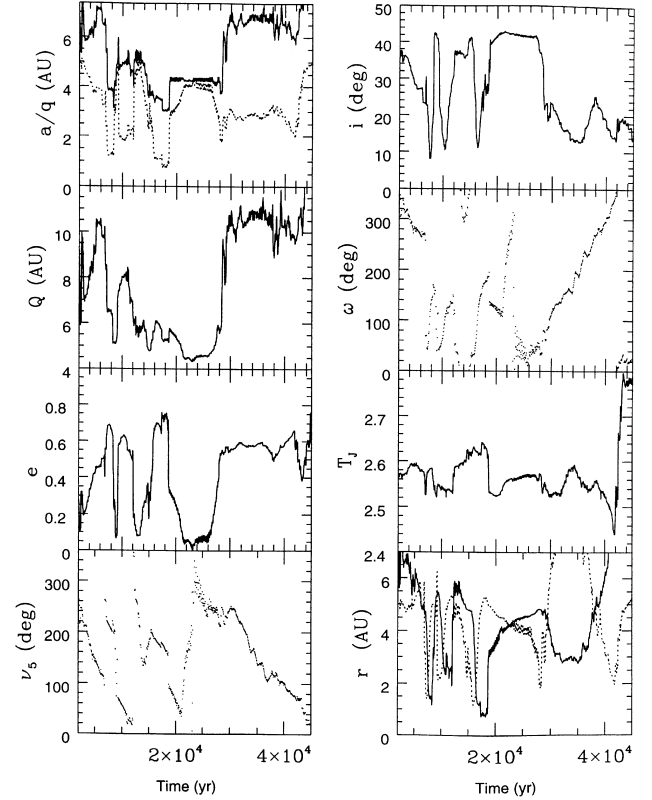


Figure 3. Evolution of a typical orbit from Ensemble 2. The parameters shown are semimajor axis a , perihelion distance q , aphelion distance Q , eccentricity e , critical argument of the ν_5 secular resonance, inclination i , argument of perihelion ω , Tisserand parameter with respect to Jupiter T_J , and heliocentric distance of the ascending and descending nodes r . The object survives on a Class 1 orbit for around 4 kyr in total, corresponding to about 10 per cent of its lifetime on a Jupiter-family ($P < 20$ yr) orbit. See text for further details.

column 7). Here, if a comet has performed a total of 1000 perihelion passages on an orbit with $q < 1.4$ au (not necessarily during a single visit to this region), it becomes inactive and hence unobservable as a comet. The table shows that, for this particular example, the mean observable lifetime of a JFC with $q < 1.4$ au is around 3.8 kyr. The Catalogue of Cometary Orbits (Marsden & Williams 1996) lists 41 active JFCs with $q < 1.4$ au. We would therefore require an injection rate, R_{inj} , of about 41 comets every 3.8 kyr into the $q < 1.4$ au region, or around 1.08 per century (cf. Fernández 1985) in order to maintain the observed active JFC population in a steady state. The last column of Table 1 shows that the mean *dynamical* lifetime of a JFC within this region is around 15.5 kyr. For the purposes of this calculation there is no restriction on the active lifetime. Therefore, returning to the 1000-revolutions case, the steady-state number of inactive JFCs in this region, N_{SS} , should equal $[(0.0108 \text{ yr}^{-1} \times 15\,500 \text{ yr}) - 41]$, or around 130 bodies. The calculations for the $q < 3.0$ au zone are performed in a similar way except that the number of active JFCs in this region is taken as 147. It should be noted that the injection rate and steady-state number of cometary asteroids for the $q < 3.0$ au region are lower limits, as the observed sample of active JFCs in this region (down to the same limiting magnitude as for the $a < 1.4$ au region) is likely to be far from complete.

Table 2 shows the number of bodies that survive for longer than a certain number of perihelion passages on Class 1 orbits ($Q > 4.2$ au),

Table 1. Mean lifetime \bar{L} (yr), and injection rate R_{inj} , of JFCs and steady-state number N_{SS} , of inactive cometary asteroids within perihelion distance q ($P < 20$ yr) as a function of active lifetime (revolutions).

Ensemble	10	50	100	200	500	1000	2000	5000	10000	∞
2				active	lifetime	(revs)				
\bar{L} ($q < 1.4$ au) (yr)	60	300	600	1100	2100	3800	6200	10800	15000	15500
R_{inj} (per 10^2 yr)	70.69	13.67	6.83	3.81	1.95	1.08	0.66	0.38	0.27	0.26
N_{SS}	10930	2080	1020	550	260	130	60	20	1	0
\bar{L} ($q < 3.0$ au) (yr)	90	500	900	1700	3700	6200	9600	15900	23600	32500
R_{inj} (per 10^2 yr)	167.05	30.31	15.91	8.62	3.97	2.36	1.53	0.92	0.62	0.45
N_{SS}	54220	9720	5030	2660	1150	620	350	150	60	0
Ensemble	10	50	100	200	500	1000	2000	5000	10000	∞
3				active	lifetime	(revs)				
\bar{L} ($q < 1.4$ au) (yr)	120	500	900	1700	4100	7900	14800	31000	49400	109900
R_{inj} (per 10^2 yr)	35.04	8.87	4.70	2.36	0.99	0.52	0.28	0.13	0.08	0.04
N_{SS}	38450	9700	5120	2550	1050	530	270	100	50	0
\bar{L} ($q < 3.0$ au) (yr)	130	500	1000	1900	4400	8300	15900	36600	63800	268400
R_{inj} (per 10^2 yr)	110.53	29.94	15.44	7.95	3.35	1.77	0.92	0.40	0.23	0.05
N_{SS}	296550	80220	41300	21190	8850	4600	2320	930	470	0

Table 2. Number of bodies that survive on Class 1 orbits ($q < 1.4$ au; $Q > 4.2$ au; $P < 20$ yr) for longer than the assumed active lifetime, the production rate of Class 1 cometary asteroids PR_{CA} , the mean lifetime as inactive Class 1 cometary asteroids \bar{L}_{CA} (yr), and the steady-state number N_{SS} as a function of active lifetime (x revolutions).

Ensemble	10	50	100	200	500	1000	2000	5000	10000
2				active	lifetime	(revs)			
No. (from 18)	17	16	14	10	9	6	4	2	1
%	94	89	78	56	50	33	22	11	6
PR_{CA} (per 10^6 yr)	667630	121510	53120	21170	9750	3600	1470	420	150
\bar{L}_{CA} (yr)	16400	17100	19200	26000	26800	35200	41700	42800	7900
N_{SS}	10930	2080	1020	550	260	130	60	20	1
Ensemble	10	50	100	200	500	1000	2000	5000	10000
3				active	lifetime	(revs)			
No. (from 96.45)	96.45	90.2	90.2	89.2	84.07	80.65	72.52	52.43	41.47
%	100	94	94	92	87	84	75	54	43
PR_{CA} (per 10^6 yr)	350400	82950	43950	21830	8630	4350	2110	710	340
\bar{L}_{CA} (yr)	109700	117000	116500	116900	121300	121900	126400	145100	140700
N_{SS}	38450	9700	5120	2550	1050	530	270	100	50

the production rate of inactive Class 1 cometary asteroids, their mean dynamical lifetime as inactive bodies, and their steady-state number as a function of active lifetime. As mentioned earlier, 18 from 51 particles in Ensemble 2 evolved on to orbits with $q < 1.4$ au. Table 2 shows that a third of these survived on such orbits for a total period in excess of 1000 revolutions. Therefore, if the injection rate of ‘new’ JFCs into this region is 1.08 per century (from Table 1) and 0.33 of these perform more than 1000 perihelion passages in such orbits and hence become inactive, then the production rate of Class 1 cometary asteroids is around 3600 per 10^6 yr. Note that this value is an order of magnitude higher than estimates of the injection rate of km-sized fragments from the main asteroid belt. However, the mean dynamical lifetime of those bodies which survive for more than 1000 revolutions is around 35 kyr (considering only the inactive phase). Therefore the steady-state number of Class 1 cometary asteroids should be given by $(0.0036 \text{ yr}^{-1} \times 35 \text{ 200 yr})$, or around 130 bodies (the same number as shown in Table 1).

A key point is that the objects that evolve on to Class 1 orbits from Ensemble 2 have relatively short dynamical lifetimes against

ejection by Jupiter, typically in the range 10–100 kyr. On average the bodies spend approximately 53 kyr in total on orbits with $q < 7.37$ au and $P < 20$ yr, and they spend only a small fraction of their total bound dynamical lifetime on Class 1 orbits (on average only about 15.5 kyr). This contrasts sharply with results from orbital integrations of the *observed* population of Class 1 NEOs. These seem to be dominated by bodies having long lifetimes on Class 1 orbits (> 100 kyr) (see Table 3). These results were obtained by considering long-term numerical integrations of individual test particles with orbits close to those of various ‘real’ objects amongst the apparently cometary Class 1 NEOs, such as (3552) Don Quixote, (4015) = 107P/Wilson-Harrington, (5324) Lyapunov, (5370) Taranis, 1982YA, 1994AB₁, 1983LC, 1984QY₁ and 1994LW. For comparison, we also integrated some observed objects currently in Class 2 orbits such as 1993TR₂, 2P/Encke and (4503) Cleobulus. The mean lifetimes (on Class 1/Class 2 orbits) for these objects were calculated from ten 1-Myr integrations per object. It can be seen from Table 3 that all the observed objects integrated have mean lifetimes considerably longer than the

Table 3. Initial orbits, mean lifetime \bar{L} (yr) on Class 1/Class 2 orbits, and resonant state (nr = non-resonant) for some *observed* NEOs.

Name	q_0 (au)	Q_0 (au)	a_0 (au)	i_0 (au)	\bar{L}_{CA} (yr)	Jovian resonance
1984 QY1	0.25	5.70	2.97	15.5	82000	7:3
1983 LC	0.76	4.50	2.63	1.52	100000	nr
(3552) Don Quixote	1.21	7.26	4.24	30.78	122000	4:3
1982 YA	1.12	6.28	3.70	34.66	240000	5:3
1994 AB1	1.16	4.53	2.84	4.53	460000	5:2
1994 LW	1.20	5.12	3.16	23.02	560000	nr
(5370) Taranis	1.23	5.47	3.35	19.00	600000	2:1
(5324) Lyapunov	1.14	4.78	2.96	19.48	620000	7:3
1993 TR2	1.34	3.92	2.63	15.20	>800000	nr
2P/Encke	0.33	4.09	2.21	11.93	900000	nr
(4503) Cleobulus	1.31	4.13	2.72	2.55	>1140000	8:3
107P/Wilson-H'ton	1.00	4.29	2.64	2.78	1220000	nr

Table 4. Mean lifetime \bar{L} (yr) on Class 1/Class 2 orbits ($q < 1.4$ au, $P < 20$ yr) for hypothetical fragments from resonance-crossing asteroid families. The numbers in parentheses to the right of each mean lifetime indicate the number of particles involved in the calculation.

Family name	Jovian Resonance	a_{res} (au)	\bar{L} (yr)			
			All Q	$Q > 4.2$ au	$Q > 4.63$ au	$Q > 5.0$ au
Maria	3:1	2.501	2326000 (156)	669000 (155)	301000 (151)	197000 (79)
Vesta	3:1	2.501	1080000 (92)	369000 (92)	153000 (81)	39000 (42)
Nysa	3:1	2.501	1399000 (143)	286000 (140)	101000 (132)	36000 (57)
MEAN	3:1	2.501	1694000 (391)	459000 (387)	196000 (364)	108000 (178)
Chloris	8:3	2.705	1332000 (61)	547000 (56)	107000 (53)	23000 (36)
Dora	5:2	2.825	301000 (148)	192000 (148)	64000 (148)	19000 (91)
Gefion	5:2	2.825	251000 (141)	200000 (141)	80000 (141)	18000 (104)
Koronis	5:2	2.825	209000 (84)	95000 (84)	26000 (82)	12000 (34)
MEAN	5:2	2.825	261000 (373)	173000 (373)	62000 (371)	18000 (229)
Koronis	7:3	2.957	51000 (45)	49000 (45)	19000 (44)	1000 (6)
Eos	9:4	3.030	995000 (37)	213000 (37)	87000 (37)	14000 (21)
Themis	2:1	3.277	480000 (28)	480000 (28)	479000 (28)	484000 (26)

mean for Ensemble 2 (Table 2), although the Class 1 lifetimes of one or two longer lived examples from Ensemble 2 (see, e.g., Fig. 7) agree reasonably well with the first three entries in Table 3. Most of the observed objects tend to be ‘protected’ from close planetary approaches for relatively long periods of time by mean-motion resonances and Kozai librations, or simply due to the fact that their initial orbits are sufficiently decoupled from that of Jupiter to avoid strong orbital perturbations (e.g., the last four entries in Table 3). It is, of course, the case that a randomly selected sample of objects from a population having a wide range of dynamical lifetimes will tend to favour objects with longer lifetimes, but considerably longer mean lifetimes for the majority of the objects in Table 3 are not immediately reconciled with their having originated from a ‘flat’ cometary source region such as that leading to Ensemble 2. The alternative explanations are (i) that these longer lived observed bodies have evolved on to more stable orbits by the action of rare terrestrial planet encounters or non-gravitational forces, (ii) that they originate from an asteroidal source region, for example, the main belt, or (iii) that they originate from another cometary source such as the outer Oort Cloud.

Using data obtained from the results of the GAPTEC project (Gladman et al. 1997), we have calculated the mean lifetime on Class 1/Class 2 orbits for hypothetical bodies originating from various asteroid collisional families that cross Jovian mean-motion resonances in the main belt. The dynamical lifetime of bodies that may potentially become NEOs are typically on the order of a few Myr. NEOs from these sources are removed efficiently by Jovian close encounters and solar collisions. Table 4 lists the mean lifetime

on orbits with $q < 1.4$ au, $P < 20$ yr as a function of minimum aphelion distance for hypothetical fragments from various resonance-crossing families. The numbers in brackets indicate the number of test particles involved in the calculation of the mean lifetime. The lifetime on these orbits includes phases of resonant and non-resonant motion. It is clear that bodies from these sources can survive on Class 1/Class 2 (i.e., $q < 1.4$ au, $P < 20$ yr) orbits on average for periods that agree reasonably well with those of the observed objects in Table 3. There is even a hint of agreement between the mean lifetime of the hypothetical bodies and that of the observed bodies in the same resonances. It thus seems likely that some of the observed Class 1 NEOs could have their origin in the outer main belt (beyond the 3:1 resonance).

However, investigation of a third sample, which we denote Ensemble 3, has shown that comets can also be scattered on to these long-lived Class 1 orbits. Ensemble 3 contained 52 objects which had been captured into short-period orbits ($P < 20$ yr) from the outer Oort cloud. (Their original orbits were specified as having an isotropic distribution of inclinations, $2 \times 10^4 < a < 3 \times 10^4$ au and $q < 31$ au; see Emel’yanenko & Bailey 1998.) Each of the 52 objects carries a weighting factor designed to ensure that their original perihelia ($q < 31$ au) were distributed uniformly. At the start of this third integration the bodies had $P < 20$ yr and $q < 1.5$ au, and their Tisserand parameters covered the approximate range $-0.3 < T_J < 3$ [i.e., the ensemble contained a mixture of conventional JFCs and short-period ($P < 20$ yr) Halley-type comets ($T_J < 2$), such as (for example) 96P/Machholz 1].

The evolution of Ensemble 3 was followed for 1 Myr using the

same integration procedure as described before. Again no objects were found to evolve to the Class 2 region. The relevant results are displayed in Tables 1 and 2. The calculations were performed in the same way as for Ensemble 2. The mean Class 1 dynamical lifetime (∞ revs in Table 1) is more than 7 times the mean for Ensemble 2 (i.e., ~ 110 kyr). This is a lower limit, since ~ 20 per cent of Ensemble 3 remained on JFC orbits at the end of the 1-Myr integration compared to only 2 per cent (i.e., one object) for Ensemble 2. The mean lifetime of these objects as cometary asteroids, \bar{L}_{CA} (Table 2) is in reasonable agreement with those in Table 3, and 15/52 of the objects in Ensemble 3 have Class 1 lifetimes in excess of 100 kyr (5/52 have lifetimes in excess of 300 kyr). Note that 43 per cent of Ensemble 3 survive on Class 1 orbits for more than 10 000 revolutions compared to only 6 per cent of Ensemble 2.

A typical example of the orbital evolution is shown in Fig. 4. This object has a Class 1 lifetime of around 200 kyr. As for the observed objects, many of the orbits in Ensemble 3 tend to be protected from the disturbing effects of planetary close approaches by mean-motion resonances, Kozai librations ($e-i$ coupling), or due to the fact that the encounter velocities are generally higher than those in Ensemble 2, as the Tisserand parameters with respect to Jupiter can be close to or less than 2. It thus seems that the outer Oort Cloud is a credible source of long-lived Class 1 cometary asteroids. However, there is a suggestion that this source region produces too many highly inclined ($i > 30^\circ$) and retrograde Class 1 orbits as compared to the observed inclination distribution of JFCs and NEOs. This may be explained by the possibility that higher inclination objects are more difficult to detect than those on

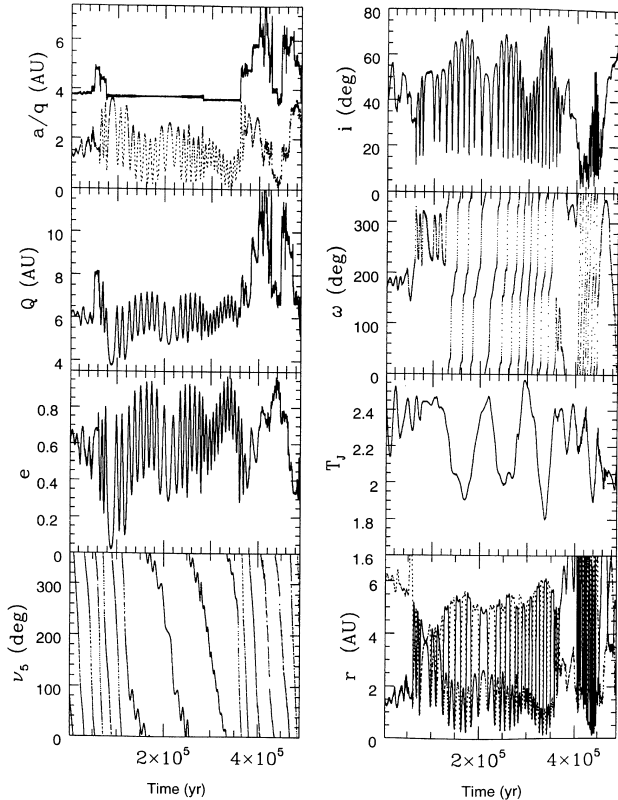


Figure 4. Evolution of a typical orbit from Ensemble 3. The parameters shown are the same as in Fig. 3. This object survives on a Class 1 orbit for around 200 kyr, or around 40 per cent of its Jupiter-family lifetime. See text for further details.

low-inclination, direct orbits due to the bias against discovery of high-inclination objects by CCD or photographic surveys that are concentrated along the ecliptic and near opposition. In fact, observations of radar meteors and meteoroid streams suggest that inactive (or barely active) high-inclination and retrograde JFCs are present on short-period Earth-crossing orbits (Olsson-Steel 1988; McBride et al. 1996; Taylor & McBride 1997).

It is interesting to note the preponderance of the Sun-grazing state in Ensemble 3. Approximately 28 per cent of Ensemble 3 evolve on to Sun-grazing orbits ($q < 0.02$ au, or about 4 solar radii), and around 23 per cent evolve further to become Sun-colliders. None of the orbits in Ensemble 2 evolve to become Sun-grazers.

2.3 Dynamical evolution: Class 2 orbits

Among the 360 objects from Ensemble 1, we found only two which experienced evolution on to Class 2 orbits, and then only for short periods, lasting in total 708 and 3220 yr respectively. In both cases the aphelion distances were greater than 4 au, indicating that even for these objects their classification as Class 2 rather than Class 1 is marginal. There were no examples of long-term transitions to Class 2 orbits over the time-scale investigated for Ensembles 1, 2 or 3 (which considered a total of 429 orbits with $q < 1.4$ au), so the transition probability for a JFC to evolve on to a Class 2 orbit by purely gravitational means (i.e., due to terrestrial planet encounters) is probably less than $1/429$, i.e., < 0.0023 .

The radius of the Jovian sphere of influence, R_J , is given by the approximate expression

$$R_J = \left(\frac{M_J}{M_\odot} \right)^{0.4} a_J \quad (1)$$

where M_J and a_J are the mass and orbital semimajor axis of Jupiter respectively, and M_\odot is the mass of the Sun (see, e.g., Roy 1988, p. 170). Inserting appropriate values into the above equation gives $R_J \sim 0.322$ au. We can therefore hypothesize that, in the case of a restricted Sun–Jupiter–body framework (in which secular resonances are absent), the smallest aphelion distance, Q_{\min} , above which passages through the Jovian sphere of influence are possible is roughly

$$Q_{\min} = q_J - R_J = 4.629 \text{ au}, \quad (2)$$

where q_J denotes the Jovian perihelion distance. This theoretical limit is plotted in Fig. 5(a) together with the current positions of 185 active short-period comets (SPCs) in the (q, e) -plane. The bold line describes the equation

$$q = 4.629 \frac{(1-e)}{(1+e)}, \quad (3)$$

and represents the ‘ Q_{\min} barrier’ (4.629 au) in this plane. Points lying above this line can in principle enter the Jovian sphere of influence. The Halley-types can be distinguished from the JFCs as a separate clustering of high-eccentricity points towards the top-left of the plot. The only observed JFCs that lie below the theoretical Q_{\min} barrier are (from top-left to bottom-right) 2P/Encke, 107P/Wilson-Harrington, 39P/Oterma and 111P/Helin-Roman-Crockett (82P/Gehrels 3 is also close to the barrier).

The last three objects (including 82P/Gehrels 3) provide a possible clue to the source of such orbits. The 1933–41 encounter of 39P/Oterma and the 1963–76 encounter of 82P/Gehrels 3 with Jupiter are typical examples of nearly tangent encounters. After a strong gravitational interaction during a nearly tangent encounter with Jupiter (in which a temporary satellite capture may occur, cf.

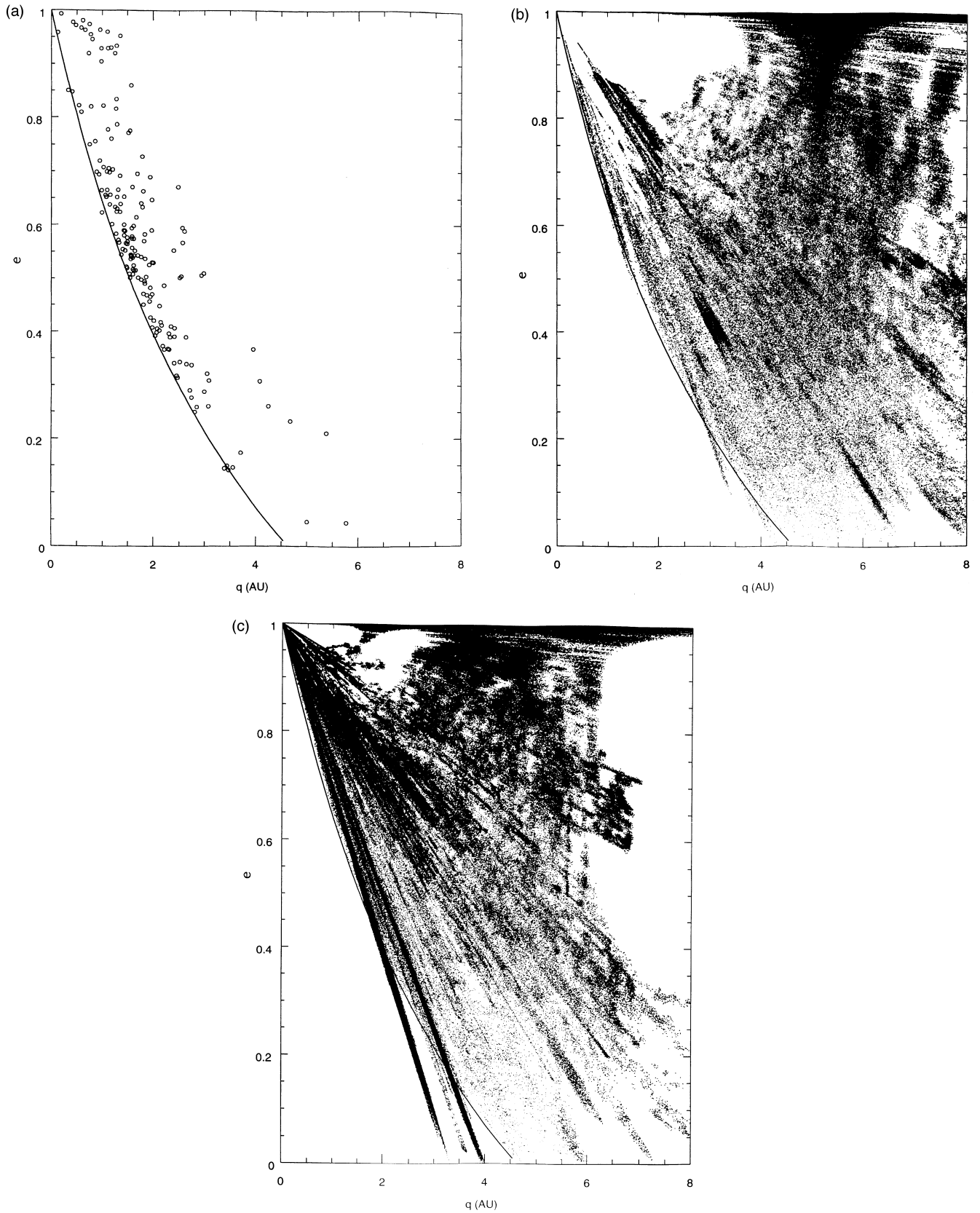


Figure 5. (a) the positions of 185 observed SPCs in the (q, e) -plane. The Halley-types can be seen as a separate grouping towards the top-left of the diagram. The bold curve is a line of constant aphelion distance ($Q = 4.629$ au) and represents a theoretical lower limit for the orbital aphelia of Jupiter-family comets (see text for details). (b) Evolution of Ensemble 2 in the (q, e) -plane. (c) Evolution of Ensemble 3 in the (q, e) -plane.

D/1993 F2 Shoemaker-Levy 9) the pre- and post-encounter orbits are essentially determined by the mass of the perturbing planet, a process which potentially allows comets to cross the Q_{\min} barrier. Following Valsecchi (1992), this means that, for the case of Jupiter, $e \sim 0.2$ and $a \sim 7$ au for an object originating from or ending in an exterior orbit, and $e \sim 0.2$, $a \sim 4$ au for the other case. These estimates compare favourably with the pre- and post-encounter orbits of 39P/Oterma and 82P/Gehrels 3 (see Carusi et al. 1985). For both of these orbits the pre-encounter perihelion distance was around 5.7 au and the orbital inclination close to zero ($i \sim 3^\circ$). After the encounters the final orbital aphelia were well inside the orbit of Jupiter ($Q < 4.629$ au) and the semimajor axes close to 4 au (note that the 3:2 Jovian mean-motion resonance lies at $a \sim 3.97$ au).

It is interesting to note that D/1993 F2 Shoemaker-Levy 9, 82P/Gehrels 3 and 111P/Helin-Roman-Crockett were all in the vicinity of Jupiter at the same time during their 1970 close encounters, and the last two also had remarkably similar orbits (Tancredi, Lindgren & Rickman 1990). Moreover, following Bailey, Emel'yanenko & Scotti (1994, unpublished), there is not a single documented case of a comet surviving passage through the Roche limit without having been disrupted (Kresák 1981), and, by analogy with the Kreutz Sun-grazing group, these three comets can be suggested to be physically related (Bailey et al. 1994, unpublished), their immediate progenitor having passed exceptionally close to Jupiter in 1970 and undergone tidal splitting into at least three fragments. A fourth fragment may have been observed impacting Jupiter on 1983 July 26 shortly before the final close encounter of

Helin-Roman-Crockett during 1983 August before it escaped from the Jovian sphere of influence (Hammel & Nelson 1993).

Figs 5(b) and (c) show the corresponding (q, e) -plots for Ensembles 2 and 3 respectively. It is clear that, when we take into consideration all the major perturbers, a few comets are able to cross the Q_{\min} barrier temporarily. In all but one of these cases the orbital evolution follows lines of nearly constant semimajor axis with oscillatory evolution of the eccentricity owing to mean-motion, secular and Kozai resonances (see Fig. 6). The result of this is that when the aphelia are at a minimum, the perihelia are at a maximum (i.e., the eccentricities are at a minimum). Consequently, when these objects have low, subJovian aphelia ($Q < 4.629$ au) their perihelia tend to lie outside the terrestrial planet zone ($q > 1.66$ au) so that they cannot become dynamically decoupled from Jovian control by close encounters with Venus, Earth or Mars. Moreover, the $e-i$ coupling (due to Kozai librations) ensures that the orbital inclination is at a maximum during these phases, further reducing the chance of a strong gravitational interaction with one of the terrestrial planets. Conversely, when the aphelia and eccentricities are at a maximum, the perihelia and inclinations are at a minimum. However, when these comets have moderate eccentricities and perihelia low enough to be observed/discovered (say, $e \sim 0.6$, $q < 1.5$ au), i.e., when ω is close to 0° or 180° , their orbital inclinations are still close to their maximum values. It is only when the eccentricity is greater than about 0.9 (when ω approaches 90° or 270°) that the inclination is reduced to low ($i < 30^\circ$) values.

The 2:1 and 3:2 Jovian mean-motion resonances feature prominently in Fig. 5(c) as the two dark lines running from top-left to bottom-middle. In fact, 39P/Oterma, 111P/Helin-Roman-Crockett and 82P/Gehrels 3 lie very close to the 3:2 resonance (at around $a = 3.97$ au), representing a group of three active comets within the Hilda region of the main asteroid belt. We would therefore expect to find inactive cometary asteroids orbiting temporarily on low-eccentricity ($e < 0.1$) orbits in the outer parts of the main asteroid belt (from the 2:1 resonance outwards), although such orbits will tend to have high orbital inclinations ($i > 30^\circ$).

Examination of Fig. 5(b) reveals an object from Ensemble 2 that crosses the Q_{\min} barrier at around ($q = 1$, $e = 0.62$). Notice that the position of this body in the (q, e) -plane is similar to that of 107P/Wilson-Harrington. The complete orbital evolution of this body is shown in Fig. 7. The object spends the first half of its Jupiter-family membership on a low-eccentricity orbit with perihelion distance oscillating around 3 au. The object makes a number of excursions below the $Q = 4.629$ au line during this period (cf. Oterma and Helin-Roman-Crockett). Notice how the circulation of the critical argument of the ν_5 secular resonance is correlated with the long-term oscillations in orbital eccentricity (i.e., the eccentricity oscillations reach a maximum when the critical argument passes through 0°). The perihelion distance is eventually reduced to terrestrial-planet-crossing values due to Jovian close encounters, and the continuing secular oscillations in eccentricity cause the object to cross the Q_{\min} barrier after about 120 kyr. However, during the majority of this transient phase, the perihelion lies outside the Earth's orbit, so the probability of decoupling from Jovian control is extremely low.

If we assume that a typical JFC completes 1000 perihelion passages before becoming inactive, and we take the JFC injection rate for Ensemble 2 (Table 1), then an upper limit to the rate of production of Class 2 cometary asteroids is $0.0108 \text{ yr}^{-1} \times 0.0023$, or around 25 bodies per 10^6 yr. This maximum production rate can vary, according to the assumed active lifetime and injection rate, R_{inj} , by a factor of $R_{\text{inj}}/0.0108$ (from Table 1 this factor can range

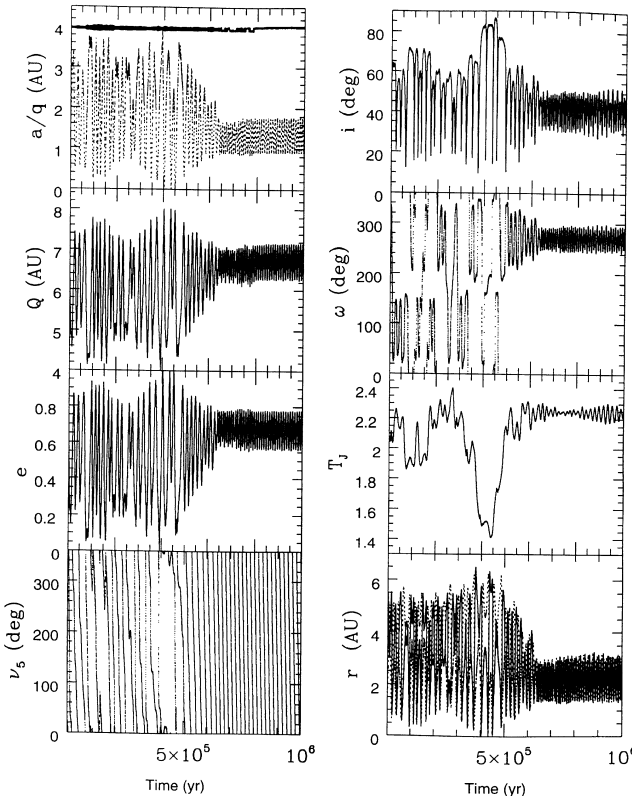


Figure 6. An example of orbital evolution within the 3:2 mean-motion resonance with the added protection of Kozai librations around $\omega = 90^\circ$, 270° . This is one of the longer lived examples from Ensemble 3, with a Class 1 lifetime of around 430 kyr. Notice the correlation between i , q and e .

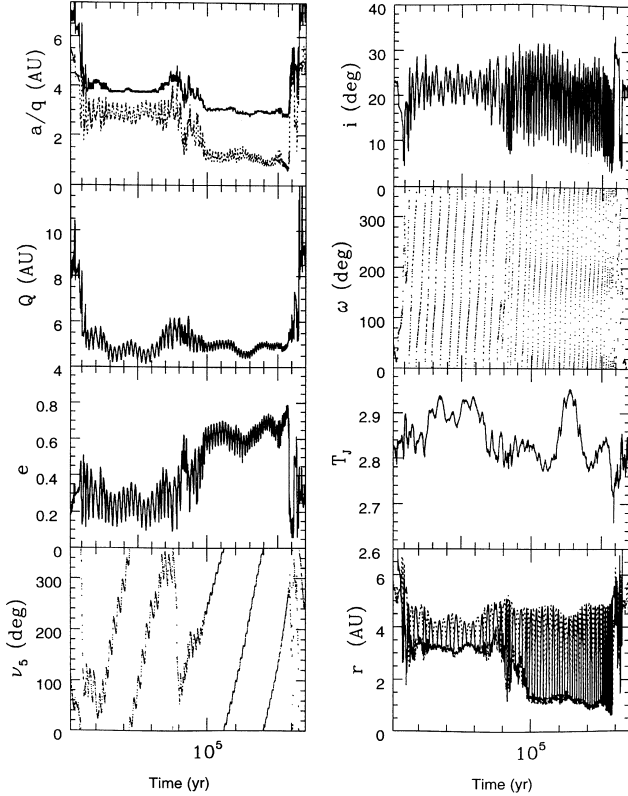


Figure 7. Orbital evolution of an Ensemble 2 object which crosses the theoretical Q_{\min} barrier while its perihelion distance is still within the terrestrial planet zone (cf. 107P/Wilson-Harrington). Notice the correlation between the circulation of ν_5 and the secular oscillations in orbital eccentricity.

between about 0.25 and 6, corresponding to active lifetimes of 10 000 and 100 revolutions respectively). Comparing the estimate of 25 bodies per 10^6 yr with the main-belt asteroid injection rate estimated by Menichella et al. (1996), namely ~ 370 km-sized NEOs per 10^6 yr, and assuming that the objects being compared are of roughly similar dimensions, these results suggest that considering gravitational mechanisms alone and assuming that the average JFC physical lifetime is around 1000 revolutions, the majority (i.e., > 93 per cent) of Class 2 NEOs originate in the main asteroid belt (for active lifetimes of 100 and 10 000 revolutions the corresponding percentages are > 70 and > 98 per cent respectively). The typical dynamical lifetimes of Class 2 NEOs are ~ 100 kyr for ‘fast-track’ objects (i.e., those that evolve through secular perturbations or secular resonances to hit the Sun or are ejected on to hyperbolic orbits after becoming planet-crossing), and a few times 10^6 yr for ‘slow-track’ non-resonant NEOs evolving mainly under the influence of close encounters with the terrestrial planets (Milani et al. 1989). Since about 80 per cent of the current NEO population are slow-track objects, we expect the steady-state JFC contribution to Class 2 NEOs, assuming an active lifetime of 1000 revolutions, to be less than 100 bodies (the numbers considering active lifetimes of 10 000 and 100 revolutions are less than 25 to 600 bodies respectively).

2.4 Non-gravitational forces

These results, indicating a very low cometary contribution to Class

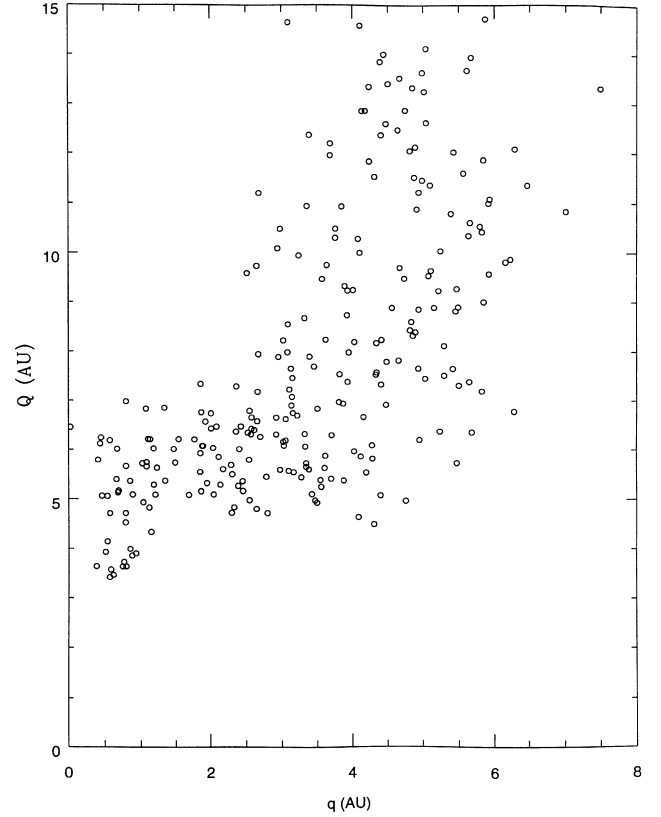


Figure 8. The evolution of 360 hypothetical JFCs in the (q, Q) -plane including the effects of non-gravitational forces. In this case a small population of Class 2 NEOs is produced within $\sim 10^3$ perihelion passages.

2 NEOs, and a marginal cometary contribution to Class 1 NEOs, if the JFCs primarily come from the Oort Cloud, have been obtained using models of the dynamical evolution that neglect non-gravitational forces. However, as we have described, the principal distinguishing characteristic of comets is outgassing, and this inevitably produces a non-gravitational jet-reaction force on the nucleus. The effect of such forces may be included in the dynamical model by adopting the conventional (A_1, A_2, A_3) non-gravitational formalism (Marsden, Sekanina & Yeomans 1973). Here we restrict attention in the first instance to the transverse component of the force, A_2 , which is the dominant factor that systematically affects the semimajor axis. Values of non-gravitational parameters for observed JFCs are given in the Catalogue of Cometary Orbits (Marsden & Williams 1996), and in this preliminary investigation we have adopted constant values of A_2 distributed in the interval $(-0.40, 0.40) \times 10^{-8} \text{ au d}^{-2}$ according to a triangle law. The standard deviation of this distribution, σ_{A_2} , is $0.16 \times 10^{-8} \text{ au d}^{-2}$.

The initial ensemble of 360 orbits, namely Ensemble 1, was integrated including non-gravitational forces in the same model Solar system as before for a time-span of 10 kyr. When (and if) an object had performed 1000 revolutions at $q < 1.4 \text{ au}$ its evolution was halted, as the object was assumed to have become inactive and hence the actions of any non-gravitational forces would cease. Fig. 8 shows that after this period of time 12 test particles had evolved to Class 2 orbits ($Q < 4.2 \text{ au}$) and 10 to ‘stable’ Class 2 orbits ($Q < 4.0 \text{ au}$) from a total of 35 particles that had performed at least 1000 revolutions at $q < 1.4 \text{ au}$. This can be compared with

the initial results from Ensemble 1 where non-gravitational forces were ignored. Here two temporary Class 2 orbits were produced from a total of 77 objects that had performed at least 1000 revolutions at $q < 1.4$ au. Therefore, for this example, the effect of non-gravitational forces produces more than 13 times as many Class 2 orbits than the purely gravitational model. This corresponds to a net injection rate in excess of 300 Class 2 NEOs per million years, a result comparable to the estimates rate of fragment injection from the main belt. We emphasize that the model of non-gravitational forces is extremely simple, and that a more thorough investigation is required before firm conclusions can be drawn. Nevertheless, our work indicates a possibly important mechanism by which comets might be inserted on to Class 2 NEO-type orbits within their physically active lifetime (e.g., 2P/Encke) (cf. Steel & Asher 1996).

3 CONCLUSIONS

Long-term numerical integrations, considering purely gravitational effects, of three ensembles of hypothetical JFCs show that less than 0.23 per cent of objects evolve on to Class 2 NEO orbits ($q < 1.4$ au, $Q < 4.2$ au, $P < 20$ yr), suggesting that most such NEOs (> 90 per cent) probably originate in the main asteroid belt. However, when a simple model of non-gravitational forces is incorporated into the calculation, the number of Class 2 cometary asteroids becomes comparable to the number of bodies injected from the main asteroid belt. Of course, it is difficult to know whether our adopted non-gravitational parameters are realistic, or in fact are likely to remain approximately constant throughout the active ‘cometary’ phase of evolution (a few 100 to a few 1000 revolutions). Our results therefore only show that, in principle, non-gravitational forces can substantially affect the rate of production of Class 2 NEOs from JFCs, suggesting that a significant fraction of NEOs may be of cometary origin.

The short Class 1 ($q < 1.4$ au, $Q > 4.2$ au, $P < 20$ yr) mean lifetime for JFCs captured from a flat ($i < 30^\circ$) source region ($\sim 15\,500$ yr, Ensemble 2) suggests that the total steady-state population of Class 1 cometary asteroids is on the order of 100 objects (assuming a cometary active lifetime of ~ 1000 revolutions; this estimate increases to 1000 bodies assuming an active lifetime of 100 revolutions). However, some observed NEOs on apparently ‘cometary’ orbits and JFCs captured from the outer Oort Cloud (Ensemble 1) can have lifetimes on Class 1 orbits of a few 100 kyr. The same is true for asteroid fragments from resonant regions within the main belt. If the outer Oort Cloud is the dominant source of JFCs, (Emel’yanenko & Harris 1998), the steady-state number of Class 1 cometary asteroids (i.e., extinct JFCs) may be as many as 500 bodies (this figure increases to 5000 bodies if the active lifetime is decreased to 100 revolutions).

ACKNOWLEDGMENTS

It is a pleasure to thank J. E. Chambers, V. V. Emel’yanenko, F. Migliorini and W. M. Napier for helpful discussions. The calculations for this study were carried out on Starlink computers, and the work was supported by DENI and PPARC.

REFERENCES

- Asher D. J., Bailey M. E., Hahn G., Steel D. I., 1994, *MNRAS*, 267, 26
 Bailey M. E., Chambers J. E., Hahn G., 1992, *A&A*, 257, 315
 Bowell E., Muinonen K., Wasserman L. H., 1994, in Milani A. et al., eds, *Proc. IAU Symp. 60, Asteroids, Comets, Meteors 1993*. Kluwer, Dordrecht, p. 477
 Carusi A., Kresák L., Perozzi E., Valsecchi G. B., 1985, *Long-Term Evolution of Short-Period Comets*. Hilger, Bristol
 Emel’yanenko V. V., Bailey M. E., 1998, *MNRAS*, in press
 Emel’yanenko V. V., Harris N. W., 1998, *MNRAS*, submitted
 Everhart E., 1985, in Carusi A., Valsecchi G. B., eds, *Proc. IAU Colloq. 83, Dynamics of Comets: Their Origin and Evolution*. Reidel, Dordrecht, p. 45
 Fernández J. A., 1985, *Icarus*, 64, 308
 Gladman B. J. et al., 1997, *Sci*, 277, 197
 Hammel H. B., Nelson R. M., 1993, *Nat*, 366, 117
 Harris N. W., Bailey M. E., 1996, *Irish Astron. J.*, 23 (2), 151
 Ipatov S. I., Hahn G., 1997, *Lunar Planet. Sci. Conf. (Abstracts)*, 28, 619
 Kozai Y., 1962, *AJ*, 67, 591
 Kresák L., 1981, *Bull. Astron. Inst. Czech.*, 32, 19
 Marsden B. G., Williams G. V., 1996, *Catalogue of Cometary Orbits 1996*, 11th edition. Minor Planet Centre, Cambridge, Massachusetts
 Marsden B. G., Sekanina Z., Yeomans D. K., 1973, *AJ*, 78, 211
 Marzari et al., 1995, *A&A*, 299, 267
 Marzari et al., 1997, *Icarus*, 125, 39
 McBride N., McDonnell J. A. M., Gardner D. J., Griffiths A. D., 1996, *ESA Symposium Proceedings, SP-392*, 335
 Menichella M., Paolicchi P., Farinella P., 1996, in *Earth, Moon, and Planets*, 72, 133. Kluwer Academic Publishers
 Milani A., Carpino M., Hahn G., Nobili A. M., 1989, *Icarus*, 78, 212
 Morrison D., ed., 1992, *The Spaceguard Survey: Report of the NASA Near-Earth Object Detection Workshop*. JPL, Pasadena
 Olsson-Steel D. I., 1988, in Clube S. V. M., ed., *Catastrophes and Evolution: Astronomical Foundations*. Cambridge Univ. Press, Cambridge, p. 169
 Rabinowitz D., Bowell E., Shoemaker E., Muinonen K., 1994, in Gehrels T., ed., *Hazards due to Comets and Asteroids*, p. 285
 Rickman H., 1992, in Benest D., Froeschlé C., eds, *Interrelations between Physics and Dynamics for Minor Bodies in the Solar System*. p. 197
 Roy A. E., 1988, *Orbital Motion*, 3rd edn. Adam Hilger, Bristol, p. 170
 Scotti J. V., 1994, in Milani A., Di Martino M., Cellino A., eds, *Proc. IAU Symp. 160, Asteroids, Comets, Meteors 1993*. Kluwer, Dordrecht, p. 17
 Steel D. I., Asher D. J., 1996, *MNRAS*, 281, 937
 Tancredi G., Lindgren M., Rickman H., 1990, *A&A*, 239, 375
 Taylor A. D., McBride N., 1997, *ESA Symposium Proceedings, SP-393*, 375
 Valsecchi G. B., 1992, in Fernández J. A., Rickman H., eds., *Periodic Comets*. p. 81