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Jupiter family comets in near-Earth orbits: Are some of them interlopers from the asteroid belt?

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ABSTRACT

We analyze a sample of 58 Jupiter family comets (JFCs) in near-Earth orbits, defined as those whose perihelion distances at the time of discovery were $q_{disc} < 1.3$ au. In our definition JFCs have Tisserand parameters $2 < T < 3$ and orbital periods $P < 20$ yr. We integrated the orbits of these objects, plus 50 clones for each one of them, for 10^4 yr in the past and in the future. We find that most of them move on highly unstable orbits, having fallen in their current near-Earth orbits in the recent past, going from less than one hundred years to a few thousands years. They experience frequent close encounters with Jupiter down to distances $\lesssim 0.1$ au. This is the expected behavior for comets whose limited physical lifetimes in the near-Earth region make them unlikely to survive there for more than about a few hundred revolutions. In this sense the orbits of most JFCs are typically "cometary", and they should be regarded as newcomers in the near-Earth region. Yet, a minor fraction of JFCs (less than about one third) are found to move on stable orbits for the past $\sim 10^4$ yr, and in some cases are found to continue to be stable at 5×10^4 yr in the past. They also avoid very close encounters with Jupiter. Their orbital behavior is very similar to that of NEAs in cometary orbits. While "typical" JFCs in unstable orbits probably come from the trans-Neptunian region, the minor group of JFCs in asteroidal orbits may come from the main asteroid belt, like the NEAs. The asteroidal JFCs may have a more consolidated structure and a higher mineral content than that of comets coming from the trans-Neptunian belt or the Oort cloud, which could explain their much longer physical lifetimes in the near-Earth region. In particular, we mention comets 66P/du Toit, 162P/Siding Spring, 169P/NEAT, 182P/LONEOS, 189P/NEAT, 249P/LINEAR, 300P/Catalina, and P/2003 T12 (SOHO) as the most likely candidates to have an origin in the main asteroid belt. Another interesting case is 207P/NEAT, which stays near the 3:2 inner mean motion resonance with Jupiter, possibly evolving from the Hilda asteroid zone.

1. Introduction

Jupiter family comets (JFCs) are assumed to come from the trans-Neptunian region after a dynamical process in which they pass from the gravitational control of Neptune to the control of the other Jovian planets until ending under the dynamical control of Jupiter (Fernández, 1980; Duncan et al., 1988; Levison and Duncan, 1997). While in the trans-Jovian region, the transit bodies are called Centaurs, the direct progenitors of the JFCs. Once Centaurs fall under the gravitational control of Jupiter, their dynamical lifetimes should be short. Furthermore, given their icy nature and brittle structure, we should expect that physical lifetimes for JFCs coming close to the Sun should be a tiny fraction of the dynamical lifetime, since phenomena such as sublimation, outbursts and splittings will limit enormously the number of passages in the Sun's vicinity. The observational evidence supports this conjecture (Kresák, 1981; Sekanina, 1984).

The dynamical lifetime of JFCs is found to be about 1.5×10^5 yr, but they stay in near-Earth orbits ($q < 1.3$ au) for only a fraction of this time (∼a few 10^3 yr) (Fernández et al., 2002). As mentioned before, these comets should have short physical lifetimes, so it is very likely that they will fade before being ejected, or their perihelia raised to distances such that their sublimation rate becomes negligible. From the analysis of the periodic comets that ceased to be observed in favorable apparitions, Kresák (1981) estimated a mean physical lifetime of ∼ 400 revolutions for a comet in a short-period orbit with $q \simeq 1.5$ au (about 2500–3000 yr). Later, Kresák and Kresáková (1990) reanalyzed this problem by considering the secular brightness decrease in JFCs. They found a decrease rate of ∼0.015 mag per revolution for a comet with $q \simeq 1.5$ au, which amounts to about 500 revolutions in good agreement with the previous result. Fernández (1985) and Sosa et al. (2012) used a

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different approach to estimate the dynamical lifetime that consisted in the comparison of the past evolution of the average perihelion distance, $\bar{q}$, of the observed near-Earth JFCs with the evolution of $\bar{q}$ in the future. A rapid drop of $\bar{q}$ in the past, as compared to a slow increase in the future, was interpreted due to a finite physical lifetime between about 3000 and 12,000 yr for comets with $q \lesssim 2$ au. From numerical simulations that considered dynamical as well as physical losses, di Sisto et al. (2009) found a mean physical lifetime of ~150–200 revolutions (~ 10^3 yr) for JFCs with radii $R > 1$ km and $q < 1.5$ au. Summing up, there are several pieces of evidence suggesting short physical lifetimes – of the order of a few 10^3 yr – for JFCs in Earth-approaching orbits ($q \lesssim 1.5$ au).

We should also mention that, besides disintegration, active comets may become dormant or extinct by building insulating dust mantles (Shul'man et al., 1972; Brin, 1980; Rickman et al., 1990). In this case they will look as asteroids. Yet, dynamical studies suggest that most near-Earth asteroids in seemingly "cometary" orbits move on dynamically stable orbits coming from the main asteroid belt, in particular the 2:1 mean motion resonance (Fernández et al., 2002, 2014). Therefore, NEAs in cometary orbits do not necessarily have a comet origin, and it is even possible that the great majority of them are *bona fide* asteroids. The most common end state of comets in the near-Earth region seems to be disintegration into meteoritic dust and chunks of devolatized material (Sekanina, 1984; Weaver et al., 2001). In this scenario, an object like 2003 WY25, identified with comet 289P/Blanpain (Jewitt, 2006), could actually be a big fragment of the comet that has passed through a steady devolatilization and disintegration process.

This paper is a spinoff of a previous work in which we studied the dynamical histories of NEAs in cometary orbits (defined as those with aphelion distances $Q > 4.8$ au), aimed at detecting comet interlopers in the NEA population (Fernández et al., 2014). In order to distinguish a typical "asteroidal" orbit from a typical "cometary" one, we also integrated the orbits of a sample of near-Earth JFCs. We actually found that most NEAs move on stable orbits on the studied time scale (10^4 yr in the past and 10^4 yr in the future), with a few exceptions of objects whose orbits were quite unstable, suggesting a recent capture by Jupiter in their current near-Earth orbits. The latter objects were found to have very frequent close encounters with Jupiter, so their orbital evolution resemble that of JFCs. We considered these objects to be prime candidates to have a comet origin whose lack of observed activity may be due to their being covered by insulating dust mantles. On the other hand, we were surprised to find that not all the near-Earth JFCs of our sample had rapidly-evolving orbits subject to frequent close encounters with Jupiter. The orbits of some of these JFCs looked quite asteroidal, remaining stable during all the studied period. It is therefore the aim of this paper to analyze in more depth the orbital characteristics of the sample of near-Earth JFCs (NEJFCs) to try to find out if there are some "asteroids disguised as comets" among the objects in our sample.

Table 1
List of Jupiter family comets

comet	Disc. yr	q (au)	a (au)	i (deg)	H_T	H_N
3D/Biela	1772	0.990	3.612	17.1	6.9	–
5D/Brorsen	1846	0.650	3.141	30.9	8.6	–
6P/d'Arrest	1851	1.173	3.443	13.9	8.7	16.5
7P/Pons-Winnecke	1819	0.772	3.140	10.7	8.6	16.3
11P/Tempel-Swift-LINEAR	1869	1.063	3.109	5.4	11.1	>17.6
15P/Finlay	1886	0.997	3.533	3.0	7.5	17.2
18D/Perrine-Mrkos	1896	1.110	3.454	13.7	10.0	–
21P/Giacobini-Zinner	1900	0.932	3.472	29.8	9.8	17.6
24P/Schaumasse	1911	1.225	4.001	17.7	7.6	17.8
26P/Grigg-Skjellerup	1808	0.732	2.856	3.5	12.2	17.2
34D/Gale	1927	1.214	5.032	11.6	9.4	–
41P/Tuttle-Giacobini-Kresak	1858	1.140	3.058	18.9	10.4	18.4
45P/Honda-Mrkos-Pajdusakova	1948	0.559	3.009	13.2	10.7	20.0
54P/deVico-Swift-NEAT	1844	1.186	3.100	2.9	7.8	18.5
66P/duToit	1944	1.277	6.023	18.7	9.6	19.3
67P/Churyumov-Gerasimenko	1969	1.285	3.502	7.1	8.3	16.0
72P/Denning-Fujikawa	1881	0.725	4.232	6.9	8.3	–
73P/Schwassmann-Wachmann 3	1930	1.011	3.080	17.4	11.6	17.7
79P/duToit-Hartley	1945	1.250	3.034	6.9	11.2	17.2
85P/Boethin	1975	1.094	4.955	5.9	7.8	–
103P/Hartley 2	1986	0.952	3.398	9.3	8.6	17.2
141P/Machholz 2-A	1994	0.753	3.015	12.8	10.4	20.6
162P/Siding Spring	2004	1.227	3.047	27.8	13.5	13.7
169P/NEAT	2002	0.605	2.602	11.3	13.7	15.8
181P/Shoemaker-Levy 6	1991	1.132	3.849	16.9	12.0	19.0
182P/LONEOS	2001	0.976	2.928	16.9	17.6c	19.7
185P/Petriew	2001	0.946	3.114	14.0	10.4	>16.9
189P/NEAT	2002	1.174	2.916	20.4	15.8	18.7
197P/LINEAR	2003	1.063	2.868	25.5	16.6c	17.7
207P/NEAT	2001	0.937	3.872	10.2	15.0c	18.4
209P/LINEAR	2004	0.912	2.932	19.1	16.6	17.4
210P/Christensen	2003	0.549	3.211	10.1	12.8	>17.9
217P/LINEAR	2001	1.254	3.968	13.5	10.1	>15.9
222P/LINEAR	2004	0.782	2.864	5.1	16.0	>19.0
225P/LINEAR	2002	1.192	3.548	20.7	16.7c	>19.8
249P/LINEAR	2006	0.511	2.777	8.4	17.1c	>17.2
252P/LINEAR	2000	1.003	3.058	10.4	18.2c	>19.4
255P/Levy	2006	0.989	3.015	18.3	9.2	>19.5
263P/Gibbs	2006	1.251	3.029	14.5	16.0c	>18.5
289P/Blanpain	1819	0.892	2.963	9.1	8.3	21.7
300P/Catalina	2005	0.826	2.693	5.7	15.6	18.7
317P/WISE	2010	1.198	2.918	10.6	–	>18.4
D/1884 O1 (Barnard)	1884	1.279	3.067	5.5	8.2	–
D/1894 F1 (Denning)	1894	1.147	3.797	5.5	10.0	–
D/1895 Q1 (Swift)	1895	1.298	3.729	3.0	10.7	–
D/1978 R1 (Haneda-Campos)	1978	1.101	3.287	5.9	11.4	–
P/1999 RO28 (LONEOS)	1999	1.232	3.527	8.2	17.8c	20.8
P/2003 O3 (LINEAR)	2003	1.246	3.105	8.4	17.6c	>19.8
P/2003 T12 (SOHO)	2003	0.575	2.569	11.5	–	–
P/2004 R1 (McNaught)	2004	0.988	3.107	4.9	17.1c	>18.6
P/2007 T2 (Kowalski)	2007	0.696	3.093	9.9	15.0c	>19.4
P/2008 S1 (McNaught)	2008	1.190	3.568	15.1	14.7c	>17.4
P/2008 Y1 (Boattini)	2008	1.272	4.798	8.8	13.0c	>16.2
P/2009 L2 (Yang-Gao)	2009	1.296	3.419	16.2	13.8	>19.1
P/2009 WX51 (Catalina)	2009	0.798	3.077	9.6	17.6c	>19.9
P/2011 NO1 (Elenin)	2011	1.243	5.565	15.3	13.0c	>17.8
P/2013 CU129 (PANSTARRS)	2013	0.798	2.879	12.2	15.2c	>18.1
P/2013 TL117 (Lemmon)	2013	1.118	3.604	9.4	16.5c	>18.9

2. The sample

We analyzed a sample of 58 JFCs with Tisserand parameters $2 < T < 3$ and orbital periods $P < 20$ yr (Table 1). This sample includes all the JFCs discovered through 2013 that reached perihelion distances $q < 1.3$ au at the moment of their discovery. The constraint of near-Earth orbit allows us to have a more complete sample, with the additional advantage that these comets are excellent probes to analyze their survival through successive perihelion passages close to the Sun. Furthermore, objects with some volatile content that approach the Sun will probably develop some activity, that otherwise would not be present or detectable were these objects on more distant orbits.

2.1. Absolute total and nuclear magnitudes

Total and nuclear magnitudes are both very important for the characterization of a certain comet population. The nuclear magnitude is related to the size and albedo of the comet nucleus; the total magnitude gives information on the activity and the

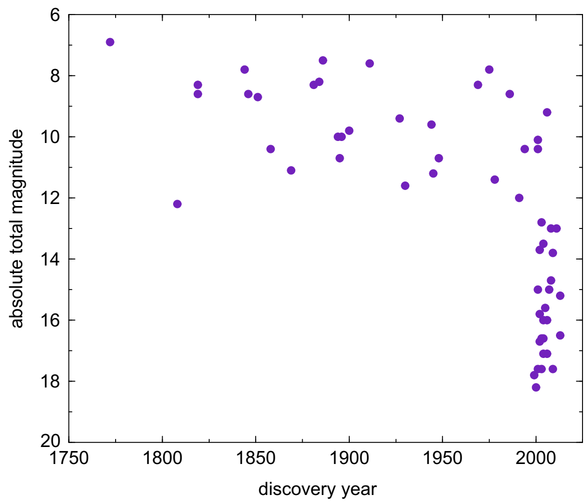

Fig. 1. Absolute total magnitudes of JFCs with perihelon distances $q < 1.3$ au at the moment of their discovery versus the discovery year.

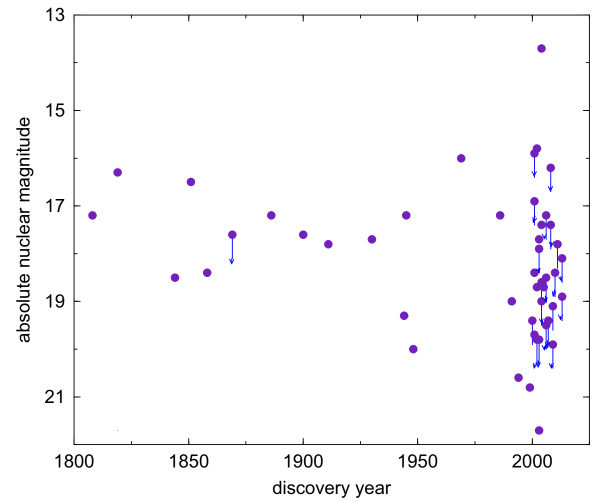

Fig. 2. Absolute nuclear magnitudes of the JFCs of our sample versus the discovery year. The arrows attached to some of the comets indicate that the estimated values of H_N are upper limits.

probability of detection. The problem of defining the "total" magnitude of an extended source, like a comet, is very complex and it depends on the instrument employed. The situation is even worse for distant comets, since we need to extrapolate the total magnitude measured at large heliocentric distances to a standard heliocentric distance of one au, in order to obtain an absolute total magnitude. These extrapolations are of dubious value since the photometric index (that defines how the total brightness increases as the heliocentric distance r decreases) varies from comet to comet. Fortunately, since we limit our comet sample to those that approach the Sun, we do not need to make large extrapolations to get the total brightness at $r=1$ au. In this regard, our absolute total magnitudes H_T are more reliable. Traditionally, the estimates of total magnitudes have been done visually, with small telescopes or binoculars. The best database of H_T values of JFCs has been compiled by Kresák and Kresáková (1990). We used this database for JFCs discovered before 1990. We have updated it by adding JFCs discovered between 1990 and 2013. Their H_T values were derived from the photometric reports that appeared in the IAU Circulars, Minor Planet Electronic Circulars, and the Spanish network "Cazadores de cometas" (http://www.astrosurf.com/cometas-obs/). JFCs discovered more recently from large sky surveys are too faint to have visual total magnitudes, so in these cases we were forced to use CCD total magnitudes. Fernández and Sosa (2012) found that CCD total magnitudes are systematically fainter than the visual ones for the same objects. They found an empirical correction $m_{vis} \simeq m_{CCD} - 1.5$, and we used this correction for the absolute magnitudes determined by CCD photometry. The H_T values of Table 1 followed by the letter "c" have been derived from CCD photometry, and we have applied the previous correction to obtain an equivalent visual total magnitude. The uncertainties in these estimates are large (> one magnitude) and they should give only a hint of the intrinsic brightness of the comet.

As shown in Fig. 1, the discovery rate of NEJFCs brighter than $H_T \simeq 12$ has remained more or less constant since around 1850. On the other hand, the discovery rate of very faint NEJFCs ($H_T \gtrsim 12$) has greatly increased in the last couple of decades thanks to several large sky surveys as, for instance, LINEAR, LONEOS, NEAT, Catalina, Siding Spring and Pan-STARRS.

Despite the difficulties inherent to try to estimate true nuclear magnitudes of bodies surrounded by a coma, it is possible to provide for most of the NEJFCs of our sample rough estimates of their absolute nuclear magnitudes (and sizes), or in some cases to set upper limits. This effort has been possible through extensive observing campaigns of the comets near aphelion where they are almost inactive, or using techniques of coma substraction, infrared observations with Spitzer, or in a few cases accurate sizes were measured from spacecrafts in flyby missions (Tancredi et al., 2006; Snodgrass et al., 2011; Fernández et al., 2013). Most of the comets discovered after 2000 are fainter than $H_N=17$ (sub-kilometer nucleus radii). As we see in Fig. 2, the trend toward the discovery of smaller comets is not so neat since the discovery probability depends more on the activity than on the size. By comparing Figs. 1 and 2 we infer that we are now discovering those NEJFCs that are very small and/or little active.

3. The numerical integrations

The orbits of the NEJFCs were integrated in a heliocentric frame for 10^4 yr, in the past and in the future with respect to the present epoch following the procedure developed by Fernández et al. (2014). We defined the present epoch as JD 2456200.500, i.e. CE 2012 September 30, 00:00:00 UT, Sunday. The orbital data were extracted from the NASA/JPL Small-Body Database,[1] as known by the end of 2013. For the numerical integrations we used the Bulirsch–Stoer code which is included within the MERCURY package (Chambers, 1999). We considered the gravitational forces of the Sun and the eight planets. We found the B–S code very accurate, in particular when very close encounters with planets are involved. The computed orbital data was stored every year. For every JFC we generated 50 clones with orbital elements chosen randomly within Gaussian distributions, whose mean values and standard deviations were the nominal osculating values and uncertainties for the present epoch.

We neglected in our integrations discussed below nongravitational (NG) forces. But, in order to check their influence in the comet evolution, we also integrated some orbits with NG terms in the case their estimated values were provided in the comet catalog. We did not find significant differences between the orbits computed with and without NG terms, so our neglect of this effect seems to be appropriate.

A JFC or any of its clones was considered as 'ejected' if it reached a heliocentric distance $r > 100$ au. We also registered all

[1] http://ssd.jpl.nasa.gov/sbdb.cgi

the close encounters with Jupiter at Jovicentric distances smaller than 3 Hill radii.

4. The results

4.1. Stable and unstable orbits

A quick inspection of the orbit evolution of JFCs in the past and future 10^4 yr allows us to conclude the following: most JFCs move indeed on very unstable orbits and are subject to frequent close encounters with Jupiter, which leads to short residence times in the near-Earth region ($q < 1.3$ au), of not more than some hundreds to a few thousands years. Yet, there are a few JFCs that show quite stable orbits resembling those of most NEAs in cometary orbits, as analyzed by Fernández et al. (2014). We show in Fig. 3 examples of a JFC in an unstable orbit and other in a stable one. In the 6 panels of each column we record (from top to bottom): (1) close encounters with Jupiter within 3 Hill radii; (2) perihelion distance (q); (3) semimajor axis (a); (4) inclination (i); (5) argument of perihelion (ω); and (6) longitude of the ascending node (Ω). As shown, 54P suffers very close encounters with Jupiter that cause large changes in its orbit, in such a way that its perihelion was close to Jupiter's orbit only ~270 yr ago. In other words, 54P has become a near-Earth comet in the recent past. On the other hand, we find that comet 182P has stayed on a very stable orbit for the past 10^4 yr, avoiding encounters with Jupiter to distances $\lesssim$0.9 au.

We then proceeded to characterize such orbits. Given the chaotic nature of the orbital motion, a particular comet will have a certain probability to follow a given trajectory. It may change for a clone of the object. Therefore, the orbital history of a JFC can only be described in statistical terms and, for this purpose, we have defined a set of useful parameters that characterize the degree of stability (or instability) of a given JFC orbit. Most of the parameters used for JFCs are similar to the ones used before for NEAs in cometary orbits (Fernández et al., 2014). As a matter of completeness, we will quickly review the definitions of these parameters. For further details, we remit the reader to Fernández et al. (2014).

4.2. Characterization of the degree of instability of the comet orbit

Since comet orbits are in general very chaotic, we define a *likely dynamical path* as the average of the set of results obtained for a given object and its clones. Its degree of instability can be characterized through the following parameters:

4.2.1. The f_q index

This was already introduced by Fernández et al. (2014), and it is defined as the fraction of time in the last 10^4 yr that a given JFC or any of its clones moves on an orbit with a perihelion distance $q > 2.5$ au, or attains heliocentric distances $r > 100$ au, so it can be computed as

$$f_q = \frac{\sum_{j=1}^{N+1} \Delta t_j}{(N+1) \times 10^4} \quad (1)$$

where Δt_j is the time span (in years) during which the object and its clones, $j = 1, \ldots, N$, have $q > 2.5$ au, or move in an orbit that reaches $r > 100$ au, in the last 10^4 yr. For this study we have taken $N = 50$ clones.

In general we find that once a comet reaches $q > 2.5$ au, it stays there for the rest of the computed time in the past 10^4 yr. This can be understood in terms of the dynamics of a population of JFCs evolving under the gravitational influence of Jupiter. They will spend most of their dynamical lifetime in orbits with perihelia close to Jupiter's orbit, while their incursions near the Sun ($q < 1.3$ au) will be for brief periods (Fernández, 1984).

4.2.2. The f_a index

It was also defined by Fernández et al. (2014) as the fraction of time in the last 10^4 yr that a JFC or any of its clones moves on an orbit with a semimajor axis $a > 7.37$ au ($P > 20$ yr) so, according to

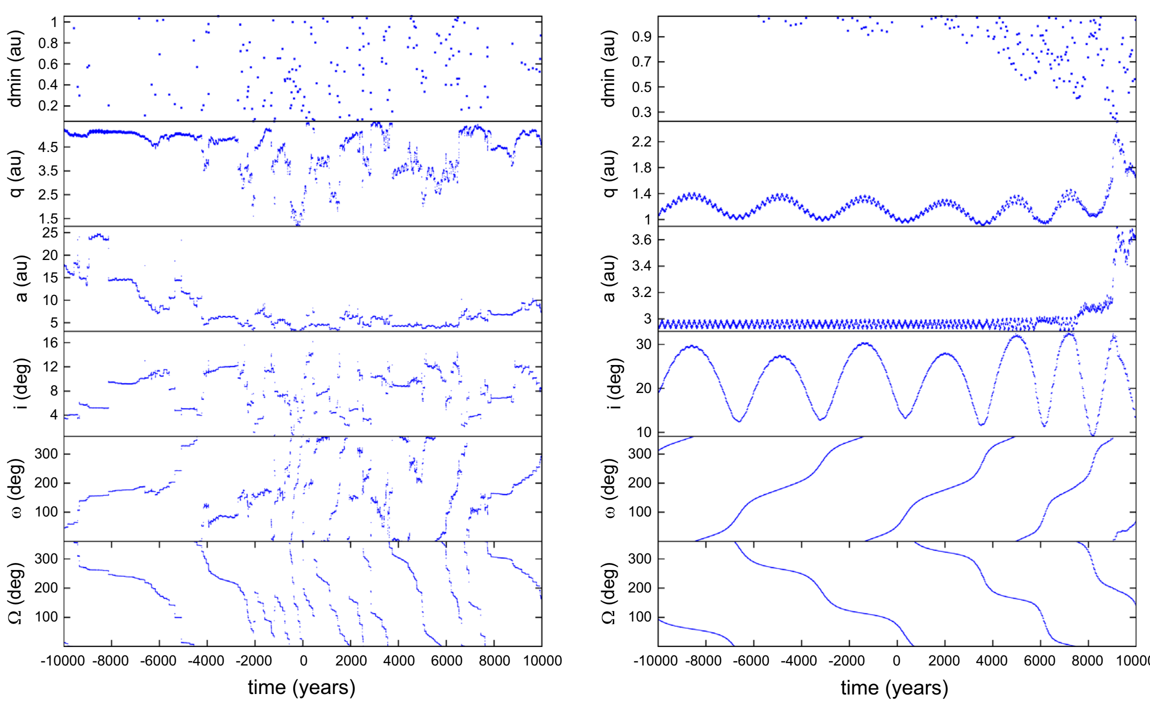

Fig. 3. Examples of comets on stable and unstable orbits: 54P/de Vico-Swift-NEAT has a highly unstable orbit with numerous close encounters with Jupiter (left). 182P/LONEOS moves on a stable orbit, avoiding close encounters with Jupiter (less than about 0.9 au) during the past 10^4 yr (right). The plots are based on the nominal orbital elements.

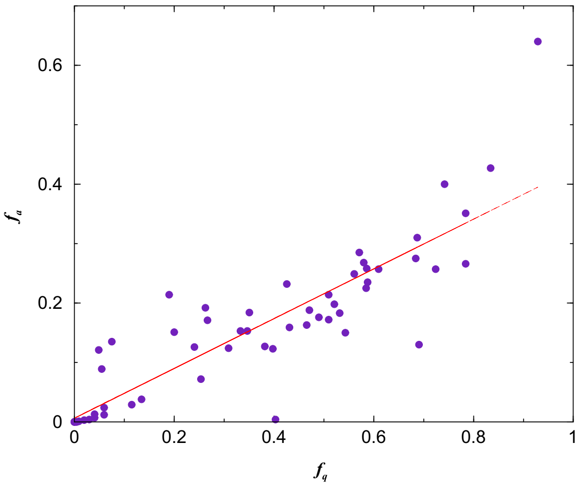

Fig. 4. Correlation between the indices f_q and f_a.

our definition, it was no longer a 'Jupiter family comet'. We computed it as

$$f_a = \frac{\sum_{j=1}^{N+1} \Delta t'_j}{(N+1) \times 10^4}, \tag{2}$$

where $\Delta t'_j$ is the time span (in years) during which the object and its clones, $j = 1, \ldots, N$, have $a > 7.37$ au.

As expected, we find a good correlation between the indices f_q and f_a, with a correlation coefficient of 0.877 (Fig. 4). Comets in unstable orbits will have indices f_q and f_a well above zero, indicating that they spend a considerable fraction of the last 10^4 yr with $q > 2.5$ au and/or $a > 7.37$ au. We find that most NEJFCs of our sample have indeed $f_q > 0.2$ and $f_a > 0.1$. Yet, a minor fraction have $f_q \sim f_a \sim 0$ which indicates that they move on stable orbits. Comet 207P/NEAT is the only one that clearly departs from the linear fit (it is the point in Fig. 4 laying close to the f_q-axis departed from the origin). It has a rather high value of $f_q (\sim 0.4)$ while $f_a \simeq 0$. We will analyze the dynamics of this peculiar object in Section 5.1.

4.2.3. The capture time

We can complement the two indices defined above with a new one associated to the average behavior of the perihelion distance in the past 10^4 yr for a given comet and its N=50 clones. To this end let us define the average perihelion distance $\bar{q}(t)$ for a JFC and its clones at a certain time t as

$$\bar{q}(t) = \frac{1}{N+1} \sum_{j=1}^{N+1} q_i(t) \tag{3}$$

We define the *capture time* t_{cap} as the time in the past at which $\bar{q}(t)$ increased by one au with respect to the observed value at the discovery time t_{disc}, namely

$$q(t_1) = q(t_{disc}) + 1 \tag{4}$$

$$\Longrightarrow \quad t_{cap} = t_{disc} - t_1 \tag{5}$$

The capture time thus gives an idea of the time span in which the comet has been in the Earth's vicinity. An increase in q by one au will raise the comet's perihelion at $q \sim 2$ au, well beyond the near-Earth region. We stress that the computed t_{cap} value has a statistical meaning since different clones may have different behaviors, leading to different individual capture times. The chosen increase $\Delta q = 1$ au to define t_{cap} is admittedly somewhat arbitrary. In order to check how it varies with Δq we tested a

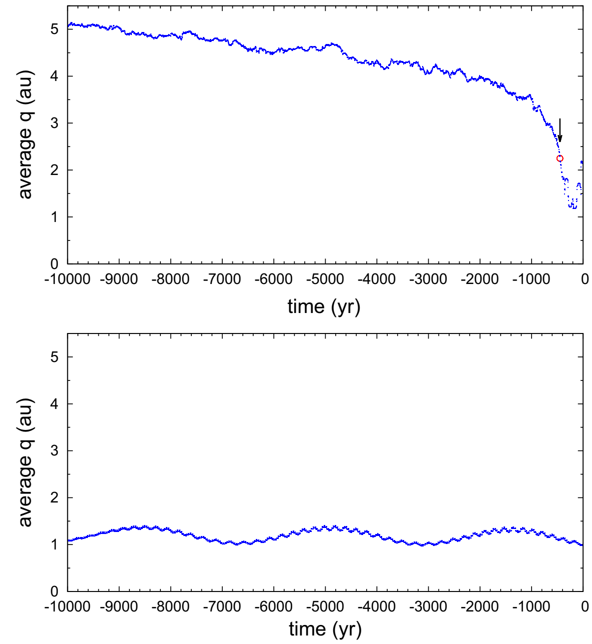

Fig. 5. q-average as a function of time for comets: 54P/de Vico-Swift-NEAT+50 clones. The red circle indicates the time when $\bar{q} = q_{disc} + 1$ (upper panel); 182P/LONEOS+50 clones, which shows stability through all the computed period (lower panel). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

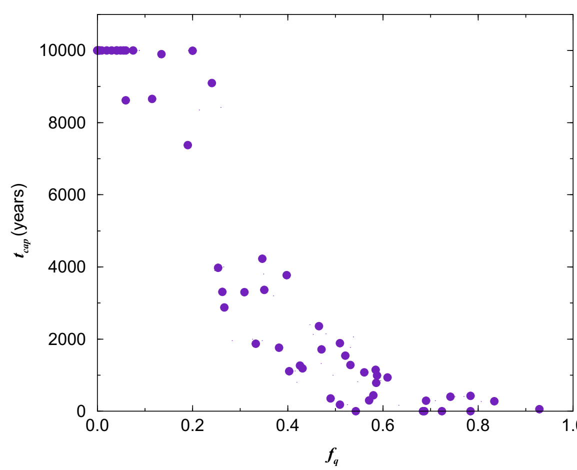

Fig. 6. The index f_q versus the capture time. We note that comets located at $t_{cap} = 10^4$ yr, actually have $t_{cap} > 10^4$ yr.

different change: $\Delta q = 0.5$ au. We obtained computed values of t_{cap} well correlated with those obtained from Eqs. (4) and (5) for the standard $\Delta q = 1$ au (correlation coefficient=0.895), with a linear fit: $t_{cap}(\Delta q = 0.5) = 0.295 t_{cap}(\Delta q = 1) + 457$. Therefore, in relative terms the behaviors of $t_{cap}(\Delta q = 0.5)$ and $t_{cap}(\Delta q = 1)$ are similar, so irrespective of the precise value of Δq adopted, t_{cap} is a good indicator of the degree of orbit stability.

We show in Fig. 5 the average $\bar{q}(t)$ for the comets shown in Fig. 3. As expected, for 54P $\bar{q}(t)$ rapidly increases in the past, giving a short capture time of ~270 yr. On the other hand, for 182P $\bar{q}(t)$ stays stable over the whole studied period.

4.3. The f_q index versus the capture time

We show in Fig. 6 the index f_q plotted against the capture time t_{cap}. We find two distinct groups of JFCs: (1) the larger one consisting of the typical JFCs in unstable orbits (bottom-right); and

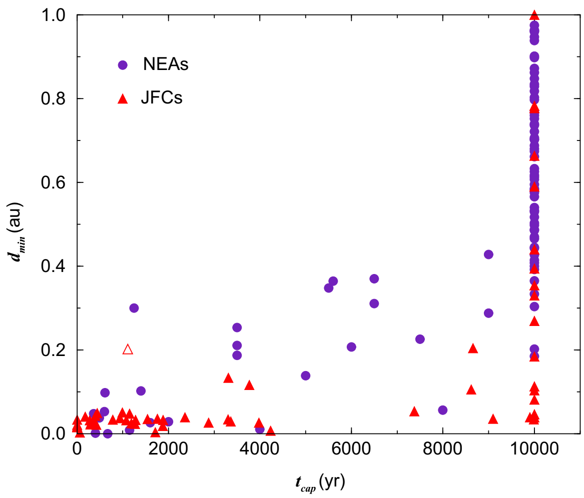

Fig. 7. The distance of closest approach to Jupiter versus the capture time for NEJFCs (red triangles) and NEAs in cometary orbits (aphelion distances $Q > 4.8$ au) (filled circles). The NEJFCs and NEAs located at $t_{cap} = 10^4$ yr actually have longer capture times. The open triangle is for comet 207P/NEAT that shows periodic variations in q raising above 2.5 au. The data for NEAs was taken from Fernández et al. (2014). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

(2) the smaller one in stable orbits (upper-left). The alignment of comets at $t_{cap} = 10,000$ yr is just an artifact of the model since we stopped the computation there. In a second stage (cf. Section 4.5) we continued the integration up to 5×10^4 yr in the past. Many of these comets still continued in near-Earth orbits at the end of the extended integration period.

4.4. Closest approach to Jupiter versus the capture time

We show in Fig. 7 the distance of closest approach to Jupiter plotted against the capture time t_{cap} for NEJFCs and for the sample of NEAs in cometary orbits analyzed by Fernández et al. (2014). As in the previous graph, we find two distinct groups: one on unstable orbits on the bottom-left of the diagram, including typical JFCs and a few NEAs, and the other one located at the right that includes most NEAs and the minor group of NEJFCs on stable orbits. Again, we note that the alignment at $t_{cap} = 10^4$ yr is an artifact of the model that finished the integrations at that point.

4.5. Extended integration for the NEJFCs with $t_{cap} > 10^4$ yr

For those comets with computed capture times >10, 000 yr we extended the integrations for another 40,000 yr in the past, setting as initial conditions the final orbital elements computed in the former integrations at $t = -10,000$ yr. In the same manner, we set the initial conditions for the planets. The condition for terminating the integration remained the same as in the previous integrations (cf. Section 3). We found that some of these stable comets continued to be stable for the extended period, while others were removed from the near-Earth region between $10^4 < t < 5 \times 10^4$ yr. The computed t_{cap} values are shown in Tables 2–4.

5. Discussion

5.1. Near-Earth JFCs in stable 'asteroidal' orbits

The results discussed here have a statistical meaning since the clones of a given object may have different outcomes, so we have to evaluate the 'average' behavior. We detected in our sample of

Table 2
Highly asteroidal.

Object	$R^{(*)}$ (km)	f_q	f_a	d_{min} (au)	t_{cap} (10^4 yr)
66P/du Toit	0.46	0.000	0.000	1.000	>5
162P/Siding Spring	6.03	0.005	0.000	0.330	>5
169P/NEAT	2.29	0.000	0.000	0.777	>5
182P/LONEOS	0.38	0.000	0.000	0.440	>5
189P/NEAT	0.60	0.001	0.000	0.590	>5
249P/LINEAR	<1.20	0.009	0.001	0.355	4.6
300P/Catalina	0.60	0.000	0.000	0.664	>5
P/2003 T12 (SOHO)	<0.26	0.004	0.000	0.783	>5

[(*)] The nucleus radii were computed assuming a geometric albedo p_V=0.04.

Table 3
Moderately asteroidal.

Object	$R^{(*)}$ (km)	f_q	f_a	d_{min} (au)	t_{cap} (10^4 yr)
197P/LINEAR	0.73	0.041	0.007	0.269	1.9
207P/NEAT	0.69	0.403	0.004	0.203	0.11
209P/LINEAR	1.52	0.030	0.004	0.184	4.5
210P/Christensen	<0.87	0.041	0.013	0.103	1.2
217P/LINEAR	<2.10	0.020	0.003	0.082	2.8
P/2010 K2 (WISE)	<0.55	0.060	0.024	0.394	2.0

Table 4
Maybe asteroidal.

Object	$R^{(*)}$ (km)	f_q	f_a	d_{min} (au)	t_{cap} (10^4 yr)
34D/Gale	–	0.049	0.121	0.047	>5
72D/Denning-Fujikawa	–	0.055	0.089	0.039	0.97
141P/Machholz-A	0.25	0.060	0.012	0.106	0.86
P/2011 NO1 (Elenin)	<1.0	0.075	0.135	0.113	3.9
P/2013 CU129 (PANSTARRS)		0.115	0.029	0.204	0.86

JFCs a small group whose orbits are *highly* stable for the past 5×10^4 yr. These comets are shown in Table 2. The great majority ($\gtrsim 90\%$) or, in some cases, the totality of the clones of the objects of Table 2 also show stable orbits, which indicates that the conclusion about their stability is very robust. We assess the degree of stability through the different indicators defined before, namely f_q, f_a, t_{cap} and the distance of closest approach to Jupiter, d_{min}. Comets of Table 2 have f_q, $f_a < 0.01$ (and in most cases $=0$), $t_{cap} \gtrsim 5 \times 10^4$ yr, and $d_{min} > 0.3$ au.

The objects shown in Table 3 are found to have highly stable orbits for a large fraction of clones. Yet, a minor fraction are found to have less stable or unstable orbits, so we give less confidence to their stability. This assessment can be checked through the set of indicators f_q, f_a, t_{cap} and d_{min}. We note again that 207P shows periodic large oscillations of q, so either its f_q or t_{cap} computed values do no reflect its stable and periodic motion.

Finally, the objects of Table 4 are found to move predominantly on rather stable orbits for periods ranging from near 10^4 yr to more than 5×10^4 yr. Yet, some of their clones are highly unstable (about 10–30%), due to the occurrence of encounters with Jupiter to less than 0.2 au, more in consonance with the evolution of typical JFCs so, in the balance, the asteroidal nature of the motion is more uncertain.

We have also checked possible correlations between the indicators characterizing the degree of asteroidal or cometary orbit with the Tisserand parameter with respect to Jupiter T_J. For instance, we find that some asteroidal NEJFCs with $f_q \sim f_a \sim 0$ have indeed T_J values close to three (in the range $2.8 < T_J < 3$), namely close to the boundary between 'cometary' and 'asteroidal' orbits, though there are also several 'cometary' NEJFCs with T_J in the same range and $f_q, f_a \geqslant 0$. On the other hand, three of our asteroidal NEJFCs have values of T_J between 2.1 and 2.3, i.e. well detached from the asteroid range. Two of these objects, 72P and P/2011 NO1, have orbits classified as maybe asteroidal, so their rather low values of T_J might weakened the hypothesis of their provenance from the asteroid belt. The other one, 66P, defined as highly asteroidal, is in the 4:5 mean motion resonance (MMR) with Jupiter, and is also a Saturn crosser, so T_J may not be a good indicator of its dynamical history.

We found that some of the objects are trapped in MMRs with Jupiter. In a MMR the critical angle σ for a k-order resonance, $|p+k|$: $|p|$, is given by

$$\sigma = (p+k)\lambda_P - p\lambda - k\varpi, \tag{6}$$

where p and k are integers, λ_P and λ are the mean longitudes of the planet and the body, respectively, and ϖ is the longitude of perihelion of the body. We found that 66P/du Toit has been in the 4:5 MMR with Jupiter, with σ librating around $\sigma = 180°$ with a semiamplitude $A \sim 20°$ for the last ~ 5000 yr. Further in the past the critical angle jumps to other values: $\sigma = 120°$, 60° and 90° for another ~ 4000 yr. Comet 182P/LONEOS is found to be trapped in the 7:3 MMR with Jupiter for the last 10^4 yr with a critical angle drifting slightly between $\sigma = 225°$ and 195° and an amplitude $\sim 95°$. We also found that 141P/Machholz is trapped in the 9:4 MMR with Jupiter for the last ~ 5000 yr with $\sigma = 180°$ and a semiamplitude $A \sim 100°$. This result agrees with the one found by Asher and Steel (1996). The most remarkable case is 210P/Christensen which is locked in the 2:1 MMR with Jupiter for the last 10^4 yr with $\sigma = 180°$ and a semiamplitude $A \sim 120°$. It is suggestive that a large fraction of NEAs in extreme cometary orbits (aphelion distances $Q > 4.8$ au) are also found in the 2:1 MMR with Jupiter. As discussed by Fernández et al. (2014), these bodies could have been transferred from the asteroid belt to near-Earth orbits keeping all the way in the 2:1 MMR with Jupiter.

Another peculiar comet is 207P/NEAT. In this case the rather high value of the computed index $f_q (= 0.405)$ is misleading since it is not due to a migration of q to the region near Jupiter's orbit in the past milennia, but to cyclic variations of q between about 0.94 au and 3.8 au, coupled to variations in the inclination between ~10° and ~50°, by the Kozai mechanism, that seems to play an important role in the evolution of many periodic comets (Bailey et al., 1992). The secular perturbation theory applied to the three-body system Sun-Jupiter-comet gives as constants of motion a and the parameter $H = \sqrt{1-e^2}\cos i$. For 207P we find a value $H = 0.642$. As discussed by Fernández et al. (2014), when $H \lesssim 0.7$ the topology of the energy level curves allows connection between high and low values of q. Fig. 8 illustrates how the variation of q are correlated with librations of the argument of perihelion ω around 270° during the past 10^4 yr. The evolution of 207P in the parametric plane (ω, q) matches quite well Kozai's map of energy level curves for this given H (cf. Figure 10 of Fernández et al., 2014). It is interesting to see that during part of the evolution 207P occupies a nearly circular orbit in the Hilda zone, suggesting an origin in this region. That the Hildas may be a source of JFCs has already been discussed by several authors (di Sisto et al., 2005; Toth, 2006), though this should be the first NEJFC suspected to have origin in this region.

In the most conservative case that only the orbits of NEJFCs of Table 2 are truly asteroidal, we get a fraction $8/58 \simeq 0.14$ of NEJFCs in asteroidal orbits. On the other hand, under the most optimistic assumption that all the orbits of Tables 2–4 are truly asteroidal, the fraction of asteroidal orbits will raise to $19/58 \simeq 0.33$. The broad range 0.14–0.33 can give only a rough idea of the proportion of asteroidal NEJFCs currently observed. A more detailed analysis is beyond the scope of this research. The first problem we face is to

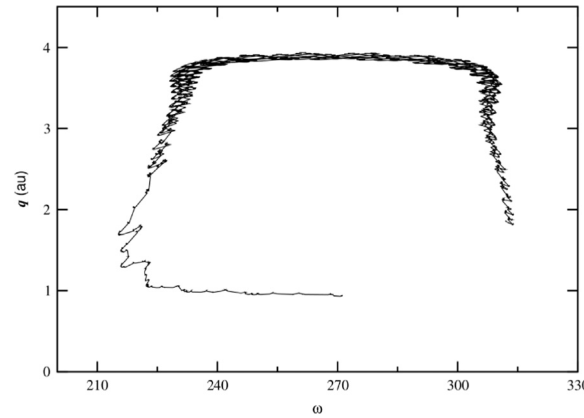

Fig. 8. Evolution of comet 207P/NEAT in the plane perihelion distance q versus argument of perihelion ω during the past 10^4 yr that shows a connection between a near-circular orbit in the Hilda zone and the current high-eccentricity, near-Earth orbit. The comet starts its evolution backwards in time at the bottom end.

know for sure which objects of Tables 2–4 are truly asteroidal. Furthermore, we must take into account possible biases in the detection probability between 'asteroidal' and 'cometary' NEJFCs, and their different physical lifetimes in the near-Earth region. Some of these biases may tend to cancel out, for instance the presumably greater detection probability of a cometary NEJFC in comparison to an asteroidal one of similar size, because the former is very likely more active, may be counterbalaced by the longer lifetime of the latter in the near-Earth region.

5.2. Observations of NEJFCs in asteroidal orbits

We will present here a summary of the most relevant observations (discovery circumstances, photometry, degree of activity) of the NEJFCs grouped in three categories according to the likelihood of their orbits being truly asteroidal.

5.2.1. 'Highly asteroidal' orbits

NEJFCs in this type of orbits tend to display extremely low activity, despite their proximity to the Sun, and in many cases they were reported as of asteroidal appearance.

- *Comet 66P/du Toit*: It was discovered in 1944 by Daniel Du Toit at Bloemfontein, South Africa, as a 10^m object. It was observed again in 1974 on photographic plates taken at Cerro El Roble, Chile, as a faint object of magnitude 18–19, and recovered in 2003 by Scotti (2003) with the 1.8 m-Spacewatch II telescope. It seems to be a very faint comet which explains why it has been missed in its 1959 and 1989 returns. Its relatively high brightness observed at discovery might have followed an outburst.
- *Comet 162P/Siding Spring*: It was discovered by the Siding Spring Survey showing a nuclear region of stellar appearance, though with a display of a short tail (cf. IAUC No. 8436). Campins et al. (2006) found that its spectral shape matched quite well that of Trojan asteroids. From the analysis of its thermal emission, Fernández et al. (2006) derived a large nucleus of an effective radius 6.0 ± 0.8 km and a visual geometric albedo of 0.034 ± 0.013. Its total magnitude is slightly brighter than its nuclear magnitude, which indicates an extremely low dust (gas?) production rate.
- *Comet 169P/NEAT*: It was discovered by NEAT in 2002 as an asteroid and given the designation 2002 EX_{12}. Activity was later reported by B.D. Warner and A. Fitzsimmons (cf. IAUC No. 8578). It has been identified as the parent body of the α-Capricornid meteoroid stream (Jenniskens and Vaubaillon, 2010). Toshihiro et al. (2010) found a point source-like surface brightness for the

comet, and derived an effective radius of 2.3 ± 0.4 km, a visual geometric albedo $p_v \simeq 0.03 \pm 0.01$, and a rotation period of 8.4096 ± 0.0012 h. They found no significant coma at the observing time, which allowed them to set for the mass loss an upper limit of $\sim 10\,\mathrm{g\,s^{-1}}$, implying an upper limit $f \sim 10^{-4}$ to the fraction of active surface area, much less than those found for active JFCs.

- *Comet 182P/LONEOS*: It was discovered by LONEOS as an asteroidal object and designated 2001 WF_2. Later observations by T.B. Spahr showed a well defined 45″ tail, while C. Hergenrother found a stellar central condensation (cf. IAUC No. 7827). From its reflection spectrum, DeMeo and Binzel (2008) assign a T taxonomic class to this body. It has always appeared as very faint and low active, even near perihelion. In its recovery in 2006 by Christensen (2006) it showed no sign of coma.
- *Comet 189P/NEAT*: It was discovered by Pravdo and Lawrence (2002) during the course of the NEAT search and given the designation 2002 O5. It showed a clear activity with a ~6″ coma and a 12″ tail.
- *Comet 249P/LINEAR*: It was reported by the LINEAR survey as an asteroidal object and later reported to show cometary appearance by several observers (cf. IAUC No. 8763). It was designated as P/2006 U1. It was recovered by Elenin (2011) as a slightly diffuse object with no visible tail.
- *Comet 300P/Catalina*: This object was discovered by the Catalina Survey as an asteroidal object and designated as P/2005 JQ_5. It was later reclassified as a comet when it showed a coma. Radar observations by Harmon et al. (2006) showed a rapidly rotating (spin period <7 h), small nucleus (diameter ~ 1.4 km) with a low dust production rate ($\dot{M} \simeq 10^3\,\mathrm{g\,s^{-1}}$), about two orders of magnitude smaller than that of other small active comets like C/1983 H1 (IRAS-Araki-Alcock). These authors found a low visual albedo of 0.033 for the nucleus. The extremely low dust production rate may explain its physical survival in the Sun's neighborhood for so long and its steady spun-up by outgassing torques to reach its current high rotation state. It is possible that mass shedding due to the fast spin rate might explain, at least in part, its current activity.
- *Comet P/2003 T12* (*SOHO*): It was discovered by Danaher (2001) on images taken by the LASCO C3 telescope on the SOHO spacecraft and recovered in 2012. Hui (2013) studied its lightcurve near perihelion and at large phase angles, finding an enhanced forward scattering by the dust grains of the coma, and a very steep lightcurve. The author finds an absolute total magnitude $H_T = 20.5$. Even if we assume that this value is close to the nuclear magnitude, its corresponding radius (for a visual albedo $p_v = 0.04$) would be only $R = 0.26$ km. Therefore, we are dealing with a very small comet nucleus.

5.2.2. 'Moderately asteroidal' orbits

Comets of this group also show in general little activity as compared to normal active comets. In one of them (209P) it was possible to estimate a very low fraction of active surface area of $\sim 10^{-4}$.

- *Comet 197P/LINEAR* : It was discovered by LINEAR as an asteroidal object and given the designation 2003 KV_2. Later Brinkworth and Burleigh (2003) found a small coma somewhat larger than the surrounding field stars and a tail ~4″–5″ long. The comet was recovered in 2008 by the Catalina Sky Survey showing again a very faint, near stellar image. It seems that we are dealing with a very low active comet.
- *Comet 207P/NEAT* : It was discovered by Pravdo et al. (2001) as a part of the NEAT survey program. It appeared diffuse with a 15″ coma. It was recovered in 2008 by Kadota (2008) showing a central condensation with a coma diameter 0′.5–0′.6 and no tail.
- *Comet 209P/LINEAR*: It was discovered by LINEAR as an asteroidal object and given the designation 2004 CB. McNaught (2004) found a narrow 1′.1 tail. The comet was recovered by Hug (2008) showing a stellar appearance. From narrow-band photometry, Schleicher (2014) derived a water production rate $Q_{H2O} = 2.5 \times 10^{25}$ molecules $\mathrm{s^{-1}}$ at $r = 0.99$ au, which implies an effective active area of only about 0.01 $\mathrm{km^2}$. For a nucleus radius $R = 1.52$ km and an effective total area $S \simeq 28.9\,\mathrm{km^2}$, the fraction of active area turns out to be $\sim 3.5 \times 10^{-4}$. This is about two orders of magnitude less than those of typical JFCs.
- *Comet 210P/Christensen*: It was discovered by Christensen (2003) as part of the Catalina Sky Survey and designated as C/2003 K2. It showed an obvious cometary nature with a 10″ coma and a 30″ tail. This seems to be a small (radius $\lesssim$0.87 km) and rather active comet.
- *Comet 217P/LINEAR*: The comet was discovered by Blythe (2001) and later identified with object 2001 MD_7. Later observations by Sarounova (2001) showed a bright nucleus and a faint coma. An outburst was reported by Sarugaku et al. (2010) in the following apparition, right after perihelion when the comet was at a heliocentric distance $r \sim 1.3$ au. The total released mass was estimated to be between 10^6 and 10^9 kg (brightening by 1.7–2.3 mag).
- *Comet 317P/WISE*: It was discovered by the WISE spacecraft without description of its nature. Later, Scotti (2010) found a cometary appearance with a coma of 7″ and a tail 0′.25 long. This seems to be a very small comet of no more than about 0.5 km radius.

5.2.3. 'Maybe asteroidal' orbits

Some of the comets of this group are by now considered lost. Since they are still in the near-Earth region, we may conclude that either they disintegrated, or exhausted their volatile content (if they were of comet nature), or remain inactive – and thus hard to observe – if they are mostly of rocky (asteroid) composition. At least one of the comets of this group (141P) displayed activity that led to its discovery, presumably after a disruption event:

- *Comet 34D/Gale*: It was discovered by W.F. Gale (Sydney, Australia) in 1927 as a circular condensed $8^m.0$ nebula (Vsekhsvyatskii, 1964). It was recovered in 1938, and then missed in the following 6 returns, so it is by now considered lost. The 1927 and 1938 returns were quite favorable, and in its second return it was observed within a heliocentric distance $r \lesssim 1.4$ au, and a geocentric distance $\Delta \lesssim 0.45$ au. Its observation only within very favorable observing conditions suggests that it is a faint small object, perhaps in its way to disintegration.
- *Comet 72P/Denning-Fujikawa*: This comet was discovered by F. W. Denning in 1881 and then missed by several returns until it was recovered by Fujikawa in 1978. It was again missed in its returns in 1987, 1996 and 2005, until it was recovered again by Sato (2014) looking as a moderately condensed object with a coma 25″ in diameter. Kresák and Kresáková (1989) estimated absolute total magnitudes (H_{10}) 8.9 and 12.6 for the 1881 and 1978 returns, respectively. From the observed magnitudes reported by Sato (2014) return, we estimate a magnitude $H_{10} \sim 15.9$. Even though estimates of total magnitudes may be quite uncertain and instrument-dependent, it seems that the comet has become increasingly fainter with the number of perihelion passages. We may interpret these observations as either the comet is approaching its final demise, disintegrating into meteoroids, or that it experienced an outburst prior to its 1881 discovery leading to a transient rejuvenation, and that it is now returning to its previous quiescent state.
- *Comet 141P/Machholz-A*: It seems that it is a very small and faint object whose discovery was possible after experiencing a

sudden outburst and splitting (Asher and Steel, 1996) that left at least two long-lasting fragments (A and D). It was discovered in 1994, and then recovered in 1999 and 2005. It was not observed in its quite unfavorable 2010 apparition where it reached perihelion close to its superior conjunction with the Sun. This comet seems to be close to its disintegration, being likely the remains of a larger parent comet.

- *Comet P/2011 NO1 (Elenin)*: Its discovery was reported by Elenin (2011), and a cometary appearance was quickly noted by several observers displaying a diffuse coma of size $4'' \times 7''$. We can set for its radius an upper limit of about 1 km.
- *Comet P/2013 CU129 (PANSTARRS)*: It was discovered by Pan-STARRS. From the reported magnitudes (cf. MPEC 3013-L63) we can estimate an upper limit for its absolute nuclear magnitude of about 19.6, which corresponds to a nucleus radius $\lesssim$0.6 km.

5.3. *Comets in stable orbits and associated meteor streams*

Some of the JFCs of Tables 2–4 are found or suspected to be associated to meteoroid streams. Eleven of these comets cross Earth's orbit which, combined to their long residence times in Earth-crossing orbits, would give them the potential to deliver large swarms of Earth-crossing debris. These debris might become easily visible meteor showers when their orbits intersect the Earth's orbit following the precession of the argument of perihelion. For instance, 169P/NEAT is found to be the parent body of the α-Capricornid meteoroid stream (Jenniskens and Vaubaillon, 2010; Kasuga et al., 2010). Jenniskens and Vaubaillon (2010) argue that this stream will become a major annual shower within about 200 yr when the bulk of this material will cross Earth's orbit. Other comets have also been investigated as producers of meteoroid streams as in the case of 141P/Machholz (Asher and Steel, 1996), 72P/Denning-Fujikawa (Beech, 2001), and 209P/LINEAR (Ye and Wiegert, 2014). In particular, one of the nodes of the orbit of 249P/LINEAR is currently near Earth's orbit so one could expect to observe some meteors associated to this comet.

5.4. *What is a comet and what is an asteroid?*

The boundary between asteroids as rocky, inert bodies, and comets as icy, active bodies has become fuzzier, in particular among the near-Earth objects, where activity develops if volatiles are present on the surface. The discovery of activity in (3552) Don Quixote from near-Earth observations with the Spitzer Space Telescope, consisting of a coma and a tail of CO_2 (Mommert et al., 2014), suggests that some activity might be rather common among NEAs. This is in consonance with the discovery of activity in some objects of the main asteroid belt, the so-called *main belt comets* (Hsieh and Jewitt, 2006). At this point we should warn that 'activity' does not necessarily mean the presence of volatiles. As discussed by Jewitt (2012), there are several processes that can generate dusty activity without requiring volatiles as, for instance, impacts with meteoroids, mass shedding by rotational instability, or thermal stresses. If we define a comet by the presence of volatiles, the detection of activity will not necessarily imply that we are dealing with a body of cometary nature.

The idea comes that the asteroid belt may be also a reservoir of JFCs, in particular of some NEJFCs, despite our reservations about whether the activity observed in main-belt comets is related to the presence of volatiles. Nevertheless, the repeated activity observed in some objects, like 238P/Read, tells in favor of some sublimation from water ice (Jewitt, 2012). From a dynamical point of view, the orbits of NEJFCs coming from the asteroid belt should be more stable than those of bodies coming from the trans-Neptunian belt. The latter bodies are subject to frequent close encounters with Jupiter, responsible for switching their orbits from the outer to the inner planetary region. From a physical point of view, JFCs from the asteroid belt may be predominantly rocky with a minor ice content, which would give them more resilience to withstand some 10^3–10^4 passages near the Sun.

Comets are very dark objects with (visual) geometric albedos mostly in the range $p_v \sim 0.02$–0.06 (Lamy et al., 2004; Kim et al., 2014). This surface property is shared by asteroids coming from the outer main belt ($r \gtrsim 2.6$ au) that belong to the C, P, D or T taxonomic classes (Lazzarin et al., 1995). Kim et al. (2014) conclude that $\sim$ 80% of the asteroids in comet-like orbits (defined as those with aphelion distances $Q > 4.5$ au, and Tisserand parameters $T_J < 3$) have low albedos $p_v < 0.1$, and DeMeo and Binzel (2008) estimate that $54 \pm 10\%$ of NEAs in cometary orbits have $p_v < 0.075$ and are thus viable as comet candidates. We note that NEAs in cometary orbits are transferred from the outer main belt to the near-Earth region through their injection in unstable dynamical regions associated to some MMRs with Jupiter, like 5:2, 7:3, 2:1 and 3:2 (Fernández et al., 2002, 2014). Three of our candidates asteroidal NEJFCs are found to have very low albedos: 162P ($p_v = 0.034 \pm 0.013$), 169P ($p_v = 0.03 \pm 0.01$), and 300P (p_v=0.033). Their spectral features show that 162P is an object similar to a D class, and 169P to a T class (DeMeo and Binzel, 2008). Summing up, a JFC origin in the outer main belt is compatible with the observed albedos and spectral features in some 'asteroidal' NEJFCs.

Actually the idea that JFCs might have other source regions closer to the Sun is not new. For instance, the Jupiter's Trojans have been suggested as a potential source (Levison et al., 1997; Marzari et al., 1997), though some estimates of the escape rate of Trojans show that their contribution should be negligible (Levison and Duncan, 1997; Volk and Malhotra, 2008). As discussed above (cf. Section 5.1), the Hildas in the 3:2 MMR with Jupiter may be another potential source (di Sisto et al., 2005; Toth, 2006), and we find that 207P/NEAT is indeed very close to this resonance. Asteroids in the main asteroid belt diffusing from the 2:1 MMR with Jupiter, like the Griquas, may be an important source of NEAs with aphelion distances $Q > 4.8$ au (Fernández et al., 2014), and perhaps of some JFCs like 210P/Christensen.

It has been argued that comets approaching the Sun might build insulating dust mantles that prevent them from further sublimation, thus becoming dormant (Shul'man et al., 1972; Brin, 1980; Rickman et al., 1990). Yet, to build insulating dust mantles, comets require a certain minimum mass in order to keep the dust particles released upon sublimation on the surface by the nucleus' gravity. The maximum radius, a_M, of the escaping dust particles is given by (Fernández, 2005)

$$a_M = \frac{9}{16\pi} \frac{u_g Z m_{H2O}}{\rho_N \rho_P G R_N}, \tag{7}$$

where u_g is the thermal expansion speed of the sublimating gases, Z the gas production rate in number of molecules per unit area and unit time, m_{H2O} the mass of the water molecule, ρ_N and ρ_P the densities of the nucleus and dust particles respectively, G the gravitational constant, and ρ_N the radius of the nucleus. By using appropriate values for the physical parameters, and assuming a nucleus radius R_N=0.5 km at a helicentric distance r=1 au, we get $a_M \sim 70$ cm. Therefore, only large dust grains of radii $a \gtrsim 70$ cm will stay on the nucleus surface. If dust particles are mostly in the range $10^{-5} < a < 10$ cm (Jewitt, 2012), it is clear that all the dust will be purged from the nucleus surface, hindering the formation of an insulating dust mantle. This is in agreement with the results found by Rickman et al. (1990) who showed that stable dust mantles on the whole nucleus surface can form only for perihelion distances $q \sim 3$ au.

As we can see in Tables 2–4, most of the comet nuclei are too small to hold dust particles on the surface by gravity, so we see more plausible that they are mostly rocky with some ice content. Their mineral, refractory matrices are what may explain their survival in the Sun's neighborhood for periods $>10^4$ yr. No wonder that most of them show correlated extremely low levels of activity that translate into "fractions" of active surface areas $\lesssim 10^{-3}$, as in the cases of comets 169P and 209P (cf. Section 5.2).

6. Conclusions

We can summarize the main results of our research as follows:

- Most JFCs in near-Earth orbits move in highly unstable orbits, due to the occurrence of frequent close encounters with Jupiter (jovicentric distances $\lesssim 0.1$–0.2 au), with capture times in their current near-Earth orbits < a few 10^3 yr. These are compatible with the expected physical lifetimes of a few hundreds revolutions for a km-size comet nucleus. They usually look very active, displaying extense gas and dust comae, frequent outbursts and, in some cases, splittings. Their mean densities are very low, of about 0.4 g cm^{-3} (Sosa and Fernández, 2009), which suggests icy and porous structure. They probably come from the trans-Neptunian region.
- Yet, a minor fraction (between about 0.14–0.33) show stable "asteroidal" orbits, with residence times in near-Earth orbits $>10^4$ yr. Since several of them are sub-km size bodies, their long survival in the near-Earth region might be explained if they are mostly rocky, so they might have a different source region, for instance the outer main asteroid belt. While main-belt comets may be the active counterpart of the main-belt asteroids, the 'asteroidal' NEJFCs may be likewise the active counterpart of the seemingly inert NEAs. Therefore, a fraction of the asteroid population may have the potential to become active by different physical causes.
- We expect that the low albedos and spectral taxonomic classes of bodies coming from the outer main belt will be similar to those of comets. Yet, while active comets have typically equivalent fractions of active surface area >0.01, most of the 'asteroidal' NEJFCs are found to be little active with equivalent fractions $\lesssim 10^{-3}$.
- Asteroidal JFCs with long residence times in Earth-crossing orbits are potential candidates to produce visible meteor showers. This is actually the case of comet 169P/NEAT associated to the α-Capricornid meteoroid stream.

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References

Asher, D.J., Steel, D.I., 1996. The orbital evolution of P/Machholz 2 and its debris. Mon. Not. R. Astron. Soc. 280, 1201–1209.
Bailey, M.E., Chambers, J.E., Hahn, G., 1992. Origin of sungrazers: a frequent cometary end-state. Astron. Astrophys. 257, 315–322.
Beech, M., 2001. Comet 72P/Denning-Fujikawa: down but not necessarily out. Mon. Not. R. Astron. Soc. 327, 1201–1207.
Blythe, M., 2001. IAUC No. 7660.
Brin, G.D., 1980. Three models of dust layers on cometary nuclei. Astrophys. J. 237, 265–279.
Brinkworth, C., Burleigh, M., 2003. IAUC No. 8139.
Chambers, J.E., 1999. A hybrid symplectic integrator that permits close encounters between massive bodies. Mon. Not. R. Astron. Soc. 304, 793–799.
Christensen, E.J., 2003. IAUC No. 8136.
Christensen, E.J., 2006. IAUC No. 8776.
Campins, H., Ziffer, J., Licandro, J., Pinilla-Alonso, N., Fernández, Y.R., de León, J., Mothé-Diniz, T., Binzel, R.P., 2006. Nuclear spectra of comet 162P/Siding Spring (2004 TU12). Astron. J. 132, 1346–1353.
Danaher, J., 2001. IAUC No. 8344.
DeMeo, F., Binzel, R.P., 2008. Comets in the near-Earth object population. Icarus 194, 436–449.
di Sisto, R.P., Brunini, A., Dirani, L.D., Orellana, R.B., 2005. Hilda asteroids among Jupiter family comets. Icarus 174, 81–89.
di Sisto, R.P., Fernández, J.A., Brunini, A., 2009. On the population, physical decay and orbital distribution of Jupiter family comets: numerical simulations. Icarus 203, 140–154.
Duncan, M., Quinn, T., Tremaine, S., 1988. The origin of short-period comets. Astrophys. J. 328, L69–L73.
Elenin, L., 2011. IAUC No. 9194.
Fernández, J.A., 1980. On the existence of a comet belt beyond Neptune. Mon. Not. R. Astron. Soc. 192, 481–491.
Fernández, J.A., 1984. The distribution of the perihelion distances of short-period comets. Astron. Astrophys. 135, 129–134.
Fernández, J.A., 1985. Dynamical capture and physical decay of short-period comets. Icarus 64, 308–319.
Fernández, J.A., 2005. Comets. Nature, Dynamics, Origin, and their Cosmogonical relevance. Springer, Dordrecht, pp. 240–246.
Fernández, J.A., Gallardo, T., Brunini, A., 2002. Are there many inactive Jupiter Family Comets among the near-Earth asteroid population? Icarus 159, 358–368.
Fernández, J.A., Sosa, A., 2012. Magnitude and size distribution of long-period comets in Earth-crossing or approaching orbits. Mon. Not. R. Astron. Soc. 423, 1674–1690.
Fernández, J.A., Sosa, A., Gallardo, T., Gutiérrez, J.N., 2014. Assessing the physical nature of near-Earth asteroids through their dynamical histories. Icarus 238, 1–12.
Fernández, Y.R., Campins, H., Kassis, M., Hergenrother, C.W., Binzel, R.P., Licandro, J., Hora, J.L., Adams, J.D., 2006. Comet 162P/Siding Spring: a surprisingly large nucleus. Astron. J. 132, 1354–1360.
Fernández, Y.R., Kelley, M.S., Lamy, P.L., Toth, I., Groussin, O., Lisse, C.M., A'Hearn, M. F., Bauer, J.M., Campins, H., Fitzsimmons, A., Licandro, J., Lowry, S.C., Meech, K.J., Pittichová, J., Reach, W.T., Snodgrass, C., Weaver, H.A., 2013. Thermal properties, sizes, and size distribution of Jupiter-family cometary nuclei. Icarus 226, 1138–1170.
Harmon, J.K., Nolan, M.C., Margot, J.-L., Campbell, D.B., Benner, L.A.M., Giorgini, J.D., 2006. Radar observations of comet P/2005 JQ5 (Catalina). Icarus 184, 285–288.
Hsieh, H.H., Jewitt, D., 2006. A population of comets in the main asteroid belt. Science 312, 561–563.
Hug, G., 2008. IAUC No. 9002.
Hui, M.-T., 2013. Observations of comet P/2003 T12 = 2012 A3 (SOHO) at large phase angle in STEREO-B. Mon. Not. R. Astron. Soc. 436, 1564–1575.
Jenniskens, P., Vaubaillon, J., 2010. Minor planet 2002 EX_{12}(=169P/NEAT) and the alpha Capricornid shower. Astron. J. 139, 1822–1830.
Jewitt, D., 2006. Comet D/1819 W1 (Blanpain): not dead yet. Astron. J. 131, 2327–2331.
Jewitt, D., 2012. The active asteroids. Astron. J. 143, 66–79.
Kadota, K., 2008. IAUC No. 8996.
Kasuga, T., Balam, D.D., Wiegert, P.A., 2010. Comet 169P/NEAT(=2002 EX_{12}): the parent body of the α-Capricornid meteoroid stream. Astron. J. 139, 1822–1830.
Kim, Y., Ishiguro, M., Usui, F., 2014. Physical properties of asteroids in comet-like orbits in infrared asteroid survey catalogs. Astrophys. J. 789, 151–158.
Kresák, L., 1981. The lifetimes and disappearance of periodic comets. Bull. Astron. Inst. Czech. 32, 321–339.
Kresák, L., Kresáková, M., 1989. The absolute magnitudes of periodic comets. I. Catalogue. Bull. Astron. Inst. Czech. 40, 269–284.
Kresák, L., Kresáková, M., 1990. Secular brightness decrease of periodic comets. Icarus 86, 82–92.
Lamy, P.L., Toth, I., Fernández, Y., Weaver, H.A., 2004. The sizes, shapes, albedos, and colors of cometary nuclei. In: Festou, M., Keller, H.U., Weaver, H. (Eds.), Comets II. Univ. Arizona Press, Tucson, pp. 223–264.
Lazzarin, M., Barbieri, C., Barucci, m.A., 1995. Visible spectroscopy of dark primitive asteroids. Astron. J. 110, 3058–3072.
Levison, H.F., Duncan, M.J., 1997. From the Kuiper belt to Jupiter-family comets: the spatial distribution of ecliptic comets. Icarus 127, 13–32.
Levison, H.F., Shoemaker, E.M., Shoemaker, C.S., 1997. Dynamical evolution of Jupiter's Trojan asteroids. Nature 385, 42–44.
Marzari, F., Farinella, P., Davis, D.R., Scholl, H., Campo Bagatin, A., 1997. Collisional evolution of Trojan asteroids. Icarus 125, 39–49.
McNaught, R.H., 2004. IAUC No. 8314.
Mommert, M., Hora, J.L., Harris, A.W., Reach, W.T., Emery, J.P., Thomas, C.A., Mueller, M., Cruikshank, D.P., Trilling, D.E., Delbo, M., Smith, H.A., 2014. The discovery of cometary activity in near-Earth asteroid (3552) Don Quixote. Astrophys. J. 781, 25–34.
Pravdo, S., Helin, E., Lawrence, K., 2001. IAUC No. 7623.
Pravdo, S., Lawrence, K., 2002. IAUC No. 7942.

Rickman, H., Fernández, J.A., Gustafson, B.Å.S., 1990. Formation of stable dust mantles on short-period comet nuclei. Astron. Astrophys. 237, 524–535.
Sarounova, L., 2001. IAUC No. 7660.
Sarugaku, Y., Ishiguro, M., Ueno, M., Usui, F., Watanabe, J., 2010. Outburst of comet 217/LINEAR. Astrophys. J. 724, L118–L121.
Sato, H., 2014. CBET No. 3908.
Schleicher, D., 2014. CBET No. 3881.
Scotti, J.V., 2003. IAUC No. 8093.
Scotti, J.V., 2010. IAUC No. 9150.
Sekanina, Z., 1984. Disappearance and disintegration of comets. Icarus 58, 81–100.
Shul'man, L.M., 1972. The evolution of cometary nuclei. In: Chebotarev, G.A., Kazimirchak-Polonskaya, E.I., Marsden, B.G. (Eds.), The Motion, Evolution of Orbits, and Origin of Comets IAU Symposium No. 45, Reidel, Dordrecht, Holland.
Snodgrass, C., Fitzsimmons, A., Lowry, S.C., Weissman, P.R., 2011. The size distribution of Jupiter family comet nuclei. Mon. Not. R. Astron. Soc. 414, 458–469.
Sosa, A., Fernández, J.A., 2009. Cometary masses derived from non-gravitational forces. Mon. Not. R. Astron. Soc. 393, 192–214.
Sosa, A., Fernández, J.A., Pais, P., 2012. On the asymmetric evolution of the perihelion distances of near-Earth Jupiter family comets around the discovery time. Astron. Astrophys. 548, 64–73.
Tancredi, G., Fernández, J.A., Rickman, H., Licandro, J., 2006. Nuclear magnitudes and the size distribution of Jupiter family comets. Icarus 182, 527–549.
Toshihiro, K., Balam, D.D., Wiegert, P.A., 2010. Comet 169P/NEAT(=2002 EX_{12}): the parent body of the α-Capricornid meteoroid stream. Astron. J. 140, 1806–1813.
Toth, I., 2006. The quasi-Hilda subgroup of ecliptic comets—an update (Research Note). Astron. Astrophys. 448, 1191–1196.
Volk, K., Malhotra, R., 2008. The scattered disk as the source of Jupiter family comets. Astrophys. J. 687, 714–725.
Vsekhsvyatskii, S.K., 1964. Physical Characteristics of Comets. Israel Program for Scientific Translations, Jerusalem.
Weaver, H.A., Sekanina, Z., Toth, I., et al., 2001. HST and VLT investigations of the fragments of comet C/1999 S4 (LINEAR). Science 292, 1329–1333.
Ye, Q., Wiegert, P.A., 2014. Will comet 209P/LINEAR generate the next meteor storm? Mon. Not. R. Astron. Soc. 437, 3283–3287.