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The quasi-Hilda subgroup of ecliptic comets – an update *(Research Note)*

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ABSTRACT

Context. The importance of the Hilda zone is obvious in the main belt asteroid – ecliptic comet relationship.
Aims. The inventory of the quasi-Hilda comet group is updated by taking into account the data bases of new discoveries performed by large survey programs.
Methods. We examined the Hilda zone objects according to their Tisserand parameter with respect to Jupiter, orbital excitation parameter, as well as their distribution in the Langrangian orbital elements space.
Results. We found 11 new members of the quasi-Hilda cometary subgroup of ecliptic comets, so that altogether there are now 15 known comets in the Hilda asteroid zone. In addition, we found 23 outliers of the Hilda family in the (k, h) Lagrangian orbital elements space, which can be dormant or extinct comet nuclei. This proposition should be checked by both observations of the physical properties and investigation of the long-term evolution of the orbits of these objects.

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

1. Introduction

Details of the interrelations between primitive asteroids and comet nuclei are not very well known, especially the orbital and physical properties of those comet nuclei that orbit in the main asteroid belt. The most abundant comet population resides in the Hilda asteroid zone. This asteroid family is located in the outer main belt in the semimajor axis range of $3.70 \leq a \leq 4.20$ AU at eccentricities $e \leq 0.30$ and inclinations $i \leq 20°$ (Zellner et al. 1985). The Hilda-type asteroids reside in the 3:2 inner mean motion resonance (MMR) with Jupiter. The orbital dynamics and long-lasting stability of the Hilda asteroid zone have been studied by Schubart (1991), Moons (1997), Nesvorný & Ferraz-Mello (1997), while very recently a formal solution of proper elements was constructed by Miloni et al. (2005).

Accordingly, not only do minor planets reside in this zone but there are also comets associated with this asteroid region, even as there are comets that can leave this zone and later be captured by Jupiter. The most prominent example for this route is D/Shoemaker-Levy 9 (D/SL9 hereafter) that was tidally split into fragments by Jupiter in 1992 and whose fragments hit the giant planet in July 1994. It was truly a comet (Weissman 1996; Weissman et al. 2002, see the review chapters in Noll et al. 1996) but it did dwell in the Hilda asteroid zone before its breakup (Yeomans & Chodas 1994; Chodas & Yeomans 1995, 1996; Benner & McKinnon 1995; Tancredi & Sosa 1996). Benner & McKinnon (1995) pointed out that the inner distribution of possible pre-capture orbits for D/SL9 overlaps a group of known comets, referred to as quasi-Hildas by Kresák (1979).

Very recently, Di Sisto et al. (2005) performed numerical simulation to analyze the dynamical evolution that Hildas follow after escaping from the resonance, which is their contribution to the Jupiter family comet (JFC, cf. Levison 1996) population, and they conclude that 8% of the particles leaving the resonance end up impacting Jupiter and that 98.7% of the escaped Hildas live at least 1000 years as a JFC with a mean dynamical lifetime of 1.4×10^6 years. In addition, their results support D/SL9 having escaped from the Hilda zone; and in this case, it would be possible to give stronger constraints to its pre-capture orbital elements. Observations of the physical properties of Hildas show that these asteroids and comet nuclei are similar from a compositional point of view (Dahlgren & Lagerkvist 1995; Dahlgren et al. 1997, cf. review by Barucci et al. 2002). As a result, the importance of the Hilda zone is obvious in the main belt asteroid – ecliptic comet relationship. In this paper we are going to update the inventory of the quasi-Hilda cometary group (Sect. 2), while looking for any Hilda asteroids that may be comet-like objects: dormant or extinct comet nuclei.

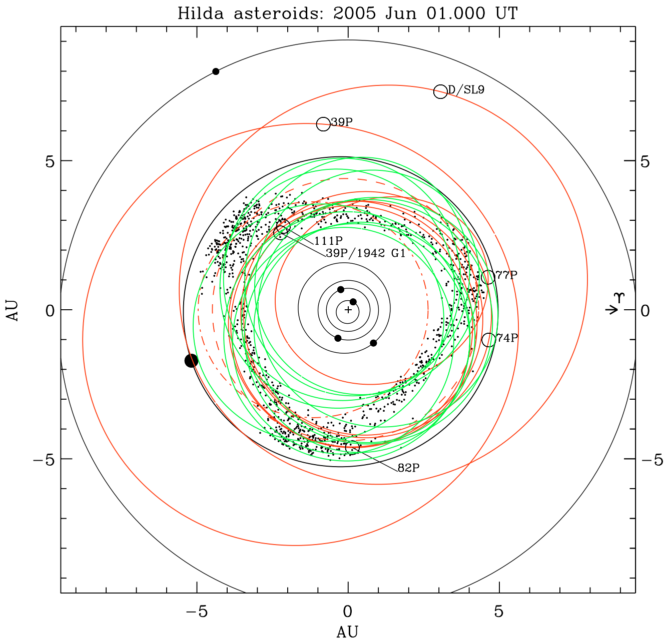

Fig. 1. Orbits of the quasi-Hilda comets and the instantaneous positions of the Hilda asteroids (black dots) projected onto the plane of ecliptic for the date UT 0 h 1 June 2005. The well-known members of the quasi-Hilda cometary group are shown with red solid lines and their names indicated at their orbit. The red dashed and dash-dot lines are two extremal pre-captured orbits of D/SL9. The orbit of 39P/Oterma formed after the close approach to Jupiter in 1963, and the orbit of D/SL9 (the encounter orbit) are also drawn. Other green solid lines are those orbits of the new quasi-Hilda comets that are identified in this work (cf. Table 1). The orbits of the major planets from Mercury to Saturn are drawn with black solid lines for scale. The location of major planets is indicated by large black dots, and the Vernal Equinox direction is indicated.

2. The quasi-Hilda cometary group

First of all, we investigate the orbits of the Hilda-zone-related comets in the ecliptic coordinate system (Fig. 1) and then in the phase spaces defined by ecliptic orbital elements and the Lagrangian elements of orbit. To search for the new members of the quasi-Hilda cometary group, we used the ASTORB database of the osculating elements for the asteroids, which is maintained by E. L. G. Bowell of Lowell Observatory, and the DASTCOM database of the osculating elements of comets provided by the Solar System Dynamics Group of the JPL. In order to compare the location of the Hilda asteroids in the phase space, we also applied the proper elements from the data base supervised by A. Milani of the University of Pisa.

2.1. Ecliptic orbits

At first, we examining the plot of the orbits of the quasi-Hilda comets together with the instantaneous positions of the Hilda asteroids projected onto the plane of ecliptic (Fig. 1). We observe that the quasi-Hilda comets reside in the Hilda zone comfortably. These are already known and numbered ecliptic comets like: 74P/Smirnova-Chernykh, 77P/Longmore in a new orbit, 82P/Gehrels 3, 111P/Helin-Roman-Crockett, the earlier orbit of 39P/Oterma (1942 G1) prior to its close encounter with Jupiter in 1963 (Kresák 1979), and the pre-capture orbits of D/SL9 (1) and (2), encounter orbit of fragment D/SL9 (D/1993 F2-K). For the purpose of illustration we selected two extrema of the pre-capture orbits from the results of numerical simulations (Fig. 5 of Chodas & Yeomans 1996): D/SL9 (1) with $a = 4.40$ AU, $e = 0.020$, and D/SL9 (2) with $a = 3.80$ AU, $e = 0.305$. These orbits have $q = 4.31$ AU and $Q = 4.49$ AU, as well as $q = 2.64$ AU and $Q = 4.96$ AU; respectively, i.e., these pre-breakup orbits of D/SL9 are close to the Hilda asteroid zone. We performed a search for further members of the quasi-Hilda comets in the DASTCOM data base and found 11 new comets whose recent orbits reside in the Hilda zone, including for example 36P/Whipple, which is a numbered ecliptic comet, but it has not been involved yet in any inventory of the quasi-Hildas (Table 1, Fig. 1).

We explore the location of the objects according to both their Tisserand parameter and a parameter that describes their orbital excitation. The reason for using the Tisserand parameter is its usefulness classifying comets and asteroids, while the second parameter characterizes the orbital excitation, since the collisional evolution is taking place in the Hilda zone, and because the comets mostly have primarily excited orbits.

The Tisserand parameter with respect to Jupiter, T_J, which is a constant of the motion in the circular restricted three-body problem (CR3BP), provides a useful measure for distinguishing the ecliptic comets and asteroids. For reference, the Jupiter family of ecliptic comets have $2 < T_J \leq 3$, and asteroids have $T_J > 3$ (cf. Levison 1996). However, there are asteroids with $T_J < 3$ (e.g., the Damocloids) and ecliptic comets with $T_J > 3$ (e.g., 2P/Encke), so that the above definition is less definitive for some cases but is useful for practical applications. In the spatial CR3BP the Tisserand parameter with respect to Jupiter is

$$T_J = \frac{a_j}{a} + 2\sqrt{\frac{a}{a_J}(1-e^2)}\,\cos(i_m). \qquad (1)$$

Since the basic plane in the CR3BP is the orbit plane of Jupiter, the mutual inclination i_m between the orbits of the small body and Jupiter should be taken into account as follows:

$$\cos(i_m) = \cos(i)\cos(i_J) + \sin(i)\sin(i_J)\cos(\Omega - \Omega_J). \qquad (2)$$

In Eqs. (1), (2) a, e, i, and Ω are the semimajor axis, eccentricity, inclination, and longitude of ascending node of the small body, while a_j, i_J, and Ω_J for the semimajor axis, inclination, and longitude of ascending node of the orbit of Jupiter, respectively.

The populations in the outer asteroid belt are dynamically stable, but collisions eject fragments onto unstable orbits that are then lost from the system; i.e., they leave their original zone (Davis et al. 2002). In general terms the orbital excitation of the objects can be defined by

$$\mathcal{E} = \sqrt{e^2 + \sin^2(i)} \qquad (3)$$

where the term e corresponds to the object's radial velocity, and the $\sin(i)$ term is related to the velocity perpendicular to the ecliptic plane (Stern 1996; Hainaut & Delsanti 2002).

Table 1. The quasi-Hilda cometary group.

Object	a (AU)	e	i (°)	q (AU)	Q (AU)	P_{orb} (yr)	T_{J}	$\mathcal{E}$
39P/1942 G1 (Oterma)[1]	3.96	0.145	4.0	3.39	4.54	7.89	3.037	0.161
39P/Oterma[2]	7.25	0.246	1.9	5.47	9.03	19.53	3.003	0.248
74P/Smirnova-Chernykh[2]	4.17	0.149	6.6	3.55	4.79	8.52	3.010	0.189
77P/Longmore[3]	3.60	0.358	24.4	2.31	4.89	6.83	2.861	0.547
82P/Gehrels 3[2]	4.14	0.124	1.1	3.63	4.65	8.42	3.026	0.125
111P/Helin-Roman-Crockett[2]	4.05	0.140	4.2	3.48	4.61	8.14	3.030	0.159
D/Shoemaker-Levy 9[4]	6.81	0.210	5.9	5.38	8.25	17.79	2.986	0.234
D/SL9 (1)[5]	4.40	0.020	0.0	4.31	4.49	9.23	3.021	0.020
D/SL9 (2)[5]	3.80	0.305	0.0	2.64	4.96	7.41	2.997	0.305
36P/Whipple	4.17	0.259	9.9	3.09	5.24	8.51	2.952	0.311
117P/Helin-Roman-Alu 1	4.08	0.256	8.7	3.04	5.13	8.25	2.972	0.297
129P/Shoemaker-Levy 3	3.74	0.249	5.0	2.81	4.67	7.23	3.024	0.264
135P/Shoemaker-Levy 8	3.83	0.290	6.1	2.72	4.94	7.50	2.990	0.308
147P/Kushida-Muramatsu	3.80	0.277	2.4	2.75	4.86	7.42	3.011	0.280
P/Catalina (1999 XN120)	4.18	0.214	5.0	3.29	5.07	8.55	2.985	0.231
P/LINEAR (2001 YX127)	4.18	0.180	7.9	3.43	4.93	8.53	2.993	0.226
P/LINEAR-NEAT (2003 CP7)	4.02	0.249	12.3	3.02	5.01	8.05	2.965	0.328
P/NEAT (2002 O8)	4.03	0.199	12.8	3.23	4.84	8.10	2.980	0.298
P/NEAT (2004 F3)	4.02	0.287	16.0	2.86	5.17	8.05	2.923	0.398
D/Skiff-Kosai (1977 C1)	3.85	0.259	3.2	2.85	4.84	7.55	3.013	0.265

Note:
a, e, i: semimajor axis, eccentricity, inclination; q, Q: perihelion and aphelion distances; P_{orb}: orbital period; T_{J}: Tisserand parameter with respect to Jupiter. $\mathcal{E} = \sqrt{e^2 + \sin^2(i)}$: excitation of the object's orbit.
[1] 39P/1942 G1 (Oterma): Marsden & Williams (1999). [2] Chodas & Yeomans (1995). [3] 77P/Longmore new orbit from JPL DASTCOM; Kresák (1979). [4] Chodas & Yeomans (1996); orbit of fragment K of D/SL9 (1993 F2). [5] Selected pre-capture orbits of D/SL9 (cf. Fig. 5 of Chodas & Yeomans 1996).

The osculating orbital elements of the Hilda asteroids are used to calculate T_{J} and $\mathcal{E}$. The bulk of the Hilda asteroids have Tisserand parameter values ranging from 2.84 to 3.06. With Tisserand parameter values ranging from 2.90 to 3.04, the quasi-Hilda comets also have asteroid-like orbits (Fig. 2). The pre-1963 orbit of 39P/Oterma is included, but the new orbit of 39P was omitted from the statistical analysis. The mean value of $\mathcal{E}$ for the Hilda asteroids is 0.22 ± 0.06 (1σ) and is 0.27 ± 0.09 (1σ) for quasi-Hilda comets. The distribution of the parameter of orbital excitation of the quasi-Hilda comets is very similar to the Hilda asteroids, but there is a slight displacement with $\Delta\mathcal{E} \sim 0.05$ for comets toward the higher values. There are even comets in the range of $0.5 < \mathcal{E} < 0.6$. Accordingly, the orbits of the quasi-Hilda comets are more dynamically excited than those of the Hilda asteroids. In the plot of the parameter of orbit excitation versus Tisserand parameter the most of the quasi-Hilda comets have larger scatter than do asteroids. The parameter of orbit excitation pulls the comets away from the strip of the Hilda asteroid in the $(T_{\mathrm{J}}, \mathcal{E})$ plane; i.e., these objects are more dispersed in this plane. Due to its large e and i values, 77P/Longmore falls far from the vast majority of the Hilda zone objects; i.e., 77P has "more comet-like" orbital characteristics. The orbital evolution of 77P displays general trend rather than rapid changes. Carusi et al. (1985) showed that this comet is within the quasi-Hilda parameters in the past, but now it does not really appear to be a member. While the aphelion remains constantly not far from the orbit of Jupiter, the perihelion distance decreases and the T_{J} tends to increase with time. There are other comets that lie inside or close to the Hilda asteroid zone (Table 1, Fig. 2).

2.2. Distribution in the phase space

Distribution of the Hilda asteroids and quasi-Hilda comets are explored in the (e, a) and $(e, \sin(i))$ sections of the phase space. For a comparison, the location of the Hilda asteroids with known proper elements are also plotted using the data base provided by A. Milani, but for the bulk of the asteroids only the osculating elements are available (ASTORB data base). However, it would be much better to examine the location of the asteroids in the proper element spaces, but because of the lack of more appropriate elements, we should confine ourselves to the osculating elements. The results are displayed in the panels of Fig. 3. The Hildas with known proper elements are largerly close to the 3:2 MMR in the (e, a) plane. The quasi-Hilda

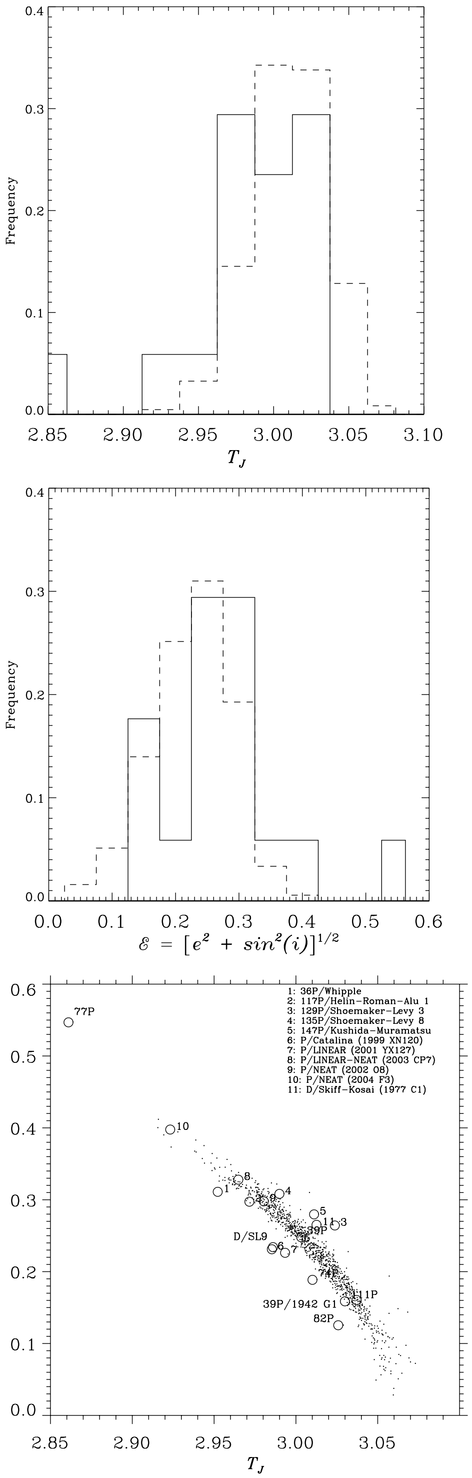

Fig. 2. Normalized distribution of the Tisserand parameter with respect to Jupiter (*top panel*) and the orbital excitation parameter $\mathcal{E}$ (*mid panel*) of the Hilda asteroids (dashed line) and quasi-Hilda comets (solid line). Orbital excitation $\mathcal{E}$ versus Tisserand parameter with respect to Jupiter T_J of the Hilda asteroids (dots) and quasi-Hilda comets (open circles) are shown in the *bottom panel* (cf. Table 1).

comets occupy the same region in these phase spaces as the Hilda asteroids, although they are not in the 3:2 MMR, as are the Hildas. The quasi-Hilda comets spread around the strip that is drawn by the Hilda asteroids in the (e, a) plane, however there are comets close to the Hildas. In the $(e, \sin(i))$ plane, the quasi-Hilda comets are almost evenly distributed. In both the (e, a) and $(e, \sin(i))$ planes, the comets are offset toward the larger e and i values. Moreover, the comet 77P falls outside of the bulk of the distribution due to its large e and i values.

2.3. Distribution in the spaces of Lagrangian elements

The horizontal and vertical components of eccentricity $\boldsymbol{e} = (e_x, e_y) = (k, h)$ and inclination $\boldsymbol{i} = (i_x, i_y) = (q, p)$ planes of Lagrangian elements, as well as the semimajor axis $\boldsymbol{a} = (a_x, a_y)$ "vectors" are as follows, in that order

$$k = e\cos(\varpi - \varpi_\mathrm{J}), \quad h = e\sin(\varpi - \varpi_\mathrm{J}) \tag{4}$$

$$q = \tan(i)\cos(\Omega - \Omega_\mathrm{J}), \quad p = \tan(i)\sin(\Omega - \Omega_\mathrm{J}) \tag{5}$$

$$a_x = a\cos(l - l_\mathrm{J}), \quad a_y = a\sin(l - l_\mathrm{J}) \tag{6}$$

where ϖ is the longitude of pericenter, l the mean longitude of orbit of the small body, ϖ_J the longitude of pericenter, and l_J is the mean longitude of orbit of Jupiter, since we perform the calculations with respect to Jupiter in the arguments of the sine and cosine. Additionally, we use $\tan(i)$ instead of i (cf. Eq. (7.19) of Murray & Dermott 1999). The results for the Hilda asteroids and quasi-Hilda comets are displayed in the panels of Fig. 4. The bulk of the objects are within a circle in the (k, h) plane. The radius of this circle is defined by $2 \times \mathrm{Max}(\sigma_k, \sigma_h)$, where σ_k and σ_h are the standard deviations of k and h coordinates. In the (k, h) plane the Hilda asteroids are within a circle and there are obvious outliers that have similar distribution to the quasi-Hilda comets. There are Hilda asteroid outliers in the (q, p) and (a_x, a_y) planes, but the asteroid outliers can be identified most conspicuously in the (k, h) plane. We found 23 outliers of the Hilda asteroids that have elongated, comet-like orbits (Table 2), and their orbit excitation parameter has high values (cf. Table 1 and Fig. 2). Unfortunately, the taxonomic classes and other physical parameters have not been reported yet for these objects.

3. Conclusions

In summary, we have reached the following conclusions.

- The inventory of the quasi-Hilda comet group has been updated. We found 11 new members of the quasi-Hilda cometary group of ecliptic comets.
- We observed the orbital excitation parameter versus Tisserand parameter (w.r.t. Jupiter), the phase spaces (e, a), $(e, \sin(i))$, as well as the (k, h), (q, p) planes of the Lagrangian elements. In addition, we also examined the (a_x, a_y) plane. These planes are useful tools in searching for outliers in the Hilda asteroid family. We conclude that the (k, h) plane of Lagrangian elements is the best for this purpose.
- Examining the (k, h) Lagrangian elements space, we searched for outliers of the Hilda family that have similar location to the quasi-Hilda comets. We found 23 outliers

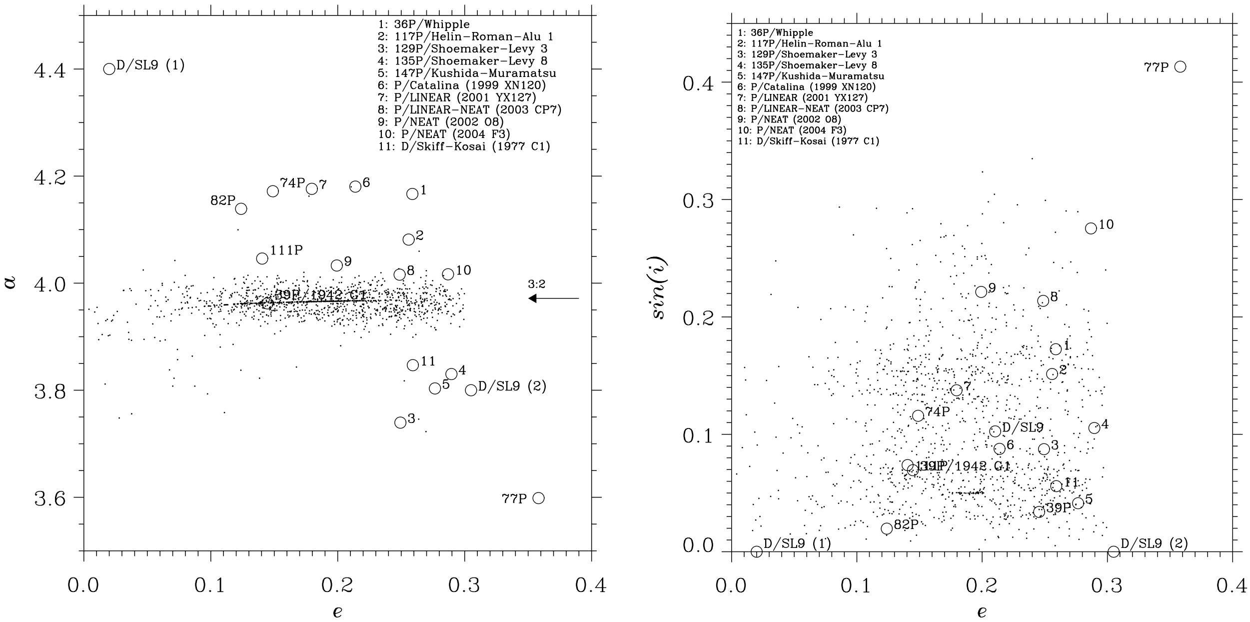

Fig. 3. Location of the Hilda asteroid family members and the quasi-Hilda comets in the (e, a) plane (*left panel*) and in the $(e, \sin(i))$ plane (*right panel*). The 3:2 mean motion resonance is indicated in the (e, a) plane. The Hilda asteroids for which proper elements are available are shown with small dots and the others are plotted with large dots. The quasi-Hilda comets are indicated by open circles (cf. Table 1).

Table 2. Hilda asteroid outliers in the $(e_x, e_y) = (k, h)$ plane.

Object	a (AU)	e	i (°)	q (AU)	Q (AU)	P_{orb} (yr)	T_{J}	$\mathcal{E}$	k	h	Taxon. class
4446 Carolyn	3.98	0.282	7.2	2.86	5.10	7.94	2.972	0.309	0.10	–0.26	?
39266 2001 AT2	3.97	0.252	7.0	2.97	4.97	7.91	2.993	0.280	0.04	–0.25	?
70032 1999 CZ13	3.75	0.264	9.4	2.76	4.73	7.25	3.008	0.310	–0.25	0.09	?
85142 1981 EO29	3.99	0.196	5.0	3.21	4.78	7.98	3.011	0.214	–0.19	–0.03	?
94299 2001 DB108	3.99	0.187	11.9	3.24	4.73	7.96	2.990	0.279	–0.15	–0.10	?
1998 HP43	3.93	0.183	2.6	3.21	4.65	7.80	3.032	0.188	–0.17	–0.08	?
2000 OE9	3.98	0.225	6.5	3.08	4.87	7.93	3.003	0.252	–0.02	–0.22	?
2001 PC54	3.98	0.270	2.2	2.91	5.06	7.95	2.989	0.273	0.13	–0.24	?
2001 RN145	3.95	0.277	5.6	2.86	5.05	7.85	2.982	0.294	0.14	–0.24	?
2001 SD255	3.97	0.288	5.1	2.82	5.11	7.91	2.976	0.302	0.15	–0.24	?
2001 TQ85	3.95	0.244	8.7	2.99	4.91	7.85	2.983	0.287	–0.00	–0.24	?
2002 CF140	3.82	0.253	11.5	2.85	4.78	7.46	2.988	0.322	–0.24	0.08	?
2002 KM4	3.94	0.181	3.1	3.23	4.66	7.83	3.031	0.189	–0.14	–0.11	?
2003 CR4	3.99	0.244	8.5	3.01	4.96	7.96	2.982	0.285	–0.07	0.23	?
2003 FK28	3.95	0.245	10.6	2.98	4.91	7.84	2.985	0.306	0.04	–0.24	?
2003 KB11	3.98	0.250	4.0	2.98	4.97	7.93	2.998	0.259	–0.02	–0.25	?
2004 BU122	3.72	0.269	0.8	2.72	4.73	7.19	3.027	0.270	–0.08	0.26	?
2004 CS16	3.95	0.213	7.3	3.11	4.79	7.85	3.003	0.248	–0.19	0.10	?
2004 FM24	3.95	0.250	17.4	2.96	4.94	7.84	2.919	0.390	–0.17	–0.18	?
2004 NZ18	3.96	0.285	5.0	2.84	5.09	7.89	2.980	0.298	0.13	–0.25	?
2004 QS3	3.99	0.230	8.1	3.07	4.91	7.97	2.988	0.270	–0.04	–0.23	?
2004 QS14	3.97	0.268	10.4	2.90	5.03	7.90	2.959	0.323	–0.06	–0.26	?
2005 GO136	3.95	0.188	8.0	3.20	4.69	7.84	3.015	0.234	–0.18	0.04	?

Note: see also the notes at Table 1.
(k, h): Lagragian elements of orbit; Number of all Hildas = 1056, outliers = 23, 2.18%.

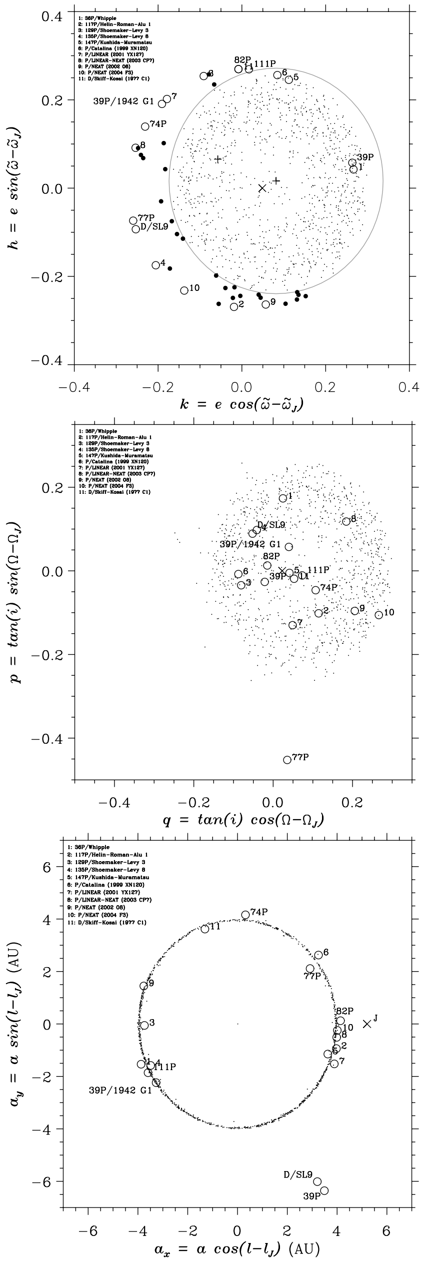

Fig. 4. Location of the Hilda asteroid family members and the quasi-Hilda comets in the Lagrangian elements $(e_x, e_y) = (k, h)$ plane (*top panel*), $(i_x, i_y) = (q, p)$ plane (*mid panel*), and in the semimajor axis vector (a_x, a_y) plane (*bottom panel*). The Hilda asteroids are shown with dots and the quasi-Hilda comets represented by open circles. The newly identified Hilda asteroid outliers are highlighted with large dots in the top panel (cf. Table 2). The mean value of the k and h coordinates of the samples of Hilda asteroids and quasi-Hilda comets are shown with a plus sign (+) in the top panel. The location of Jupiter is shown with a cross (×) in each panel. The bulk of the objects are within a circle in the (k, h) plane (*top left panel*). The radius of this circle is defined by $2 \times \mathrm{Max}(\sigma_k, \sigma_h)$, where σ_k and σ_h are the standard deviations of k and h coordinates.

of the Hilda asteroid family in the (k, h) and we suspect that there could be some dormant or extinct comet nuclei among these asteroidal objects. We suggest that among the relatively excited orbits of outliers there are also comet-like objects. However, this proposition has to be proved and it can be checked by both observation of the physical properties and investigation of the long-term evolution of the orbits of these objects.

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