84. ON THE DIVIDING LINE BETWEEN COMETARY AND ASTEROIDAL ORBITS

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Abstract. A simplified form of the Jacobi integral in the three-body system Sun-Jupiter-comet or asteroid provides an excellent method for discriminating between cometary and asteroidal orbits. Omitting the librating bodies, unambiguous separation is obtained for all known objects with reliable orbital data, i.e., about 600 comets and 1800 asteroids. The only exception is the peculiar asteroid 944 Hidalgo – which is presumably a comet. The intermediate region is occupied exclusively by bodies revolving in resonance with Jupiter, and the value of the libration argument yields a sharp secondary criterion in these cases. Besides the direct perturbational capture of long-period comets from high-eccentricity orbits into Jupiter's family, a ring of nearly circular orbits between Jupiter and Saturn is suggested as another significant source of short-period comets. For these comets the subsequent operation of nongravitational effects gives a better chance of injection into small orbits of the Apollo type and for the formation of short-period meteor streams. Some phenomena (the outbursts of P/Schwassmann-Wachmann 1, the probable recent splitting of one parent body into P/Whipple and P/Shajn-Schaldach) give reasons for speculation about the population of this region, too distant for the discovery of typical asteroids or comets, by interplanetary particles up to sizeable solid bodies.

The clear physical distinction between comets and minor planets is connected in a regular way with characteristic differences in their orbits. However, there are also some bodies moving in cometary orbits, the appearance of which is entirely asteroidal (944 Hidalgo) or intermediate (P/Arend-Rigaux, P/Neujmin 1, P/Väisälä). Some orbits of very short period are at variance both with those of normal asteroids and short-period comets (P/Encke; limiting Apollo asteroids like 1566 Icarus and Adonis; meteor streams like the Geminids and Arietids, presumably generated by unknown comets), while in some problematical cases the orbits are essentially indeterminate (P/Wilson-Harrington, P/Kulin). The evolutionary significance of the limiting objects has been stressed by Öpik's (1963) suggestion that most Apollo asteroids are extinct comet nuclei, and by Marsden's (1970) suggestion of a transitional phase between the two types of objects, represented by comets in librating motion avoiding approaches to Jupiter. A correct discrimination is of particular importance in the domain of small interplanetary particles, cometary or asteroidal fragments observed as meteors, where the orbital data available are strongly biased by the Earth-crossing condition, and the physical differences appear in a more subtle and complicated form (Cook *et al.*, 1963; Jacchia *et al.*, 1967; Ceplecha, 1967; Kresák, 1968, 1969; Verniani, 1969).

For the discrimination between cometary and asteroidal orbits, the set of six conventional elements can be divided into three groups:

(1) Semimajor axis a and eccentricity e, determining the size and shape of the orbit, are undoubtedly of primary significance.

(2) The regularities impressed on the angular elements i, Ω, ω by the origin and evolution – the ecliptical concentration of orbital planes, direct motion, and alignment

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of the lines of apsides with that of Jupiter – are practically irrelevant. As far as only short-period orbits are concerned, the effects are very much alike in both systems and the distributions in i and $\pi = \Omega + \omega$ overlap so widely that individual values are useless.

(3) The time of perihelion passage T is often erroneously disregarded as insignificant. However, in conjunction with a it implicitly involves the position relative to Jupiter, which is of fundamental importance for the character of resonant orbits.

Two-dimensional distributions of minor planets and short-period comets in a and e are intercompared in Figure 1. All numbered minor planets and all Apollo and Albert asteroids ($q < 1.25$) are shown as black dots, except for the librating bodies which are denoted by triangles. The latter include, from above, 14 Trojans around the triangular libration points with Jupiter (resonance 1:1), 279 Thule (4:3), 19 minor planets of the Hilda group (3:2), 1101 Clematis and 1362 Griqua (2:1), 887 Alinda and 1953 EA (3:1). A few additional asteroids are either very near the libration limit or the accuracy of their elements does not allow a check on the stability. These are 334 Chicago and 1256 Normannia (3:2), 978 Aidamina and 1125 China (2:1), 1381 Danubia and 1722 = 1938 EG (3:1). Further data on the librating asteroids can be found in the recent papers by Schubart (1968), Schweizer (1969), Sinclair (1969), and Marsden (1970). The heavy circles denote the present state of the system of short-period comets under observation, i.e., the osculating elements of the comets determined during the last or last but one revolution. The last observed returns of the other comets are indicated by light circles; these include disrupted comets (P/Biela, P/Taylor), those ejected by perturbations into unobservable orbits (P/Lexell, P/Oterma), lost by fading or, more frequently, due to the insufficient accuracy of predictions for recovery. Six comets were omitted because their orbits were considered too inaccurate (P/La Hire, P/Grischow, P/Perrine, P/Kulin, P/Wilson-Harrington, and P/Anderson).

The distribution of the objects in the a/e diagram is interesting in many respects. As regards the dividing line between the comets and the asteroids, we see that this can be drawn quite easily in the range of medium eccentricities, say $0.3 < e < 0.6$. For $e < 0.3$ data on comets are lacking because greater perihelion distances of Jupiter comets make only exceptionally bright objects observable. For $e > 0.6$ the separation is good, but the asteroid side is occupied by the Apollo objects, the original nature of which is uncertain. Formal criteria for meteor orbits, fitting arbitrary functions of the elements to the statistics of known comets and asteroids, the K-criterion ($K = \log a(1+e)(1-e)^{-1} - 1 \lessgtr 0$; Whipple, 1954) and Pe-criterion ($Pe = a^{3/2}e \lessgtr 2.5$; Kresák, 1967), deviate markedly from one another just in these two regions.

While it appears that there are no more live comets in the latter area, except for the marginal case of P/Encke and the doubtful case of P/Wilson-Harrington, some information on the population of the former area is available from the integrations of the prediscovery and future comet orbits. The computations by Kazimirchak-Polonskaya (1967) and Belyaev (1967), extending from 1660 to 2060, reveal besides P/Schwassmann-Wachmann 1 two other comets that revolved, not long ago, in nearly circular orbits between Jupiter and Saturn: P/Whipple and P/Shajn-Schaldach. A fourth comet, P/Oterma, left this region in 1937 and returned back in 1963 (see also Marsden, 1961). The orbits of these comets for 1660 and 2060 are plotted as open squares. The elements of P/Whipple and P/Shajn-Schaldach strongly suggest that these are two parts of a single body that split apart about 250–300 yr ago. This evidence, together with the

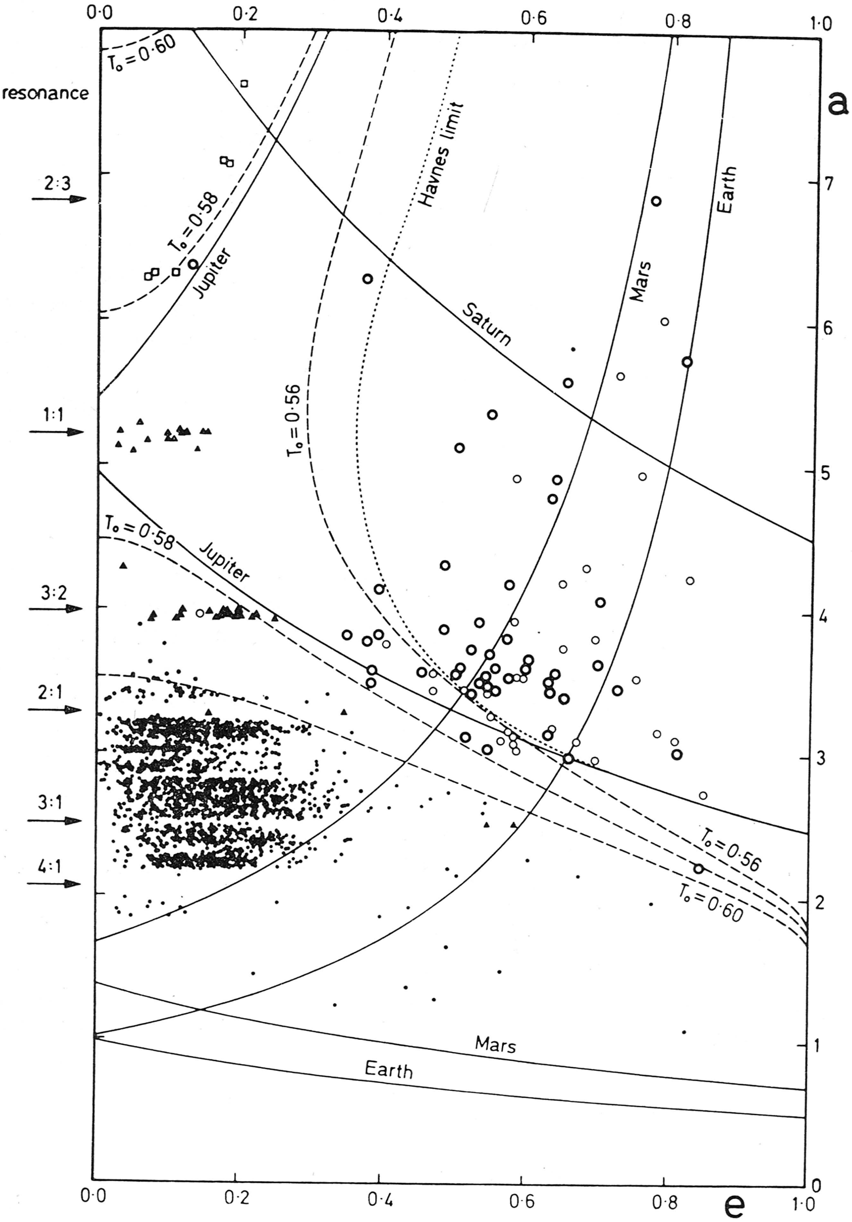

Fig. 1. The *a*/*e* diagram.

repeated outbursts of P/Schwassmann-Wachmann 1, shows that even in this region, far remote from the Sun, comets exhibit significant activity.

The full lines in Figure 1, labelled with the names of planets on the inner side, delimit the areas where close approaches to the respective planets are possible. Of the two principal areas of avoidance of any encounter, the lower one is occupied by the asteroid belt between Mars and Jupiter, the upper one by the hypothetical comet belt between Jupiter and Saturn. Its largest member is P/Schwassmann-Wachmann 1; its only other known present member, P/Oterma, owes its discovery to a temporary change of orbit in 1937–1963. Comets of normal size would remain there undiscovered as long as strong perturbations would not force them into orbits of much smaller perihelion distance. The comets captured in this way apparently evolved tending to avoid the 2:3 resonance with Jupiter. This fact, however, does not rule out the presence of librating objects near exact commensurability, which would be prevented from stronger perturbations as in the Neptune-Pluto case, and hence could not move into the range of visibility. It may be noted that P/Neujmin 1 was found to librate in the resonance 2:3 for at least 3400 yr (Marsden, 1970) in spite of having perihelion distance $q = 1.5$ and almost intersecting the orbit of Jupiter. Possible librating orbits between Jupiter and Saturn pose intriguing problems (e.g., the effect of the Jupiter-Saturn resonance 5:2) and would repay a closer study. Anyway, it can be inferred that this region contains a number of invisible comets, and one can speculate whether it does not also contain some asteroids and an abnormal concentration of meteor dust.

The Jupiter-Saturn belt is important also as a potential alternative source of the Jupiter family of comets. The results on perturbational capture by Jupiter obtained by Havnes (1969), with a refinement accounting for the solar perturbations on the jovicentric hyperbolic arc, delimit the elements which can result from captures from nearly parabolic orbits. This limit in a and e is indicated in Figure 1 by the dotted line. Evidently, neither the Jupiter-Saturn belt nor a considerable part of the Jupiter family satisfies this condition. 30% of known comets with $a < 8$ lie outside, but if we take into account the selection effect of perihelion distance on discovery, we can estimate that the real contribution is as high as 60 to 70%. This figure is in surprising agreement with the number of three comets known to have been captured from the Jupiter-Saturn belt (P/Whipple in 1852, P/Shajn-Schaldach in 1875, P/Oterma in 1937), against one comet captured from a nearly parabolic orbit (P/Kearns-Kwee in 1855 and 1961).

It has been shown earlier (Kresák, 1967, 1969) that the value of the Jacobi constant in the restricted three-body problem Sun-Jupiter-comet/asteroid, or the Tisserand invariant, provides a good dividing line between cometary and asteroidal orbits. Neglecting the mass ratio Jupiter:Sun, Jupiter's orbital eccentricity and inclination, we have

$$T = a^{-1} + 2a_J^{-3/2}a^{1/2}(1 - e^2)^{1/2} \cos i, \tag{1}$$

and neglecting also the inclination of the third body,

$$T_0 = a^{-1} + 2a_J^{-3/2}a^{1/2}(1 - e^2)^{1/2}. \tag{2}$$

The latter quantity, although involving an additional approximation, appears preferable for two reasons:

(1) It can be directly plotted on the *a*/*e* diagram, as is done in Figure 1 by the dashed lines for $T_0 = 0.56$, 0.58, and 0.60.

(2) The families of librating bodies are more compact in T_0 than in T. For direct short-period orbits the difference $T_0 - T$ is generally insignificant, exceeding 0.02 for 10% of the short-period comets ($a < 8$) and 5% of the minor planets; $T_0 - T > 0.05$ for no more than two short-period comets (P/Pigott, P/Tuttle) and four asteroids (944 Hidalgo, 1208 Troilus, 1373 Cincinnati, 1580 Betulia). The osculating elements obviously have to be determined at sufficient distances from Jupiter to make the additional terms in the Jacobi integral, with Jupiter's mass in the numerator, negligible.

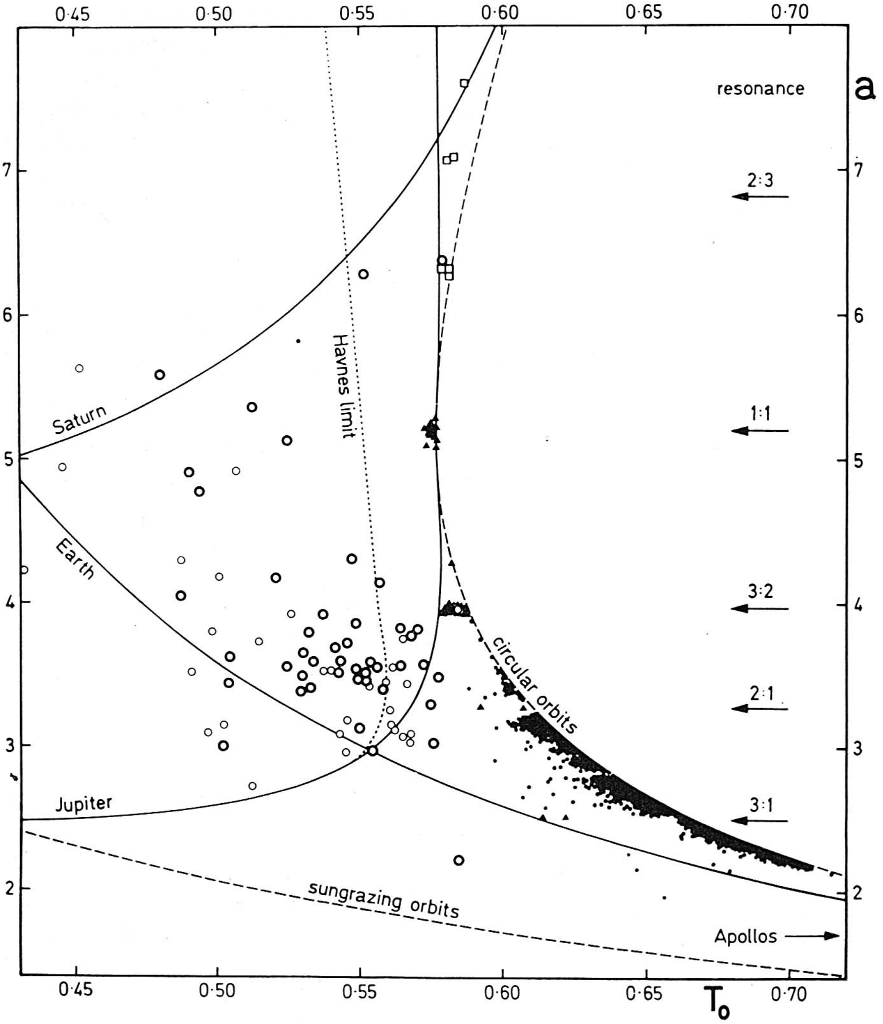

Fig. 2. Plot of T_0 against *a*.

The values of T_0 are plotted against a in Figure 2 for the objects shown in Figure 1, using the same notation. The area of real orbits is limited by the two dashed lines (circular and sungrazing orbits); the regions where encounters with the Earth, Jupiter, and Saturn are possible are limited by the full lines, Havnes' condition by the dotted line. The displacement of individual objects by the perturbing action of Jupiter follows the vertical direction. The separation of the comets from the asteroids by $T_0 \simeq 0.58$ and the restriction of Jupiter's capture from elongated orbits by $T_0 < 0.56$ is clearly recognized, as well as the position of the Trojans and the Hilda group near the critical limit. Of special interest is the concentration of the extrapolated orbits in the Jupiter-Saturn belt (the segment running in the centre from the upper edge), with $0.58 < T_0 < 0.59$. These orbits would be kept by Jupiter at the critical limit, as demonstrated by the transitional orbit of P/Oterma (1958) embedded in the Hilda group. If this comet had passed at a slightly smaller distance from Jupiter in 1937, so as to come at the next encounter in 1963 in front of instead of behind it, there might have occurred the interesting case of injection of a comet into an orbit of extremely short period, required for the subsequent evolution into an object of Encke or Apollo type. Such an evolution of comets captured from the Jupiter-Saturn belt may present a clue to the origin of the Apollo objects and of the parent bodies of short-period meteor streams. Perturbations in inclination affecting the difference $T_0 - T$ may become important in this process, in particular at low eccentricities.

Since the parameter T_0 implicitly involves the perihelion distance, the observed distribution in T_0 is subject to selection effects of discovery. Their operation is illustrated by Figure 3, showing T_0 plotted against the absolute magnitudes. The comet values, $H_{10} = M - 5 \log \Delta - 10 \log r$, are taken from Vsekhsvyatskij's catalogue and its supplements (Vsekhsvyatskij, 1958, 1962, 1966), plus recent data from other sources. For the comets of more than one apparition the median value is used, irrespective of the secular variation. For the asteroids, the absolute magnitudes g are taken from the list by Gehrels (1967; Chebotarev, 1969). The notation is analogous to Figures 1 and 2; the limits of apparent magnitude M for a given absolute magnitude H_{10} or g are indicated by the curves. For the comets, $r = q$, $\Delta = q - 1$ is assumed, so that a comet of absolute magnitude H_{10} situated below the curve cannot appear brighter than apparent magnitude 15, unless irregular flares occur. Three cases are indicated, with separate scales of perihelion distance q at the bottom: (1) parabolic orbit (dashed line); (2) elliptical orbit with $n/n_J = 1.5$ (resonance 2:3, centre of the Jupiter-Saturn belt); (3) elliptical orbit with $n/n_J = 0.5$ (resonance 2:1, main commensurability gap near the inner fringe of Jupiter's family). For the asteroids the dotted line refers to the mean opposition magnitude at $r_c = a$, $\Delta = a - 1$ (circular orbit, $i = 0$), so that an asteroid of higher eccentricity situated below the line may on favourable occasions appear considerably brighter even than apparent magnitude 18.

The figure demonstrates that quasi-parabolic orbits with $T_0 > 0.58$ are virtually unobservable because their perihelia must lie beyond the orbit of Jupiter. For the comets of the Jupiter-Saturn belt the situation is similar, and only the absolutely brightest of all short-period comets, P/Schwassmann-Wachmann 1, is observable at present in this region. For Jupiter comets around the resonance 2:1 the situation is much more favourable. While the absence of objects near the lower left edge ($T_0 < 0.53$, $q_{\mathrm{III}} < 1.1$) indicates that the statistics are essentially complete in this range (as a matter of fact, only one of 21 comets with $q < 1$, $P < 100$ yr, P/Honda-Mrkos-Pajdušáková, has been discovered since 1902), a number of faint comets with $0.56 < T_0 < 0.58$ ($1.5 < q_{\mathrm{III}} < 2$) evidently remain undetected. On the other hand, the absolute absence of short-period comets near $T_0 = 0.60$ ($2 < q_{\mathrm{III}} < 2.5$) can hardly be attributed to observational selection. Similarly, the discovery conditions obviously tend to reduce the proportion of known asteroids with lower values of T_0, but the sharp cut-off of non-librating objects near $T_0 = 0.60$ ($r_c \simeq 3.5$) is evidently real.

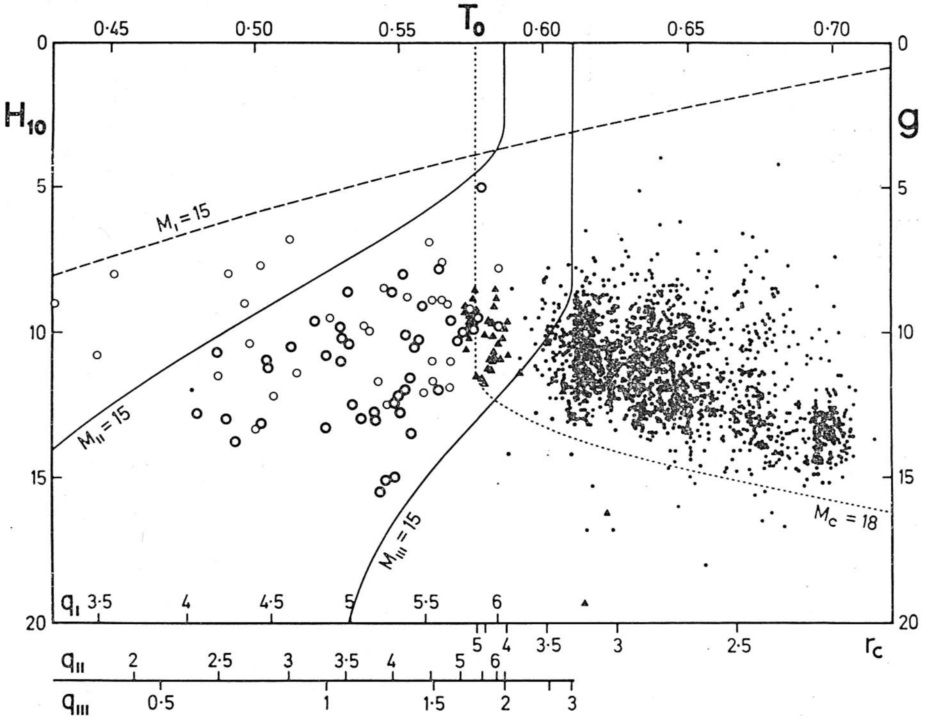

Fig. 3. Plot of T_0 against absolute magnitude.

The comets with the highest values of T_0 and the asteroids with the lowest values of T_0 are listed in Table I. We see that there is practically no overlapping, the only object for which the classification according to T_0 evidently disagrees with the physical appearance being 944 Hidalgo. This is almost certainly an extinct comet nucleus. There exist undoubtedly also other objects of this type, but their detection is very difficult in photographic work, including the minor planet searches, and utterly impossible in visual comet searches. It may also be noted that the extreme cases of T_0 include all comets detached recently from the Jupiter-Saturn belt, and that the remaining cases, with aphelia distinctly inside the orbit of Jupiter, may represent results of similar evolution in the past. On the other hand, librating bodies strongly prevail among the extreme asteroidal cases.

TABLE I

Comets with highest and asteroids with lowest values of T_0

		T_0	q(AU)	Q(AU)	n/n_J	Note
P/Oterma	1958	0.584	3.39	4.53	1.51	resonance 3:2
	1660	0.587	6.01	9.14	0.57	J-S belt
	2060	0.583	5.88	8.31	0.63	J-S belt
P/Encke	1967	0.584	0.34	4.09	3.60	Apollo region
P/Schwassmann-Wachmann 1	1957	0.579	5.54	7.21	0.74	J-S belt
	1660	0.580	5.79	8.35	0.63	J-S belt
	2060	0.581	5.85	6.74	0.75	J-S belt
P/Schwassmann-Wachmann 2	1968	0.577	2.15	4.83	1.82	Jupiter family
P/Tempel 2	1967	0.576	1.37	4.69	2.25	Jupiter family
P/Tempel 1	1967	0.575	1.50	4.73	2.15	Jupiter family
P/Johnson	1970	0.574	2.20	4.96	1.75	Jupiter family
P/Whipple	1970	0.570	2.47	5.16	1.59	Jupiter family
	1660	0.580	5.64	7.00	0.75	J-S belt
P/Neujmin 2	1927	0.568	1.34	4.84	2.18	Jupiter family
P/Shajn-Schaldach	1949	0.565	2.23	5.28	1.63	Jupiter family
	1660	0.581	5.85	6.78	0.75	J-S belt
Other comets (~600)		0.018	0.01	4.81	0.00	
		0.567	4.71	∞	2.64	
944 Hidalgo		0.479	2.00	9.64	0.84	cometary orbit
Trojans (14)		0.572	4.40	5.32	0.98	libration 1:1
		0.577	5.07	5.98	1.04	
Hilda group (19)		0.579	2.97	4.23	1.48	libration 3:2
		0.587	3.65	4.88	1.52	
279 Thule		0.582	4.14	4.42	1.34	libration 4:3
1256 Normannia		0.588	3.65	4.22	1.52	near 3:2
1373 Cincinnati		0.588	2.31	4.51	1.88	
334 Chicago		0.589	3.66	4.11	1.55	near 3:2
1362 Griqua		0.592	2.16	4.40	2.00	libration 2:1
1144 Oda		0.592	3.41	4.09	1.63	
225 Henrietta		0.594	2.37	4.32	1.94	near 2:1
Other belt asteroids (~1700)		0.596	1.39	1.92	1.72	
		0.770	3.37	4.26	4.72	
Apollo + Albert groups (23)		0.607	0.19	1.66	2.74	
		1.026	1.22	4.10	10.60	

The discrimination according to T_0 becomes ambiguous only for the librating objects like the Trojans or the Hilda group. The oversimplified definition that a comet is a body which can closely approach Jupiter (say, to within 1.0 AU) whereas an asteroid cannot, is also reflected in this anomaly. Moreover, as pointed out by Marsden (1968, 1970), the two comets which for centuries avoided encounters with Jupiter (P/Arend-Rigaux and P/Neujmin 1) are conspicuous by nearly asteroidal appearance and the absence of nongravitational effects in their motions. In the limiting cases of T_0 the value of the libration argument with respect to Jupiter,

$$\sigma = (A - B)\pi - A\lambda_J + B\lambda, \tag{3}$$

where A, B are relatively prime integers, $A/B = n/n_J$, yields a sharp secondary comet-asteroid criterion.

Figure 4 shows the absolute value of the libration argument σ plotted against the mean diurnal angular motion n (in degrees) around the exact resonances 1:1, 3:2, 2:1, and 3:1 (full horizontal lines). The dashed lines indicate the combinations of $|\sigma|$, n for which the orbits of the respective perihelion distance cross the orbit of Jupiter, assumed circular. For the comets only the elements from observed returns are plotted, and the connecting lines show which positions refer to the same body. The last observed returns are denoted by heavy circles. The positions of the asteroids refer to the epochs for which the elements are listed in the latest issue of the Minor Planet Ephemerides (Chebotarev, 1969).

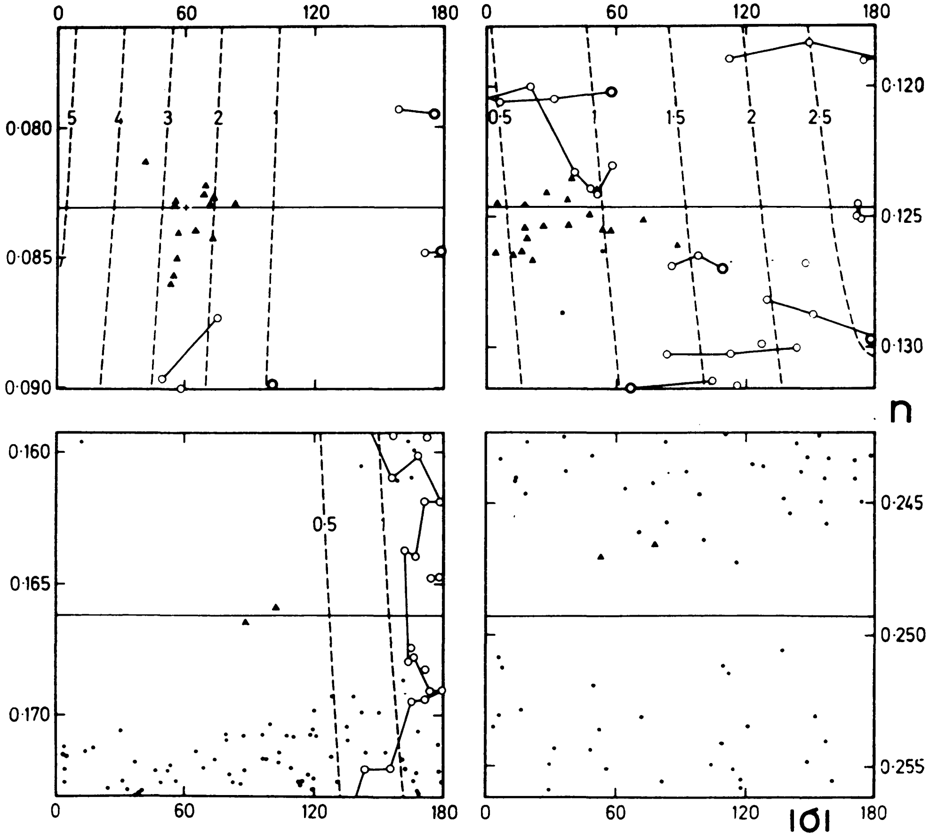

Fig. 4. Plot of libration argument σ against mean daily motion n around the resonances 1:1, 3:2, 2:1, and 3:1 with Jupiter.

At the resonance 1:1, the cluster of Trojans surrounds the libration centres L_4, L_5 ($|\sigma| = 60°$, a cross). Two comets in temporary resonance, P/Slaughter-Burnham and P/Van Biesbroeck, are situated near $|\sigma| = 180°$, i.e., in the region of no encounters with Jupiter, and three other comets are slightly beyond the zone of significant resonance. At 3:2 the Hilda group extends up to $|\sigma| = 90°$, and a number of comets are irregularly distributed over the whole area. The fact that any value of σ permits an approach to Jupiter for a value of $q < 3$ is the reason why no distinct gap is formed. The temporary resonance of P/Oterma appears at the extreme right; the next comets closest to the exact resonance with Jupiter are P/Schaumasse and P/Arend. At 2:1 and 3:1 the distribution of asteroids reverses and resonance gaps are observed, much wider and asymmetric in the former case. Comets appear only around the 2:1 resonance. All six of them are pronouncedly concentrated towards $|\sigma| = 180°$ where the lengthy passage of P/Pons-Winnecke from 1869 to 1951 appears. The two librating asteroids, 1101 Clematis and 1362 Griqua, are prevented from entering this zone; for Griqua $|\sigma|$ is always less than 100° (Marsden, 1970). A similar restriction is put on the motion of the two librating asteroids of the last diagram, 887 Alinda and 1953 EA, where $|\sigma|$ steadily remains greater than 40° (Marsden, 1970).

Figure 4 includes only those comets whose osculating mean motions were near the resonance at the time of perihelion passages. There were many other cases where a comet crossed the resonance zone or even several zones during a single encounter with Jupiter, while moving along the outer arc of the orbit. The change of n of P/Lexell was as large as $+0\overset{\circ}{.}069$ in 1767 and $-0\overset{\circ}{.}173$ in 1779, that of P/Oterma $+0\overset{\circ}{.}070$ in 1937 and $-0\overset{\circ}{.}073$ in 1963, P/Brooks 2 $+0\overset{\circ}{.}103$ in 1886, P/Kearns-Kwee $+0\overset{\circ}{.}092$ in 1961, etc., much greater than the total range of $\pm 0\overset{\circ}{.}007$ represented in each diagram of Figure 4. These rapid passages obviously concentrate to the region of lowest stability, e.g., to $|\sigma| = 180°$ for the 2:1 case with $q \geq 1.5$. The long-term integrations of 10 comets published by Kazimirchak-Polonskaya (1967) and Belyaev (1967) give an average number of five crossings of the principal resonance zones (2:3, 1:1, 3:2, and 2:1) per millennium, one of them over more than one zone during a single revolution. The data are not quite representative, as there was a tendency to select the most complex, and hence most interesting, orbital evolutions, and also because comets are often discovered after drastic changes in their orbits, during the return immediately following a reduction of the perihelion distance. Nonetheless, a characteristic time interval between two crossings is several centuries, or less than 100 revolutions for a typical short-period comet. Most resistive to such changes are those comets which are temporarily librating around higher-order resonances, like P/Arend-Rigaux (7:4) P/Tempel 2 (9:4); the interval is shortest when a comet happens to be injected into a resonant orbit and ejected again at the next occasion, like P/Oterma (3:2) or P/Lexell (2:1). The population of the resonance gaps ($\Delta n = \pm 0\overset{\circ}{.}002$ to $0\overset{\circ}{.}003$) can be estimated at about 30 to 40% of the surroundings. This contrasts with the asteroid system where no crossings occur, except for the low-amplitude periodic variations of the librating bodies, and the resonance gaps within the main belt are much more pronounced. In the 2:1 gap the relative population is 5% of the outer adjacent zone (around 1.9:1), and 1% of the inner adjacent zone (around 2.1:1).

Thus the libration parameters can be applied as a secondary comet-asteroid criterion in the very rare cases where the Jacobi constant (T_0-test) does not give a clear answer. An excellent example is the orbit of P/Oterma, 1937–1963. Its orbital elements were in fact entirely unrecognizable from the Hilda asteroids (see Figures 1 and 2, with P/Oterma embedded right in the middle of the Hilda group). But its libration argument $|\sigma|$ was greater than 170°, whereas it is less than 90° for all Hilda asteroids. Consequently, the resonance of P/Oterma persisted only for 25 yr, or 1/10 of one libration period of the Hilda asteroids.

The T_0-criterion locates the Apollo objects at the opposite extreme of the asteroid system from the comet limit, thus qualifying them as indubitable minor planets. At the same time, if we consider whether they may have detached from the main asteroid belt or from Jupiter's family of comets, a preceding capture from the Jupiter-Saturn belt seems to represent a possible mechanism whereby their aphelia could cross Jupiter's perturbational barrier and come to the outskirts of the Apollo region. Subsequent reduction of semimajor axes might be due to nongravitational forces, which affect the motions of live comets and meteoroids, but hardly of extinct comets and minor planets.

The Apollo objects obviously need not all be of the same nature and origin. Marsden (1970) suggests that periodic variations in brightness, betraying rotating fragments of irregular shape (like those observed in 433 Eros or 1620 Geographos) can be used for discriminating the true asteroids from the extinct comet nuclei. This approach appears promising, but unfortunately 14 of 23 asteroids with $q < 1.25$ have been lost and some others are too faint for high-precision photometry. Even so, the collection of photometric data for as many Apollo objects as possible would be very desirable. Physical observations of 944 Hidalgo and the few comets of almost asteroidal appearance would be of great interest, as well as the search for possible physical differences between the short-period comets captured from nearly parabolic orbits and those transferred from the Jupiter-Saturn belt. The discovery of additional members of this belt would be very important, as their existence and orbital history may remove some difficulties of the capture theory. Model computations of the evolution of orbits similar to P/Oterma may assist in explaining the injection of comets into the region of the terrestrial planets and the origin of meteor streams of very short period.

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Discussion

G. A. Chebotarev: How closely do you think the Jupiter-Saturn comet belt resembles the Jupiter-Mars asteroid belt?

L. Kresák: Unfortunately, all our information on the Jupiter-Saturn belt is based on the orbits of four comets, and only one of the comets is actually observable there. Nevertheless, the low probability of the strong perturbations experienced by the others suggests that the number of invisible comets within the belt is very great indeed. The belt is evidently confined to the region between Jupiter and Saturn and to the vicinity of the ecliptic plane. It possibly includes a slight decrease in the distribution of semimajor axes near the 2:3 resonance with Jupiter ($a = 6.8$, $P = 17.8$).

S. K. Vsekhsvyatskij: A number of asteroids have been observed to exhibit diffuse envelopes. What are the orbital characteristics of these asteroids? Do you agree with Marsden about the transformation of a number of the Jupiter-family comets into asteroids?

L. Kresák: Slight indications of diffuse envelopes have been observed on a few occasions, but without recurrence, around normal belt asteroids. To my knowledge, there exists no photographic record of one, and although some of these phenomena have been reported by very experienced observers (e.g., Hind), I do not think that we can accept them as observational evidence before we have an unambiguous confirmation. These envelopes have never been seen around any Apollo asteroid or Hidalgo. The fact that the comets of quasi-asteroidal appearance have librating orbits is very interesting and can hardly be explained by chance. The two examples, P/Neujmin 1 and P/Arend-Rigaux, are quite normal comets as to their values of T_0. On the other hand, as I have shown in my paper, the T_0-criterion may fail if the body librates.

B. G. Marsden: How certain are you of a physical connection between P/Whipple and P/Shajn-Schaldach? It would be very exciting to find that two distinct periodic comets were formerly one single comet, but this is of course extremely difficult to establish unequivocally. Other pairs of comets with orbits that were formerly very similar are P/Borrelly and P/Daniel, P/Perrine-Mrkos and P/Honda-Mrkos-Pajdušáková.

L. Kresák: The suggestion of a common origin is based on the striking similarity of all six orbital elements for several decades around 1700. P/Shajn-Schaldach is a one-apparition comet, and both it and P/Whipple underwent very strong perturbations by Jupiter in the nineteenth century. This makes the backward computations less reliable, but all things considered, the agreement is very satisfactory indeed.