COMETS (EXISTING POPULATIONS)

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Abstract. The definition, population, extent, origin and evolution of the individual subsystems of comets and transitions between them are discussed, together with presentation of the relevant statistical data and their changes with time. The largest outer subsystems are unobservable, but their existence is documented by the necessity of progressive replenishment of the observable populations, with limited survival times. There is persuasive evidence for two different evolutionary paths, one from the Oort cloud and another from the Kuiper belt. While the extent and accuracy of the data available is increasing rapidly, the Jupiter family of comets is the only one for which the evolutionary time scales do not exceed by many orders of magnitude the history of astronomical observations. The individual comet populations differ from one another not only by the distribution of orbits, but also by the size distribution and aging rate of their members. Their dynamical evolution is coupled with disintegration processes, which make it questionable whether the present state can be interpreted as a long-term average.

Keywords : Comets – populations, dynamics, evolution

1. Introduction

The huge system of comets consists of several different populations. As to the appearance, volatility and activity, there are no systematic differences between their members (Whipple, 1992a,b) which can be identified only by the orbit determination. However, there are enormous differences in their populations, in the space occupied by them, and in their evolutionary time scales. The volume of the Oort cloud is about 10^{12}-times larger than that of the Jupiter family of comets. The revolution period of a new comet is only about 1/1000 of its age, and the whole active lifetime of a comet of the Jupiter family is still 1000-times shorter. This, and the long-term dynamical integrations, require progressive transitions between the individual populations, replenishment of those evolving on shorter time scales, and transformation into inactive asteroid-like objects and interplanetary dust.

The main restriction of our knowledge is that the comets become detectable only when they approach the Sun within less than 1/10000 of the radius of the Oort cloud. Comets with perihelia beyond this limit remain unobservable all the time. New comets in Oort's sense, passing inside for the first time - and most of them also for the last time - can only be traced for 10^{-7} to 10^{-6} of their revolution. Another complication comes from the nongravitational accelerations, which do not allow an extrapolation of the motion of the individual objects over sufficiently long time spans. And finally, one cannot be sure that the available observations, covering a few centuries, are representative for a long-term average or a state of equilibrium.

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Stellar passages through the Oort cloud, encounters with giant molecular clouds, or disruptions of large objects into a number of smaller ones can introduce substantial temporary changes. Thus all that we know about the cometary populations reflects only the present state.

2. Classification

The main classification of cometary populations is based on the revolution periods. The boundary between the short- and long-period comets, at $P = 200$ years, is rather conventional. It was introduced as the upper limit for those which already could have been reliably observed at more than one apparition, and because at that time there was no well-determined comet orbit with P between 160 and 250 years. Much better defined is the upper limit of the Jupiter family, $P = 20$ years. We currently know about 150 of its members, all moving in direct orbits, while only four comets have P between 20 and 50 years, and the orbits of two of them are retrograde. Comets with P between 20 and 200 years are called the Halley type. The third limit, at $P = 1\ 000\ 000$ years, separates the old long-period comets from the new ones, in Oort's sense (1950). Due to the third Kepler's law, the classification according to the revolution period is equivalent to that according to the semimajor axis a $(=P^{2/3})$, or binding energy $1/a$ $(= P^{-2/3})$.

Another classification with good dynamical reasoning is that by the Tisserand invariant with respect to Jupiter

$$J = \frac{a_J}{a} + 2\sqrt{\frac{a}{a_J}(1-e^2)}\cos i = \frac{2a_J}{q+Q} + 2\sqrt{\frac{2qQ}{a_J(q+Q)}}\cos i$$

where a, e, i, q and Q are the semi-major axis, eccentricity, inclination, perihelion distance and aphelion distance of the comet's orbit, and a_J the semi-major axis of Jupiter. Since J is a function of the unperturbed encounter velocity with Jupiter, proportional to $\sqrt{3-J}$, this parameter measures also the degree of stability of the comet's orbit. Due to the substantial impact of orbital inclination, J does not present any separation between Halley type, old and new comets. On the other hand, for the Jupiter family it allows a meaningful subdivision by $J = 2$, $2^{3/2}$ and 3. In the restricted three-body problem Sun/Jupiter/comet, the subgroup of $2 < J < 2^{3/2}$ may be subject to the ejection from the solar system; that of $2^{3/2} < J < 3$ to a temporary satellite capture; and that of $J > 3$ to the transfer of the orbit from completely outside to completely inside the orbit of Jupiter, and inversely (Kresák 1982, Carusi and Valsecchi, 1985). The limit of $J = 2$ separates the Jupiter family from all the other cometary populations. It coincides with the classification by the revolution periods for more than 99% of the known comets. $P < 20$ years and $J < 2$ applies only to P/Tuttle, P/Machholz and P/IRAS - the three Jupiter family comets with highest inclinations; and $P > 20$ years and $J > 2$ to 1905 IV Kopff, 1957 VI Wirtanen and 1982 I Bowell - all with low inclinations and abnormally large perihelion distances.

A third acceptable classification is that by the aphelion distance. For the long-period comets it is essentially identical with that by the revolution period, because $Q \simeq 2a$, and for the Halley type it is rather close to it. For the Jupiter family it presents a better view on the degree of dynamical stability, including also information on the potential perturbations by other planets than Jupiter. All of the classification parameters are obviously varying with the planetary perturbations; and this is just an indication of the dynamical evolution and transfer between the individual comet populations.

3. Observed populations

Figure 1 shows the distribution of comets according to the aphelion distance Q (above) and Tisserand invariant J (below). Only the best determined orbits from Marsden's catalogue (1992) are included : those of short-period comets of more than one apparition, long-period comets of class 1A or 1B, and comets of Halley type with comparable orbital accuracy. The data for the individual populations are approximately normalized to their observed proportion, and the steps are twice as long for the long-period comets, where the data are also smoothed by taking the averages from pairs of neighbouring intervals. Even on the logarithmic scale of Q, the required accuracy of astrometric observations increases steeply towards right, and thus the peak corresponding to the new comets may be in fact much narrower and higher.

There is a clear separation of the four main comet populations in the lower, complete part of the diagram, based on the original values of $\log Q$ before entering the inner solar system. In the upper part of the diagram the future values, after leaving it, are plotted. The immediate mixing of the populations of new and old comets is evident, as well as the ejection of nearly one half of the new comets from the solar system - outside the right margin of the diagram.

In the upper left corner the positions corresponding to the mean heliocentric distances of the four giant planets are indicated. The highly prevailing binding effect of Jupiter is evident. The perturbations by Jupiter are statistically 10-times stronger than those by Saturn, and 100-times stronger than those by any other planet (Everhart and Raghavan, 1970; Rickman and Huebner, 1990). Therefore, it has little sense to speak about observed populations associated with other planets.

The same concentration of short-period comets into the Jupiter family is reflected by the lower diagram, with the relative number of observed comets plotted against the Tisserand invariant J (lower horizontal scale) and the corresponding unperturbed encounter velocity with Jupiter V (upper horizontal scale, in km/s). This diagram shows a close similarity between the distribution of new and old comets, a broad range for the Halley type, and a rather sharp separation of the Jupiter family.

A general view on the whole system of comets is presented by Fig. 2. Although this is meant as a scheme, its co-ordinates are scaled. The vertical scale of $\log Q$,

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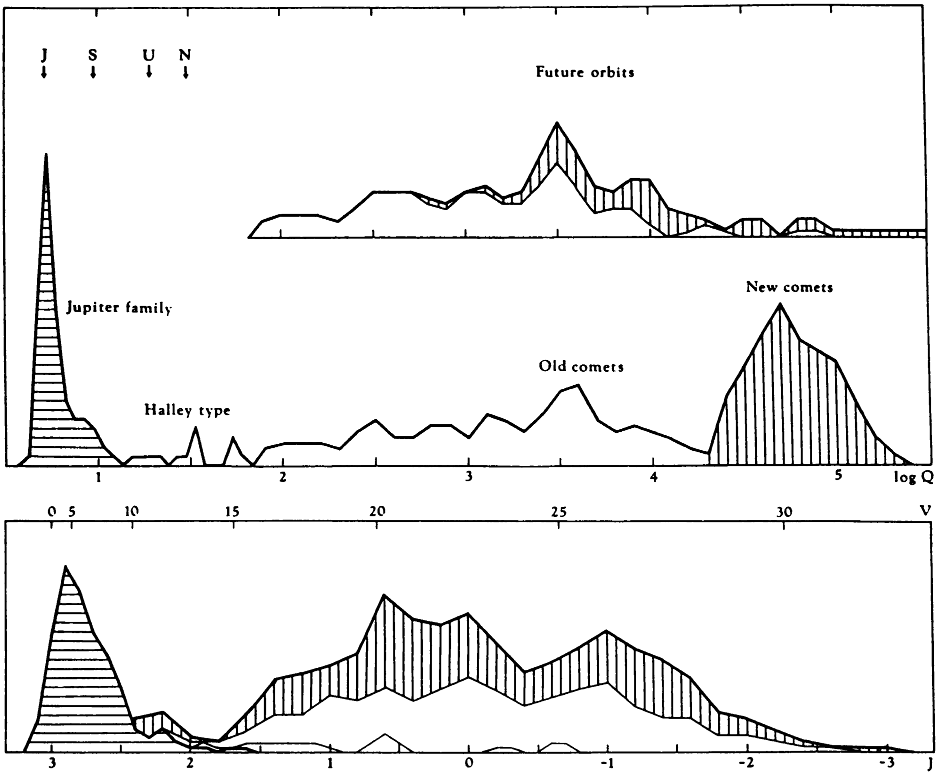

Fig. 1. The distribution of comets with well determined orbits according to the aphelion distance Q (on a logarithmic scale, above), and according to the Tisserand invariant J with respect to Jupiter (below).

identical with the horizontal scale of Fig. 1, delimits the individual populations; each rectangle includes more than 90% of their members, and the medians are marked by dots. The position on the horizontal scale of $\log q$ governs the detectability of each comet. Only those situated on the right, i.e. passing close enough to the Sun, can be observed.

The void space on the left can be called "terra incognita" or "hic sunt leones". The high occurrence rate of new comets demonstrates the presence of the Oort cloud, in the upper left corner. This is subject to the perturbations by our galactic environment (Biermann et al., 1983; Bailey, 1986: Delsemme, 1987; Matese and Whitman, 1992). Stars passing through it remove one half of the objects encountered from the solar system (upwards), and transfer the other half into smaller orbits. For original low-eccentricity orbits in the outer Oort cloud the heliocentric

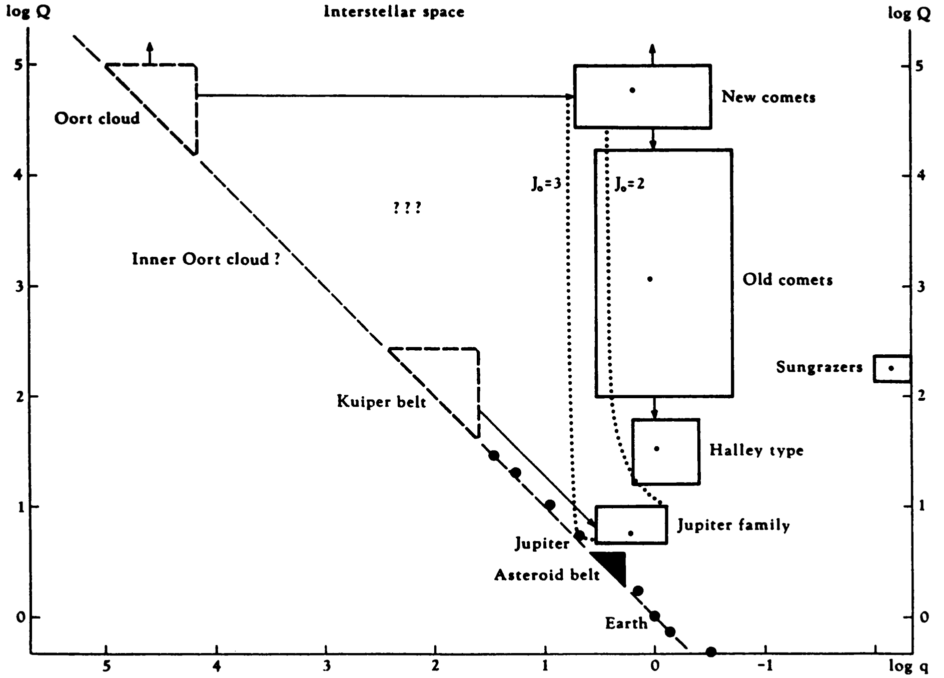

Fig. 2. A schematic view on the distribution and evolution of the cometary populations in the $\log Q/\log q$ reference frame.

velocities are typically 100 - 150 m/s, but the comet must be decelerated to less than 2 - 3 m/s to move towards the Sun, start its activity, and become observable 2 - 3 $\times 10^6$ years later. This strict condition is the main proof of the enormously large population, where 10^{12} of individual objects is considered as the lower limit (Weissman, 1985).

According to Yabushita (1991) there is statistical evidence that some of the new comets - those with original values of $1/a < -4\times 10^{-5}\mathrm{AU}^{-1}$ - did not come from the Oort cloud but from the interstellar space. A more detailed examination has shown, however, that there is not yet a single case where this hyperbolic excess could not be attributed to the nongravitational accelerations and computing uncertainties (Kresák, 1992).

4. Origin and evolution

After the first passage near the Sun, nearly one half of the new comets escape from the solar system (upwards), and the other half joins the population of old comets.

Only for 5% of them planetary perturbations on the path inwards and outwards balance so that a and Q remain within the limits acceptable for new comets. The high proportion of new comets among those of long period - more than one third - is indicative of their total extinction, substantial reduction of their gas and dust production (Oort, 1990), or some so far unidentified long-term rejuvenation process within the Oort cloud (Kresák, 1977). However, as already mentioned, the present state cannot be interpreted with certainty as a long-term average.

The probability of a direct conversion into a comet of Halley type is about 1/1000, and no such transfer has been recorded as yet. Thus this rough estimate is only based on the extrapolation of the distribution of the absolute energy perturbations taken from Marsden's catalogue (1992) and reproduced in Fig. 3. A direct conversion would require $\Delta E < 29 \times 10^{-4}$ AU^{-1}. Since all comets cannot be considered as objects of equal active survival times, and the number of comets of Halley type is relatively low, there is no contradiction to the assumption that they have evolved via new - old comets. This interpretation is supported by the low upper limit of their perihelion distances ($q < 2$), compatible with the blow–off effect (Whipple, 1978; Rickman et al., 1991). Both the distribution of their perihelion distances and their inclinations (3 : 1 in favour of direct orbits) agrees very well with the dependence of the energy perturbations on these two elements, as shown in Fig. 3, and with the expected role of the Tisserand invariant.

Much more difficult is the explanation of the origin of the Jupiter family. The nongravitational effects do not allow an extrapolation of their motion back over the requisite time spans. The only feasible approach is the use of modelling experiments, the results of which depend on the adopted starting conditions and are still contradictory (Duncan et al., 1988; Quinn et al., 1990; Rickman and Huebner, 1990; Valsecchi, 1992). For a long-period comet of very low inclination and perihelion near the orbit of Jupiter, an extremely close encounter with this planet can, in principle, result in such a transformation. The potential way is limited by the two dotted curves corresponding to $J = 2$ and $J = 3$ for $i = 0^o$; with increasing inclination these limits shift to the left until they disappear at $i = 45^o$. However, the occurrence rate of such phenomena must be very low, definitely incompatible with the current population of the Jupiter family and active survival times of its members, estimated at 3,000 - 10,000 years (Kresák, 1985; Rickman, 1992). Even the extension of the total lifetimes by dormant phases (Kresák, 1987) does not appear sufficient to solve this problem.

This was the main reason for suggesting the presence of the Kuiper belt (Kuiper, 1951; Bailey, 1992). Its position is indicated by the triangle in the middle of Fig. 2. Transfer of its invisible members would require a longer interaction with the outer planets, because the effect of the galactic environment is too weak and rare. Objects on this way may be 2060 Chiron, 5145 Pholus, 1992 QB1, 1993 FW and 1993 HA2; all of them are formally classified as asteroids, but for Chiron an outburst of cometary activity was recently recorded (Meech and Belton, 1989; Meech, 1991). Other alternatives for the structure of the inner Oort cloud are summarized and

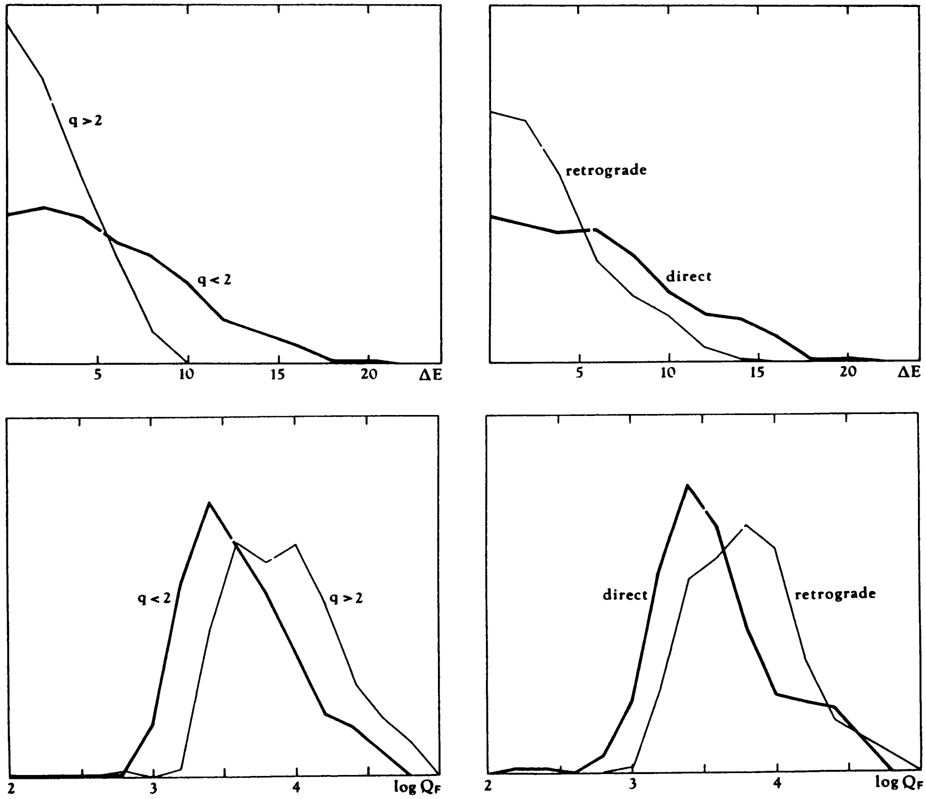

Fig. 3. Distribution of the absolute energy perturbations $\Delta E = \mid \Delta(1/a) \mid$, in 10^{-4} AU^{-1}, and aphelion distances Q (on a logarithmic scale), by their first passage through the inner planetary region. The four plots illustrate the dependence of these quantities on the perihelion distance q and orbital inclination i.

intercompared by Bailey (1990, 1992).

5. Perturbing encounters

The first evolutionary phase of the population of new comets is governed by the efficiency of planetary perturbations around their single perihelion passage. Figure 3 compares this efficiency for two significant parameters : perihelion distance q smaller or greater than 2 AU and inclination i lower or higher than 90° (direct/retrograde). The distributions are derived from all comet orbits listed by Marsden (1992) with the original and future values of $1/a$. The upper half of the figure shows the changes of the binding energy, and the lower half those of the aphelion distance (on a logarithmic scale). One can see that the median changes of the binding energy, marked by small gaps, are almost doubled for $q < 2$, and also for $i < 90^o$. The same applies to the reduction of the aphelion distance after the first perihelion passage near the Sun. This implies an acceleration of the next perihelion passage by a factor of 2.5 and 2.7, respectively.

For the further evolution of all populations, the frequency of passages through different heliocentric and jovicentric distances is essential. Figure 4 shows, on the left, the average annual numbers N of comets of different types passing perihelia at $q < 2$, as observed in 1940-1990. Members of the Kreutz group are omitted, and the numbers of new and old comets are multiplied by 1.5 to account for those objects whose original orbits were indeterminate. The ephemeris-aided recoveries and low

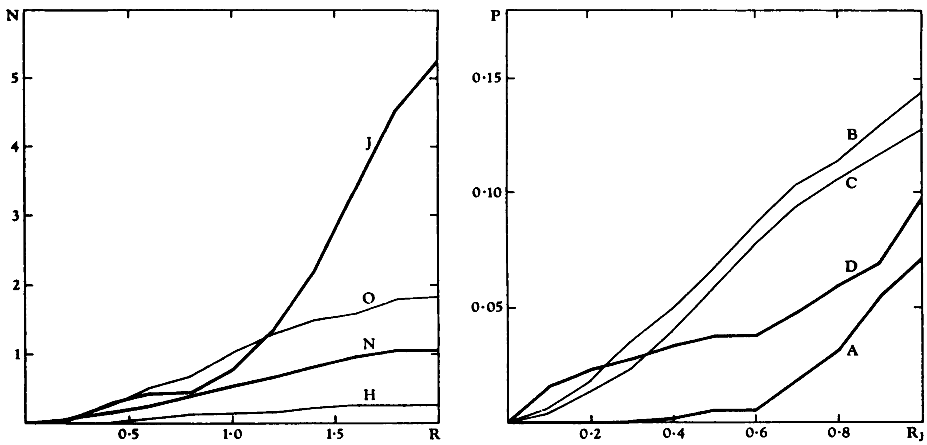

Fig. 4. The average number N of comets belonging to the four basic populations, and passing annualy within different heliocentric distances R (J = Jupiter family, H = Halley type, O = old long-period comets, N = new long-period comets); and probabilities P of passing within different jovicentric distances R_J per revolution for the four subclasses of the Jupiter family (A : $J < 2$, B : $2 < J < 2^{3/2}$, C : $2^{3/2} < J < 3$, D : $J > 3$).

inclinations make the data for the Jupiter family relatively more complete with increasing q. Nevertheless, the differences are definitely too large to be attributed to any observational biases. For the Jupiter family the number of apparitions increases by a factor of 7 when passing from $q < 1$ to $q < 2$, and by a factor of 10 when the peculiar P/Encke is omitted. For all the other populations the corresponding increase is much slower, by a factor of 1.8 to 2.0 ($\simeq 7^{1/3}$). This point is of special interest in connection with the rapid increase of the population of the Jupiter family with q found by Fernández et al. (1992), and the dependence of the aging rate on the perihelion distance.

For these comets the frequency of efficient perturbing encounters with Jupiter is high, and statistically tied with the Tisserand invariant. The plot on the right is based on the long-term integrations by Carusi et al. (1985a), and limited by $R_J = 1$ AU. This corresponds, e.g., to a complete destruction of the compact dust trail behind the comet (Sykes and Walker, 1992; Kresák, 1993). The average frequency of such encounters is once per 14 revolutions for class A ($J < 2$), once per 7 revolutions for class B ($2 < J < 2^{3/2}$), once per 8 revolutions for class C ($2^{3/2} < J < 3$), and once per 10 revolutions for class D ($J > 3$). There is an evident difference between the distribution functions of class A and D, caused by the much lower iovicentric velocities of the latter. These result in a substantial reduction of the perturbed minimum distance against the unperturbed one, and sometimes also in a temporary satellite capture and in a discovery immediately thereafter.

6. Changes in the Jupiter family

The Jupiter family, with 10 members already followed over more than 20 revolutions, is the only population in which the evolutionary changes can be directly observed. The orbital integrations of all such comets of more than one apparition, extending more than four centuries back and forward (Carusi et al., 1985a) were used to determine the frequency of significant processes occuring on time scales comparable with their mean active lifetimes. Based mainly on the cases of disappearance, this was estimated at about 300 $q^{1/2}$ revolutions, or 2500 - 3000 years (Kresák, 1985). However, the detection of their dormant phases (Kresák, 1987), supported recently by the discovery of P/Machholz, P/Takamizawa and P/Hartley 2, suggests that the active lifetime of a comet is not always a single continuous period, but may consist of recurring active phases separated by temporary extinctions. Accordingly, 5000 - 7000 years now seems to be a more reasonable estimate of the total active lifetime. This value is also in better agreement with the results of Weissman (1980), Fernández (1985) and Rickman (1992), obtained by different approaches.

The statistical data are listed in Tables I and II. Table I reflects the asymmetry between the injection of comets into the inner solar system and ejection from it, as already pointed out by Fernández (1985). The disproportion of 2 : 1, referring only to a limited range of revolution periods and perihelion distances, and including the symmetrical libration phenomena, reflects the physical aging of comets and necessity of their supply from outer sources. The total disproportion can be estimated at one order of magnitude. Conversion into asteroid-like objects or total disintegration seems to be the end fate of 90% of these objects, and escape from the Jupiter family only of the rest. This conclusion is supported by the number of small asteroidal objects discovered within the Spacewatch project (Rabinowitz, 1993). There is also a number of larger asteroids the orbits of which are practically indistinguishable from those of the Jupiter family (Kresák, 1985; Kresák and Štohl, 1990), and long-term integrations indicate their similar orbital evolution (Milani et al., 1989).

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TABLE I

Mean time spans Δt between significant orbital changes of the comets of the Jupiter family, observed at more than one apparition, in years

Orbital change	Δt (years)
Halley type → Jupiter family	8 000
Jupiter family → Halley type	16 000
$P > P_J \rightarrow P < P_J$	2 800
$P < P_J \rightarrow P > P_J$	3 400
Reduction of q by more than 1 AU	1 800
Increase of q by more than 1 AU	3 000
Entry into libration	2 300
Exit from libration	2 300
Separation of active fragments	600
Splitting into surviving components	6 000
Period of active lifetime	3 000
Total active lifetime	6 000

The frequency of splits of cometary nuclei is given in the lower part of Tab.I. Separation of active fragments surviving not more than 1-2 perihelion passages is a rather frequent phenomen (see P/Biela, P/Brooks 2, P/Giacobini, P/Taylor, P/duToit-Hartley, P/Chernykh). Since there is only one case of formation of a pair of long-lived objects of comparable size, P/Neujmin 3 and P/Van Biesbroeck (Carusi et al., 1985b), the estimated occurrence rate of such events must be taken with reserve. As to the long-period comets, the frequency of splits is higher if referred to their revolutions, but lower if referred to their active lifetimes (Kresák, 1985). The existence of the Kreutz group of sungrazers and of the Taurid complex points to the possibility that disintegrations of extremely large objects may affect substantially the comet populations at a given time, and make them quite different from the long-term average (Steel et al., 1992; Clube, 1992). The existence of objects like 2060 Chiron or P/Schwassmann-Wachmann 1 lends support to the opinion that the disintegration of larger objects may play even a more important role in the replenishment of the inner comet subsystems than the individual dynamical captures.

The chaotic dynamical evolution of short-period comets can be temporarily stabilized by a transient stay in the libration regime. Its efficiency is illustrated by Tab. II, based on the orbit integrations of more-than-one-apparition comets with revolution periods less than that of Jupiter (Carusi et al., 1985a). The table shows that at any time every fourth such comet is librating. The typical duration of one libration cycle, 150 to 200 years, is essentially independent of the resonance ratio. The total duration indicates that a member of the Jupiter family experiences, on the average, two or three libration periods during its active lifetime.

TABLE II

Librations of comets of the Jupiter family about orbital resonances with the planet, at $P < P_J$

Resonance ratio	Objects librating at a time (percentage)	Median duration of one cycle (years)	Mean/median total duration (years)
1/2	11	170	600/400
4/7 or 3/5	4	180	> 700/550
2/3	6	170	> 900/400
3/4 or 4/5	1.5	180	300/250
1/1	1.5	180	250/250
Total	24	170	600/400

Librations about the 5/1, 6/1 and 7/1 resonances with Jupiter play an important role in the dynamical evolution of the comets of Halley type. Their proportion experiencing libration at a time is similar to that in the Jupiter family, but the cycles are twice as long, and the whole libration periods much longer (Carusi et al., 1987).

7. Selection effects

Our present statistical data are obviously very strongly affected by observational biases. One view on this problem is presented by the historical evolution, illustrated by Tabs. III and IV. Table III shows the increase in the number of comets listed in seven main catalogues published since the beginning of orbit computations. Table IV shows the present state for comets which passed their perihelia within the last seven half-centuries. One can see, e.g., that while the number of Halley-type comets increased by a factor of two, that of the Jupiter-family comets increased by a factor of 20 during the last 150 years!

The principal factors on which the discovery or miss of a comet of given size, composition and structure depends are : 1. perihelion distance, determining its maximum heliocentric brightness; 2. observing geometry, determining the maximum geocentric brightness, solar elongation and ecliptical latitude around the perihelion passage; and 3. revolution period, determining the recurrence rate of potential apparitions.

The effect of perihelion distance makes the largest and most stable systems of comets - those with perihelia beyond the orbit of Saturn - entirely unobservable. Further inwards, the detection limit varies with the absolute brightness of the comet and, as far in as the orbit of Mars the discoveries of active comets become fairly complete. The effect of observing geometry is statistically unimportant within the

TABLE III
Cometary orbits listed in different catalogues

	Halley (1705)	Pingré (1783)	Galle (1894)	Baldet (1952)	(1972)	Marsden (1982)	(1992)
S-P comets, all	1	2	29	82	97	121	179
> 1 apparition	1	1	15	35	63	78	102
> 5 apparitions	0	0	5	13	19	28	34
> 10 apparitions	0	0	1	5	8	10	13
> 20 apparitions	0	0	1	2	2	2	2
> 5 revolutions	0	0	8	20	31	42	51
> 10 revolutions	0	0	3	11	19	25	27
> 20 revolutions	0	0	1	3	4	7	10
> 40 revolutions	0	0	0	1	1	1	2
L-P comets, all	21	61	316	453	503	589	672
Sum of orbits	24	67	411	763	924	1109	1353
Sum of objects	22	63	345	535	600	710	851

individual populations. It only prefers the discoveries of short-period comets by the repetition of their returns. This, and the low inclinations in the Jupiter family, enable each of them sooner or later to pass the perihelion near the opposition, where it becomes brighter than at other apparitions, and where also the systematic large-scale surveys concentrate. This is also the reason why more than 90% of them were discovered photographically during the last 50 years, while for the long-period comets the share of photographic discoveries was only 50%. At the time of discovery, the long-period comets were estimated about 100-times brighter, with a median apparent magnitude 10.5 against 15.5. However, since the brightest short-period comets were already known at that time (their ephemeris-aided recoveries are not included in these statistics), and since the subtraction of instrumental effects reduces the difference from 5 to 2–2.5 magnitudes (Kresák and Kresáková, 1990), the apparent brightness alone cannot be taken as a quantitative indicator of the degree of completeness.

During the last 150 years, well covered by observations, most comets of the Jupiter family have made 10 to 30 returns and most of Halley type 1 to 3 returns, but for a majority of long-period comets this time span covers less than 1/100 of their revolution periods. The new comets exceed it even by a factor of 10^4 to 10^5. Assuming a long-term equilibrium, we would have to multiply their observed number by this factor when comparing it with the population of short-period comets. On the other hand, the whole space occupied by new comets is 10^{12}-times larger, which makes their mean spatial density negligible against the Jupiter family.

The increase of the discovery rates of the two main types of comets is illustrated by Fig. 5. The average annual numbers are derived from their totals within 20-

TABLE IV

Cometary apparitions from 50-year intervals, for which orbits of different type and quality are available

	1640 - 1690	1690 - 1740	1740 - 1790	1790 - 1840	1840 - 1890	1890 - 1940	1940 - 1990
All comets :							
apparitions	15	14	39	70	198	249	606
objects	15	14	39	60	161	170	355
Jupiter family :							
apparitions	1	0	5	16	57	121	366
objects	1	0	5	6	20	42	117
Halley type :							
apparitions	1	1	2	5	10	8	13
objects	1	1	2	5	10	8	11
L-P comets :							
all	12	13	32	49	131	120	227
parabolic	11	13	30	42	71	37	66
elliptic	1	0	2	7	48	47	87
hyperbolic	0	0	0	0	12	36	74
old	0	0	0	4	33	39	90
new	0	0	0	0	7	30	64
sungrazers	0	0	0	0	4	0	20

year intervals, with the comets discovered from spacecraft omitted. For the Jupiter family the discovery rate was nearly constant in 1870-1970 at $q < 2$, but since then it increases rapidly. While there is also an increasing proportion of large-q objects, the general trend indicates that the application of modern search techniques has led mainly to discoveries of smaller and absolutely fainter objects, and not to a simple extension of the space covered. For long-period comets the discovery rate - in this case identical with the appearance rate - was relatively stable for a still longer period, since 1840. The subsequent increase was less steep, in particular for comets with $q < 2$.

As a counterpart to Fig. 1, Fig. 6 shows the distributions of perihelion distances for different cometary populations. They are normalized to uniform sums of objects, and reveal substantial differences. Comets of Halley type exhibit a very sharp and symmetrical maximum around $q = 1$, and a void region beyond $q = 2$. For the Jupiter family, a lack of objects with $q < 1$, possibly associated with their shorter survival times, is followed by a less sharp maximum around $q = 1.6$ and a steep drop towards $q = 3$. According to the estimates by Fernández et al. (1992) there is in fact a steep increase for smaller and less active objects. For the long-period comets, the distributions are much smoother on both wings. The only significant difference between new and old comets appears around $q = 4$. A feasible explanation

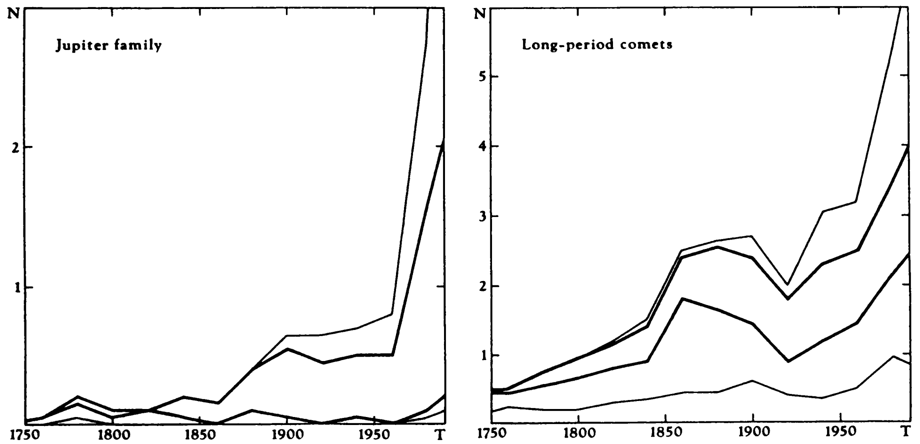

Fig. 5. Changes in the average annual discovery rates N of the members of the Jupiter family (on the left), and long-period comets (on the right) during the last 250 years. The thick lines correspond to $q < 1$ and $q < 2$, and the thin lines to $q < 0.5$ and the total.

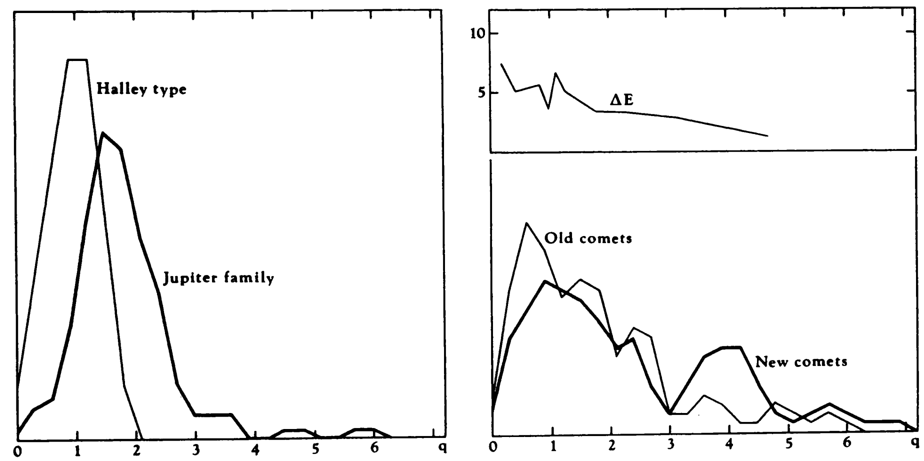

Fig. 6. Normalized distributions of the perihelion distances q of comets belonging to different populations. The plot in the upper right indicates the variations of the median absolute energy perturbations $\Delta E = \mid \Delta(1/a) \mid$, in 10^4 AU^{-1}, for the same scale of q.

is an unavoidably wrong classification of those objects for which the planetary perturbations have nearly compensated, resulting in an approximate conservation of the original binding energy $1/a$. This possibility is supported by the dependence of the energy perturbations on perihelion distance. The plot in the upper right gives the medians of the absolute values of ΔE, obtained for 12 equally populated ranges of q from all comets with determined original and future orbits (Marsden, 1992). After a transient decrease of the number of objects at $q = 3$, only the new comets exhibit a secondary maximum, simultaneously with the drop of the typical values of $| \Delta(1/a) |$ below 0.0002 AU^{-1}. In fact, a transfer of about five comets from new to old (i.e., the same as predicted by the whole distribution pattern and, hence, quite acceptable) would remove the whole discrepancy, and also improve the agreement at small perihelion distances.

Figure 6 demonstrates that significant differences between the individual comet populations do not appear only in the distribution of revolution periods, aphelion distances and inclinations, but also in that of the perihelion distances. This, together with Fig. 5, indicates that there are also significant differences in the distribution of absolute magnitudes and sizes of cometary nuclei. Apparently, this is tied with different dynamical evolution and disintegration processes.

A rough overview of the immense range of sizes and evolutionary time scales, mentioned in the introduction, is presented by Tab. V, in which both of these parameters are scaled by a factor of 1000, with selected illustrative examples. Note that when passing from the linear size to the volume, each step changes into an increase by a factor of 1,000,000,000 !

TABLE V

Size and time scales with a factor of 1000, and a total span of 1 : 10^{18}

Size/distance (unit ~ 10^4 km)	Scale	Time/duration (unit ~ 5 years)
Particle producing a bright meteor	10^{-9}	Meteor outburst
Smallest asteroid observed as yet	10^{-6}	Displacement by the Earth radius at $r = 1$ AU
Nucleus of comet P/Halley	10^{-3}	Comet outburst
The Earth	1	Revolution of a short-period comet
Closest comet approach every few decades	10^3	Total active lifetime of a short–period comet
Kuiper belt	10^6	Revolution of a new comet
Outer Oort cloud	10^9	Age of the solar system

The viewpoints of different investigators on the open problems mentioned in this review are still controversial. Illustrating and stimulating are the extensive round-table discussion records from the Montevideo Workshop, held two years ago (in : Periodic Comets, eds. J.A. Fernández and H. Rickman, 1992, pp. 97-111 and 209-220).

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References

Bailey, M.E. : 1986, "The mean energy transfer to comets in the Oort cloud and implications for cometary origins." *Mon. Not. R. Astron. Soc.*, **218**, 1-30.

Bailey, M.E. : 1990, "Short-period comets : probes of the inner core." In *Asteroids, Comets, Meteors III* (C.-I. Lagerkvist, H. Rickman, B.A. Lindblad and M. Lindgren, Eds.), 221-230, Univ. of Uppsala Press.

Bailey, M.E. : 1992, "Origin of short-period comets." *Celest. Mech.*, **54**, 49-61.

Baldet, F., de Obaldia, G. : 1952, *Catalogue Général des Orbites de Comètes*, CNRS, Paris.

Biermann, L., Huebner, W.F., Lüst, R. : 1983, "Aphelion clustering of new comets : Star tracks through Oort's cloud!" *Proc. Natl. Acad. Sci. USA*, **80**, 5151-5155.

Carusi, A., Valsecchi, G.B. : 1985, "Statistical and numerical studies of the orbital evolution of short-period comets." In *Dynamics of Comets : their Origin and Evolution* (A. Carusi and G.B. Valsecchi, Eds.), 261-278, D. Reidel, Dordrecht.

Carusi, A., Kresák, Ľ., Perozzi, E., Valsecchi, G.B. : 1985a, *Long-term Evolution of Short-period Comets*, A. Hilger, Bristol (together with data for a new edition).

Carusi, A., Kresák, Ľ., Perozzi, E., Valsecchi, G.B. : 1985b, "First results of the integration of motion of short-period comets over 800 years." In *Dynamics of Comets : their Origin and Evolution* (A. Carusi and G.B. Valsecchi, Eds.), 319-340, D. Reidel, Dordrecht.

Carusi, A., Kresák, Ľ., Perozzi, E., Valsecchi, G.B. : 1987, "High-order librations of Halley-type comets." *Astron. Astrophys.*, **187**, 899-905.

Clube, S.V.M. : 1992, "The fundamental role of giant comets in the Earth history." *Celest. Mech.*, **54**, 179-193.

Delsemme, A.H. : 1987, "Galactic tides affect the Oort cloud : an observational confirmation." *Astron. Astrophys.*, **187**, 913-918.

Duncan, M., Quinn, T., Tremaine, S. : 1988, "The origin of short-period comets." *Astrophys. J.*, **328**, L69-L73.

Everhart, E., Raghavan, N. : 1970, "Changes in total energy for 392 long-period comets, 1800-1970." *Astron. J.*, **75**, 258-272.

Fernández, J.A. : 1985, "Dynamical capture and physical decay of short-period comets." *Icarus*, **64**, 308-319.

Fernández, J.A., Rickman, H., Kamél, L. : 1992, "The population size and distribution of perihelion distances of the Jupiter family." In *Periodic Comets* (J.A. Fernández and H. Rickman, Eds.), 143-157, Univ. Montevideo Press.

Galle, J. : 1894, *Verzeichniss der Elemente der bisher berechneten Cometenbahnen*, W. Engelmann, Leipzig.

Halley, E. : 1705, "Tabulae astronomicae." *Phil. Transactions R. Astron. Soc.*, **24**, 1882.

Kresák, Ľ. : 1977, "An alternate interpretation of the Oort cloud of comets?" In *Comets, Asteroids, Meteorites* (A.H. Delsemme, Ed.), 93-97, Univ. Toledo Press, Ohio.

Kresák, Ľ. : 1982, "Dynamical evolution and disintegration of comets." In *Sun and Planetary System* (W. Fricke and G. Teleki, Eds.), 361-370, D. Reidel, Dordrecht.

https://doi.org/10.1017/S0074180900046477 Published online by Cambridge University Press

Kresák, Ľ. : 1985, "The aging and lifetimes of comets." In *Dynamics of Comets : their Origin and Evolution* (A. Carusi and G.B. Valsecchi, Eds.), 279-302, D. Reidel, Dordrecht.

Kresák, Ľ. : 1987, "Dormant phases in the aging of periodic comets." *Astron. Astrophys.*, **187**, 906-908.

Kresák, Ľ. : 1991, "Evidence for physical aging of periodic coemts." In *Comets in the Post-Halley Era* (R.L. Newburn, Jr., M. Neugebauer and J. Rahe, Eds.), 607-628, Kluwer Acad. Publ., Dordrecht.

Kresák, Ľ. : 1992, "Are there any comets coming from interstellar space?" *Astron. Astrophys.*, **259**, 682-691.

Kresák, Ľ. : 1993, "Cometary dust trails and meteor storms." *Astron. Astrophys.*, in press.

Kresák, Ľ., Kresáková, M. : 1990, "Secular variations of absolute magnitudes of periodic comets." *Icarus*, **86**, 82-92.

Kresák, Ľ., Štohl, J. : 1990, " Genetic relationships between comets, asteroids and meteors." In *Asteroids, Comets, Meteors III* (C.-I. Lagerkvist, H. Rickman, B.A. Lindblad and M. Lindgren, Eds.), 379-388, Univ. Uppsala Press.

Kuiper, G.P. : 1951, "Origin of the Solar system." In *Astrophysics* (J.A. Hynek, Ed.), 357-424, McGraw-Hill, New York.

Marsden, B.G. : 1972, *Catalogue of Cometary Orbits* (1st edition), Minor Planet Center, SAO, Cambridge, MA.

Marsden, B.G. : 1982, *Catalogue of Cometary Orbits* (4th edition), Minor Planet Center, SAO, Cambridge, MA.

Marsden, B.G. : 1992, *Catalogue of Cometary Orbits* (7th edition), Minor Planet Center, SAO, Cambridge, MA.

Matese, J.J., Whitman, P.G. : 1992, "A model of the galactic and tidal intercation with the Oort comet cloud." *Celest. Mech.*, **54**, 13-35.

Meech, K.J. : 1991, "Physical aging of comets." In *Comets in the Post-Halley Era* (R.L. Newburn, Jr., M. Neugebauer and J. Rahe, Eds.), 629-669, Kluwer Acad. Publ., Dordrecht.

Meech, K.J., Belton, M.J.S. : 1989, "(2060) Chiron." *IAU Circ.* No. 4770.

Milani, A., Carpino, M., Hahn, G., Nobili, A.M. : 1989, "Project Spaceguard : Dynamics of planet-crossing asteroids." *Icarus*, **78**, 212-269.

Oort, J.H. : 1950, "The structure of the cloud of comets surrounding the Solar System, and a hypothesis concerning its origin." *Bull. Astron. Inst. Neth.*, **11**, 91-110.

Oort, J.H. : 1990, "Orbital distribution of comets." In *Physics and Chemistry of Comets* (W.F. Huebner, Ed.), 235-244, Springer-Verlag, Berlin.

Pingré, P. : 1784, *Cométographie ou Traité historique et théorique des Comètes*, Impr. Royale, Paris.

Quinn, T., Tremaine, S., Duncan, M. : 1990, "Planetary perturbations and the origin of short-period comets." *Astrophys. J.*, **355**, 667-679.

Rabinowitz, D.L. : 1993, "The size distribution of Earth-approaching asteroids." *Astrophys. J.*, in press.

Rickman, H. : 1992, "Structure and evolution of the Jupiter family." *Celest. Mech.*, **54**, 63-69.

Rickman, H., Huebner, W.F. : 1990, "Comet formation and evolution." In *Physics and Chemistry of Comets* (W.F. Huebner, Ed.), 245-303, Springer-Verlag, Berlin.

Rickman, H., Froeschlé, C., Kamél, L., Festou, M.C. : 1991, "Nongravitational effects and the aging of periodic comets." *Astron. J.*, **102**, 1446-1463.

Steel, D., Asher, D. J., Clube, S. V. M. : 1992, "Giant comet origin for the Taurid complex." In *Periodic Comets* (J.A. Fernández and H. Rickman, Eds.), 189-200, Univ. Montevideo Press.

Sykes, M.V., Walker, R.G. : 1992, "Cometary Dust Trails. I. Survey." *Icarus*, **95**, 180-210.

Valsecchi, G.B. : 1992, "Close encounters, planetary masses and the evolution of cometary orbits." In *Periodic Comets* (J.A. Fernández and H. Rickman, Eds.), 81-96, Univ. Montevideo Press.

Weissman, P.R. : 1980, "Physical loss of long-period comets." *Astron. Astrophys.*, **85**, 191-196.

Weissman, P.R. : 1985, "Dynamical evolution of the Oort cloud." In *Dynamics of Comets : their Origin and Evolution* (A. Carusi and G.B. Valsecchi, Eds.), 87-96, D. Reidel, Dordrecht.

Whipple, F.L. : 1978, "Cometary brightness variation and nucleus structure." *Moon and Planets*, **18**, 343-359.

Whipple, F.L. : 1992a, "A new activity index of comets." In *Asteroids, Comets, Meteors 1991* (A.W. Harris and E. Bowell, Eds.), 633-640, Lunar Planet. Inst., Houston.

Whipple, F.L. : 1992b, "The activities of comets related to their aging and origin." *Celest. Mech.*, **54**, 1-11.

Yabushita, S. : 1991, "Maximum nongravitational acceleration due to outgassing cometary nuclei." *Earth, Moon and Planets*, **52**, 87-92.