DYNAMICAL INTERRELATIONS BETWEEN THE SMALLER BODIES OF THE SOLAR SYSTEM

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ABSTRACT. Population of the solar system by different types of interplanetary objects is reviewed. Their sources, evolution and interrelations are discussed, in particular in terms of their degree of stability, potential evolutionary paths and survival times.

At the end of the nineteenth century, when celestial mechanics was by far the most developed discipline of astronomy, the solar system seemed to consist of a few well-defined classes of objects, clearly distinguished by their orbits and appearance. The eight major planets were moving in widely spaced, nearly circular and co-planar orbits, and the same held for their satellites. The gap between Mars and Jupiter was occupied by a belt of minor planets, resembling miniatures of the major planets. And all this flat system was imbedded in a much larger cloud of comets and meteoroids which did not display any apparent relation to it, except for a concentration of the aphelia of short-period comets around the orbit of Jupiter.

The first addition to this simple picture took place in 1898-1908 by the discovery of the first faint irregular satellites (S9 Phoebe, J6 Himalia, J7 Elara, J8 Pasiphae), the first Amor asteroid (433 Eros) and the first Trojan asteroids (588 Achilles, 617 Patroclus, 624 Hector). One generation later, in 1929-1937, another series of surprising discoveries followed: a comet moving in a nearly circular orbit between Jupiter and Saturn (P/Schwassmann-Wachmann 1), the planet Pluto crossing the orbit of Neptune, and the first Apollo asteroids crossing the orbit of the Earth (1862 Apollo, 2101 Adonis, 1937 UB Hermes). A third peak of discoveries, starting in 1973, included two asteroids with inclinations exceeding 60° (1973 NA, 2102 Tantalus), five long-period comets with perihelia between Jupiter and Saturn (1974 XII Van den Bergh, 1975 II Schuster, 1976 IX Lovas, 1976 XII Lovas, 1977 IX West), three Aten asteroids with semimajor axes smaller than that of the Earth (2062 Aten, 2100 RaShalom, 2340 Hathor) and the peculiar object 2060 Chiron crossing the orbit of Saturn and approaching that of Uranus.

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Problems arising from the observational uniqueness of the solar system were alleviated by the finding that rather complex subsystems exist just within it, surrounding the giant planets. New types of objects include the rings of Uranus and Jupiter, ringlets within planetary rings, guardian satellites, and small satellites associated with the libration points of larger regular satellites. Pluto was found to be a binary system of two objects of comparable size, and evidence is increasing that a number of minor planets also have satellites.

Table 1 illustrates how the boundaries of the region inhabited by known interplanetary objects are becoming more and more diffuse. There has been little change with respect to the comets which essentially occupy the whole solar system. The progressive increase of the maximum perihelion distance is just a result of improving detection techniques, and was by no means unexpected. What was unexpected indeed was the extension of the system of asteroidal objects from a 2 AU-wide ring between Mars and Jupiter to within the orbit of Mercury and to Uranus; and the broad variety of the types of motion involved. The most interesting objects are close to the limit of the detection capabilities of present-day observing techniques, and one must infer that still unknown types await discovery in regions which currently seem to be void of interplanetary objects.

The concept of a few clearly distinguished and mutually independent classes of objects is no longer tenable. It appears that we face the remains of a continuous primordial population in which some areas have been depleted by evolutionary processes, and some have only temporary inhabitants. It must be borne in mind that the revolution periods in that part of the system which is accessible to observation, are 7 to 10 orders of magnitude shorter than the age of the solar system. Therefore, most of the depletion process must have occurred during the earliest evolutionary phase (Lecar and Franklin, 1974) and what we see today is a quasi-equilibrium. Only in limited areas and limited size ranges can this equilibrium be temporarily upset by rare events, such as the passage of a star close to the Sun or the disintegration of a larger object into a number of smaller ones.

TABLE 1. Extremes of perihelion distance q and aphelion distance Q :

	100 years ago	50 years ago	Present
Comets			
Min. q	0.005 (1880 I)	0.005 (1887 I)	0.002 (1979 XI)
Min. Q	4.09 (P/Encke)	4.09 (P/Encke)	4.09 (P/Encke)
Max. q	4.05 (1729)	5.47 (P/Schw-W 1)	6.88 (1975 II)
Asteroids			
Min. q	1.61 (132 Aethra)	1.13 (433 Eros)	0.19 (1566 Icarus)
Min. Q	2.35 (207 Hedda)	1.78 (433 Eros)	1.14 (2062 Aten)+
Max. q	3.40 (153 Hilda)	5.03 (624 Hector)	8.42 (2060 Chiron)
Max. Q	4.63 (190 Ismene)	9.69 (944 Hidalgo)	18.83 (2060 Chiron)

+ Q = 1.07 for the poorly determined orbit of 1954 XA.

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There is some analogy with the radioactive decay sequences. We can observe objects revolving in orbits which remain stable over periods comparable with the age of the solar system; and we can observe unstable objects as derived from this stable population. Thus, objects observed simultaneously in entirely different types of orbits may represent different stages of the same evolutionary sequence. Unlike the radioactive decay, the process is dynamically reversible in each step, or may be terminated by the destruction of the object or by its hyperbolic escape from the solar system. Numerical modelling experiments assist us to specify also the unobserved connecting links, as represented in our analogy by isotopes of very short half-life. Unfortunately, since some of the evolutionary mechanisms are of nongravitational nature (collisions, outgassing jet effects) a purely gravitational model cannot describe faithfully the real situation. This applies to a greater degree to all processes which have occurred during the earliest evolutionary phases of the solar system, when planetary masses and environments were different from today. Examples are the possible captures of minor satellites from circumsolar orbits.

The main division into the asteroidal and cometary component of interplanetary population reflects the presence of two long-lived reservoirs of objects, one between the zones of terrestrial and giant planets and one at the outskirts of the solar system, and the respective two sources of destabilizing perturbations, the planets and the passing stars. The major difference in the solar distances of the two reservoirs makes the provenance of most of the observed objects (but not of all of them !) readily distinguishable by appearance: asteroidal for the inner source of inactive solid objects, and cometary for the volatile-rich outer source.

The dynamical situation is depicted in Fig. 1, which is perhaps the simplest possible representation of the solar system population. For each object, distinguished by appearance, the aphelion distance Q is plotted against the perihelion distance q. For practical reasons, logarithmic scales are used. The small inset at the lower right shows the entire situation, with the distance scale ranging from the solar limb to the closest neighbouring star. The outer dynamically stable area (shaded vertically) stretches upward to the diffuse boundary of the Oort cloud, beyond which comets have already been eliminated by past stellar passages. The innermost dynamically stable area (shaded horizontally), the size of which is strongly exaggerated by the logarithmic scale, is situated between the Sun and Mercury. The framed region of the planetary system, which alone is accessible to observation, is shown in a 10-fold enlargement in the main figure.

The diagonal, with all the major planets situated close to it, corresponds to circular orbits, and loci of constant eccentricity run parallel to it. Perturbations by the planets would leave rings of stable orbits only in the gaps between them which appear as diagonally shaded triangles. Obviously, this two-dimensional representation applies only to orbits of low inclination. For a high-inclination orbit a heliocentric distance equal to that of a planet does not imply close encounters, as the object may be far away from the planet's orbital

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plane at this point. However, unless its perihelion argument librates, secular perturbations would, after some time, bring the node into the critical position. This interval is sufficiently short to affect all orbits of short period. Long-period comets can avoid planetary encounters over their whole evolutionary history, even if their perihelia fall within the planetary zone (Everhart, 1979).

A strong perturbation can also occur without intersection, i.e. with the orbits situated entirely one within the other. From modelling experiments (Carusi et al., 1982) the critical distance D can be tentatively defined as five times the heliocentric distance of the planet multiplied by the square root of the mass ratio planet/Sun. Numerical values of D range from 0.00063 AU at the inner side of the orbit of Mercury to 1.092 AU at the outer side of the orbit of Neptune. For the most important planet, Jupiter, we have D = 0.765 AU at the inner side and D = 0.843 AU at the outer side. The staircase-like line refers to the orbits with the same longitudes of perihelia, the margins of the shaded triangles to those with longitudes differing by 180°. In the first approximation we should expect to find stable objects inside the shaded areas and unstable objects outside them.

For longer time spans the situation is complicated by the long-period perturbations in eccentricity. These make the planets oscillate perpendicular to the zero-eccentricity diagonal, compressing and expanding the areas where perturbing encounters are impossible. The amplitudes of these oscillations are 0.02 - 0.10 AU for the terrestrial planets and Jupiter but reach as much as 0.63 AU for Uranus. Since the neighbouring low-eccentricity orbits are affected in a similar way, the tendency towards the alignment of perihelia prevents any substantial influence on the degree of stability.

Still more important are the long-period oscillations in the eccentricity of the interplanetary objects themselves. These can make an object, originally situated within a stable area, move outside and experience destabilizing perturbations. Thus, unless the triangle is large enough, it does not constitute a really stable area. This is apparently the reason why there are no belts of asteroidal objects between the orbits of planets other than Mars and Jupiter (the largest triangle). Numerical experiments by Everhart (1973) have shown that the mean lifetime of an object started in a circular orbit between Jupiter and Saturn is 100,000 years, a fraction of the age of the solar system. Proceeding outwards, the time scales of similar evolutions increase, and it appears quite possible that orbits stable over periods comparable to the age of the solar system can exist on both sides of Uranus. Whether or not some belts of stable objects exist in these regions, is still an open question, the only object observed there, 2060 Chiron, being unstable.

The amplitude of the variations in eccentricity would become enhanced by the resonance in the mean motion, but in this case the object can settle in an orbit which, due to a phase shift maintained by libration, remains forever at a sufficient distance from the planet. Examples are the Trojans, the Hilda and Griqua groups of asteroids,

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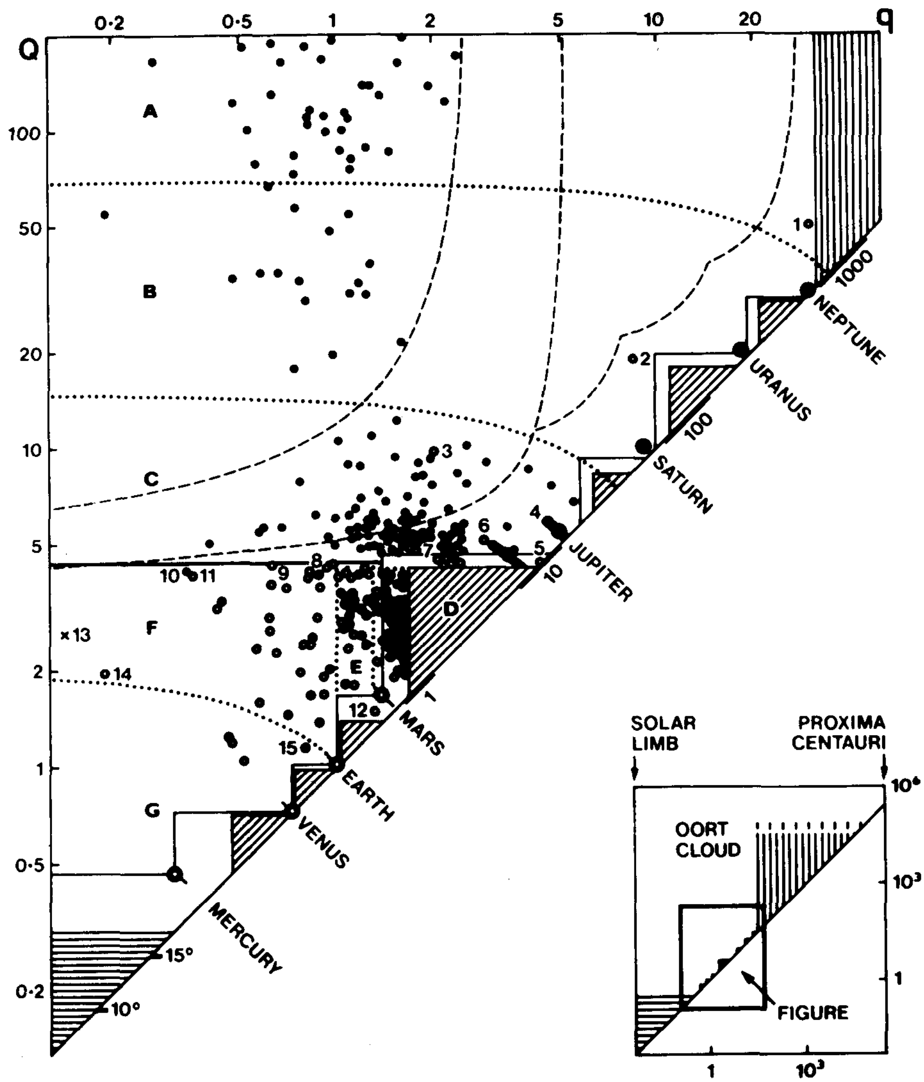

FIGURE 1. Distribution of different types of interplanetary objects in perihelion distance q and aphelion distance Q. Dots = cometary appearance, circles = asteroidal appearance. A = long-period comets, B = periodic comets of the Halley type, C = short-period comets of the Jupiter family, D = main-belt asteroids, E = Amor objects, F = Apollo objects, G = Aten objects. 1 = Pluto + Charon, 2 = 2060 Chiron, 3 = 944 Hidalgo, 4 = Trojans, 5 = 279 Thule, 6 = Hilda group, 7 = Griqua group, 8 = 1973 NA, 9 = 1981 VA, 10 = P/Encke, 11 = 2212 Hephaistos, 12 = 1951 Lick, 13 = Geminid meteors, 14 = 1566 Icarus, 15 = 2062 Aten. For further explanation see text.

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which in this diagram penetrate far into the region of instability. A special case is 1373 Cincinnati whose approaches to Jupiter are prevented by the libration of the perihelion argument around 90°, keeping the aphelion permanently at a safe distance from Jupiter.

The two basic types of interplanetary objects, the active comets (dots) and the asteroids (circles), are confined to different regions of the diagram. The comets evolving downwards from the Oort cloud populate the area above the horizontal thick line, the Jupiter barrier. In conformity with the current taxonomy, the dotted curves delimit the regions of long-period comets (A: $P > 200$ yr), periodic comets of the Halley type (B: $20 \text{ yr} < P < 200$ yr), and short-period comets of the Jupiter family (C: $P < 20$ yr). For the first two types the inclinations are often high and about one half of the orbits are retrograde.

From the distribution of the comets over the diagram it might seem that they are simply dropping downwards as their binding energy increases. This is actually not the case, however. Perturbations by the major planets, among which Jupiter plays the dominant role, tend to deflect the paths to the left, so that observable long-period comets cannot evolve into typical short-period comets of the Jupiter family (the marginal case being P/Tuttle). Typical paths, assuming zero inclination and only perturbations by Jupiter moving in a circular orbit, are represented by two dashed curves. The shorter curve corresponds to the Tisserand invariant with respect to Jupiter $C = 2$, the longer one to $C = 2\sqrt{2}$.

The former value approximately separates the Jupiter family from the other comets. The latter is a limiting case between two alternatives. If the comet is situated outside (i.e., to the left and up), it may have been captured by Jupiter alone from Everhart's "capture zone" of the Oort cloud ($4 \text{ AU} < q < 6$ AU), and can be ejected by Jupiter alone from the solar system; but it cannot become a temporary satellite of Jupiter. For the comets situated inside (to the right and down) Jupiter needs the assistance of the outer planets both to deliver the comet into an observable orbit (small q) and into a short-period orbit (small P). It also needs their assistance in ejecting such comets from the solar system. On the other hand, temporary satellite captures are only possible for these types of objects (Carusi et al., 1982, Kresák, 1982). A similar rule holds as well for the other planets, the limiting path being represented by the wavy dashed line in the upper right. Below this line, the comets entering the Jupiter family must undergo a multi-stage capture process (Kazimirchak-Polonskaya, 1972, Everhart, 1977), approaching the Sun "downstairs", and often returning to the preceding step. Obviously, the real conditions differ somewhat from this simplified scheme, owing to the eccentric orbits of the planets and to the interplay of their perturbations.

The lower part of the diagram, below the Jupiter barrier, is occupied by inactive objects of asteroidal appearance. These are, from right to left: the main-belt asteroids (D: $q > 1.3$ AU), the Amor objects (E: $1.0 \text{ AU} < q < 1.3$ AU), and the Apollo objects (F: $q < 1.0$ AU) including below the Aten objects (G: $P < 1.0$ yr). The only exception

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is Comet Encke, situated near the inner side of the barrier, in the immediate vicinity of the Apollo object 2212 Hephaistos. On the high-q side of the Amors one can see the leakage from the asteroid belt via Mars crossers.

There is a distinct difference in the density decrease at the low-q and high-Q boundaries of the belt. The diffuseness and overlapping of the former is connected with a much slower evolution set by a much smaller perturbational cross section of Mars. In fact, these two planets, Mars and Jupiter, are extremes in this respect. A low-eccentricity Mars crosser of 10^{o} inclination would approach the planet to within the distance D once in 230,000 years; while a similar Jupiter-crosser would only need 320 years, on the average. On the other hand, while resonances with Mars are destroyed rapidly by other planets, the resonances of 1/1 (Trojan), 3/2 (Hilda) and 2/1 (Griqua) with Jupiter produce sharp irregularities at the outer boundary.

In order to explain the population of the Amor-Apollo region, nongravitational effects must be taken into account. For the comets it is the momentum imparted by the progressive asymmetric mass loss. Since the active lifetimes of typical short-period comets are limited to a few hundred revolutions (Dobrovolskij, 1972, Kresák, 1981), one can reasonably expect that almost all objects of cometary origin inhabiting this region should be extinct nuclei of asteroidal appearance. The problem is that a long avoidance of approaches to Jupiter and a very rapid mass loss are required. The observed nongravitational displacement of the aphelia of short-period comets crossing the orbit of Mars is only 0.00015 AU per revolution, on the average (Marsden, 1972). At a constant rate of change, the required minimum displacement of 0.5 AU would take more than 3000 revolutions, which is one order of magnitude longer than the potential active lifetimes of such comets, and two orders of magnitude longer than the mean interval between two close encounters with Jupiter. While very close perturbing approaches to the terrestrial planets cannot be ruled out, they are too rare and too inefficient to be considered as a general evolutionary mechanism. If there were no Comet Encke, the evolution of comets into the Apollo objects would hardly be considered as a plausible possibility; it is just this unique object which lends support to the cometary hypothesis.

Additional nongravitational momentum is also required for destabilizing the orbits of the main-belt asteroids, and their inevitable collisions represent an appropriate mechanism. Small relative velocities of the fragments tend to restrict the destabilization process to those objects which were originally on the verge of instability. This need not necessarily imply a location at the inner boundary of the asteroid belt as perturbed by Mars. In the phase space of orbital elements of the asteroids several critical regions exist, and their avoidance by known objects indicates that they have been depleted in favour of other regions. The gaps are due either to period-to-period resonances or to secular resonances (Greenberg and Scholl, 1979, Shoemaker et al., 1979). Intensified oscillation due to the resonance can pump up the aphelion distance to a critical value, and when the reso-

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nance is destroyed, a closer approach to Jupiter can destabilize the motion.

Extensive model computations on the origin of very small orbits were performed by Wetherill (1979) and others. The models agree fairly well with observation, except for a significantly higher predicted Amor/Apollo ratio, and an injection rate from the asteroid belt which is one order of magnitude too low. Since the steady-state distributions for the cometary and asteroidal sources almost entirely overlap, these cannot be distinguished by the statistics of orbits.

The diagram shows only larger objects observed in interplanetary space. For the sector up and to the left of the Earth's position we have additional orbital information on many small objects appearing as meteors at the entry into the Earth's atmosphere. The accuracy of their orbits is insufficient for investigating their previous dynamical history individually; however, it generally allows us to specify the positions of their aphelia with respect to the Jupiter barrier. For the objects recovered as meteorites, the aphelia are consistently located inside the barrier, and the exposure ages indicate a production by collisional fragmentation of Apollo objects. As argued by Levin and Simonenko (1981; see also Galibina et al., 1980), the structure of meteorites is incompatible with their formation within icy-conglomerate cometary nuclei, favouring very strongly parent objects of asteroidal nature and, consequently, the origin of the Apollo and Amor objects in the asteroid belt. The aphelia of friable fireballs leaving no meteorites are mostly situated on the other side of the barrier, suggesting a cometary origin analogous to the origin of meteor streams (Ceplecha, 1977). However, there also exist orbits similar to those of the Apollo objects. The most convincing case is the Geminid meteor stream, the position of which is marked (13) in Fig. 1. Its degree of concentration rules out the possibility that it could have been transported into the present location from a Jupiter-crossing orbit. Accordingly, its immediate parent object must have already revolved in an orbit of Apollo type. Just as the structure of meteorites argues against their origin in comets, the structure of the Geminid stream argues against its origin in an asteroid. Thus the Amor and Apollo objects apparently represent a mixture, in proportion as yet unknown, of extinct comets and real asteroids. The asteroidal component seems to prevail, in particular in the Amor group. First-rank candidates for a cometary origin are 2212 Hephaistos, 1973 NA, and 1981 VA; more details on these and other marginal objects can be found in Kresák (1979a, 1980).

On the outer side of the asteroid system there are two unique objects. The orbit of the asteroid 944 Hidalgo is absolutely cometary, leaving little doubt that we are dealing with an extinct cometary nucleus of exceptional size, 60 km across. The reflectance spectrum of Hidalgo resembles the spectra of comets at the time of very low activity (Degewij and Tedesco, 1982). From the dynamical point of view, 2060 Chiron is a comet, too. However, its estimated size (at least 300 km in diameter, according to Degewij and Tedesco) exceeds Öpik's (1973) admissible upper limit for cometary nuclei by more than two

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orders of magnitude in mass. Computations by Oikawa and Everhart (1979) suggest that after several tenthousands of years Chiron will probably enter a short-period cometary orbit. At that time, if it is really a volatile-rich dormant object, it should produce a most spectacular display of activity. Its recent discovery suggests that there may be still a number of similar objects awaiting discovery in the outer regions of the planetary system.

The discovery conditions for inactive objects, which primarily depend on their perihelion distances q, are also illustrated by Fig. 1. The markings at the diagonal show where inactive objects of 1, 10, 100 and 1000 km in diameter should attain the apparent photographic magnitude 20.0 at a perihelion opposition. The left end of each dash corresponds to dark carbonaceous surfaces of C- or RD-types of asteroids, the right end to brighter stony surfaces of S-type asteroids. It is evident that we can say almost nothing about the interplanetary population beyond the orbit of Saturn. As regards the outer stable region beyond Neptune, any objects of less than 1000 km in diameter revolving there would certainly still escape detection. Pluto seems to be more akin to Chiron than to Neptune. It is only its 2/3 resonance with Neptune which prevents close encounters, but it would be too daring to extrapolate this situation to periods comparable with the solar system age (Williams and Benson, 1971). There may be some association between Triton and the system Pluto-Charon (Harrington and Harrington, 1980).

The detection limits for comets, although less strict, make it impossible to specify their evolutionary paths into the Jupiter family. We are unable to recognize which of them have been captured by Jupiter from the capture zone of the Oort cloud and which have inspiralled from Neptune through a sequence of low-eccentricity orbits between the outer planets. The time scales of these two extremes of evolution are substantially different: the mean period required for a capture by Neptune or Uranus is 4×10^8 yr, or 1/10 of the age of the solar system, while the corresponding value for Jupiter is only 2×10^5 yr (Everhart, 1977). The problem is that the two evolutionary paths converge into one before the perihelion distance becomes small enough to make the comet detectable (see Fig. 1 and Kresák, 1982).

It is an inherent feature of the unstable orbits, which Everhart (1979) fittingly calls "chaotic" and which occupy the blank area of Fig. 1, that they freely change from one pattern into another of entirely different shape and location. There are potential evolutionary paths linking up such dissimilar orbits as those of Chiron, of temporary satellites, of Trojans and horseshoes of the giant planets, and of normal comets. But there is no path between two very similar nonresonant asteroid orbits situated on different sides of a Kirkwood gap, without the interaction of nongravitational effects.

The population of the innermost stable region within 0.3 AU of the Sun is also an open problem. Even at the largest aphelion elongation, no object revolving there would ever leave the zone of astronomical twilight. Limiting solar elongations of 10° and 15° are marked

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on the lower left of Fig. 1. Objects of several tens of kilometers across could easily escape detection under such circumstances. All we can infer about the population of the regions within Mercury and beyond Neptune is the upper mass limit above which the objects would manifest themselves by perturbations of the planets. While the observed motion of Mercury is consistent with the computations including the relativity terms, there are still small systematic residuals in the positions of the outer planets when their prediscovery observations are to be represented (Seidelmann and Duncombe, 1982).

Our present information on the population of interplanetary space is based on the orbit determinations of over 7500 individual objects, not including the meteors. These split into stable asteroids, active comets and unstable asteroidal objects in a proportion very close to 100 : 10 : 1. This ratio, however, is strongly biased by observational selection. The Apollo and Amor objects can be observed down to considerably smaller sizes than normal asteroids, and more effort is made to follow them up and to determine their orbits. Main-belt asteroids with diameters exceeding some 10 km are detectable with present means and can be located annually, but orbits are not available for all of them. Much smaller comets would become bright enough for detection when near the Sun. However, this would only happen once per several million years with comets with aphelia at the outskirts of the Oort cloud, and would not happen at all with comets of large perihelion distance. In fact, no estimates of the total number of comets are reliable, perhaps with the exception of the very small subsystem of short-period comets of the Jupiter family which consists of about 1000 objects in equilibrium between source and sink (Kresák, 1979b). We evidently do not know the largest representatives of the long-period comet class.

TABLE 2. Numbers of known orbits N and cumulative tracking times ΣT (in years) of different types of interplanetary objects.

	N	%	ΣT	%
New comets	87	1.15	105	0.06
Other long-period comets	471	6.23	156	0.09
Halley type	17	0.22	3719	2.18
Jupiter family	109	1.44	3750	2.20
--- Comets, all	684	9.05	7730	4.53
Apollo objects	33	0.44	341	0.20
Amor objects	31	0.41	541	0.32
Hidalgo	1	0.01	61	0.04
Chiron	1	0.01	87	0.05
--- Unstable asteroids, all	66	0.87	1030	0.60
Main-belt asteroids	6666	88.15	158808	93.09
Hilda group	55	0.73	1912	1.12
Trojans	91	1.20	1113	0.65
--- Stable asteroids, all	6812	90.08	161833	94.86
--- Grand total	7562	100.00	170593	100.00

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Table 2 lists, for each object class, the number of individual objects N for which orbit determinations are available, and their total observing time (between the first and last observation of each body) ΣT. For the sake of comparison, the percentages of N and ΣT for each class of objects are also shown.

In Figure 2 the ΣT-values are compared with the ages and median recurrence periods of different events relevant to the evolution of the interplanetary population. It must be pointed out that the median lifetimes may be in some cases appreciably shorter than the survival times of the oldest objects, because some depleting mechanisms tend to produce long-lived distribution tails (Wetherill, 1979). One can see that most of the events of crucial importance are so rare that they could not be witnessed in a single period equal to the entire history of observational astronomy. This refers, in particular, to the collisional events between asteroids and to the production of the Amor-Apollo objects and meteorites. As regards the short-period comets, the situation is more favourable, in that events like drastic transformations of orbits, temporary satellite captures, outgassing and splitting of their nuclei occur on a much shorter time scale. Unfortunately, nongravitational effects and limits of measuring accuracy preclude reliable extrapolation of the motion over more than several centuries or, more precisely, over more than one close approach to Jupiter on each side of the observing interval.

Most of our knowledge of the dynamical evolution of comets is therefore based on modelling experiments with samples of fictitious objects. Constraints are: difficulties with choosing the proper starting conditions; difficulties with treating the resonance effects; and, in particular, the presence of nongravitational forces. Purely gravitational solutions yield a clearcut distinction between stable and unstable orbits (Everhart, 1979). In special cases the real situation is undoubtedly more complicated than the models, and can lead to some leakage between these basic classes of orbits. However exceptional this may be, it can become significant for special types of objects on a long evolutionary time scale.

An interesting example is the temporary capture of comets into satellite orbits around the planets. P/Gehrels 3 was recently captured by Jupiter for 7 years (Rickman and Malmort, 1982), and at least six other known comets for shorter periods - P/Oterma and P/Kowal 1 even twice (Carusi and Valsecchi, 1982). Captures for more than 100 years result from modelling experiments with orbits very similar to those of real comets (Carusi et al., 1981). The duration of the status of a temporary satellite of Jupiter is subject to appreciable variations by the perturbing action of the Galilean satellites (Carusi and Valsecchi, 1979). Since many comets are active at the distance of Jupiter, it is plausible that the associated nongravitational effects could represent the necessary increment in stabilizing the circumplanetary orbit. The same holds for non-destructive collisions. Both mechanisms evidently require a quite exceptional concurrence of circumstances; but the high rate of temporary satellite captures and the long age of the solar system could make this process work for a real fraction of

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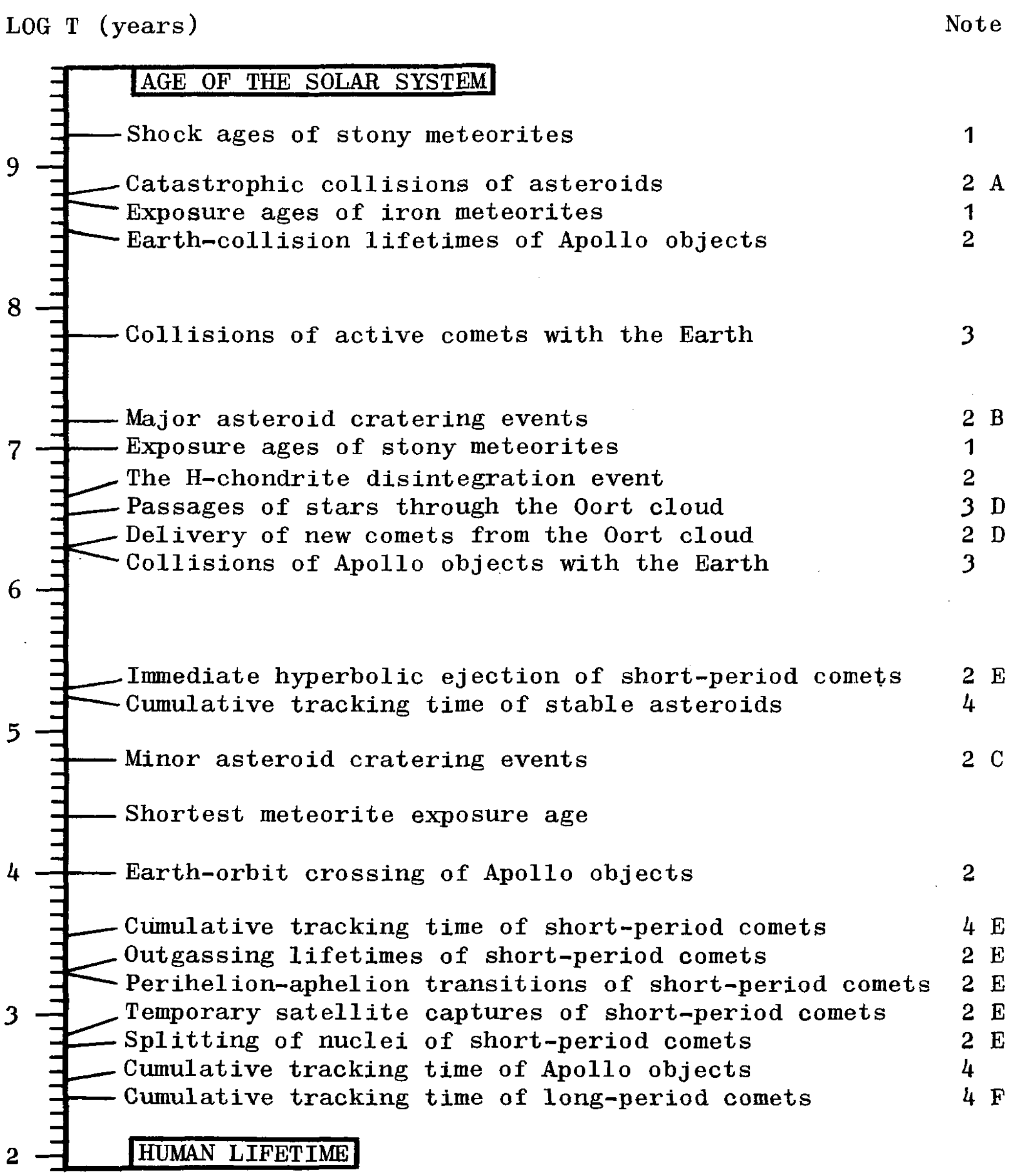

FIGURE 2. Notes : 1 = median age, 2 = median time interval relevant to the evolutionary history of a single interplanetary object, 3 = median time interval between events with different interplanetary objects involved, 4 = sum of the time intervals between first and last observation. A = log target/projectile mass ratio < 4, B = log target/projectile mass ratio < 6, C = log target/projectile mass ratio < 9, D = solar distance of 50,000 AU, E = revolution period < 20 years, F = revolution period > 200 years.

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the multitude of comets. The reverse process is equally possible, so that there may be interplanetary objects which have spent a part of their evolutionary history as planetary satellites.

To summarize the open problems: In the outer regions of the solar system they are set by the very limited number of observable objects and by their long evolutionary time scales. For example, the grouping of Jupiter's irregular satellites by period and inclination still remains unexplained, but seems to point to some capture/collisional mechanism. We are not certain about the long-term persistence of the resonances preventing planetary encounters (Trojans-Jupiter, Pluto-Neptune), and hence about the leakage between circumsolar and circumplanetary orbits. We are also uncertain about the nature of Chiron. If it is a huge dormant comet, one of many as yet unknown similar objects, our current ideas about the total mass of the Oort cloud will probably need a revision, with important consequences for its origin.

In the inner planetary zone, where the full scale of object sizes down to micrometeorites is accessible to observation, we do not know how to distinguish between the two components of asteroidal and cometary origin. We have very little information on the optical properties of cometary nuclei, and there is no definite correspondence between individual classes of asteroids and meteorites. We are unable to explain quantitatively the transport of cometary aphelia to far inside the Jupiter barrier - a process which seems to be quite frequent, in particular for small objects of supposedly cometary origin. The final stages of decay of cometary nuclei and the dynamical consequences of collisions between asteroids are not well understood. Even the origin of our closest neighbours after the Moon, the Apollo objects, is a matter of controversy, most of which is negative opinion about the other alternative.

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