Part 4

COMETS AND TRANS-NEPTUNIAN OBJECTS

Dynamics of Populations of Planetary Systems
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Transport of comets to the Inner Solar System

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Abstract. Recent years have seen a revolution in the possibility to understand cometary capture, i.e., the origin of the cometary population that moves in orbits confined to the inner Solar System. This is due to the discovery of the major source populations: the Edgeworth-Kuiper belt, and the scattered disk. We review the current understanding of the links between the distant sources, including the Oort cloud, and the observed, short-period population, and the problems that remain. Some highlights of present research in this field will serve to illustrate recent progress and major issues that are currently arising.

Keywords. Comets, cometary capture, Jupiter family, Oort cloud, Edgeworth-Kuiper belt, scattered disk

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1. Introduction

One of the first facts that became known about cometary orbits is that the periods of revolution vary over a wide range. One often refers to long-period and short-period comets, but this distinction is mostly of historical interest, and the terms will not be used in a strict sense in this paper. Nonetheless, the fact that some comets are confined to the innermost part of the Solar System, while others make only temporary visits from very remote regions, is remarkable.

It was also realized long ago (Lexell 1778, 1780) that comets may pass close to Jupiter and receive perturbations that change their orbits drastically. Such instability offers a way for comets to evolve dynamically between long and short periods and thus to be "captured", at least temporarily, into the inner Solar System. The next important finding was that, in a physical sense, comets do not live forever. Especially famous are the 19th century cases of comets 3D/Biela, which disappeared after a major splitting, and 5D/Brorsen, which ceased to be observed for no obvious reason. This adds a new dimension to the capture issue in that there may be a sink of comets – especially those of short periods that return more frequently to the vicinity of the Sun and may hence be more vulnerable to destruction.

Another aspect is that comets are generally observable only when they penetrate deep within Jupiter's orbit and H_2O ice can sublimate efficiently from their nuclei. This means that the perihelion distance plays a crucial role for cometary discovery bias. Furthermore, all observable comets are ephemeral, since they can not live longer than the time it takes to exhaust their inventory of H_2O ice. The problem of comet evolution is very complex, involving both physical and dynamical effects as well as their mutual interactions – see (Jewitt 2004) for a recent review. At this point, suffice it to say that not only changes of orbital period are of interest. The delivery of comets into observable orbits by decrease of the perihelion distance is even more fundamental to our understanding of cometary populations.

This paper aims to describe the current understanding of how comets are transferred from distant source populations into observable orbits, especially those with short periods. To this end, the basic concepts will first be introduced by means of a historical background. The rest of the paper will discuss the most important current problems and some recent work on a few major issues.

2. Conceptual History

While, in principle, comets might be thought of as a temporary phenomenon that we happen to observe because we live at a privileged time, it is evidently necessary to look for a steady-state situation, where the losses are balanced by infeed from a source population. And even though there is no guarantee that the present cometary population is indistinguishable from that at other times, e.g. $\sim 10^7$ or 10^8 years ago, the latter pursuit has always proved successful. Typically, a source population and associated infeed mechanism has first been suggested on theoretical grounds, and later on the suggestion has been verified by observations – either partially or fully.

The first major structure to be recognized in the observed cometary population was the Jupiter family. Its primary characteristics – low inclinations and aphelia near the orbit of Jupiter – at once suggested gravitational captures by the giant planet during close encounters as the explanation. However, the source population remained elusive for a long time. The reason is obvious from the Tisserand criterion, which is derived from the Jacobi integral of the circular restricted three-body problem (see e.g. Danby 1962):

$$T = \frac{a_J}{a} + 2\sqrt{\frac{a}{a_J}(1-e^2)}\cos i \tag{2.1}$$

where a and a_J are the semimajor axes of the comet and Jupiter, and e and i are the comet's eccentricity and inclination, respectively.

The comets of the Jupiter family have $\cos i \simeq 1$ and values of T between 2 and 3 (see Kresák 1972; Carusi *et al.* 1987). Since T is quasi-conserved for perturbations due to close encounters with Jupiter, the only possible connection with long-period orbits occurs for inclinations that remain low and perihelion distances that increase toward or just beyond a_J (see Fig. 1). Therefore, until improvements in observational techniques allowed the discovery of comets with perihelia near Jupiter's orbit, the source population had to remain hidden from view.

Only with the discovery of the 'Oort peak', i.e., a conspicuous pile-up of original, long-period cometary orbits with $0 \lesssim 1/a_{\rm orig} \lesssim 1 \cdot 10^{-4}$ AU^{-1} creating a sharp peak in the distribution of binding energies, and the suggestion that this reveals a distant reservoir of comets (Oort 1950), was there an independent basis for identifying a particular source for the Jupiter family. Such a giant cloud, referred to as the 'Oort cloud', would be subject to external perturbations from passing stars and – as has later been realized – the tidal effects of the whole Galactic disk and bulge. The energy $H \propto a^{-1}$ is not very sensitive to those perturbations, but the angular momentum L may vary dramatically and reach values near zero, so that the perihelion distance $q \simeq L^2/2GM_\odot$ (for $e \simeq 1$) drops to observable values. On the way, comets would pass the region with $a_J/a \simeq 0$ and $q \simeq a_J$ in Fig. 1 and might thus offer a suitable source for the Jupiter family.

Orbital integrations including repeated encounters with Jupiter for a large sample of fictitious starting orbits (Everhart 1972) appeared to confirm this expectation, showing that captures into short-period orbits happened most easily for $\cos i_0 \simeq 1$ and $q_0 \simeq a_J$. However, problems remained. One was related to the efficiency of Everhart's capture process (Joss 1973), which relates the expected flux of Oort cloud comets in the 'capture

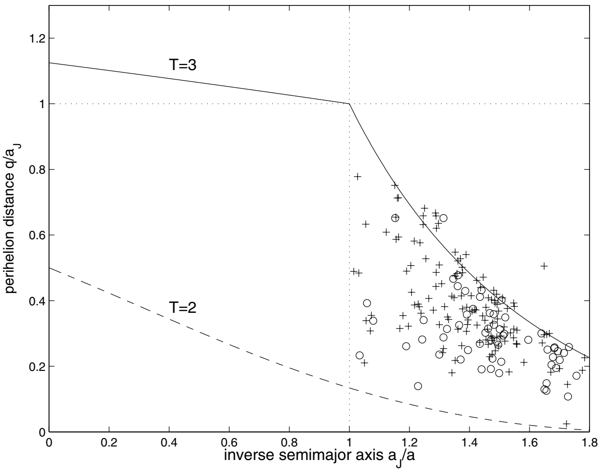

Figure 1. Perihelion distance is plotted vs inverse semimajor axis, both in units of Jupiter's semimajor axis. The solid and dashed curves show the relation given by the Tisserand criterion for zero inclination with two values of the Tisserand parameter T, as indicated. The symbols show the locations of all known comets with orbital periods shorter than Jupiter according to recent statistics. Circles denote comets discovered before 1950, and plus signs show more recent discoveries. The isolated symbol high above the $T = 3$ line is the peculiar comet 133P/Elst-Pizarro.

region' to the steady-state number of Jupiter family comets. This is a complex topic, clouded by uncertainties over the size and brightness distributions as well as fadings and observable lifetimes. A more straightforward argument came from the need to explain why the Jupiter family with its low inclinations is such an outstanding feature.

Simulations by Duncan *et al.* (1988) and Quinn *et al.* (1990) showed a general trend for the inclinations to stay within the range of the starting orbits, and the question hence arose: if the source population is isotropic with a flat distribution of $\cos i$, why is the Jupiter family so strongly concentrated to $\cos i \simeq 1$? High-inclination comets would run a larger risk of hyperbolic ejection before capture but, once captured, they would stay longer before being expelled again.

This issue is also somewhat confused by uncertainties over cometary lifetimes, because the lack of high-inclination, short-period comets might be partly explained, if such comets fade beyond detectability or disappear before they have time to be captured. But a consensus has grown around the inadequacy of such an explanation, and the need for a flattened, low-inclination source population has become generally accepted.

A very important concept was introduced by Kazimirchak-Polonskaya (1972) in a paper entitled 'The Major Planets as Powerful Transformers of Cometary Orbits', where she used a set of orbital integrations largely based on observed Jupiter family comets to suggest that comets could be captured via a multi-stage process involving all the giant planets. Each planet would be responsible for one part of the process, decreasing the orbital period and shifting the perihelion inward to the next planet while keeping the inclination low, as illustrated in Fig. 2. Further progress in understanding the dynamics of transformations between orbits nearly tangent to that of the planet at perihelion and aphelion was achieved by Carusi *et al.* (see Carusi and Valsecchi 1985).

This scenario invites a discussion of other sources for the Jupiter family, but even when restricting attention to the Oort cloud, it is seen that Jupiter does not need to capture comets single-handedly. In fact, each of the giant planets is able to start the process, if the

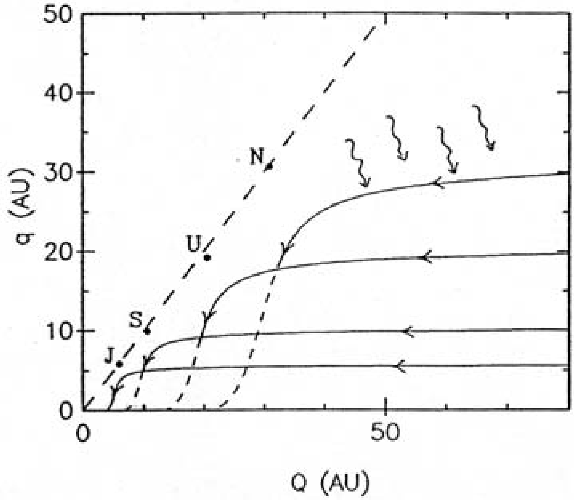

Figure 2. Low-inclination evolutionary tracks in the plane of aphelion distance (Q) vs perihelion distance (q) for multi-planet cometary capture. The solid curves indicate tracks of constant T as defined for each giant planet separately, and the dashed parts at the lower left are those where the planet in question does not dominate the evolution. From Rickman (1992).

perihelion of the comet falls in the vicinity of the planetary orbit. To this comes another feature, i.e., that the Oort cloud should have a broad energy distribution, where the Oort peak only represents the outer part for which the external perturbations are strong enough to bring the perihelia across the range of the giant planets in one revolution. Inside this there should be an inner core, for which the perihelia evolve in small steps, so that perturbations of orbital energy by the giant planets intervene before the comets become observable. As a result, hyperbolic ejections may occur but also captures of the multi-planet type illustrated in Fig. 2.

Bailey (1986) showed that this is likely to be important, but the intricate interplay of weak perturbations by the exterior giant planets and by Galactic tides for the inner core remains to be elucidated. Another idea, sketched by the wiggly arrows in Fig. 2, is that a source of comets is located just beyond the orbit of Neptune.

Whipple (1972) made interesting remarks about such a transneptunian comet belt but could not identify it as a source for the Jupiter family, since the dynamical mechanisms for a leakage from such a belt into Neptune-crossing orbits were not known. Fernández (1980) indeed proposed a transneptunian source for the Jupiter family as a remedy for the failure of jovian captures to produce the family directly from the Oort cloud. Finally, Duncan *et al.* (1988) used the argument of the inclination distribution to add further weight to the requirement of a flattened transneptunian source of comets, and they called this source the ‘Kuiper belt’ in remembrance of Kuiper’s (1951) suggestion of a remnant, icy planetesimal population beyond Neptune’s orbit.

The discovery of minor planet 1992 QB$_1$ (Luu and Jewitt 1993) marked the beginning of a new era in Solar System astronomy, where the exploration of the transneptunian population is one of the major issues. The number of discovered transneptunian objects is rapidly approaching 1000 (see `http://cfa-www.harvard.edu/iau/lists/TNOs.html`), and the amount of information on their physical properties is also growing quickly. We are now able to distinguish several major components of this population, all of which may contribute to the flux of captures into the Jupiter family. Fig. 3 shows how the transneptunians are distributed over semimajor axes and perihelion distances.

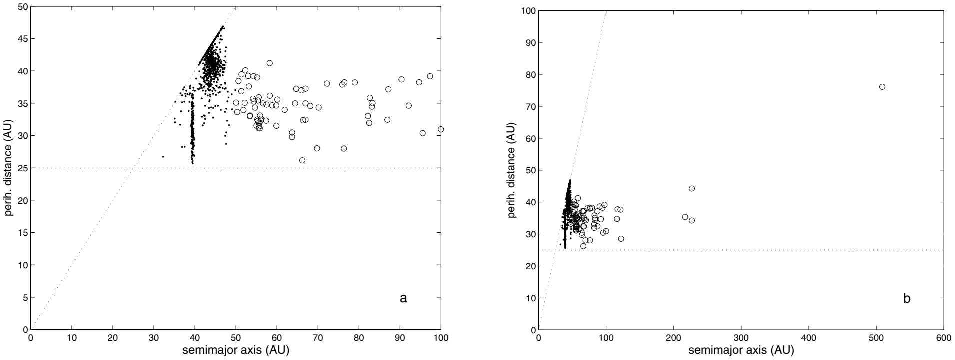

Figure 3. Perihelion distances vs. semimajor axes for the transneptunian population, according to recent data from the IAU Minor Planet Center web page. Only objects with $q > 25$ AU have been included. Dots denote objects with semimajor axes $a < 50$ AU, and circles show more distant orbits reaching further out. The latter roughly correspond to the scattered, and extended scattered disks. (a) Plot limited to $a < 100$ AU. (b) Plot showing all discovered objects.

The Plutinos are locked in a stable 2:3 resonance with Neptune and are not directly subject to captures. However, upon collisions with other transneptunian objects, fragments of Plutinos may approach Neptune and be transferred into the inner Solar System. The classical Kuiper belt, which is sometimes called the Edgeworth-Kuiper belt (see Edgeworth 1949), is a planetesimal population that derives from the cold disk resulting from the preplanetary accretion phase. For as yet unknown reasons this has been heated to significant eccentricities and inclinations, and the population is collisionally evolved (for a review, see Morbidelli and Brown 2004). Following collisions, small objects may enter into resonances and slowly reach eccentricities large enough to become planet-crossing, after which captures may occur.

The scattered disk is a distinct population of objects that originate from Neptune's accretion and have been expelled into orbits that often reach far outside all planets. They are not always able to approach Neptune in their current orbits, since long-term interactions with the planets may temporarily displace their perihelia somewhat (see e.g. Gladman *et al.* 2002). This was hypothesized by Fernández (1985). Subsequently, Duncan and Levison (1997) were able to demonstrate both that the scattered disk should exist (i.e., not all original objects have been removed) before the first object was discovered, and that it offers a viable source for the Jupiter family due to the continued approaches to Neptune. Duncan *et al.* (2004) estimate that the scattered disk predominates over the Edgeworth-Kuiper belt as such a source, based on available data on population sizes and dynamical time scales (see Section 3.2).

3. Current Problems

The orbital distribution of the Jupiter family can be adequately explained as a result of gravitational captures from either part of a low-inclination, transneptunian population via a process where all the giant planets participate. A detailed description of how this mechanism works is best offered by the team behind the simulations of such a capture (Duncan *et al.* 2004). The only additional assumption in order to produce an essentially perfect fit involves the observable lifetimes of Jupiter family comets. Newly captured comets tend to have very low inclinations, but repeated encounters with Jupiter thereafter scatter the inclinations over a range wider than observed. Fitting the observed inclination range is achieved by assuming an active lifetime between 3 000 and 25 000 years (Levison and Duncan 1997).

If the rest of the dynamical residence time in the Jupiter family is spent in a dormant state, then for each active comet there should be from two to six dormant ones. The statistics of observed asteroids in Jupiter family orbits appear to be consistent with this estimate (Rickman *et al.* 2001a), but no firm conclusions can be drawn at this stage.

3.1. *Population Characteristics*

A daunting, yet urgent task that has not yet been realized is to specify exactly what constraints can be placed on the abundance of the source. This means to specify the necessary rate of captures, based on the number of comets in the Jupiter family and their lifetimes. Therefore we need to characterize this population in terms of the distribution of brightness or nuclear size as well as that of perihelion distance. This is a very active area of research due to the compilation of large data bases on nuclear magnitudes (Fernández *et al.* 1999; Tancredi *et al.* 2000) or special observational programmes using front-line telescopes (Lamy *et al.* 2003; Meech *et al.* 2004). More research is needed in order to reach a coherent picture as to the power-law index for nuclear radius, and thus to define accurately the requirement on the capture rate.

The other major problem is to estimate the population sizes of the transneptunian sources and the associated infeed rates into Neptune-crossing orbits. Obviously, then, the observations so far refer to large objects with diameters $D \gtrsim 100$ km, and an estimate of the number of transneptunians with sizes similar to the observed Jupiter family comets must involve both a number $N(D \gtrsim 100 \text{ km})$ derived from observations, and a slope of the size distribution – assumed to be a power law, connecting with the number $N(D \lesssim 10 \text{ km})$. The latter is not very well constrained by observations and hence represents a significant source of uncertainty.

Jewitt *et al.* (1998) found the number of Edgeworth-Kuiper belt objects with $D \gtrsim 100$ km to be $\sim 1 \cdot 10^5$. The power-law slope of the differential distribution of radii appears to be $\alpha \simeq 4$, yielding an estimate of $\sim 1 \cdot 10^{10}$ for the number with diameters from 2 to 20 km. The scattered disk is less well constrained by observations, but Trujillo *et al.* (2000) found $N(D \gtrsim 100 \text{ km})$ to be $\sim (2-5) \cdot 10^4$ for $\alpha = 4$ and half of that number for $\alpha = 3$. If one prefers to use $\alpha = 4$ because this fits with the estimate for the Edgeworth-Kuiper belt, one gets $\sim 4 \cdot 10^9$ objects with $2 < D < 20$ km. Caution is however called for, since it is not certain that the scattered disk is collisionally evolved to the same degree as the Edgeworth-Kuiper belt. Using $\alpha = 3$ would yield 100 times fewer small-size objects.

For the scattered disk one may use the results by Duncan and Levison (1997) to relate the number of objects to that of the scattered-disk contribution to the Jupiter family with $q < 2.5$ AU. Thus, the ratio between those numbers was found to be $R = 1.3 \cdot 10^6$. If we take the analysis of the Jupiter family population and size distribution by Fernández *et al.* (1999), we get $N_{JF} \simeq 400$ for $D \gtrsim 2$ km and $q < 2.5$ AU. Taking the above R at face value, we would get $N_{SD} \simeq 5 \cdot 10^8$ for $D > 2$ km, which might appear to be on the low side. However, on the one hand there are uncertainties over the numbers and slope factors involved, and on the other hand it is likely that a typical Jupiter family comet has had its nucleus eroded by sublimation, so that the current radius may be about half of the original one. Allowing for this would increase the estimate of N_{SD} to $\sim 4 \cdot 10^9$, in perfect agreement with the above $\alpha = 4$ estimate.

3.2. *Capture Efficiencies*

The time scales of infeed into Neptune-crossing orbits for the Edgeworth-Kuiper belt and the scattered disk are worthy of further investigation, in particular as regards the values that prevail at the present time. This is particularly important, if the underlying history of the populations is considered in a more realistic way than previously. The scattered disk is the favoured source of Jupiter family comets, because its infeed time scale is believed to be much shorter than for the Edgeworth-Kuiper belt; thus the ratio R should be much larger for the latter source. However, the real infeed rate for the Edgeworth-Kuiper belt is difficult to determine, since it is set by resonant interactions that increase the eccentricities, and collisional evolution that produces an infeed into the resonances. The rate of this evolution depends on the population size and other uncertain parameters. The infeed rate for the scattered disk must be much smaller today than it was, when the Solar System was young, since the current population is made up of long-term survivors, protected by temporary displacement of the perihelia beyond Neptune's reach. Hence the ratio R must also have grown substantially, and the question remains, if the above value from Duncan and Levison (1997) is the one prevailing today. In conclusion, even if current evidence favours the scattered disk, the question of the main source for the Jupiter family is not yet definitively answered.

When estimating the infeed rate from the scattered disk, it is also important to consider all relevant perturbations. The effects of random passages of field stars, leading typically to changes of q up to several AU (Rickman *et al.* 2004), have not previously been included but may apparently influence the variation $R(t)$. But stellar perturbations may in fact have played a much more significant role in shaping the transneptunian population. Fernández (1997) drew attention to the possible importance of a dense stellar environment around the early Solar System for the formation of the Oort cloud, and Fernández and Brunini (2000) further explored the idea of the Sun's natal stellar cluster steering the early ejection of comets from the planetary accretion zones, creating a denser inner core of the Oort cloud than would otherwise have resulted. Ida *et al.* (2000) suggested that a close stellar encounter might have stirred up the early Edgeworth-Kuiper belt with important implications for its structure and collisional evolution.

3.3. *The Extended Scattered Disk*

However, the most important impulse to such research came with the discovery of minor planet 2003 VB_{12}, which is represented by the isolated data point at the upper right in Fig. 3b, and has a diameter $\simeq 3/4$ that of Pluto. Brown *et al.* (2004) described the discovery and its implications for the existence of a massive population of very remote objects, which may be identified with the "extended scattered disk" (Gladman *et al.* 2002) but turns out to be more significant than had earlier been expected. They also suggested that a slow and close encounter with a cluster star would offer the most likely mode of formation, by extracting the perihelia of scattered disk objects to large distances. This suggestion was supported by actual simulations (Morbidelli and Levison 2004), while Rickman *et al.* (2004) by their simulations found that random field stars passing during the age of the Solar System would also lead to a large, extracted population including orbits like that of 2003 VB_{12} via perturbations on the scattered disk (see Fig. 4).

The open questions now mainly concern the timing of the decisive event, and whether it had to occur early enough to strongly suggest a cluster star. A very early event might be required, if the mass of the extracted population demands that the scattered disk must have been very massive (e.g., ~ 10 Earth masses) by the time of the stellar encounter. The answer likely has to await relevant simulations of the evolution of the scattered disk in a realistic stellar environment as well as better knowledge of the population characteristics following further discoveries.

In any case, whatever the nature of the stellar passage, it also led to a massive injection of scattered-disk objects into the inner Solar System (see Fig. 4). Thus a random field star

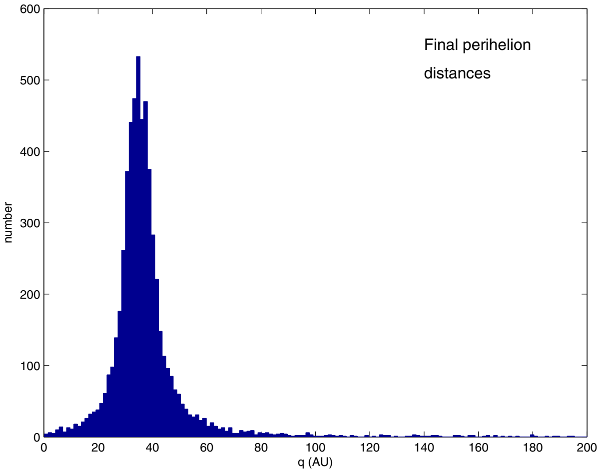

Figure 4. Distribution of perihelion distances acquired through passages of random field stars during 4 Gyr, according to a Monte Carlo simulation. Heliocentric impulses for a sample of 10 000 comets have been crudely estimated by the classical impulse approximation, and only those with an absolute value exceeding 0.00363 AU/yr have been considered as significant. The starting orbit in each case had a perihelion distance of 35 AU and an aphelion distance of 1000 AU. From Rickman *et al.* (2004).

passing ~ 4 Gyr ago may have triggered the late heavy bombardment, as mentioned by Rickman *et al.* (2004), along the lines first discussed by Mottman (1977). This illustrates very clearly that the cometary capture problem is not only relevant for explaining the observed distribution of cometary orbits; it also has implications for the cratering history of the terrestrial planets and, very likely, their history of volatile delivery.

Note that the extended scattered disk shares an interesting property with the inner core of the Oort cloud, namely, that on rare occasions it may be the source of strong, episodic infeed of cometary objects into the inner Solar System as a result of close stellar encounters. The term “cometary showers” (Hills 1981) has been coined to describe such events for the inner core, and the typical time scale for those is $\sim 10^7 - 10^8$ yr. Possibly, even more intense showers might arise from the extended and, to some extent, the normal scattered disk on a time scale of 10^9 yr due to even closer stellar encounters.

3.4. *Halley-Type Comets*

Comets with short orbital periods – typically, $P < 200$ years – and Tisserand parameters $T < 2$ are usually called Halley-Type Comets (HTCs; see Levison 1996). Their origin presents a separate problem, since captures from the Edgeworth-Kuiper belt or the scattered disk of the type discussed above will not produce HTCs. Many recent papers have dealt with that problem, but important issues remain to be resolved.

The Oort cloud provides an obvious source of HTCs, since it yields an infeed of Jupiter-crossing comets over the whole range of inclinations and values of T covered by the Halley-types. But other sources have recently been discussed as well, and once more we are faced with the problem to distinguish the different contributions. First, the Oort cloud flux extends over the entire planetary system with perihelia from 0 to $\gtrsim 30$ AU from the Sun, and while the simulations by Emel'yanenko and Bailey (1998) showed a predominance of original perihelia with $q_o < 2$ AU among comets captured into HTCs, the question remains how large the contribution from initial perihelia in the outer planetary system may be.

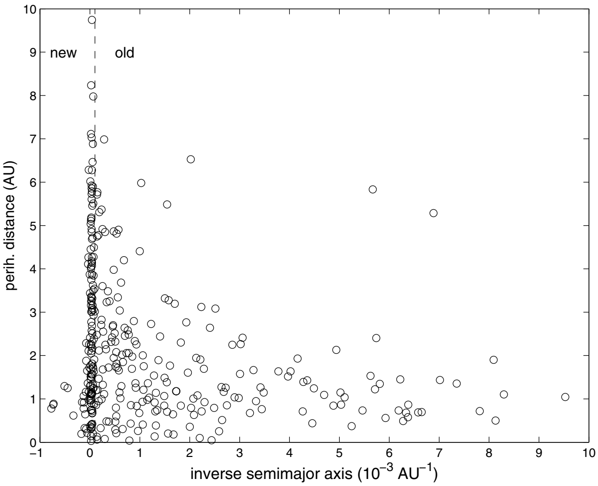

Figure 5. Perihelion distance vs semimajor axis of original orbits of long-period comets, according to a recent sample of observed comets. All quality classes of those orbits have been included. The data is from Marsden and Williams (2003).

The capture probability is then much smaller, but the flux of Oort cloud comets is larger outside the orbits of Jupiter and Saturn, where the inner core is also contributing (Hills 1981; Bailey 1990). An interesting feature of the evolution of such comets into HTCs is that the large changes of q are mostly driven by secular resonances (Bailey and Emel'yanenko 1996), which means that T is not conserved since Jupiter's eccentricity plays an essential role. Evaluation of the Oort cloud flux in the outer planetary system can only be done preliminarily as yet, based on models of the orbital energy distribution of the cloud and the effects of Galactic tides and stellar perturbations. Improvements may be expected from new developments in modelling the Galactic tides (e.g. Fouchard 2004) and the long-term effects of planetary perturbations (e.g. Rickman *et al.* 2001b).

The inclination distribution of the HTCs has been identified as a problem, if the isotropic Oort cloud is the only source, since there is a majority of prograde orbits among the HTCs. Prograde orbits are more strongly perturbed on the average than retrograde ones, but as a consequence the retrograde comets stay longer after capture and, unless physical evolution makes the comets unobservable after some limited time, there should be an excess of retrograde HTCs from the Oort cloud (Levison *et al.* 2001). These authors suggested a flattened inner Oort cloud with a preference for low inclinations as a supplement to the isotropic, outer Oort cloud, in order to solve this problem. But more work in needed, in particular on clarifying the physical evolution of HTCs and observability conditions, before we can really understand the inclination distribution. A viable idea (Levison *et al.* 2004) is that the scattered disk is feeding the HTC population with comets in preferentially prograde orbits via gravitational scattering into semimajor axes $a \gtrsim 10\,000$ AU, decrease of q by Galactic tides, and capture into HTC orbits by the giant planets.

Finally, observable lifetimes are a major issue when discussing cometary capture, especially for HTCs. The well-known "fading problem" (Weissman 1980; Bailey 1984) means that there is a lack of returning, long-period comets with respect to what would be inferred from the flux of new Oort cloud comets on the basis of pure dynamics. Fig. 5 shows statistics of original orbits of long-period comets, and it is clear that the concentration to the interval with $1/a < 1 \cdot 10^{-4}$ AU^{-1} is even sharper for large-q comets than for the classically observed, low-q comets. This must mean that there is a rapid fading or a particular brightness of new comets, or that cometary nuclei are quickly disrupted during their first passages near the Sun. Emel'yanenko and Bailey (1998) found that only $\sim 1\%$ of the Oort cloud comets with $q < 2$ AU can survive the capture into HTCs as observable objects, which is yet another indication of the same, elusive phenomenon. Levison *et al.* (2002) compared the number of thus 'unobserved' HTCs and long-period comets with the number of discovered asteroidal objects in such orbits and came to the conclusion that nearly all the Oort cloud comets must become disrupted.

However, more work is needed before we fully understand the loss of comets. One particular problem with the disruption idea, in addition to the fact that disruptions are not ubiquitously observed, is the indication from Fig. 5 that large-q comets should be preferentially affected, contrary to the intuitive picture of disruptions as caused by effects of solar heating. Another problem is that Jupiter family comets do not appear to frequently suffer disruption during their capture, in stark contrast to the HTCs, even though the objects seem to have formed under similar conditions, and other major differences of physical or chemical constitution are not known.

4. Concluding Remarks

The transport of comets from distant sources into the inner Solar System and the origin of the observed short-period cometary populations present a complex problem involving both cometary physics and dynamics. This problem is currently pursued very intensely for several reasons that go beyond the mere explanation of observed cometary populations. One is that current and future, ambitious space missions to Jupiter-family comets are largely motivated by a wish to use them as cosmogonical probes, and this requires that we understand where they were formed and how they have evolved. Another reason is that the delivery of comets into Earth-crossing orbits may have played an important role in volatile delivery to our planet and may also have made a significant contribution to the terrestrial cratering history, possibly including the late heavy bombardment.

It is fair to say that the dynamics of such transport is generally well understood, thanks to work involving numerical simulations which was carried out during the last decade or two. The main bottleneck for understanding the problem at present lies in characterizing the populations involved. Thus the Jupiter family and HTC populations are fairly well observed, but uncertainties remain over discovery biases related to perihelion distance as well as the nuclear size distribution. The transneptunian sources including the Oort cloud are still unobserved as far as comet-sized objects are concerned, and we have to rely on uncertain extrapolations from the observed data on $D \gtrsim 100$ km objects. A particular problem is presented by the scattered disk, whose orbital distribution and infeed rate into Neptune-crossing orbits must have varied during the history of the Solar System, and for which even the current orbital distribution is not very well constrained so far.

Uncertainties also remain over some aspects of the dynamics of the distant sources, including the interplay of Galactic tides and stellar perturbations in shaping the Oort cloud and regulating its infeed of comets into the planetary system. Moreover, we need to better understand the formation and evolution of all distant sources in order to answer very important questions about the transport of comets in the early Solar System.

Future progress may be expected both from deeper surveys of the sky (e.g., Pan-STARRS) that will likely multiply the number of known objects by a large factor, from continued, in-depth study of cometary nuclei and transneptunian objects, and from more ambitious or more realistic simulations of the external perturbations on the distant sources.

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