DYNAMICS OF COMETS : RECENT DEVELOPMENTS AND NEW CHALLENGES

JULIO A. FERNÁNDEZ
Departamento de Astronomía, Facultad de Ciencias,
Tristán Narvaja 1674, 11200 Montevideo, URUGUAY
E–mail julio@fisica.edu.uy

Abstract. There is a broad consensus that long-period comets come from a huge reservoir surrounding the solar system, as proposed originally by Oort. Yet, the classical picture of the Oort cloud has substantially changed during the last decade. In addition to passing stars, the tidal force of the galactic disk and giant molecular clouds have also been identified as major perturbers of the Oort cloud. In particular, the latter may be responsible for limiting the size of the stable Oort cloud to no more than $\approx 10^4 AU$, i.e. about one tenth of the classical Oort's radius.

Most comets are injected into the planetary region by the quasi-steady action of the tidal force of the galactic disk. The concentration of aphelion points of dynamically young comets toward mid-galactic latitudes is a consequence of its dominant influence. The frequency of comet passages into the inner planetary region could experience significant fluctuations with time as the Oort cloud meets random strong perturbers. The observed ordered pattern of most comet aphelia, associated with the galactic structure, argues against a recent strong perturbation of the Oort cloud.

The origin of the Jupiter family has become another point of intense debate. Jupiter family comets may come from a transneptunian comet belt -the Kuiper belt- from where they can reach the planetary region through chaotic motion. The Kuiper belt has become accessible to large telescopes, as shown by the recent discoveries of 1992QB1 and 1993FW, possibly belt members. The major challenge will be to explore the region usually inaccessible to external perturbers that goes from $\sim 30AU$ to a few thousand AU. A significant mass may have been locked there from the beginnings of the solar system, giving rise to an inner core that feeds the outer or classical Oort cloud. Our aim will be to briefly discuss some of the topics summarized here.

1. Steady and random perturbers of the Oort cloud. Comet showers

Comets in the Oort cloud evolve dynamically under the action of several external perturbers. Distant - background - stars passing at distances greater than, say $2 - 3 \times 10^4 AU$, and tides of the galactic disk exert a quasi-steady perturbing action. From time to time, the Oort cloud is strongly perturbed by stars that come very close to the Sun or by encounters with giant molecular clouds (GMCs). These sporadic encounters seem to have major effects in the dynamical stability of the Oort cloud, the injection rate of comets into the planetary region and, perhaps, in the evolution of the planetary atmospheres, life and the impact cratering rate.

The action of stellar perturbations on Oort comets has already been well studied by several authors (e.g. Rickman 1976, Weissman 1980), so we will not repeat the analysis of their dynamical effects here. For a general review see, for instance, Fernández and Ip (1991).

The tidal force of the galactic disk is very effective in changing the angular momentum or perihelion distance q of Oort comets (e.g. Byl 1983, Heisler and

A. Milani et al. (eds.), Asteroids, Comets, Meteors 1993, 223–240.

Tremaine 1986). However, its overall effect on the comet's energy is negligible. This is because the energy's perturbation along the outgoing leg of the comet's orbit roughly compensates for that along the incoming leg, so that its net effect is very small, typically of order (q/a), where a is the comet's semimajor axis (Byl 1983). Therefore the perihelia of Oort comets can be rather frequently injected into the planetary region, but the comets themselves can hardly become hyperbolic by the action of this force. Let us consider an Oort cloud comet of semimajor axis a and aphelion direction at a galactic latitude ϕ. The change in its transverse velocity due to the action of the galactic tidal force acting during an orbital revolution P is

$$(\Delta v_T)_{tide} = 3\pi G\rho a P \cos\alpha \sin 2\phi, \tag{1}$$

where α is the angle between the orbital plane and the plane perpendicular to the galactic disk containing the radius Sun-comet (assumed to keep the same direction along the àpsidal line through the orbital revolution, which is more or less fulfilled for near-parabolic comets).ρ is the density of the galactic disk in the Sun's neighborhood, which is about $0.15 M_{\odot} pc^{-3}$ (Tremaine 1993).

A population of comets thermalized by external perturbers will have randomly oriented velocity vectors so all the directions will be possible, except those falling very close to the solar direction since these comets will be quickly removed by planetary perturbations. Consequently, there will be an empty region in the velocity phase space around the solar direction known as the *loss cone* (Hills 1981).

Should the loss cone be completely empty, the Oort comets would then stay away from the planetary region. Now, the combined effect of stellar perturbations and tides of the galactic disk will cause a steady refilling of the loss cone. At the end, losses by planetary perturbations will reach an equilibrium with refilling by external perturbers, so a fraction $f \leq 1$ of the loss cone will be kept filled at any time. The fraction f will depend on the semimajor axis a of Oort comets. For larger a the action of external perturbers will be stronger, so an ever increasing fraction of the loss cone will be filled; the increase with a goes as $f \propto a^7$ (Fernández 1992). There will be a limiting semimajor axis $a = a_{fill}$ such that $f = 1$, so comets with $a > a_{fill}$ will have their loss cones permanently filled. Consequently, the influx rate of Oort comets with $a > a_{fill}$ will be constant throughout the time, no matter the random action of strong perturbers. Showers will be produced by comets with $a < a_{fill}$.

Strictly speaking, the tidal force of the galactic disk depends on the galactic latitude ϕ (cf. eq.(1)); it is maximum for $\phi = 45°$ and goes down to zero for $\phi = 0°$ or $\pm 90°$. Therefore, this force is very efficient in injecting Oort comets at mid-galactic latitudes but it cannot do that near the galactic equator or poles. In this regard the distribution of aphelion points of LP comets shows a clear concentration at mid-galactic latitudes (Delsemme 1987). Galactic tidal forces fill the loss cones of Oort cloud comets at mid-galactic latitude ($\phi \sim 30° - 60°$) for $a \gtrsim 3.3 \times 10^4 AU$, while stellar perturbations do that for comets with $a \gtrsim 4 \times 10^4 AU$ (if the latter were the only acting perturber). These results show the predominance of galactic tides in the injection rate of Oort cloud comets in the planetary region. Only at low or high galactic latitudes ($|\phi| \lesssim 15°$ or $|\phi| \gtrsim 75°$), stellar perturbations overcome galactic tidal forces (Fig.1).

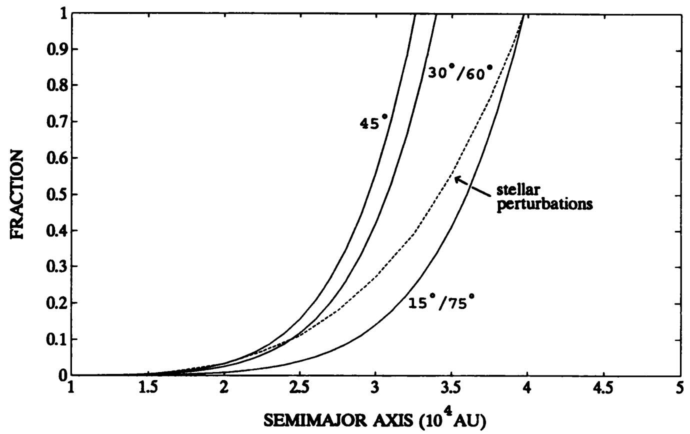

Fig. 1. Fraction of loss cone filled with comets as a function of the semimajor axis, as due to the action of stellar perturbations (dashed curve) and tides of the galactic disk (solid curves) at the galactic latitudes indicated beside each curve (adapted from Fernández 1992).

A very close stellar passage or a penetrating encounter with a GMC can perturb the inner portions of the Oort cloud where loss cones are empty, or at least partially empty, so they will be suddenly refilled. A sharp increase in the injection rate of Oort comets in the planetary region will ensue that will last until their loss cones are emptied, which is of the order of their typical orbital period P (about $10^6 yr$). Afterwards the Oort cloud will relax to the state previous to the perturbation. Hills (1981) called such a sudden enhancement in the cometary flux a *comet shower.*

The intensity of a comet shower will depend on the external perturber and on the degree of central condensation of the Oort cloud. For a heavily concentrated Oort cloud, a close stellar passage at $D_{\odot} \sim 10^4 AU$ can trigger a comet shower $\sim 10^2$ times as intense as the background comet flux at average intervals of a few 10^7 years (see numerical results by Heisler 1990 and Fernández 1992). Similar effects can be reached by penetrating encounters with GMCs.

Whether clues to past comet showers can be found in the impact cratering record is a very controversial issue. The problem is that the terrestrial cratering rate is dominated by Earth-crossing asteroids, while the steady-state flux of comets contribute to no more than $\sim 10\%$ (e.g. Bailey 1991, Weissman 1991).A simple estimate shows that the intensity of a comet shower should be at least several 10^2 times greater than the steady-state comet flux to show up in crater statistics.

The evidence that most new comets seem to be deflected to the inner planetary region by tidal torques of the galactic disk -a steady perturber- suggests that the frequency of comet passages is currently near its quiescent level. Comets injected during a shower might greatly exceed the steady supply of Oort comets to the point of erasing or severely weakening the galactic signature in the distribution of aphelion points. Indeed, there are some small aphelion clusterings (e.g. Biermann et al. 1983), suggesting that one or more stars penetrated the Oort cloud in the recent past leading to weak showers, though these seem to contribute to only a minor fraction of the overall aphelion sample.

The invoked association of aphelion clusterings with the solar antapex (e.g. Oja 1975) is another point that awaits elucidation. The major difficulty seems to be the lack of a sound physical reason to explain it. Among some possible explanations we can mention : the capture of a cloud of interstellar comets with low relative velocities in the recent past (Valtonen and Innanen 1982), and Chandrashekar's "dynamical friction" in which the massive Sun -but not the light comets- loses kinetic energy to deflected interstellar particles, thus giving comets a net acceleration in the direction of the solar motion (Brunini 1993). There is the possibility that just by chance a clustering caused by a close stellar passage (Biermann et al. 1983) happens to lie close to the antapex.

2. The Jupiter-Saturn barrier

As mentioned, under the tidal force of the galactic disk Oort comets will mainly change their angular momentum H or their perihelion distance. A change in the transverse velocity Δv_T will be associated to a change in the angular momentum $\Delta H = r \times \Delta v_T$, where Δv_T is given by eq.(1). For a comet in a near-parabolic orbit $H \simeq (2GM_{\odot}q)^{1/2}$, whereby $\Delta H = H/2 \times \Delta q/q$. By taking a time-average distance $r = 1.5a$, we obtain the relative change in the comet's perihelion distance after one orbital revolution as

$$\Delta q/q \simeq 12.7\pi^2 M_{\odot}^{-1} \rho q^{-1/2} a^{7/2} \cos\alpha \sin 2\phi. \tag{2}$$

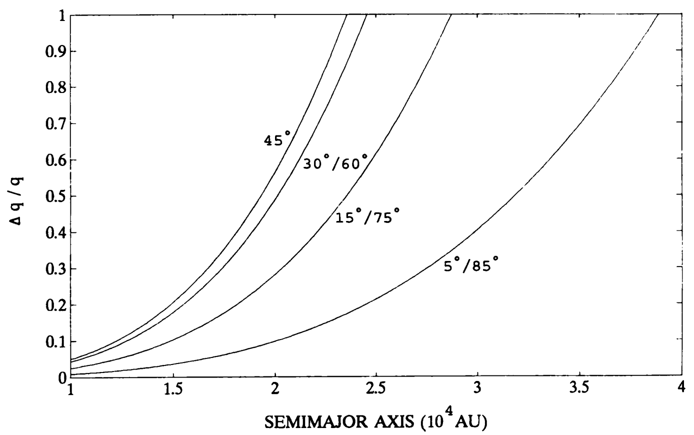

Fig. 2. Relative change in the perihelion distance of Oort comets with original $q = 7.5AU$, as caused by the tidal force of the galactic disk, as a function of their semimajor axes and for the galactic latitudes indicated beside each curve.

Computed values of the relative change $\Delta q/q$ as a function of the comet's semimajor axis a are shown in Fig.2. Note that the ratio $\Delta q/q$ depends on q. We will adopt $q = q_b = 7.5AU$ (Fernández 1992), which represents approximately the boundary between Oort comets strongly perturbed by the planets ($q < q_b$) and those weakly perturbed ($q > q_b$); in other words, the boundary between average energy changes per perihelion passage greater or smaller than $10^{-4} AU^{-1}$, respectively. We see from eq.(2) that Oort comets with rather small values of a, say $\lesssim 1.8 \times 10^4 AU$, have $\Delta q/q \lesssim 0.5$ for all galactic latitudes. Consequently, they will drift in q very smoothly under the action of galactic tidal torques. These results are in reasonable agreement with those obtained analytically by Matese and Whitman (1992) and the orbital calculations of the change in q for the observed sample of near-parabolic orbits carried out by Yabushita (1989).

Since planetary perturbations in the region of Uranus and Neptune are very weak, Oort comets with $a \lesssim 2 \times 10^4 AU$ can actually move back and forth between the Oort cloud and the outer planetary region several times without changing significantly either a or q (Fernández 1981, Weissman 1985). Once an Oort comet reaches the Jupiter-Saturn region during its slow drift in the q phase space, planetary perturbations are already strong enough to remove it from the Oort cloud. It seems then that there is no way for Oort comets with $a \lesssim 2 \times 10^4 AU$ to leap over the Jupiter-Saturn barrier and reach the region of the terrestrial planets where they become observable (Weissman 1985). The situation changes for Oort comets with larger semimajor axes, since they can experience changes in q large enough to leap over the Jupiter-Saturn barrier from the Uranus-Neptune region or beyond to the observable region (say a sphere centered on the Sun of about $3AU$ radius within which most of the discovered comets have their perihelia).

The observed distribution of the original reciprocal semimajor axis $(1/a)_{orig}$ shows a concentration in the range $2 \times 10^{-5} < (1/a)_{orig} < 5 \times 10^{-5} AU^{-1}$ (Fig.3), i.e. semimajor axes in the range $2 - 5 \times 10^4 AU$. The histogram of Fig.3 only takes into account comets with $q > 2AU$ to avoid as much as possible uncertainties in $(1/a)_{orig}$ due to nongravitational forces. The lower limit agrees well with the minimum a derived above for Oort comets to be able to leap over the Jupiter-Saturn barrier. The upper limit may indicate the distance at which the Oort cloud population has decreased substantially, as comets there have ever shorter dynamical lifetimes.

3. The stability limit of the Oort cloud. The inner core

Comets may be removed from the Oort cloud either because they enter the planetary region where they are perturbed by the planets, or because they get enough energy from external perturbers to overcome the gravitational field of the Sun. The latter will be the only loss mechanism for Oort comets whose perihelia lie outside the planetary region. It has become clear that passing stars are not the major external perturbers responsible for pumping up energies of Oort comets to escape velocities. Biermann (1978) pointed out that encounters with GMCs may have a dramatic dynamical influence, causing the disruption of the outer layers of the Oort cloud (e.g. Napier and Staniucha 1982). Typical masses of GMCs are of the order of $1 - 2 \times 10^5 M_\odot$ with mean diameters of $\sim 45pc$ (Blitz 1993). The number of penetrating encounters of the Sun with GMCs during the solar system age is ~ 5, with an uncertainty of a factor ~ 2 (Bailey 1983, Weinberg et al. 1987).

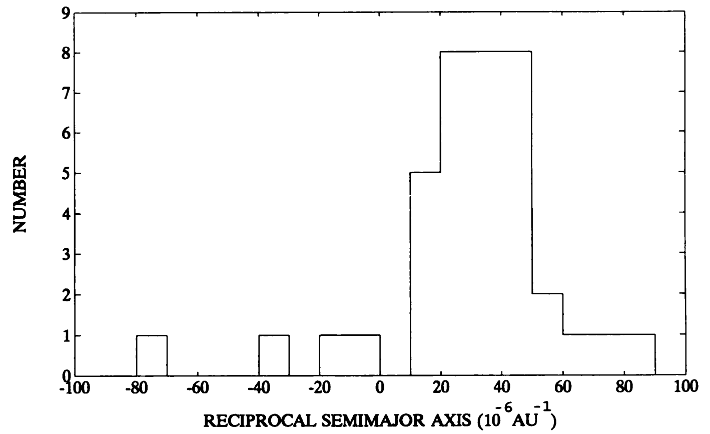

Fig. 3. Distribution of the original reciprocal semimajor axes of the observed new comets with perihelion distances $q > 2AU$ taken from Marsden and Williams (1992) catalogue. Only those comets with good orbit determinations are plotted, which the authors define as being of quality classes 1A and 1B.

GMCs are not uniform entities, but they are composed of numerous dense clumps with a wide range of masses, the largest ones being of the order of a few $10^3 M_\odot$ (Blitz 1993). Actually, during a penetrating encounter with a GMC, the largest dynamical effect on the Oort cloud may be expected to occur during close approaches to some of the most massive clumps (Stern 1990). Soft (nonpenetrating) encounters with GMCs and the more numerous penetrating encounters with less massive molecular clouds will increase somewhat the cumulative velocity perturbation and thus decrease the stability boundary.

Weinberg et al. (1987) showed that binary stars with separations $a \sim 8000AU$ have dynamical lifetimes of the order of the solar system age ($4.6 \times 10^9 yr$)(Fig.4). Hut and Tremaine (1985) found a half-life of $3 \times 10^9 yr$ for comets with $a = 25000AU$ perturbed either by stars or by GMCs; their combined effect will decrease the semimajor axis to values of $\sim 10^4 AU$ over the solar system age. Indeed, some observations tend to confirm the conclusion that the stability boundary is at about $10^4 AU$. For instance, the maximum separations of wide binary stars are of the order of $0.1pc$ (e.g. Latham et al. 1991), and they are even smaller for the presumably older late-type stars. Poveda (1988) concludes that the classical Oort cloud should not be stable over time scales longer than the solar system age for distances greater than a few $10^3 AU$. We then come to the conclusion that the outer or classical Oort cloud -from where Oort comets are driven into the observable region (cf. Fig.3)- must not be primordial. It must have been steadily replenished from a dense inner core throughout the solar system age to make up for the dynamical losses.

The realization that the stability limit of the Oort cloud is smaller than the range of semimajor axes ($2 - 5 \times 10^4 AU$) for which tidal torques of the galactic disk are effective in bringing comets into the planetary region leads to a new concept : the existence of a dense inner core of the Oort cloud. During penetrating encounters

https://doi.org/10.1017/S0074180900046568 Published online by Cambridge University Press

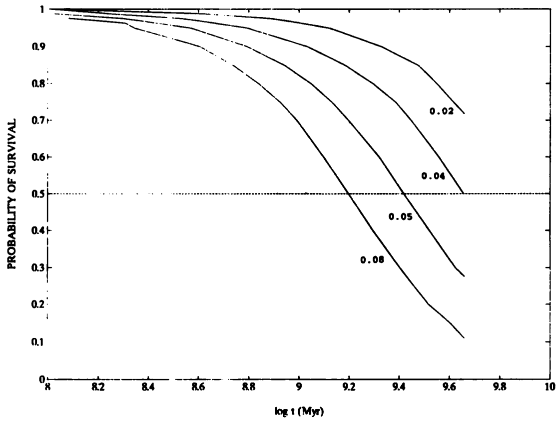

Fig. 4. Probability of survival of binaries with initial semimajor axes indicated beside each graph (in parsecs), subject to perturbations by stars and GMCs. The lifetime $t_{1/2}$ is given by the intersection of these curves with the $P = 0.5$ locus (adapted from Weinberg et al. 1987).

with GMCs or very close stellar passages some comets of the inner core gain enough energy to be transferred to the classical Oort cloud, while others will be directly injected into the planetary region causing a comet shower. The capture of transient Oort clouds from interstellar clouds has been proposed by Clube and Napier (1984) as an alternative to the inner core hypothesis. Yet, serious difficulties with capture theories have been hovering around for quite a long time, such as the very low capture efficiency of interstellar comets that would lead to extremely high mass densities of interstellar comets, or anomalously low encounter velocities, in order to produce enough captures (e.g. Valtonen and Innanen 1982, Zheng et al. 1990), and the lack of observed comets with clearly hyperbolic original orbits (Kresák 1992).

4. Multiple-step capture process of Oort cloud comets by the Jovian planets

Let us now analyze the later evolution of Oort comets injected into the observable region as *new* comets. This evolution can be approximately described as an one-dimensional random-walk in the energy space. The binding energy x of a comet is proportional to the reciprocal semimajor axis $(1/a)$, so we can take $x = (1/a)$. After a passage by the planetary region the comet will be either lost to the interstellar space (i.e. it gets an energy $x < 0$), or it remains bound to the solar system with a new energy $x' = x + \Delta x > 0$. For long-period (LP) comets the orbital energy x is the parameter that experiences the greatest variation during a passage by the planetary region. The changes in the other orbital parameters are much smaller, though their long-term effects may be non-negligible as we will see below for the inclination.

A fraction of the comets coming from the Oort cloud (i.e. energies $x \simeq 0$) can reach a certain energy level $x_f > 0$ under the action of planetary perturbations after a certain number of passages; the rest will be lost along hyperbolic orbits. The probability of capture, p_c, of a LP comet starting in a parabolic orbit to an orbit with energy x_f (assumed to be elliptic, i.e. $x_f > 0$) is given by (Fernández and Gallardo 1993)

$$p_c \simeq 0.5\sigma/x_f, \tag{3}$$

where σ is the typical energy change per passage, which can be expressed by the standard deviation of the distribution function of energy changes $\Psi(\Delta x)$, assumed to be symmetrical with respect to $\Delta x = 0$. We note that Everhart (1969) showed that the distribution of energy changes has asymmetric tails of large values of Δx; nevertheless, the symmetry hypothesis used before is still a good approximation for small Δx. For low-inclination LP comets reaching the observable region, say $q \lesssim 2-3AU$, typical energy changes are : $\sigma \sim 15 \times 10^{-4} AU^{-1}$, while for retrograde orbits $\sigma \sim 6 \times 10^{-4} AU^{-1}$. Introducing these results in eq.(3) we find that the capture probability is $\sim 2-3$ times greater for comets in direct orbits than for retrograde ones. The difference in σ between comets in direct and retrograde orbits is much larger in the outer planetary region (cf. Fernández 1981), which implies a much larger difference in their capture probabilities. We will come back to this point in the next Section. As eq.(3) shows, the capture probability is also inversely proportional to the energy level reached by the comets.

Second-order changes in the inclination may become significant after hundreds of revolutions. The main effect will be a tendency of near-perpendicular comets ($i \sim 90°$) to shift toward retrograde orbits (Fernández and Gallardo 1993). This mechanism can explain the Kreutz family of sungrazers (Bailey et al. 1992). The combined effects of the dependence of the capture probability on the inclination and the shift in inclination, make that the greater losses of retrograde orbits in small-q comets by the first effect are roughly offset by the gains by the second one, so the balance between direct and retrograde orbits is more or less kept throughout the dynamical evolution (Fig.5). When we allow for physical losses by taking a limiting number of revolutions, the resulting i-distribution shows a clear depletion of retrograde orbits in better agreement with the observed i-distribution of *old* LP comets and intermediate-period (IP) comets (say, comets with periods $20 < P < 1000 yr$) and perihelion distances $q < 2AU$. These results suggest that the observed i-distribution of small-q LP comets arises from a combination of dynamical causes and physical losses. The observed depletion of old, retrograde LP comets suggests average lifetimes of a few hundred revolutions before disintegration or deactivation.

Computer results by Fernández and Gallardo (1993) suggest that the steady-state population of IP comets with $q < 2AU$ may be of about 300 comets. The current number of comets detected in this class is 21, so the degree of completeness of the sample may be less than 10%. The difficulties at detecting IP comets are great owing to their extreme faintness; some IP comets may have become inactive, looking asteroidal as may be the case of 1991DA. The capture probability of IP comets into short-period (SP) orbits ($P < 20 yr$) turns out to be very low, of the

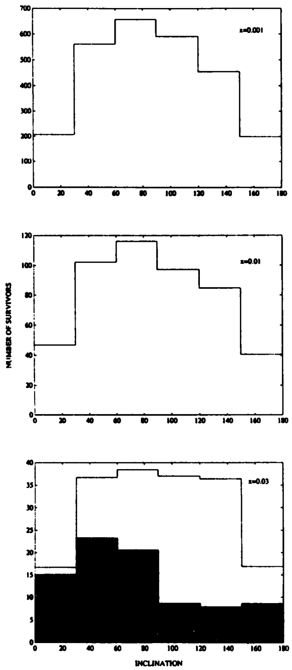

Fig. 5. Computed inclination-distributions of LP comets evolving through successive passages by the planetary region to larger energies x. The shaded histogram is for a simulation that includes physical losses by setting a limiting number of 400 revolutions (Fernández and Gallardo 1993).

order of 10^{-2}, leading to steady-state populations of captured SP comets one-two orders of magnitude too small as compared to the observed population.

5. The Jupiter family. Possible source regions

SP comets ($P < 20yr$) or Jupiter family comets form a very peculiar group clearly distinguished from a dynamical viewpoint from the other comets of longer periods. First, they have low-inclination orbits and their values of the Tisserand constant T are mainly concentrated in the range $2.5 \lesssim T \lesssim 3$, whereas the observed comets with longer periods have lower T values; for $q < 2AU$ these fall in the range $-2 < T < 2$ (Fig.6). The aphelia of SP comets tend to be concentrated around Jupiter's orbit and, in particular, around its perihelion which shows the dominant role of Jupiter in their dynamical evolution. There is a question of nomenclature that is convenient to analyze very briefly. Sometimes the term "short-period" is applied to all comets with $P < 200$ yr. Now, there is a clear distinction around $P \sim 20yr$ in the sense that comets with periods $20 < P < 200yr$, classically called "intermediate-period" comets, or more recently Halley-type comets, have Tisserand constants $T < 2$ like the ones of LP comets. On the other hand, SP comets or Jupiter family comets have $T > 2$, with only three exceptions so far : P/Tuttle, P/IRAS and P/Machholz.

Therefore, the classification of comets according to their orbital periods continues to be very useful and with some dynamical basis, adding perhaps the Tisserand constant to discriminate some uncertain cases, as Valsecchi (1992) suggested.

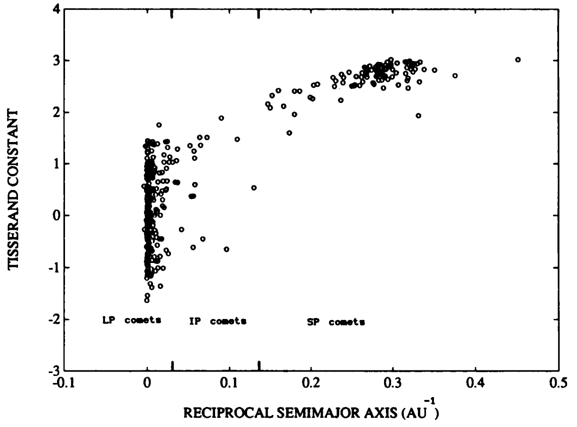

Fig. 6. Plot of the Tisserand constant T versus the reciprocal semimajor axis of the observed LP comets with well determined osculating values of $1/a$, IP comets and SP comets. We only considered comets with $q < 2AU$ for all the dynamical classes.

Much attention has been paid to the dynamical evolution of SP comets and their physical decay, which is of paramount importance to assess their population size, distribution of perihelion distances and their interrelationship with the Apollo-Amor asteroids and the meteoroidal complex. Tancredi and Rickman (1992) have carried out long-term orbital integrations of the observed Jupiter-family comets over $2000yr$ centered on the present time. They find that the mean values of q, a and i are minimum near the present. The minimum of the mean q (and mean a) may possibly be due to observational selection effects, since we tend to discover SP comets when they get closer to the Sun. The slope of the mean-q values of SP comets is steeper in the past than in the future, which was interpreted by Fernández (1985) in terms of an average physical lifetime of $\sim 10^3$ revolutions ($\sim 10^4 yr$). Tancredi and Rickman found a less pronounced past-future asymmetry which would imply a longer physical lifetime. Orbital integrations of all the known SP comets over $\pm 10^7 yr$ by Levison and Duncan (1993a) fully corroborated the minimum in the mean i at present. Why the system is so flat at present is interpreted by Levison and Duncan as due to a recent capture of comets from a flat source. As the system evolves -either into the past or into the future- it becomes much less flat as SP comets tend to occupy all the possible dynamical niches but, as the authors argue, such an evolved system of SP comets can never be observed due to their short physical lifetimes as compared to their dynamical ones.

The origin of the Jupiter family has been visualized as the dynamical end product of Oort comets captured by Jupiter through many revolutions (e.g. Everhart 1972).

There are however several independent results in conflict with this hypothesis as, for instance, the failure to produce the right number of SP comets (e.g. Joss 1973, Fernández and Ip 1983) and some computed i-distributions that yield a significant fraction of SP comets in retrograde orbits (Duncan et al. 1988, Wetherill 1991). Computed distributions of T and q are also in conflict with the observed ones (Fernández and Gallardo 1993). For instance, computed q-distributions tend to be uniform within Jupiter's orbit, while the observed one suggests a very steep increase in the number of SP comets with q, at least up to $q \sim 2.5AU$ (Fernández et al. 1992).

Given the above difficulties one has to ask whether there may be more suitable comet sources for the Jupiter family. Comets like P/Schwassmann-Wachmann 1 in the Jupiter-Saturn region may be suitable progenitors. It moves on a low-inclination ($i = 9°.4$), low-eccentricity ($e = 0.045$) orbit and has a Tisserand constant $T = 2.98$, i.e. within the range of most SP comets. Indeed P/S-W 1 may belong to a large transient population of about 30,000-100,000 comets (Delsemme 1973), large enough to keep the population of SP comets in steady-state. Such comets with $T \approx 3$ have very low relative velocities with Jupiter, so captures as temporary satellites can occur rather frequently (Carusi and Valsecchi 1981). The recently discovered comet P/Shoemaker-Levy 9(1993e) on an orbit similar to Jupiter's (IAU Circular No.5800) can be a nice example of such a kind of objects.

Since comets in the Jupiter-Saturn region have rather short dynamical lifetimes (Gladman and Duncan 1990), they must be continuously replenished from a source in the outer planetary region. Chiron may be representative of this more distant population (the sample of discovered outer solar system objects is growing very fast). The question is whether suitable storage places of outer solar system bodies exist within the planetary region. From several surveys, Shoemaker et al. (1993) have found that the number of Trojans with diameters $> 15km$ associated to the Lagrange $L4$ and $L5$ points should be of several thousand. The Trojan population down to a radius $\sim 1km$ would be of some 10^5 bodies. It is then possible that some comet-like bodies in the Jupiter's zone with a Tisserand constant $T \sim 3$ are indeed escaped Trojans as already argued by Rabe (1972). Trojan-like swarms might be associated to the Lagrange $L4$ and $L5$ points of the other Jovian planets, for which preliminary integrations tend to confirm long dynamical survivals (Holman and Wisdom 1993). Whether these might be suitable sources to provide low-inclination comets, via slow dissipation from the swarms, has to be assessed through future surveys and studies of their dynamical stability.

A possibility is that the transient populations between the giant planets mainly come from the capture of Oort comets by Saturn, Uranus and Neptune (Bailey 1986). The capture efficiency of these planets should be studied in more detail as well as their dependence on the orbital inclination; in other words, its capability to sort out high-inclination comets in order to produce a flat population of SP comets. Some preliminary results (Duncan et al. 1988, Wetherill 1991) seem to indicate that a fraction of comets with initial random inclinations in Neptune-crossing orbits will be captured in retrograde SP orbits with $q < 1.5AU$, which would argue against this source.

The results presented by Duncan et al. (1988) have been criticized by Stagg and

Bailey (1989) because of the use of artificially high masses for the giant planets in order to speed up the computations. We also note that Duncan et al. start to follow the capture process to SP orbits from comets with perihelia in the range $20 < q < 30AU$ and semimajor axis $a = 50AU$(i.e. an energy $x = 0.02AU^{-1}$), for which they assume an isotropic, prograde distribution of inclinations (i.e. uniform in $\cos i$ between 0 and 1). Now, it is very likely that the inclination distribution of comets that reach the energy level $x = 0.02AU^{-1}$ has already departed very substantially from an isotropic distribution (cf. Section 4). As eq.(3) shows, the capture probability to a certain energy state is proportional to the typical energy change σ. Now, in the outer planetary region σ decreases very sharply with the inclination, in such a way that : $\sigma(i \sim 0) \sim 10\sigma(i \sim 180°)$ (Fernández 1981), so the capture of Oort comets to the energy level $x = 0.02AU^{-1}(a = 50AU)$ will be strongly biased toward low-inclination orbits. Wetherill (1991) has used Öpik's two-body formalism to study the capture of parabolic comets with perihelia in the range $20 - 30AU$ into Jupiter-family comets with $q < 1.5AU$. He also finds that a fraction of the computed Jupiter-family comets will have retrograde orbits. Even though Wetherill is able to simulate the capture process without need of artificially increasing the masses of the Jovian planets, the problem is that Öpik's method can only handle strong perturbations in close encounters, which is not well suited to follow the dynamical evolution of comets starting in near parabolic orbits.

The above difficulties strongly favors to review the whole subject of comet capture by the Jovian planets in a more realistic way, namely adopting for the Jovian planets their actual masses and following the orbital evolution from the beginning as near parabolic comets to their final capture as SP comets.

Another interesting possibility -perhaps the most promising one- is that most Jupiter-family comets come from a comet reservoir located beyond Neptune. On cosmogonic grounds, Kuiper (1951) explained such a reservoir on the basis of residual planetesimals left after the formation of Neptune in the region between $30 - 50AU$. The *Kuiper belt* -as it was named- would have a strongly flattened, ring-shaped structure, which would explain the i-distribution of the observed SP comets. The recent discoveries of objects 1992QB1 and 1993FW located at about $40AU$ (Jewitt and Luu 1993 and IAU Circ.5370), may represent the first direct detections of bodies belonging to the Kuiper belt (for more information see Luu, this volume).

6. Kuiper belt dynamics

The question now is what might be the mechanism(s) responsible for the scattering of Kuiper belt comets to Neptune-crossing orbits. Once belt comets become Neptune-crossers, they can be handed down to the control of the other Jovian planets, so a fraction of them may end up incorporated to the Jupiter family (Fernández 1980). The existence of a number of lunar-sized objects within the belt might provide the required stirring effect (Fernández 1980, Ip and Fernández 1991). Based on the tilt of Uranus's orbit, the binary system Pluto-Charon and the retrograde orbit of Triton, Stern (1991) also argues that a primordial population of $10^3 - km$ size bodies existed in the $20 - 50AU$ region. The problem is that no such large objects have so far been discovered through several sky surveys (e.g. Luu and

Jewitt 1988, Kowal 1989, Levison and Duncan 1990), which put severe constraints on the size of the largest objects that might remain undetected in the belt. The conclusion seems to be that if such large bodies existed in the early solar system, all of them -except Pluto- are by now gone.

A major issue to be solved concerns the orbital stability of bodies stored in the Kuiper belt. The dynamical evolution of small, gravitationally noninteracting objects in the outer solar system was examined numerically by Torbett (1989) and Gladman and Duncan (1990) among others. Torbett found that the orbits of bodies initially located at radial distances less than $50AU$ will become chaotic and be quickly perturbed to Neptune-crossing orbits within $10^8 yr$, though this result will depend on their initial eccentricities and inclinations. The distinction between chaotic and regular orbits was set by determining whether the Lyapunov exponent tended to zero or to a certain positive constant within the computed period. Gladman and Duncan also concluded that orbits of small bodies that start on circular orbits within $34AU$ will become Neptune-crossers in about $20Myr$. These results suggest that the inner edge of the Kuiper belt should be detached from Neptune's orbit by several AU.

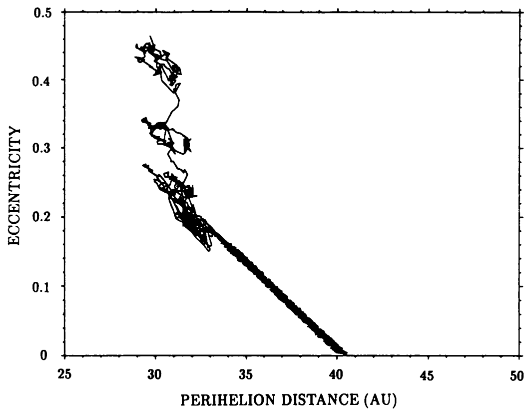

Fig. 7. Dynamical evolution in the parametric plane (q, e) of a hypothetical Kuiper-belt body initially on a circular orbit located in the invariable plane. Lines of constant semi-major axis are diagonal (Holman and Wisdom 1993).

Much more extensive numerical integrations over periods up to $10^9 yr$ have very recently been undertaken by Holman and Wisdom (1993) and Levison and Duncan (1993b) by means of a very efficient symplectic integration technique. These studies help to shed some light on the dynamical structure of the Kuiper belt. They show that the inner edge of the belt is depleted as comets become Neptune-crossers. The erosion rate of the belt follows a rather complex pattern with the heliocentric distance, where bumps are noted at the 3 : 2 and 2 : 1 mean motion resonances with Neptune (at about $40AU$ and $48AU$, respectively). It is very likely that the

https://doi.org/10.1017/S0074180900046568 Published online by Cambridge University Press

depletion within $\sim 35AU$ over the solar system age is essentially complete, and that the belt has been very heavily eroded up to $\sim 45AU$. Holman and Wisdom depict very nicely how belt comets on initially near-circular orbits beyond the planetary region evolve until they become Neptune-crossers (see Fig.7). Their results show that belt comets first tend to evolve in eccentricity and perihelion distance, keeping their semimajor axes more or less constant (represented by a diagonal in the plane (q, e)). When they become Neptune-crossers the evolution mainly proceeds in a and e, keeping in this case q more or less constant (a vertical line in the plane (q, e)). Thus, belt comets seem to diffuse through chaotic zones associated to mean motion and secular resonances in a dynamical process resembling the delivery of meteorites to the Earth's zone.

7. Summary and conclusions

In short, we can mention as some of the major advances in our understanding of comet dynamics the following :

1) Tides of the galactic disk exert a dominant influence on the evolution of the angular momentum of Oort comets and thus on the rate at which their perihelia are injected into the planetary region. This reflects in the concentration of the aphelion points of new and dynamically young comets at mid-galactic latitudes. Background stars play a minor role : they can overcome galactic tides only close to the galactic equator or the galactic poles ($|\phi| \lesssim 15°$ or $|\phi| \gtrsim 75°$).

2) The rather smooth injection of Oort comets by the quasi-steady action of galactic tidal torques and background stars is punctuated from time to time by sudden enhancements in the injection rate triggered by penetrating encounters with GMCs or very close stellar passages. There is no evidence of a shower occurring at present, though weak showers in the recent past cannot be ruled out as some small aphelion clusterings suggest.

3) The Oort cloud is dynamically unstable over the solar system age for $a \gtrsim 10^4 AU$. Penetrating encounters with GMCs and close stellar passages are responsible for disrupting the outer layers of the Oort cloud. Since most observed new comets have original semimajor axes in the range $2 - 5 \times 10^4 AU$, they may have been placed there from an inner core over time scales shorter than the solar system age. Hence the inner core appears as a necessary device to maintain the unstable, classical Oort cloud.

4) The Jupiter-Saturn barrier can be overshot by Oort comets with $a \gtrsim 2 \times 10^4 AU$ at mid-galactic latitudes (say, $\phi \sim 30° - 60°$), for which galactic tidal torques are able to sharply decrease the perihelion distances to the observable range after one revolution.

5) The observed LP comets and IP comets can be explained by a multiple-step capture process by Jupiter. The strong depletion of retrograde orbits among the old LP comets ($P \lesssim 10^3 yr$) and IP comets of perihelion distances $q < 2AU$ may be due to physical losses, implying average physical lifetimes of a few 10^2 revolutions.

6) The origin of SP or Jupiter-family comets is still controversial. The capture of comets by Jupiter from a spherical source (either the Oort cloud or the inner core) leads to a fraction of SP comets in retrograde orbits, which is not observed.

The computed values of the Tisserand constant, the distribution of the perihelion distances and the capture efficiency are also in disagreement. Additional captures of Oort comets by Saturn, Uranus and Neptune might not solve the previous discrepancies, though this is a point that deserves further study. A few storage places might still exist within the planetary region around the Lagrange $L4$ and $L5$ points of the Jovian planets (i.e. Jupiter's Trojan swarms and similar swarms for the other Jovian planets). An alternative and promising view is that SP comets come from a transneptunian comet belt, known as the Kuiper belt.

7) The problem of the dynamical stability of comets in the Kuiper belt and the rate at which they can be transferred to the planetary region is still open. Some preliminary numerical results seem to indicate that the belt has been completely depleted by planetary perturbations within $\sim 35AU$. The dynamical time scales for belt comets originally on near-circular orbits to become Neptune-crossers are of the order of the solar system age in the range $\sim 35-50AU$. Therefore, this may be the region of the belt undergoing the stronger depletion at present and, at the same time, the most suitable place to provide SP comets.

Acknowledgements

I thank G. B. Valsecchi and another anonymous referee for their useful comments on the manuscript.

References

Bailey, M.E. : 1983 "The structure and evolution of the Solar System comet cloud." ***Mon. Not. Roy. Astron. Soc.*** **204**, 603–633.

Bailey, M.E. : 1986 "The near-parabolic flux and the origin of short-period comets." ***Nature*** **324**, 350–352.

Bailey, M.E. : 1991 "Comet craters versus asteroid craters." ***Adv. Space Res.*** **11**, 43–60.

Bailey, M.E., Chambers, J.E., and Hahn, G. : 1992 "Origin of sungrazers : a frequent cometary end-state." ***Astron. Astrophys.*** **257**, 315–322.

Biermann, L. : 1978 "Dense interstellar clouds and comets." In ***Astronomical Papers dedicated to Bengt Strömgren*** (A. Reiz and T. Anderson, Eds.), 327–336, Copenhagen Observatory.

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

Blitz, L. : 1993 "Giant molecular clouds." In ***Protostars and Planets III*** (E.H. Levy and J.I. Lunine, Eds.), 125–161, Univ. of Arizona Press, Tucson.

Brunini, A. : 1993 "Dynamical friction induces perturbations on Oort cloud comets." ***Astron. Astrophys.*** **273**, 684–694.

Byl, J. : 1983 "Galactic perturbations on near-parabolic cometary orbits." ***Moon and Planets*** **29**, 121–137.

Carusi, A., and Valsecchi, G.B. : 1981 "Temporary satellite captures of comets by Jupiter." ***Astron. Astrophys.*** **94**, 226–228.

Clube, S.V.M., and Napier, W.M. : 1984 "Comet capture from molecular clouds : a dynamical constraint on star and planet formation." ***Mon. Not. Roy. Astron. Soc.*** **208**, 575–588.

Delsemme, A.H. : 1973 "Origin of the short-period comets." ***Astron. Astrophys.*** **29**, 377–381.

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

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

Everhart, E. : 1969 "Close encounters of comets and planets." ***Astron. J.*** **74**, 735–750.

Everhart, E. : 1972 "The origin of short-period comets." ***Astrophys. Lett.*** **10**, 131–135.

Fernández, J.A. : 1980 "On the existence of a comet belt beyond Neptune." ***Mon. Not. Roy. Astron. Soc.*** **192**, 481–491.

Fernández, J.A. : 1981 "New and evolved comets in the solar system." ***Astron. Astrophys.*** **96**, 26–35.

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

Fernández, J.A. : 1992 "Comet showers." In ***Chaos, Resonance and Collective Dynamical Phenomena in the Solar System*** (S. Ferraz-Mello, Ed.), , IAU Symp. No.152, 239–254, Kluwer, Netherlands.

Fernández, J.A., and Gallardo, T. : 1993 "The transfer of comets from parabolic orbits to short-period orbits : numerical studies." ***Astron. Astrophys***, in press.

Fernández, J.A., and Ip W.-H. : 1983 "Dynamical origin of the short-period comets." In ***Asteroids, Comets, Meteors*** (C.-I. Lagerkvist and H. Rickman, Eds.), 387–390 , Uppsala University.

Fernández, J.A., and Ip W.-H. : 1991 "Statistical and evolutionary aspects of cometary orbits." In ***Comets in the Post-Halley Era*** (R.L. Newburn, M. Neugebauer, and J. Rahe, Eds.), IAU Coll. No. 121, 487–535, Kluwer, Netherlands.

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

Gladman, B. and Duncan, M. : 1990 "On the fates of minor bodies in the outer solar system." ***Astron. J.*** **100**, 1680–1696.

Heisler, J. : 1990 "Monte Carlo simulations of the Oort comet cloud." ***Icarus*** **88**, 104–121.

Heisler, J. and Tremaine, S. : 1986 "The influence of the galactic tidal field on the Oort comet cloud." ***Icarus*** **65**, 13–26.

Hills, J.G. : 1981 "Comet showers and the steady-state infall of comets from the Oort cloud." ***Astron. J.*** **86**, 1730–1740.

Holman, M.J., and Wisdom, J. : 1993 "Dynamical stability in the outer solar system and the delivery of short period comets." ***Astron. J.*** **105**, 1987–1999.

Ip, W.-H., and Fernández, J.A. : 1991 "Steady-state injection of short-period comets from the trans-Neptunian cometary belt." ***Icarus*** **92**, 185–193.

Jewitt, D., and Luu, J. : 1993 "Discovery of the candidate Kuiper belt object 1992QB1", ***Nature*** **362**, 730–732.

Joss, P.C. : 1973 "On the origin of short-period comets." ***Astron. Astrophys.*** **25**, 271–273.

Kowal, C.T. : 1989 "A solar system survey." ***Icarus*** **77**, 118–123.

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

Kuiper, G.P. : 1951 "On the origin of the solar system." In ***Astrophysics*** (J.A. Hynek, Ed.), 357–427 , McGraw-Hill, New York.

Latham, D.W., Mazeh, T., Davis, R.J., Stefanik, R.P., and Abt, H.A. : 1991 "A search for wide binaries in the north galactic pole using precise radial velocities." ***Astrophys. J.*** **101**, 625–636.

Levison, H.F., and Duncan, M.J. : 1990 "A search of proto-comets in the outer regions of the solar system." ***Astron. J.*** **100**, 1669–1675.

Levison, H.F., and Duncan, M.J. : 1993a Submitted to ***Icarus***.

Levison, H.F., and Duncan, M.J. : 1993b "The gravitational sculpting of the Kuiper belt." ***Astrophys. J.*** **406**, L35–L38.

Luu, J.X., and Jewitt, D. : 1988 "A two-part search for slow-moving objects." ***Astron. J.* 95**, 1256–1262.

Marsden, B.G., and Williams, G.V. : 1992 ***Catalogue of Cometary Orbits, Seventh Edition***, Smithsonian Astrophys. Center.

Matese, J.J., and Whitman, P.G. : 1992 "A model of the galactic tidal interaction with the Oort comet cloud." ***Cel. Mech. Dyn. Astron.* 54**, 13–35.

Napier, W.M., and Staniucha, M. : 1982 "Interstellar planetesimals - I. Dissipation of a primordial cloud of comets by tidal encounters with massive nebulae." ***Mon. Not. Roy. Astron. Soc.* 198**, 723–735.

Oja, H. : 1975 "Perihelion distribution of near-parabolic comets." ***Astron. Astrophys.* 43**, 317–319.

Poveda, A. : 1988 "Distant components in double and multiple stars." ***Astrophys. Space Sci.* 142**, 67–78.

Rabe, E. : 1972 "Orbital characteristics of comets passing through the 1 : 1 commensurability with Jupiter." In ***The Motion, Evolution of Orbits, and Origin of Comets*** (G.A. Chebotarev, E.I. Kazimirchak-Polonskaya and B.G. Marsden, Eds.), IAU Symp. No. 45, 55–60, Kluwer, The Netherlands.

Rickman, H. : 1976 "Stellar perturbations of orbits of long-period comets and their significance for cometary capture." ***Bull. Astron. Inst. Czech.* 27**, 92–105.

Shoemaker, E.M., Shoemaker, C.S., and Levison, H.F. : 1993 "Survey of the Jupiter Trojans." Presented at ***Asteroids, Comets, Meteors 1993***, IAU Symp.160, Belgirate, Italy.

Stagg, C.R., and Bailey, M.E. : 1989 "Stochastic capture of short-period comets." ***Mon. Not. Roy. Astron. Soc.* 241**, 507–541.

Stern, S.A. : 1990 "External perturbations on distant planetary orbits and objects in the Kuiper belt." ***Cel. Mech. Dyn. Astron.* 47**, 267–273.

Stern, S.A. : 1991 "On the number of planets in the outer solar system : evidence of a substantial population of 1000-km bodies." ***Icarus* 90**, 271–281.

Tancredi, G., and Rickman, H. : 1992 "The evolution of Jupiter family comets over 2000 years." In ***Chaos, Resonance and Collective Dynamical Phenomena in the Solar System*** (S. Ferraz-Mello, Ed.), , IAU Symp. No.152, 269–274, Kluwer, Netherlands.

Torbett, M.V. : 1989 "Chaotic motion in a comet disk beyond Neptune : the delivery of short-period comets." ***Astron. J.* 98**, 1477–1481.

Tremaine, S. : 1993 "The distribution of comets around stars." In ***Planets around Pulsars*** (J.A. Phillips, S.E. Thorsett and S.R. Kulkarni, Eds.), Astron. Soc. Pacific Conf. Series, in press.

Valsecchi, G.B. : 1992 Round Table on Dynamics of Periodic Comets, In ***Workshop on Periodic Comets*** (J.A. Fernández and H. Rickman, Eds.), 98–100 , Univ. República, Montevideo.

Valtonen, M.J. and Innanen, K.A. : 1982 "The capture of interstellar comets." ***Astrophys. J.* 255**, 307–315.

Weinberg, M.D., Shapiro, S.L., and Wasserman, I. : 1987 "The dynamical fate of wide binaries in the solar neighborhood." ***Astrophys. J.* 312**, 367–389.

Weissman, P.R. : 1980 "Stellar perturbations of the cometary cloud." ***Nature* 288**, 242–243.

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.), IAU Coll. No. 83, 87–96, Reidel, The Netherlands.

Weissman, P.R. : 1991 "The cometary impactor flux at the Earth." In ***Global Catastrophes in Earth History*** (V. Sharpton and P. Ward , Eds.), GSA Special Papers 247, 171–180.

Wetherill, G.W. : 1991 "End-products of cometary evolution : cometary origin of Earth-crossing bodies of asteroidal appearance." In ***Comets in the Post-Halley Era*** (R.L. Newburn Jr., M. Neugebauer and J. Rahe, Eds.), Proc. IAU Coll. No. 121, 537–556, Kluwer, The Netherlands.

Yabushita, S. : 1989 "On the orbital elements of nearly parabolic comets at previous returns as perturbed by the galactic tidal field." ***Astron. J.*** **97**, 262–264.

Zheng, J.-Q., Valtonen, M.J., and Valtaoja, L. : 1990 "Capture of comets during the evolution of a star cluster and the origin of the Oort cloud." ***Cel. Mech. Dyn. Astron.*** **49**, 265–272.