SECTION II

THE OORT CLOUD OF COMETS

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THE FORMATION AND DYNAMICAL SURVIVAL OF THE COMET CLOUD

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ABSTRACT. The theory of a huge reservoir of comets (the "comet cloud") extending to almost interstellar distances is analyzed, paying special attention to its dynamical stability, formation process and orbital properties of the incoming cloud comets. The perturbing influence of passing stars and giant molecular clouds is considered. Giant molecular clouds may be an important perturbing element of the comet cloud, although they do not seem to change drastically former studies including only stellar perturbations. The more tightly bound inner portions of the comet cloud, say within 10^4 AU, would have withstood the disrupting forces over the age of the solar system. The theory of a primordial comet origin in the outer planetary region close to Neptune's orbit is specially analyzed. A primordial comet origin is consistent with the cosmogonic view that a large amount of residual material was ejected during the last stage in the formation of the Jovian planets. The smooth diffusion in the energy space of bodies scattered by Neptune guarantees that most of them will fall in the narrow range of energies close to zero (near-parabolic orbits) where passing stars and GMCs can act effectively on them. The long time scales of $\sim 10^9$ yr required for bodies scattered by Neptune to reach near-parabolic orbits would indicate that the buildup of the comet cloud was an event that took place long after the planets formed. Depending on the field of perturbing galactic objects, it is possible to conceive that most scattered comets were stored in rather tightly bound orbits ($a \sim 10^4$ AU), favoring the concept of their dynamical survival over several billion yr. Alternative theories of comet cloud formation, e.g. in-situ origin or interstellar capture, are also discussed. The main difficulty of the in-situ theory is to explain how comets could accumulate at large heliocentric distances where the density of the nebular material was presumably very low. The interstellar capture theory also meets severe dynamical objections as, for instance, the lack of observed comets with original strongly hyperbolic orbits and the extremely low probability of capture under most plausible conditions. Since our knowledge of the structure of giant molecular clouds and their frequency of encounters with the solar system is still very uncertain, the concept of capture of transient comet clouds during such encounters can be advanced very little beyond the speculative stage. Some other

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dynamical properties of relevance to theories of origin and structure of the comet cloud are also reviewed. We mention, for instance, the distribution of perihelion points on the celestial sphere. There seems to be here a well established deviation from randomness, although the debate on whether or not there is a preference of the perihelion clustering for the vicinity of the apex of the solar motion is still unsettled. The alleged correlation with the solar apex may be biased by the preference of comet discoveries in the northern hemisphere. Deviations from randomness might be caused by very close stellar passages in the recent past. The excess of retrograde orbits among the observed "new" and young comets - mainly those with $q \gtrsim 2$ AU - is another well known dynamical feature. Such an excess may probably be accounted for by the combined action of planetary and stellar perturbations. Because of the decreasing action of planetary perturbations with increasing heliocentric distances, a significant increase in the rate of passages of long-period comets is predicted for the outer planetary region.

1. OBSERVATIONAL BACKGROUND

The theory of a huge reservoir of comets surrounding the solar system (the "comet cloud") was developed by Oort (1950). Assuming that the comet cloud was thermalized by stellar perturbations, Oort was able to derive a cloud population of 2×10^{11} comets by comparing the expected theoretical influx rate of near-parabolic comets with the observed one. A somewhat smaller cloud population of a few times 10^{10} comets has been given by Fernández (1982) by arguing that cloud comets have kept rather eccentric orbits up to the present. On the other hand, Weissman (1983) obtains a much higher population of 1.4×10^{12} comets in correspondence with his assumption of a higher influx rate of near-parabolic comets. Given the different estimates of the cloud population and the average comet mass, large uncertainties are involved in any estimate of the cloud mass although several authors seem to agree that it should be of the order of a few $M_\oplus$ (Oort 1950, Öpik 1973, Fernández 1982, Weissman 1983). Given the uncertainties, this should be taken as a very preliminary result. Although the theory of the comet cloud has been questioned by some authors (e.g. Lyttleton 1974, Yabushita 1979), their criticisms have not weakened its appeal arisen from its capability for explaining some rather puzzling properties of long-period comets as we shall see below.

Comets with orbital periods P > 200 yr are usually referred to as long-period (LP) comets. One of their most important orbital parameters is certainly the "original" semimajor axis, a_{orig}, i.e. before being perturbed by the planets, that gives information about the place where LP comets come from. The orbital energy per unit mass, ε, is proportional to the reciprocal semimajor axis, $(-1/a)$, where a binding (negative) energy corresponds to an elliptc (positive a) orbit. Choosing conveniently the units we can thus set $\varepsilon = -1/a$. As seen in Fig. 1, the energy distribution of the original orbits of LP comets shows a strong concentration in the narrow range -10^{-4} AU^{-1} < ε < 0, that corresponds to near-parabolic comets reaching heliocentric distances greater than

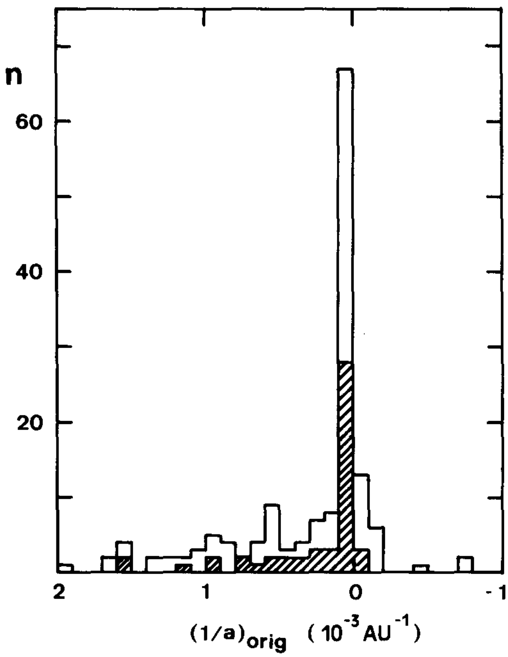

Figure 1. Distribution of the original reciprocal semimajor axes of LP comets with $(1/a)_{orig} < 2\times10^{-3}AU^{-1}$ as computed by Marsden et al. (1978) and Everhart and Marsden (1983). The shaded histogram is for those comets with $q > 2$ AU.

$\sim 2\times10^4$AU. Oort argued that these comets were driven into the planetary region by stellar perturbations. For this reason he called them "new" on the belief that they were passing through the planetary region for the first time. We will show that most of the so-called new comets have probably passed before through the planetary region, so to avoid confusions we shall use the term "cloud comets" for those with $\varepsilon > -10^{-4}AU^{-1}$ ($a_{orig}>10^4$AU). Marsden and Sekanina (1973) noted a clustering of aphelion distances around 5×10^4AU which defines the "radius" of the comet cloud.

We also note in Fig. 1 the lack of comets with strongly hyperbolic orbits ($1/a_{orig} << 0$) which seems to rule out an interstellar origin. This conclusion is strengthened when only comets with perihelion distances $q>2$ AU are considered (shaded histogram). Very few comets remain with $1/a_{orig} < 0$ which suggests that negative values of $1/a_{orig}$ are probably caused by nongravitational forces (cf. Marsden et al. 1978).

In contrast to the rest of the known solar system bodies, LP comets show an almost random distribution of their orbital inclinations i (Fig. 2). Some departure from randomness is clearly indicated by the observed excess of retrograde orbits. This effect becomes more pronounced when only comets with q>2 AU are considered (shaded histogram).

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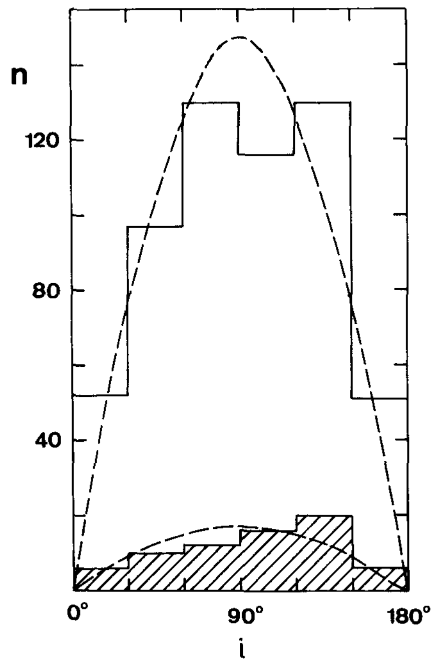

Figure 2. Inclination distribution of the LP comets appearing in Marsden's (1982) catalogue. The nine members of the Kreutz family have been considered as a single comet. The shaded histogram corresponds to the partial sample of LP comets with q > 2 AU. The (dashed) sine-curves correspond to random i-distributions.

The q-distribution of LP comets with q < 1.1 AU and discovered after 1800 is shown in Fig. 3. The choice of this rather restricted sample has the purpose of avoiding as much as possible the bias against the discovery of comets with larger q. LP comets show a steady decrease toward smaller perihelion distances. However, when only dynamically young comets with $a_{orig} > 10^3$ AU are considered, the q-distribution turns out to be rather uniform. The decrease in the number of LP comets whith decreasing q is probably an evolutionary effect due to physical decay of comets in one or a few perihelion passages (Fernández 1981a).

A departure from randomness has long been noted in the distribution of perihelion points on the celestial sphere (e. g. Tyror 1957, Hurnik 1959). The crucial point is whether there is a correlation between the direction of the solar apex and the preferred direction of the perihelia. Oja (1975) found the preferred perihelia direction to be only 7° from the solar apex. Fernández and Jockers (1982) argue however that the predominance of comet discovery in the northern hemisphere introduces a bias favoring such correlation. In this respect, Bogart and Noerdlinger (1982) find that when they only consider LP comets discovered in the 20th century - which are presumably less biased to the north - the preferred perihelia direction moves to about 50° from the solar apex.

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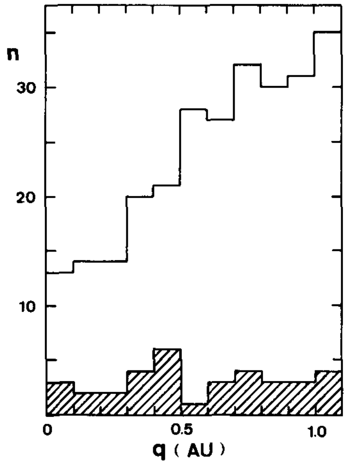

Figure 3. Distribution of the perihelion distances of LP comets with q<1.1 AU observed after 1800 as recorded in Marsden's (1982) catalogue. The shaded histogram corresponds to "new" and "young" comets with $a_{orig} > 10^3$AU.

2. FORMATION OF THE COMET CLOUD

Most authors seem to agree at present about the existence of an extended cloud of comets surrounding the solar system. Yet various views on how and when such a cloud formed appear in the literature. We can consider three fundamental currents of opinion:

a) Primordial origin. The basic idea is that comets are a byproduct of the planet formation. Some authors take this as equivalent to saying that the comet cloud is nearly as old as the solar system (cf. Oort 1950). The implicit argument is that diffusion time scales from the planetary region to the Oort region are very short as compared to the solar system age. We shall see that this might not be the case.

The primordial theory of comet origin is based on the assumption, supported by several theoretical and numerical studies, that the Jovian planets could not have reached their present masses without the ejection of a large amount of residual matter (e.g. Safronov 1969, 1972). Furthermore, some recent numerical studies have shown that bodies starting out in the outer planetary region can evolve under the combined action of planetary and stellar perturbations into Oort-cloud-type orbits (Fernández 1980, Fernández and Ip 1981, Weissman 1982).

Napier and Staniucha (1982) and Clube and Napier (1984) have criticized the theory of a primordial comet origin on the basis that an extended comet cloud would not have survived over the age of the solar system. We shall return to discuss further some aspects of this theory in Section 7.

b) In-situ formation. Some authors have proposed that comets formed in the outer regions of the collapsing solar nebula (Cameron 1973, Bier-

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mann and Michel 1978, Hills 1982). Such comets might have filled the circumsolar space up to distances of 10^3-10^4AU. Perturbations from giant molecular clouds and passing stars could remove comets from the outer portions of this more tightly bound cloud giving rise to transient loosely bound comet clouds (Bailey 1983a).

The main criticism to the in-situ theory is the seemingly lack of physical conditions for the accumulation of grains into comet-sized bodies at large heliocentric distances (Öpik 1973). Hills (1982) argues that radiation pressure from the protosun and protostars might have forced nebular grains to coagulate into comets, although his result depends on some simplifying assumptions. Little more can be added to the discussion of a more tightly bound comet cloud because it is beyond our current possibilities of detection. Bailey (1983b) and Bailey et al. (1984) have discussed some observational procedures, such as a far-infrared survey, to try to detect or at least to put upper limits to its mass.

c) Capture of interstellar comets. Laplace already visualized comets as interstellar bodies captured by the solar system mainly through Jupiter's perturbations (see modern discussions by, e.g., Radzievskii and Tomanov 1977, Valtonen and Innanen 1982). The lack of observed comets with original strongly hyperbolic orbits has been a severe objection against the capture hypothesis (Sekanina 1976). Furthermore, Valtonen and Innanen (1982) show that the probability of capture of interstellar comets into elliptic orbits by Jupiter's perturbations is extremely low so that the capture of a sizable comet cloud could only occur in the very improbable event of encounter velocities of about 0.5 kms^{-1}. Another dynamical difficulty noted by Fernández (1981a) is that capture of interstellar comets would lead to a comet population strongly concentrated toward small inclinations, which is against the observations.

Realizing the difficulties inherent to the capture mechanism by the Sun-Jupiter system, Clube and Napier (1984) argue that comet capture might occur during transits of the solar system through giant molecular clouds. Thus, they regard giant molecular clouds as hierarchic structures each comprising about 25 medium-size molecular clouds (MMC) of mass ~ $2x10^4 M_\odot$ with a fraction of it being under the form of cometary bodies. The authors conclude that encounters of the solar system with discrete MMCs would have a twofold effect: 1) disruption of already existent loosely bound comet clouds and 2) capture of transient comet clouds from MMCs as the Sun recedes from them. It is too early to judge this mechanism on a quantitative basis given our poor knowledge of the structure, size and frequency of encounters with giant molecular clouds. Valtonen (1983) has found Clube and Napier's mechanism to be inadequate to supply a sizable comet cloud unless an undetected solar companion is postulated.

From our previous discussion of comet birthplaces a key question emerges, namely: is the dynamical lifetime of the comet cloud too short as compared to the solar system age so as to preclude a primordial comet origin?. We shall next discuss this point.

3. DYNAMICAL STABILITY OF THE COMET CLOUD

Passing stars, giant molecular clouds (GMCs) and the Galaxy itself all

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perturb the orbits of cloud comets. Those cloud comets reaching the planetary region are also perturbed by the planets and actually many of them are removed from the comet cloud. We shall leave the analysis of planetary perturbations for the next section and focus now on the perturbing sources outside the solar system.

The action of stellar perturbations on solar system bodies has already been analyzed in detail, starting with Öpik's (1932) pioneer work, complemented later by Oort (1950), Sekanina (1968) and Rickman (1976) among others. Because the star's relative velocity V_* is much larger than the velocity of the comet when it moves far from the Sun, the comet can be assumed to be at rest in a heliocentric frame of reference. As a result of a stellar passage, Sun and comet will experience velocity changes given by

$$\vec{\Delta v}_{\odot} = \frac{2\mu}{V_* D_{\odot}} \frac{\vec{D}_{\odot}}{D_{\odot}} , \qquad (1a)$$

$$\vec{\Delta v}_{c} = \frac{2\mu}{V_* D_{c}} \frac{\vec{D}_{c}}{D_{c}} , \qquad (1b)$$

where $\mu = GM$, G being the gravitational constant and M the stellar mass, $D_{\odot}$ and D_c are the minimum distances to the Sun and the comet. The change in the comet's velocity with respect to the Sun will be: $\vec{\Delta v} = \vec{\Delta v}_c - \vec{\Delta v}_{\odot}$

The perturbing effect of a single star will generally be very small. Yet the effect of many stellar encounters will cumulate quadratically so as to produce significant orbital changes over long time scales. As the comet is much more strongly perturbed when it is close to its aphelion, its perihelion distance q and inclination i will be the orbital elements that undergo the greatest changes. Fernández (1980, 1981b) has derived the changes Δq and Δi experienced by a cloud comet at a heliocentric distance r perturbed by a passing star. They are

$$\Delta q = \frac{q}{v_t^2} \left(\Delta v_t^2 + 2\, \Delta v_t \times v_t \cos \beta\right) \qquad (2)$$

$$\Delta i = \frac{\Delta v_t \sin \beta \cos \alpha}{\left(\Delta v_t^2 + v_t^2 + 2 v_t \times \Delta v_t \cos \beta\right)^{1/2}} , \qquad (3)$$

where $\vec{\Delta v}_t = \vec{\Delta v} \cos \theta$ is the transverse component of the velocity change $\vec{\Delta v}$, θ being the angle between $\vec{\Delta v}_t$ and $\vec{\Delta v}$. The transverse velocity is $v_t^2 \sim 2GM_{\odot}q/r^2$. β is the angle between $\vec{\Delta v}_t$ and $\vec{v}_t$ and α the angular distance of the comet to the ascending node.

Given a stellar flux n_o, the cumulative changes of q and i after a time T will be

$$\Delta q_T^2 = \int_{D_L}^{D_U} \overline{(\Delta q^2)}\, n_o T D_{\odot} dD_{\odot} , \qquad (4)$$

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$$\Delta i_T^2 = \int_{D_L}^{D_U} (\overline{\Delta i^2}) n_o T D_\Theta dD_\Theta \,, \tag{5}$$

where $\overline{\Delta q^2}$, $\overline{\Delta i^2}$ are averages over Θ, β and α. D_L,D_U are the lower and upper limits for the stellar distances of closest approach to the Sun during T. We take $D_L = (2\pi n_o T)^{-1/2}$, i.e. the probability for a star to pass from the Sun a distance $D_\Theta < D_L$ is 0.5, and $D_U = 2.5r$ meaning that we limit ourselves to the close stellar encounters. It can be shown that the more distant encounters do not change drastically the results obtained from eqs. (4) and (5). By adopting n_o = 10 stars $pc^{-2}Myr^{-1}$, an average stellar mass of 0.7 M_Θ, and average star's relative velocity $V_* = 30$ km s^{-1} (Rickman 1976) and $T = 4.5 \times 10^9$yr, we get the results shown in Figs. 4 and 5.

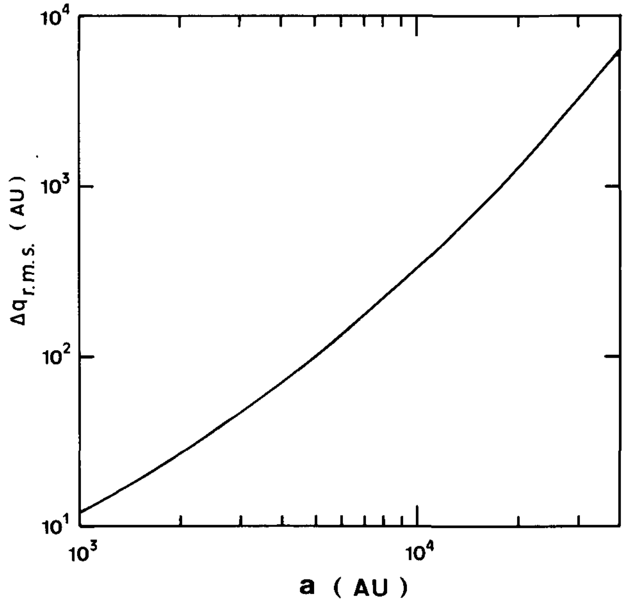

Figure 4. The expected change of the perihelion distance of a near-parabolic comet, caused by perturbing stars throughout the solar system lifetime, as a function of the comet's semimajor axis. The comet is assumed to have an initial q = 20 AU.

A sharp increase in the r.m.s. change Δq is found for increasing a (Fig.4). Comets with a $\sim 10^3$AU and perihelia within the planetary region (q<30 AU) are not expected to have their perihelia removed from the planetary region by stellar perturbations over the age of the solar system. The r.m.s. change of Δq attains several 10 AU for a of a few 10^3AU. Comets with a $\sim 10^4$AU have already an expected change of $\sim$300 AU so that we should expect their perihelia were long since removed from the planetary region. In realistic terms, the removal of the comet's perihelion from the planetary region should depend on whether the rate of change of q by stellar perturbations is greater or smaller than the diffusion speed of

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the orbital energy caused by planetary perturbations. For comets with a of a few 10^4AU will suffice a single revolution to cause a change of their perihelion distance of several 10^2AU. Summing up, comets with a ~10^4AU will be perturbed by passing stars fast enough to be removed from the planetary region in the course of a few revolutions. Such a distance defines the lower limit of the Oort region.

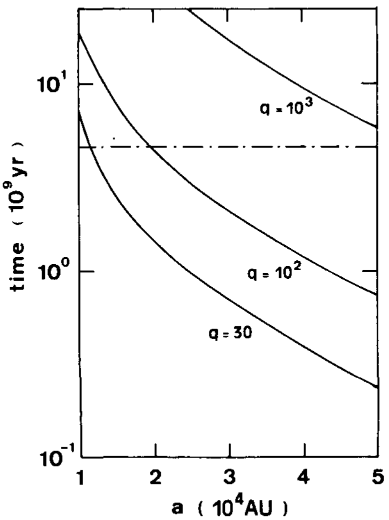

Figure 5. Time scales for randomization by stellar perturbations of the orbital planes of comets with q=30 AU and q=10^2AU , q=10^3AU as a function of their semimajor axes. The horizontal line indicates the age of the solar system.

The orbital planes of comets with $q \lesssim 100$ AU and $a \gtrsim 2 \times 10^4$AU should have got randomized by stellar perturbations over the age of the solar system (Fig. 5). The criterion for randomization is that the r.m.s. change Δi_T as given by eq. (5) reaches the value π. Should comets form close to the ecliptic plane, a certain concentration might still be present for comets with $a \lesssim 2 \times 10^4$AU. However comets driven into the inner planetary region will drastically change their inclinations so as to produce a randomly oriented influx of cloud comets.

The cumulative change of the comet's energy per unit mass can be roughly estimated by considering only close encounters, i.e. $\Delta v^2 = (\Delta\vec{v}_c - \Delta\vec{v}_\odot)^2 \sim \Delta v_\odot^2$. Thus we have

$$2\,\Delta\varepsilon_T = \int_{D_L}^{D_U} \Delta v_\odot^2 n_o T D_\odot dD_\odot$$

$$= \left(\frac{2\mu}{V_*}\right)^2 n_o\ T\ \mathrm{Ln}\left(\frac{D_U}{D_L}\right) \ . \qquad (6)$$

Introducing the numerical values quoted above with T = 4.5×10^9yr, we obtain an energy change $2\Delta\varepsilon_T = 1.15 \times 10^8$ cm^{2}s^{-2} or a r.m.s. change in the

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comet's velocity of 1.07×10^4 cm s^{-1} which is in fairly good agreement with Weissman's (1980) result and somewhat smaller than Bailey's (1983a). We should expect our result to be somewhat underestimated because of the neglect of distant encounters in eq. (6). By setting the condition $2\Delta\varepsilon_T = v_{esc}^2 = 2GM_\odot/r \sim GM_\odot/a$ we find that comets with a $\gtrsim 7.6 \times 10^4$AU have got enough energy to escape from the solar system.

No analytical or numerical studies have so far been carried out on the change of the perihelion direction of comets subject to stellar perturbations. The perihelion points of comets formed in the outer planetary region should have shown a preference for the ecliptic plane. No such a preference is currently observed in LP comets which in principle can be attributed to stellar perturbations. Quantitative studies on this problem would be highly desirable so as to ascertain time scales for randomization of perihelion directions of cloud comets as a function of their semimajor axes and perihelion distances.

Encounters with GMCs are much less frequent although their effects on the stability of the comet cloud may be much more drastic because of their large masses. GMCs have typical masses of $\sim 5 \times 10^5 M_\odot$ and radii of about 20 pc (Solomon and Sanders 1980, Gordon and Burton 1980). Sanders et al. (1984) find the surface density of H_2 - main component of the molecular clouds - to peak at $\sim$6 kpc from the Galactic center. It may be however a factor of five smaller at the Sun's distance ($\sim$10 kpc). The perturbing effects of molecular clouds on cloud comets was considered by Biermann (1978). Shortly after Napier and Clube (1979) presented a theory according to which quasiperiodic encounters of the solar system with GMCs during its passage through the spiral arms of the Galaxy would result in the capture of temporary "Oort clouds" and in a heavy comet bombardment of the planets. From numerical simulations, Napier and Staniucha (1982) have concluded that a primordial comet cloud would have been lost at present as a consequence of perturbations from GMCs. However, their results are highly sensitive to the adopted numerical values. For example, Napier and Staniucha consider rather low encounter velocities with GMCs (5 and 10 km s^{-1}) which favors their disruptive influence. This problem has been reviewed in detail by Bailey (1983a) who comes to the conclusion that an inner core of the comet cloud of radius $\sim 10^4$AU would have withstood encounters with GMCs over the age of the solar system.

We can compare the perturbation exerted by a GMC on the solar system during a penetrating encounter to that caused by a very close stellar passage. We assume the GMC to be a uniform sphere of radius R_{GMC}= 20 pc and mass $M_{GMC} = 5 \times 10^5 M_\odot$. Biermann (1978) and Bailey (1983a) have developed the mathematical expression for the mean perturbation caused by a penetrating encounter with a GMC, which can be written as

$$2\,\overline{\Delta\varepsilon}_{GMC} = \frac{2}{3}\left(\frac{2GM_{GMC}}{V}\right)^2 \frac{r^2}{b^4}\left\{1-\left(1-\frac{b^2}{R_{GMC}^2}\right)^{3/2}\right\}^2 , \qquad (7)$$

where b is the impact parameter, V is the encounter velocity and r is an average heliocentric distance for cloud comets. We shall adopt: $r \simeq 1.7a \simeq 4 \times 10^4$AU. The energy change experienced by a cloud comet due to a close stellar passage is

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$$2\ \Delta\varepsilon_* \simeq \left(\frac{2GM_*}{D_L V_*}\right)^2, \tag{8}$$

where D_L is the closest approach of a star to the Sun expected during the age of the solar system T. We have: $D_L = (\pi n_o T)^{-1/2} \sim 550$ AU.

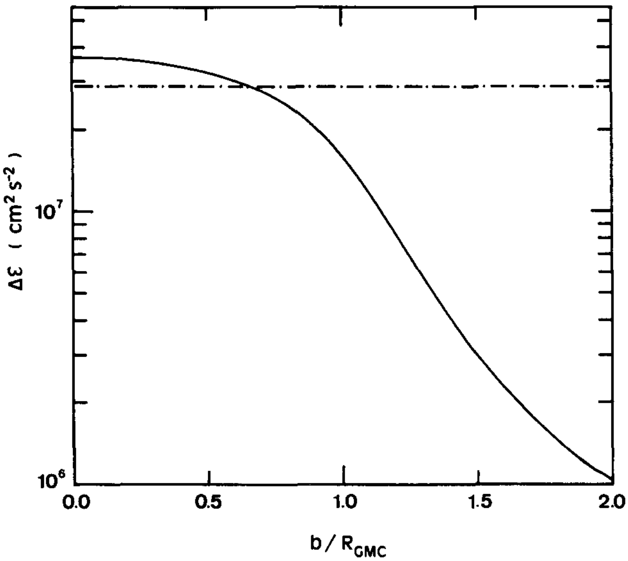

Figure 6. The mean energy change of a typical cloud comet at a heliocentric distance $r = 4 \times 10^4$ AU, due to an encounter with a GMC, as a function of the impact parameter b (in units of the radius of the GMC). The condition $b/R_{GMC}<1$ corresponds to penetrating encounters. The horizontal line indicates the energy change caused by the closest stellar approach to the Sun expected during its lifetime.

As shown in Fig.6, the energy imparted to a comet by a star passing at the closest solar distance expected during the solar system lifetime can be comparable to that imparted by a GMC in a penetrating encounter. Furthermore, penetrating encounters with GMCs do not seem to be as frequent as Napier and Clube claim. According to Bailey (1983a), the number of such penetrating encounters during the solar system lifetime can be placed in the range 1 - 10. Encounters with smaller molecular clouds are probably much more frequent. Rampino and Sothers (1984) estimate that one of such encounters takes place during every transit of the solar system through the galactic disk ($\sim$30 Myr). However the perturbation caused by a typical molecular cloud of radius $\sim$5 pc and mass $\sim 10^4 M_\odot$ is much smaller than that obtained from eq. (7) for a GMC. Of course, our assumption of a homogeneous cloud is an oversimplification. The computation of the energy transfer rate will depend somewhat on the GMC's substructure (Bailey 1983a). On the other hand, the consideration by Napier and Staniucha (1982) and Clube and Napier (1984) of GMCs as divided in 25 discrete clouds, each of mass $2x10^4 M_\odot$ and radius 2 pc, is also very likely an oversimplification. For instance, Solomon and Sanders (1980) conclude that only a small fraction of a GMC mass is in condensed cores. Summing up, even though the action of GMCs and molecular clouds should be taken into consideration as a perturbing source of cloud comets, it does not seem to change drastically the picture obtained before with the exclusive consideration of stellar perturbations (e. g. Oort 1950, Weissman 1980, Fernández 1980).

Due to galactic perturbations, stable motion is only possible for comets in eccentric orbits up to distances of $\sim 8x10^4$AU over long periods of time (Chebotarev 1966). This is beyond the limits imposed by stellar and GMC perturbations, so that galactic perturbations are not of primary concern for the stability of the comet cloud over cosmogonic time scales. Nevertheless, comets of smaller a, say $\sim 2.5x10^4$AU, will be perturbed by the Galaxy so that galactic effects might be present in the observed "new" comets. From the numerical integration of orbits in the restricted three-body problem: Sun-galactic nucleus-comet, Byl (1983) finds that changes in q of cloud comets are smallest for aphelia near the galactic equator and poles. Therefore, it may be possible that galactic perturbations introduce some correlation between the galactic structure and the aphelion distribution of LP comets.

We are still left with the possibility of an as yet undetected solar companion as a perturbing source of the comet cloud. Indeed, the discovery that most stars have stellar companions (Abt and Levy 1976) gives some support to the idea that the Sun also has or had a companion. Kirk (1978) has shown that such a hypothetical companion cannot be close to the Sun, say at $\sim 10^3$AU, otherwise we should not observe the clustering of comet energies in the interval $0>\varepsilon>-10^{-4}AU^{-1}$. A more distant solar companion with a = $8.8x10^4$AU has recently been proposed by Whitmire and Jackson (1984) and Davis et al. (1984) to explain a possible 26-Myr periodicity in biological mass extinctions. The authors suggest that the unseen companion stirs comets of the Oort cloud during its perihelion passages every 26 Myr giving rise to comet showers. The problem with a distant companion is to explain its dynamical stability over periods of more than 10^8yr (see Weissman's contribution to this book).

4. PLANETARY PERTURBATIONS

A fraction of the Oort cloud population will be deflected to the planetary region where is perturbed by the planets. Indeed, all cloud comets should have been subject to planetary perturbations at early times if they formed in the planetary region. Planetary perturbations will greatly change the orbital energy ε of long-period orbits but very little the other orbital elements (Yabushita 1972). From numerical experiments, Kerr (1961) found that the distribution of energy changes per perihelion passage, $\Delta\varepsilon$, could be fitted to a Gaussian distribution. Everhart (1968) further noted a departure from the Gaussian distribution in the form of long $\Delta\varepsilon$-tails accounting for drastic energy changes produced in close encounters. Fernández (1981a) derived as an acceptable approximation for the $\Delta\varepsilon$-distribution up to energy changes $\Delta\varepsilon \sim 2.5\ \Delta\varepsilon_T$, the expression

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$$f(\Delta\varepsilon) \propto \exp(-3/4\ \Delta\varepsilon^2/\Delta\varepsilon_T^2), \qquad (9)$$

where $\Delta\varepsilon_T$ is the typical energy change for comets with perihelion distances and inclinations in the ranges (q, q+Δq) and (i, i+Δi) computed as the r.m.s. of their energy changes per perihelion passage. As shown in Fig. 7, $\Delta\varepsilon_T$ is strongly dependent on the orbital elements q, i.

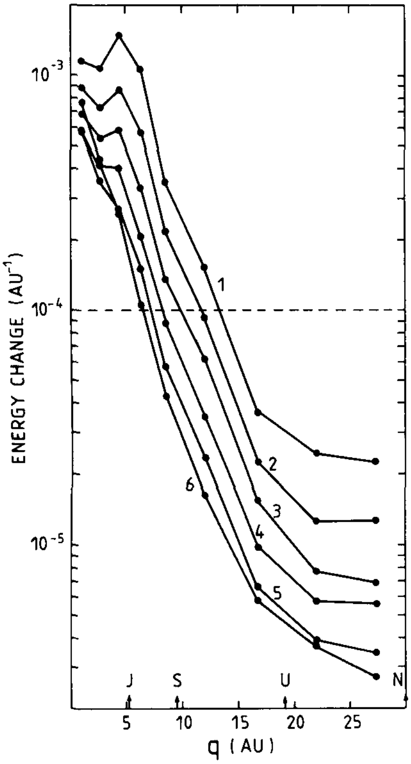

Figure 7. The typical energy change per perihelion passage as a function of the comets' perihelion distance and for six inclination ranges: $0<i<30^\circ$ (curve 1)...... $150^\circ<i<180^\circ$ (curve 6) (Fernández 1981a).

LP comets will random-walk in the energy space until they are finally lost to the interstellar space or to the inner planetary region. For a comet of orbital parameters q, i coming from the Oort region ($\varepsilon \sim 0$), its expected energy ε after n perihelion passages will be

$$\varepsilon^2 = n\ \Delta\varepsilon_T^2(q,i). \qquad (10)$$

As mentioned before, during the dynamical evolution the other orbital elements, such as q and i, are not expected to change significantly as long as the comet moves on a long-period orbit.

An initial population of N_o near-parabolic comets ($\varepsilon \sim 0$) will be dynamically depleted due to diffusion through the boundary $\varepsilon = 0$ to positive energies (hyperbolic orbits). Everhart (1976) showed from numerical experiments that the number N of comets that still remain bound to the solar system after n perihelion passages is

$$N(n) = \frac{1}{2} N_o\ n^{-1/2}. \qquad (11)$$

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As mentioned, a Gaussian distribution is valid as long as we neglect close encounters with the Jovian planets which cause drastic changes in ε. To make allowance for close encounters, $\Delta\varepsilon_T$ should be multiplied by a factor of ~ 3 (Fernández 1981a).

5. HOW MANY COMETS ARE REALLY "NEW"?

This question is of great significance for our understanding of the dynamical properties of the comet cloud. Numerical experiments carried out by Fernández (1982) have shown that $\sim 85\%$ of the so-called new comets coming into the inner planetary region have passed before by the planetary region beyond Jupiter's orbit. We can roughly estimate the fraction F of cloud comets with orbital energies $0>\varepsilon_c>\varepsilon_L(\sim -10^{-4}\text{AU}^{-1})$, passing by the planetary region with perihelion distances q, that will return to the Oort region (namely with energies $0>\varepsilon>\varepsilon_L$). For this to happen, the energy change the comet undergoes after a perihelion passage has to fall in the energy range $\varepsilon_L-\varepsilon_c< \Delta\varepsilon<-\varepsilon_c$. By using the distribution function of energy changes $f(\Delta\varepsilon)$ given by eq. (9), we can readily obtain

$$F = \int_{\varepsilon_c-\varepsilon_L}^{\varepsilon_c} f(\Delta\varepsilon)\,d\Delta\varepsilon = \frac{1}{2}\left\{ \operatorname{erf}\left[\sqrt{3/4}\left(\frac{\varepsilon_c}{\Delta\varepsilon_T}\right)\right] + \operatorname{erf}\left[\sqrt{3/4}\left(\frac{\varepsilon_L-\varepsilon_c}{\Delta\varepsilon_T}\right)\right] \right\}, \qquad (12)$$

where erf is the error function.

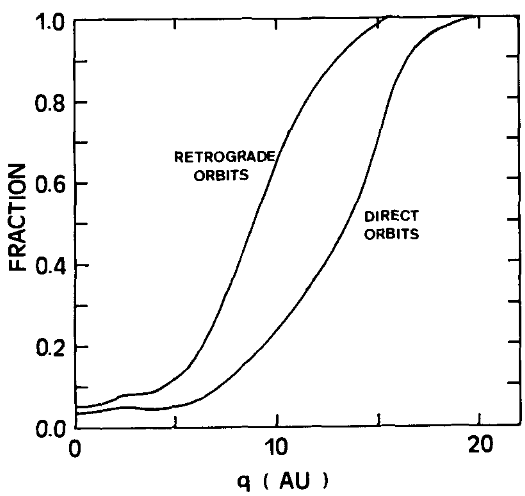

Figure 8. The fraction of cloud comets returning to the Oort region ($a>10^4$AU) after a perihelion passage as a function of the comet's perihelion distance. Results are for two groups of comets: direct and retrograde orbits, both assumed to be randomized.

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The fraction of cloud comets returning to the Oort region has been computed separately for comets in: a) direct and b) retrograde orbits. The computed values of F are presented in Fig. 8 as a function of the comet perihelion distance. We see that a large fraction of the incoming cloud comets with perihelia beyond Jupiter will return to the Oort region and that F will be greater for comets in retrograde orbits. Even for cloud comets coming into the inner planetary region we should expect that ∿5% of them will return to the Oort region, while the fraction will be close to unity for the Uranus-Neptune region.

6. THE DISTRIBUTIONS OF PERIHELION DISTANCES AND INCLINATIONS OF LONG-PERIOD COMETS

Let us start considering cloud comets driven into the planetary region by stellar perturbations for the first time. It is easy to show that such comets will have an uniform q-distribution. For this, let v_c be the velocity of a cloud comet. For comets deflected into the planetary region, v_c forms a very small angle θ with the radius vector Sun-comet. We have for the transverse comet's velocity

$$v_T^2 \simeq v_c^2\theta^2 \simeq \frac{2GM_\odot q}{r^2}$$

hence

$$v_c^2\theta \; d\theta \simeq \frac{GM_\odot}{r^2} dq \quad . \tag{13}$$

Under the assumption of randomization of the vector v_c by stellar perturbations we have

$$f_\theta(\theta) \; d\theta = \frac{1}{2} \sin \theta \; d\theta \sim \frac{\theta}{2} \; d\theta \; . \tag{14}$$

Finally, by combining eqs. (13) and (14) we get the q-distribution

$$f_q(q) \; dq = \frac{GM_\odot}{2v_c^2 r^2} \; dq \; . \tag{15}$$

As v_c and r are independent of q, the distribution f_q turns out to be uniform. This is in agreement with the q-distribution observed for dynamically young LP comets (cf. Fig.3).

Let us now compute the q-distribution for all the LP comets with different dynamical ages. For this, let us consider an initial population of N_o cloud comets passing through the planetary region with perihelia in the range (q, q+dq). The number of comets surviving dynamical ejection will decrease with the number of perihelion passages n following eq. (11). Through the whole dynamical evolution, the initial population of N_o comets will perform a number of n_T perihelion passages before being ejected or transferred to periodic orbits (T < 200 yr). From

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Fernández (1981a) we find

$$n_T = \sum_{n=1}^{n_M} \frac{1}{2} N_o n^{-1/2} \simeq N_o n_M^{1/2} \quad , \tag{16}$$

where n_M is the maximum number of perihelion passages a comet avoiding ejection can perform that brings it from a near-parabolic orbit to a periodic one. For comets random-walking in the energy space ε, the number of passages n_M required to pass from an energy $\varepsilon_o \sim 0$ to an energy $\varepsilon_p \sim -0.03$ AU^{-1} (corresponding to an orbital period P ≃ 200 yr) is

$$n_M = \frac{(\varepsilon_p - \varepsilon_o)^2}{\Delta\varepsilon_T^2} \sim \frac{\varepsilon_p^2}{\Delta\varepsilon_T^2} \ . \tag{17}$$

By substituting eq. (17) into eq. (16) we finally obtain

$$n_T \sim N_o \frac{\varepsilon_p}{\Delta\varepsilon_T} \ . \tag{18}$$

Since a population of LP comets is made up of comets with different dynamical ages, the longer their dynamical lifetime n_T, the larger their number (thus, the influx rate $\dot{N}_{LP}$) considering those LP comets with inclinations in the range (i, i+di) passing perihelion in the range (q, q+dq). Thus we have

$$\dot{N}_{LP} \propto n_T \propto \Delta\varepsilon_T^{-1} \ . \tag{19}$$

Since $\Delta\varepsilon_T$ decreases with increasing q, the influx rate $\dot{N}_{LP}$ will increase as we go farther away in the planetary region (Fig.9). The results are very impressive: we should expect the influx rate of LP comets to be about two orders of magnitude greater in the outer planetary region than in the region of the terrestrial planets. A previous numerical study by Fernández (1982) led to a similar result. As Fig. 9 shows, for Saturn's zone the influx rate of LP comets should be about one order of magnitude greater than for the inner planetary region. Analyses of the cratering rate for outer solar system bodies should take into consideration such an increase in the flux of LP comets. In this respect, a recent study by Zimbelman (1984) incorporating this effect leads to rather similar crater production rates from LP comets throughout the planetary region.

We should note that physical decay will limit the lifetime of LP comets in the inner planetary region well below their dynamical lifetime given by n_T. Obviously, the smaller q, the smaller the number of revolutions a comet can perform before physical decay which results in a decreasing number of observed LP comets as we approach the Sun (Fig. 3).

The i-distribution of LP comets should also be affected by planetary perturbations. A greater fraction of cloud comets in retrograde orbits passing through the outer planetary region will return to the Oort region as compared to those in direct orbits. This effect will be

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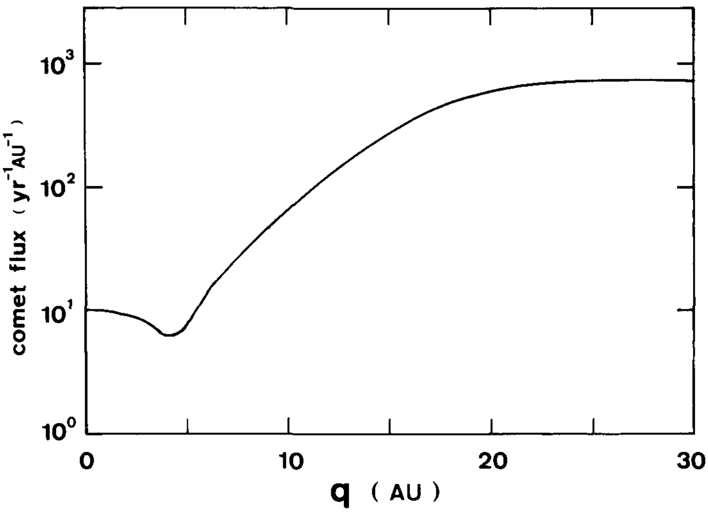

Figure 9. The computed influx rate of LP comets per unit of q as a function of the comet's perihelion distance. The ordinate values have been normalized to an influx rate of 10 LP comets per year per AU in the inner planetary region.

more pronounced in the Jupiter-Uranus region (see Fig. 8). Therefore, more cloud comets in retrograde orbits will have a chance to pass again through the planetary region, and some of them will cross Jupiter's orbit because of the diffusion of their perihelia by stellar perturbations (Fernández 1981b). We should bear in mind that a typical cloud comet with $a=2.5x10^4$AU will experience an average change of $\Delta q \sim 5$ AU in a revolution (Fernández 1980). Presumably, comets passing beyond Jupiter are not strongly depleted of their volatiles so we might expect them to show up very active when passing through the inner planetary region. The observed strong excess of retrograde orbits for dynamically young comets with q>2 AU (Fig. 2) can thus be explained in terms of the greater survival rate of cloud comets in retrograde orbits passing by the outer planetary region.

The strong excess of retrograde orbits observed for q>2 AU will tend to disappear for smaller perihelion distances following the greater variation of i that accompanies a drastic reduction of q by stellar perturbations. In addition to this dynamical effect, the author (Fernández 1981b) has shown that selection effects may favor the discovery of LP comets in prograde orbits for the range $1<q\lesssim 2$ AU. This may explain the apparent conflict with Delsemme's conclusion that a predominance of prograde orbits is present among "new" comets (see his presentation in this book). Thus, Delsemme has drawn his conclusion from the sample of observed "new" comets with well determined original orbits, the overwhelming majority of which have q<2 AU (cf. Marsden et al. (1978) catalogue).

7. COMET ORIGIN AS A BYPRODUCT OF THE FORMATION OF THE JOVIAN PLANETS

Our review of the action of stellar and planetary perturbations on cloud comets will allow us to analyze further the primordial theory of comet formation. Oort (1950) proposed that comets formed in the asteroid belt. However, by noting the icy nature of comets and because of dynamical considerations, Kuiper (1951) suggested that the region close to Neptune's orbit was a more suitable place for comet formation. From the study of the accretion of the Jovian planets, Safronov (1969, 1972) concluded that they could have reached their present masses only at the expense of ejecting large amounts of residual matter. This is specially applicable to the cases of Uranus and Neptune for which the accretion of solid bodies played a much greater role than in the hydrogen-dominated Jupiter and Saturn. Numerical experiments carried out by Fernández and Ip (1981) confirm that a large amount of matter of perhaps several tens of $M_\oplus$ is ejected during the late stage of formation of Uranus and Neptune. We can give a simple explanation of why this should happen: as proto-Uranus and proto-Neptune grew they started to stir up planetesimals of their accretion zones until their encounter velocities reached values of $U > \sqrt{2}-1$ (with respect to the circular velocity of the protoplanet). At this point, collision (accretion) with the protoplanet virtually becomes to a halt because ejection becomes a much more probable event (Weidenschilling 1975).

Comets random-walking in the energy space will finally be ejected unless stellar perturbations can remove their perihelia from the planetary region. For this to happen it is required that such comets pass by the Oort region (energies $\varepsilon_L<\varepsilon<0$). Since the typical step in the random-walk is $\Delta\varepsilon_T$, we can see from Fig. 7 that bodies under the gravitational control of Neptune will have a very smooth orbital diffusion with a large probability of passing by the Oort region since $\Delta\varepsilon_T<<|\varepsilon_L|$. By contrast, bodies under the gravitational control of Jupiter and Saturn are subjected to much stronger perturbations with $\Delta\varepsilon_T>>|\varepsilon_L|$, so that in the diffusion process such bodies will probably overshoot the Oort region. The ratios of comets placed into the Oort region to those ejected on hyperbolic orbits, as derived by Fernández and Ip (1981) from numerical experiments, are shown in TABLE I. As expected, the ratio turns out to be greater for bodies under the gravitational control of Neptune and lower for Jupiter's.

TABLE I

Ratio of comets placed into the Oort region to those ejected on hyperbolic orbits	
Jupiter	0.03 ± 0.01
Saturn	0.16 ± 0.04
Uranus	1.30 ± 0.50
Neptune	2.60 ± 0.70

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Uranus' contribution to the comet cloud was partially hindered because a large part of the residual material of its accretion zone fell under the gravitational control of Jupiter which finally ejected the bodies. This can be understood in terms of probabilities of ejection and transfer to the influence zone of an inner Jovian planet. A body of Uranus' region requires a relative velocity $U = 0.35$ to be able to reach Jupiter's influence zone. This means that before the body gets a velocity $U > \sqrt{2}-1$ for ejection to be possible, it will probably fall under the gravitational control of Jupiter (Fernández and Ip 1984). However, for a body of Neptune's region the relative velocity required for transfer to Jupiter's region is $U = 0.46$ which is larger than the velocity required for getting a near-parabolic orbit. Therefore, before falling under Jupiter's control the body can reach the Oort region.

For bodies scattered by a Jovian planet we can roughly estimate their timescale for ejection or for reaching the Oort region. In the diffusion process a body will move throughout the energy range: $\varepsilon_L - \varepsilon_o$, where ε_o is its starting energy. ε_o will be of the order of $-0.1\ \mathrm{AU}^{-1}$ for Jupiter's controlled bodies in starting low eccentricity orbits and $\sim -3\times10^{-2}\mathrm{AU}^{-1}$ for Neptune's. The probability that the body falls in a certain energy range $(\varepsilon, \varepsilon+d\varepsilon)$ during its orbital diffusion will be

$$f_\varepsilon(\varepsilon)\ d\varepsilon = \frac{d\varepsilon}{\varepsilon_L-\varepsilon_o} \sim \frac{d\varepsilon}{|\varepsilon_o|} \quad . \qquad (20)$$

The time t_{oc} that will take the comet to reach the Oort region (or to be ejected) is given by

$$t_{oc} = \sum_{n=1}^{n_M} T_n \quad ,$$

where $n_M = \frac{\varepsilon_o^2}{\Delta\varepsilon_T^2}$ is the average number of steps to cover the energy range $\varepsilon_L-\varepsilon_o$ and T_n is the comet's revolution period during the revolution n. The average revolution period $\overline{T}$ is defined as

$$\overline{T} = \frac{\int_{T_m}^{T_M} T\ f_T(T)\ dT}{\int_{T_m}^{T_M} f_T(T)\ dT} \quad , \qquad (21)$$

where $T = |\varepsilon|^{-3/2}$ and f_T is the probability distribution of T. The maximum and minimum periods T_M and T_m correspond to the orbital energies ε_L and ε_o, respectively.

From eq. (20) we obtain: $f_T(T) = C\ T^{-5/3}$, C being a normalizing factor. By introducing this relation into eq. (21) we get

$$\overline{T} = 2\ T_M^{1/3}\ T_m^{2/3} = 2\ |\varepsilon_L|^{-1/2}\ |\varepsilon_o|^{-1} \quad . \qquad (22)$$

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The time t_{oc} can then be approximated by

$$t_{oc} \simeq n_M \bar{T} = \frac{2\,|\varepsilon_o|\,|\varepsilon_L|^{-1/2}}{\Delta\varepsilon_T^2} \text{ years,} \tag{23}$$

which is appropriate for bodies of Uranus' and Neptune's region. Given the large steps $\Delta\varepsilon_T$ of bodies scattered by Jupiter and Saturn, rather than $T_M=|\varepsilon_L|^{-3/2}$ as defining the maximum revolution period, we should use $T_M=\Delta\varepsilon_T^{-3/2}$ as a more adequate value for the comet's orbital period previous to ejection. With this modification, eq. (23) becomes

$$t_{oc} \simeq \frac{2\,|\varepsilon_o|}{\Delta\varepsilon_T^{5/2}} \tag{23'}$$

suitable for bodies of Jupiter and Saturn regions.

TABLE II

Time scale for reaching the Oort region (yr)	
Jupiter	2.3×10^5
Saturn	1.0×10^7
Uranus	6.0×10^8
Neptune	1.3×10^9

Computed time scales t_{oc} are shown in TABLE II for the four giant planets. The values of $\Delta\varepsilon_T$ used in eqs. (23) and (23') have been multiplied by a factor of three (see Section 4) to make allowance for close encounters that very probably will occur during the multiple perihelion passages of the bodies. The computed times of TABLE II are in rather good agreement with those found by Ip (1977) using a Monte Carlo procedure. As seen, for bodies of Neptune's region t_{oc} is very long which suggests a slow buildup of the comet cloud (Fernández and Ip 1981). Therefore, *the formation of planets and comets would have been coeval although the buildup of the comet cloud would have occurred later on in the history of the solar system*. Furthermore, the long dynamical time scale t_{oc} for bodies under the gravitational control of Neptune suggests that a tail of more dynamically stable bodies remains bound to its influence zone forming a flat structure we can call the "cometary belt" (Fernández and Ip 1983).

The previous discussion suggests that two comet populations with different dynamical histories might reach the inner planetary region: 1) The so-called "new" comets on near-parabolic orbits. They are comets that got diffused to the Oort region where they were perturbed by passing stars and GMCs. 2) The "belt" comets coming from the above-discussed tail of bodies with long dynamical time scales. Comets with a smaller than a few 10^3AU would have kept their primordial concentration towards

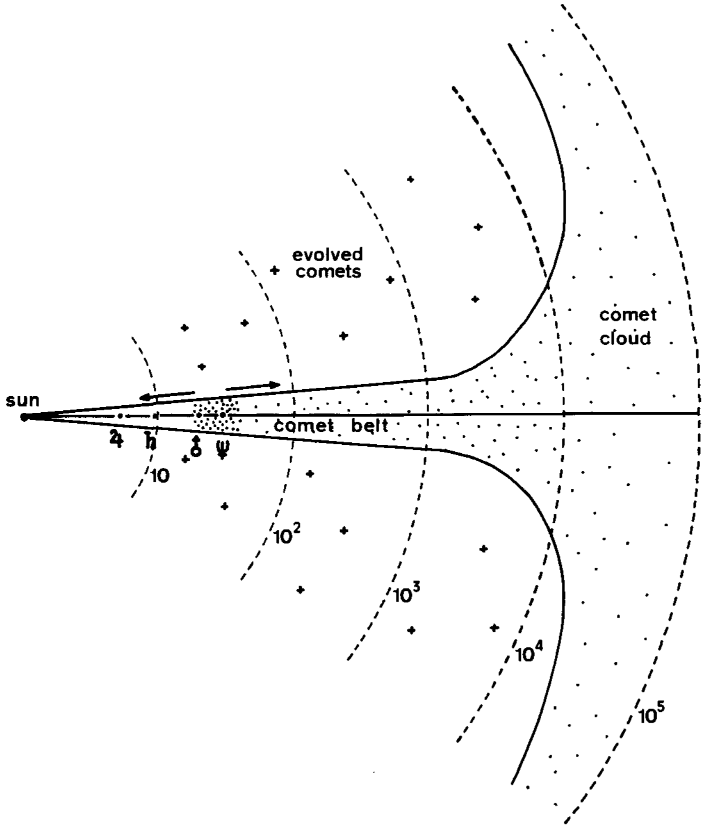

Figure 10. Hypothetical space distribution of comets bound to the solar system. A comet origin in the Uranus-Neptune region is assumed. The arrows indicate the sense of scattering of the residual bodies. "Evolved comets" would correspond to those derived from the Oort cloud whose semi major axes have been shortened by planetary perturbations.

the ecliptic plane.

According to what was discussed before, we may speculate that the i-distribution of near-parabolic comets reaching the outer planetary region presents an excess of retrograde orbits following the discussion of Section 6. In addition, there might be an excess of small-i comets from the contribution of belt comets. We might presume that the large number of observed short-period comets - not well understood as a capture process of near-parabolic comets (Joss 1973, Fernández and Ip 1983) - might be explained as an inward diffusion of low-i belt comets by perturbations of the Jovian planets. At the beginnings of the solar system, such population of belt comets might have been several orders of magnitude greater and contributed to the heavy bombardment of the terrestrial planets (Wetherill 1975, Fernández and Ip 1983). Figure 10 sums up our view of the current comet structure under the assumption of comet formation in the region of Uranus and Neptune.

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8. CONCLUDING REMARKS

Several pieces of evidence point to the presence of a large comet reservoir surrounding the solar system up to distances of several 10^4AU. Members of this reservoir evolve under the perturbing action of passing stars, sporadic encounters with GMCs and perturbations from the Galaxy itself. The ultimate fate of most cloud comets will be ejection to the interstellar space. A critical point of the discussion is how stable is the comet cloud against the disrupting forces of stars and GMCs over the age of the solar system. Supporters of an interstellar origin argue that a loose comet cloud would be dynamically unstable mainly due to catastrophic encounters with GMCs. Given the uncertainties of the parameters characterizing GMCs, this assertion may be too premature. As discussed, GMCs might have played an important role in the perturbation of the comet cloud although they do not seem to change dramatically the conclusions already reached with the exclusive consideration of stellar perturbations.

The idea of a comet origin in the planetary region is attractive because it fits current cosmogonic ideas that the Jovian planets would have formed at the expense of ejecting large amounts of residual material. The objection that a comet cloud would have been lost over the solar system age is weakened further by considering the long time scales of bodies scattered by Neptune to reach the Oort region. We should also note that a primordial comet origin would not necessarily lead to a loose comet cloud which has been the target of criticisms by supporters of the interstellar origin theory. Instead, a more tightly bound comet cloud may well be the outcome of the combined action of planetary and stellar perturbations on comets scattered from the Uranus-Neptune region. The energy range in which comets were stored should mainly depend on the field of extra solar system objects during the buildup of the comet cloud.

Finally, we shall mention several lines of research that may help to put further constraints on theories of formation of the comet cloud:

1) A better knowledge of the structure, mass and frequency of encounters with GMCs is required to assess their impact on the survival of the comet cloud.

2) A better estimate of the average comet mass and influx rate of cloud comets will allow us to set more precise limits on the total mass of the comet cloud. Hence an estimate of the mass removed by the outer planets will be possible under the assumption of a comet origin in the planetary region. The derived amount of material removed from the outer planetary region can then be compared to that expected on cosmogonic grounds.

3) Better statistics of comet orbits with large q will permit to check several theoretical forecasts, such as the excess of retrograde orbits among LP comets and the overall increase in the number of LP comets with increasing q beyond Jupiter.

4) The distribution of the perihelion points of LP comets do not show a preference for the ecliptic plane. However, comets formed in the planetary region should have had low-inclination orbits, whereby their perihelia should have been concentrated toward the ecliptic plane. We

may presume that the cometary perihelia "lost memory" of their primordial locations through the combined perturbing action of passing stars, GMCs and the planets. This still needs to be proved by numerical or analytical studies.

5) The deviation from randomness of the directions of the perihelia of LP comets needs to be further analyzed once a better comet sample in the southern hemisphere is available, in particular, to prove or disprove the alledged relationship with the solar apex.

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DISCUSSION

S. Yabushita: You say the excess of retrograde orbits is real. But by stellar encounters, direct orbits can be converted into retrograde orbits and viceversa.

J. A. Fernández: That will only occur after a long dynamical time scale provided q is not very small. A typical Oort cloud comet of, say $q \sim 10$ AU and $a \sim 2.5 \times 10^4$ AU, will experience an average inclination change of only $\sim 15°$ after an orbital revolution (see Fernández 1981b).

R. Lüst: In a sample of 89 comets with semimajor axes $> 10^4$ AU (original values from the Marsden-Sekanina-Everhart catalogue) we counted 46 comets with direct and 43 with retrograde orbits. Could you comment on your sample?.

J. A. Fernández: Your sample contains a large fraction of comets with small perihelion distances. Comets getting very small q ($\lesssim 1$ AU) will very probably be randomized by stellar perturbations. For $1 \lesssim q \lesssim 2$ AU selection effects may favor the discovery of comets in prograde orbits. The excess of retrograde orbits should show up for LP comets with rather large perihelion distances, say $q > 2$ AU. It is just for this sample that I have found about 60% of retrograde orbits.

P. Farinella: Dr. Greenberg's study on the origin of comets was based on the assumption of a 10% efficiency of Uranus and Neptune in ejecting proto-comets into the Oort cloud. Do you agree with this estimate?.

J. A. Fernández: I think this gives the correct order of magnitude, even though we should bear in mind that Neptune's efficiency is much greater than Uranus'.