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# The Formation of the Oort Cloud and the Primitive Galactic Environment

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**We analyze the conditions of formation of the Oort cloud from icy planetesimals scattered by the accreting outer planets. The combined effect of planetary and external perturbations is considered to be the mechanism of transfer from the comet's birthplace in the planetary region to the Oort cloud reservoir. If the main external perturbers from the primitive galactic environment were similar to the current ones (namely, passing stars and the tidal force of the galactic disk), the resulting Oort cloud would have probably been too loosely bound to have withstood the disrupting effect of penetrating encounters with giant molecular clouds. An additional problem is that most of the objects formed in the outer planetary region are found to be finally ejected by Saturn or Jupiter, and not by Neptune or Uranus, thus making the whole process of transfer of bodies from the planetary region to the Oort cloud very inefficient. Jupiter and Saturn perturbations are so strong that most bodies scattered by these planets are very likely to overshoot the narrow energy range of the present Oort cloud to interstellar space.**

**It is shown that the combined action of planetary and external forces would have produced a more tightly bound comet reservoir if the Solar System formed within a much denser galactic environment, perhaps a molecular cloud and/or an open cluster. This seems to be the way in which most stars form. Moreover, the time scales of formation of Uranus and Neptune could well have been very short (a few times $10^7$ years or even less), as their non-negligible contents of hydrogen and helium suggest, which would give stronger support to the idea that the massive scattering of planetesimals in the outer planetary region was produced while the Solar System was still within its natal environment. It is found that a much stronger external field, caused either by other members of an open cluster or by the tidal force of the molecular cloud itself, could have produced a much more strongly bound Oort cloud at distances of a few thousand AU. Furthermore, a widened energy range for the Oort cloud reservoir would have increased the probability of trapping bodies scattered by Jupiter and Saturn there, thus making the transfer process much more efficient. The strong external perturbations that drove comets to a much more tightly bound Oort cloud ceased to act shortly afterward, as the molecular cloud (or the open cluster) dissipated, thus preventing the formed comet cloud from being disrupted. Such a tightly bound comet cloud could have been the source from which the external Oort cloud has been replenished through the age of the Solar System.**

**An interesting by-product of our scenario of a much denser galactic environment is that not only bodies from the accretion zones of Uranus and Neptune could find their way to the Oort cloud, but also a significant number of residual planetesimals from the Jupiter and Saturn accretion zones could have been incorporated into the Oort reservoir. The physical–chemical nature of new comets may present different signatures according to their different birthplaces, thus constituting relevant pieces of information to learn about the galactic environment in which the Solar System formed.**

## 1. INTRODUCTION

Comets are thought to be very pristine bodies, leftovers of the formation of the jovian planets. Oort (1950) argued that bodies scattered by planetary perturbations to almost interstellar distances would be decoupled from the planetary region by perturbations from passing stars. This condition is essential for obtaining long dynamical lifetimes, so as to keep a large fraction of primordial bodies still revolving around the Sun, since planetary perturbations would lead to ultimate ejection within time scales considerably shorter than the age of the Solar System. Stellar perturbations would also be responsible for randomizing the orbital planes of the scattered planetesimals. The main feature of Oort's theory is thus the existence of a huge reservoir of icy bodies swarming around the Sun in a spherical structure at distances of several times $10^4$ AU. Oort also argued that stellar perturbations were also responsible for bringing some members of the comet cloud back to the planetary region where they may become detectable as "new" comets. The Oort cloud theory has been able to explain several dynamical features of comets, in particular the random orientations of the orbital planes of long-period comets and the concentration of original orbital energies $E_{\text{orig}}$ (which are usually expressed in terms of the reciprocal semimajor axis $1/a$) in the narrow energy range of near-parabolic orbits: $-10^{-4}$ AU$^{-1} < E_{\text{orig}} < 0$ (negative values of $E_{\mathrm{orig}}$, or positive values of $a_{\mathrm{orig}}$, are for elliptical orbits). The word "original" refers to the orbit the comet has before entering the planetary region, i.e., before being perturbed by the planets.

Planetary perturbations act on near-parabolic comets when they are close to perihelion, causing mainly a change in the comet's orbital energy. This is a stochastic process in which the comet receives a kick at every perihelion passage at a different energy level (it can either gain or lose energy). The result is a random walk in energy phase space. If no other forces act on the comet, the ultimate fate will invariably be ejection to interstellar space (neglecting collisions with planets or the Sun or sublimation by the Sun's radiation). It is the classical diffusion problem with a cliff at one of the extremes that has been widely studied by several authors (e.g., van Woerkom 1948, Lyttleton and Hammersley 1963). Yet, if other forces act on the comet when it is far away from the Sun (for instance, stellar perturbations), then its perihelion distance may increase beyond the reach of planetary perturbations. The comet will remain in such a loosely bound orbit until the external perturbers send it back to the planetary region or eject it to interstellar space.

Oort suggested that comets and asteroids might have had a common origin in the asteroid belt, though the different physical nature of the rocky asteroids and the icy comets was pointed out by Kuiper (1951) shortly afterward. Later studies by Safronov (1969) and Fernández (1978) showed that the Uranus–Neptune region was the most likely source of comets, since the more modest perturbations of these planets would ensure that a large percentage of the scattered comets would fall in the Oort region, namely, the region in energy space where stellar perturbations are strong enough to decouple bodies from the planetary region before ejection to interstellar space by planetary perturbations occurs.

But not only passing stars can perturb comets moving on near-parabolic orbits. Galactic tidal forces and penetrating encounters with giant molecular clouds (GMCs) can exert an even larger dynamical effect. Biermann (1978) suggested that molecular clouds can play a fundamental role in the dynamical evolution of Oort cloud comets, and Napier and Clube (1979) argued that GMCs can disrupt the outer portions of the Oort cloud. Tidal forces of the galactic disk are more intense than those of the galactic nucleus, as was shown by Byl (1983). The most important dynamical effect is to change the comet's perihelion distance, so it can be removed from or injected back into the planetary region. It can be shown that the tidal force of the galactic disk is more intense at mid-galactic latitudes [cf. eq.(8)], which is reflected in a greater concentration of the aphelion points of the observed long-period comets there (Delsemme 1987).

The dynamical studies of the Oort cloud have been complemented by numerical simulations that illustrate how comets scattered by the jovian planets become trapped in the Oort reservoir by stellar perturbations (e.g., Weissman 1979, Fernández 1980). More complete numerical simulations including the tidal force of the galactic disk were later carried out by Duncan *et al.* (1987).

So far, most studies on Oort cloud formation have implicitly assumed that the field of external perturbers has experienced little change from the early Solar System up to now. But calculations show that the Sun may have experienced radial excursions of more than $10^3$ parsecs (pc), as it moved around the galactic center to a zone where the surface density of molecular gas falls off very steeply. This has probably modulated the strength of the tidal force of the galactic disk (e.g., Hut and Tremaine 1985). Matese *et al.* (1995) have further estimated how radial variations in the galactocentric distance (and, thus, in the local density of the galactic disk), as the Solar System revolves around the galactic center, modulate the rate of comets injected into the planetary region. The fundamental question, however, is: What was the galactic environment in which the Solar System formed, since the buildup of the Oort cloud probably occurred soon after the accreting jovian planets acquired substantial masses?

It is well known that most stars tend to form in clusters within molecular clouds (e.g., Lada *et al.* 1993), so it is then probable that this was the way in which the Solar System formed. However interesting this possibility may be, very little attention has been paid to it until now. Mottmann (1977) argued that the late heavy bombardment on the surfaces of the terrestrial planets, about $4 \times 10^9$ years ago, was triggered by a very close stellar passage at an early epoch when the Sun formed part of an open cluster. He also argued that such an encounter also tilted the orbital planes of the jovian planets by $\sim 8°$ with respect to the solar spin axis. Hills (1982) later assumed that the Solar System and an inner comet cloud formed during the early collapsing stages of the nebula within a very dense star cluster. Tremaine (1991) attributed the twist of the orbital angular momentum vector of the planets to torques due to nearby mass concentrations within the solar nebula or asymmetric infall of material. Gaidos (1995) has further analyzed the dynamical consequences of Solar System formation within a dense galactic environment. He sets constraints on the local density of external perturbers from the current orbital inclinations of Uranus and Neptune. Gaidos also refers to the formation of a transient comet cloud at $\sim 3000$ AU from residual planetesimals scattered by Saturn, but he argues that it would have promptly been eroded by the strong tidal field of the dense environment and frequent stellar encounters.

We think that all the dynamical consequences of the formation of the Solar System within a dense galactic environment, in particular concerning the buildup of the comet cloud, have not been thoroughly explored. Our increasing body of observational data showing that stars form within molecular clouds, and usually in clusters of different sizes, gives relevance to this subject. Furthermore, some recent studies (e.g., Lissauer *et al.* 1995, Pollack *et al.* 1996) suggest that the outer planets formed on time scales much shorter than thought before (e.g., Safronov 1969), so the buildup of the Oort cloud might have been a very early episode in the Solar System's lifetime, probably when the Solar System was still within its natal environment. The aim of this paper is to further discuss the dynamical consequences of a dense galactic environment on the formation of the Oort cloud.

## 2. ACCRETION OF THE JOVIAN PLANETS

It is widely agreed that the mostly gaseous Jupiter and Saturn had to form before the dispersal of the hydrogen and helium of the primitive nebula on a very short time scale of a few million years (e.g., Lissauer 1987). There is strong observational support for a rapid dissipation of circumstellar gas around pre-main-sequence, low-mass stars, as the detection of "naked T Tauri" stars with ages approximately a million years old suggests (see, e.g., Walter *et al.* 1988). Recent radio CO observations by Zuckerman *et al.* (1995) confirm that the molecular gas surrounding young solar-type stars tends to dissipate very quickly, perhaps in only a few million years. Uranus and Neptune may have essentially formed by collisional accumulation of planetesimals over longer time scales. We do not yet have good theoretical or numerical models to assess how much longer these time scales were in comparison with those of Jupiter and Saturn. Fernández and Ip (1996) showed that embryo planets of Mars's size, initially spread in the outer planetary region, can grow to Neptune-size planets over time scales of $\sim 1\text{–}2 \times 10^8$ years. The fact that Uranus and Neptune contain nonnegligible fractions of hydrogen and helium, perhaps amounting to something between $1M_\oplus$ and $2M_\oplus$ (Hubbard 1989, Hubbard *et al.* 1995), suggests that they grew fast enough to be able to capture gas from the nebula before its dispersal by the strong T Tauri wind. Earth-size embryo planets in the outer planet region might have already been able to maintain extended dense atmospheres of hydrogen and helium (Lissauer *et al.* 1995) favoring their later growth. Pollack *et al.* (1996) have recently developed a sophisticated numerical model for the accretion of the jovian planets, taking into account both the gas and planetesimal accretion rates. They find that it might have taken about $1.6 \times 10^7$ years for Uranus to reach its present size (not much longer than the growth times of Jupiter and Saturn), while for Neptune the corresponding formation time might have been about $3.7 \times 10^7$ years. The authors find that these formation time scales could have been even shorter if the accretion of Uranus and Neptune was dominated by small, kilometer-sized planetesimals.

Fernández and Ip (1984, 1996) studied numerically the accretion and scattering of bodies in the Uranus–Neptune zone. One interesting and unexpected result was that the orbit of Neptune, and to a lesser extent those of Uranus and Saturn, experienced an outward drift due to exchange of angular momentum with the interacting planetesimals. The angular momentum gained by the orbital expansion of these planets was compensated by a small drift inward of the massive Jupiter. These numerical models are suggestive in that initial masses two to three times the combined masses of Uranus and Neptune (i.e., $\sim 60\text{–}100M_\oplus$) were required to form these planets; the unaccreted solid material was lost to the inner planetary region or to interstellar space. Therefore, the accretion of Uranus and Neptune seems to have been very inefficient in their late stages, which can be explained as due to the increasing probability of ejection of interacting planetesimals by rapidly growing protoplanets (say, masses $\gtrsim$ a few $M_\oplus$) as compared with collisional accretion.

The much larger population in the outer planetary zone presumably had to include many massive bodies, in addition to proto-Uranus and proto-Neptune. Stern (1991) has argued that Triton, the Pluto–Charon binary system, and the tilt of Uranus and Neptune's spin axes are fossil records of a substantial population of 1000-km-sized objects. The late heavy bombardment of the terrestrial planets that lasted until 3800 myr ago might be explained by a source of long-lived projectiles in the outer planet zone (Wetherill 1975, Fernández and Ip 1983). The above discussion then suggests that there was a massive scattering by the jovian planets of the residual population left after the formation of Uranus and Neptune and that it likely occurred early in the history of the Solar System.

## 3. EXTERNAL PERTURBERS IN THE SUN'S NEIGHBORHOOD

For a body to be stored in the Oort cloud, its perihelion distance has to be raised above Neptune's orbital radius by at least ~10–15 AU. For comets in the outer planet zone, this condition should be fulfilled when $\Delta q \sim q$. As mentioned, a comet of initial orbital energy $E_0 \propto -(1/a_0)$ (given in $\mathrm{AU}^{-1}$) will random walk in energy space due to planetary perturbations, experiencing an energy change $\varepsilon$ during each perihelion passage. Since the energy changes are stochastic, the number of revolutions required for the comet to reach a parabolic orbit ($1/a = 0$) is of the order

$$N \sim \frac{(1/a_0)^2}{\varepsilon_t^2}, \tag{1}$$

where $\varepsilon_t$ is the typical energy change per passage, com-

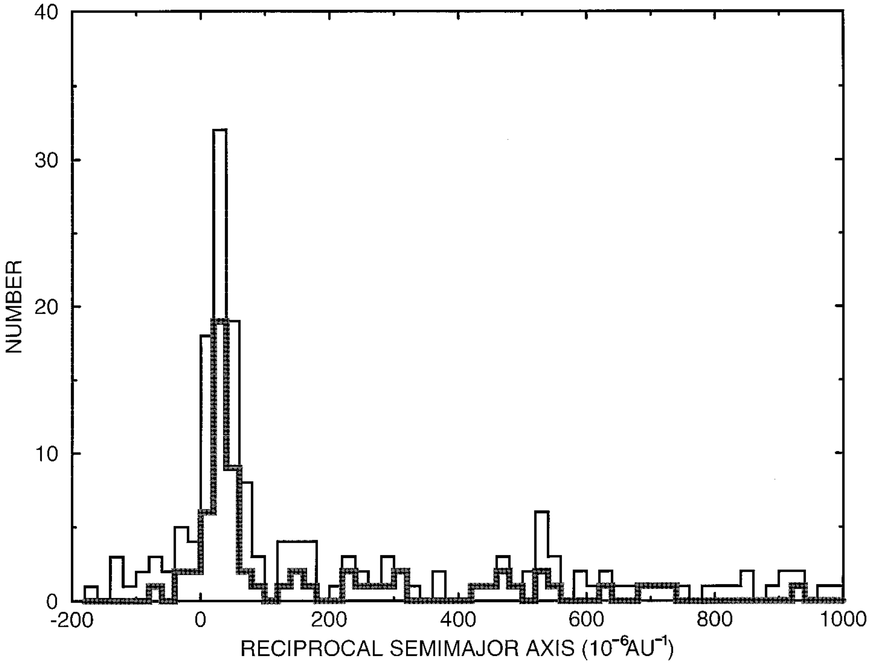

**FIG. 1.** Distribution of original reciprocal semimajor axes of the observed new and young long-period comets from Marsden and Williams' (1996) catalog with $(1/a)_{\mathrm{orig}} < 10^{-3}$ AU$^{-1}$ (i.e., comets with $a_{\mathrm{orig}} > 10^3$ AU or original hyperbolic orbits with $a_{\mathrm{orig}} < 0$). The thick histogram is for the subsample of comets of quality class 1 (as defined in the Marsden and Williams' catalog) and perihelion distances $q > 2$ AU which are presumably less affected by non-gravitational forces.

puted as the root mean square (rms) of a large sample of individual energy changes $\varepsilon$ (see Fernández 1981, Duncan *et al.* 1987). $\varepsilon_t$ is a function of the planet's mass and semimajor axis and of the encounter velocity of the comet with the planet. Therefore, for near-parabolic comets there will be a strong dependence of $\varepsilon_t$ on the comet's perihelion distance and inclination. Equation (1) is valid provided $1/a_0 > \varepsilon_t$.

If after $N$ revolutions the comet has not been decoupled from the planetary region, it will be ejected to interstellar space. Therefore, to be stored in the Oort cloud a comet of energy $-(1/a_0)$ will have to experience a change $\Delta q \sim q$ within $N$ revolutions. Strictly speaking, $a$ will change due to planetary perturbations on each perihelion passage, so we should expect that the change in $q$ required to remove the comet from the planetary region should occur before $N$ revolutions. If $N$ is smaller, $a_0$ is larger, so strictly speaking Eq. (1) will give us a lower limit for the semimajor axis $a_0$ of comets likely to be removed from the planetary region before ejection occurs.

The distribution of the original orbital energies $E_{\mathrm{orig}} = -(1/a_{\mathrm{orig}})$ of new and young comets clearly shows a spike in the energy range $-6 \times 10^{-5}$ AU$^{-1}$ $< E_{\mathrm{orig}} < 0$ (Fig. 1). The spike is equally outstanding when we limit the sample to the best-determined orbits as described in the figure caption. The observed sharp boundary at the energy level $-6 \times 10^{-5}$ AU$^{-1}$ defines the lower limit of the Oort region at $a_{\mathrm{orig}} \sim 1.7 \times 10^4$ AU.

A passing star of mass $M$ and relative velocity $V$ will impart an impulsive change in the comet's velocity relative to the Sun given by

$$\Delta\mathbf{v} = \Delta\mathbf{v}_c - \Delta\mathbf{v}_\odot = \frac{2GM}{V}\left(\frac{\mathbf{D}_c}{D_c^2} - \frac{\mathbf{D}_\odot}{D_\odot^2}\right), \qquad (2)$$

where $G$ is the gravitational constant; $\Delta\mathbf{v}_c$ and $\Delta\mathbf{v}_\odot$ are the impulses received by the comet and the Sun from the passing star, and $\mathbf{D}_c$ and $\mathbf{D}_\odot$ are the distances of closest approach of the star to the comet and to the Sun, respectively (see, e.g., Fernández and Ip 1991). For distant encounters, $\Delta\mathbf{v}_c$ and $\Delta\mathbf{v}_\odot$ become nearly parallel, so the modulus of $\Delta\mathbf{v}$ in Eq. (2) can be approximately expressed by

$$\Delta v = \frac{2GMr\cos\beta}{VD_\odot^2}, \qquad (3)$$

where $r$ is the heliocentric distance of the comet and $\beta$ is the angle between $\mathbf{D}_\odot$ and $\mathbf{r}$. We adopt in the following a time-average heliocentric distance $\langle r\rangle = a(1 + e^2/2) \sim 1.5a$ (valid for a near-parabolic orbit of eccentricity $e \sim 1$).

The cumulative change in the orbital velocity of the comet during time span $\Delta T$ will be given by

$$\Delta v_*^2 = \Delta T \int_{D_{\min}}^{D_{\max}} \Delta v^2 s(D_\odot)\, dD_\odot, \tag{4}$$

where $D_{\max}$ and $D_{\min}$ are the maximum and minimum distances of closest approach of passing stars to the Sun expected during $\Delta T$. $D_{\max}$ can be taken as infinity without too much error. $D_{\min} = (2n_*\Delta T)^{-1/2}$, where $n_*$ is the stellar flux in the Sun's neighborhood of about 7 stars myr$^{-1}$ passing through a circle of 1-pc radius, assuming a relative velocity $V = 30$ km sec$^{-1}$ (Fernández and Ip 1991). $s(D_\odot)\, dD_\odot = 2n_* D_\odot\, dD_\odot$ is the rate of stellar passages with impact parameters in the range ($D_\odot$, $D_\odot + dD_\odot$). Let us adopt for the star's mass $M = M_\odot$. The average change in the transverse velocity of the comet is

$$(\Delta v_*)_{\mathrm{T}}^2 \approx \Delta v_*^2 \langle \cos^2 \psi \rangle = \tfrac{2}{3}\, \Delta v_*^2. \tag{5}$$

The corresponding change in the perihelion distance is given by

$$\frac{\Delta q}{q} = 2\, \frac{(\Delta v_*)_{\mathrm{T}}}{v_{\mathrm{T}}} \tag{6}$$

where $v_{\mathrm{T}} \simeq (2GM_\odot q)^{1/2}/r$ is the transverse velocity of the comet (assumed to be in a near-parabolic orbit).

Let us set $\Delta T = N \times P$ in the integral of Eq. (4), where $N$ is given by Eq. (1) and $P = 2\pi(GM_\odot)^{-1/2}a^{3/2}$ is the comet's orbital period, and adopt for $\Delta v$ the approximate expression of Eq. (3), which is a reasonable assumption, except for the rare, very close encounters. In the following we consider the case of a body in Neptune's zone for which $q \sim 30$ AU and $\varepsilon_{\mathrm{t}} \sim 2.25 \times 10^{-5}$ AU$^{-1}$ (cf. Table II). If we substitute the derived value of $\Delta v_*$ in Eqs. (5) and (6), we obtain after introducing the corresponding numerical values

$$\left(\frac{\Delta q}{q}\right)_{N,\mathrm{stellar}} = 0.0226 \left(\frac{\varepsilon_{\mathrm{t}}}{2.25 \times 10^{-5}\ \mathrm{AU}^{-1}}\right)^{-1} \left(\frac{q}{30\ \mathrm{AU}}\right)^{-1/2} \left(\frac{a}{10^4\ \mathrm{AU}}\right)^{5/2}. \tag{7}$$

Since the body is at the edge of the planetary region, we assume that a change $\Delta q \sim 0.5q$ is enough to place the body beyond the perturbing influence of the planets (Everhart 1968).

If close encounters occur during the diffusion of the comet, say stars approaching the Sun to distances $\lesssim 2\langle r \rangle = 3a$, the semimajor axis computed from Eq. (7) will be somewhat overestimated. The use of a more complete equation that splits $\Delta v$ into two contributions, from close and distant encounters (cf. Fernández and Ip 1991), can lead to a decrease in the computed value of $a$ by no more than 20–40%. This variation does not qualitatively change our discussion.

At present, the tidal force of the galactic disk is mainly responsible for changes in the comet's angular momentum (and, thus, in $q$) (Byl 1983, Morris and Muller 1986, Heisler and Tremaine 1986). The change in $q$ in one orbital revolution due to this force is given by (e.g., Byl 1983, Fernández 1992)

$$\left(\frac{\Delta q}{q}\right)_1 = \frac{6\pi G\rho a P \cos\alpha \sin 2\phi}{(2GM_\odot q)^{1/2}}, \tag{8}$$

where $\rho$ is the density of the galactic disk in the Sun's neighborhood, $P$ is the comet's orbital period, $\alpha$ is the angle between the orbital plane and the plane perpendicular to the galactic disk that contains the radius vector Sun–comet $\mathbf{r}$, and $\phi$ is the galactic latitude of $\mathbf{r}$ (which, for a near-parabolic orbit, is very close to the direction of the aphelion point). As seen, the greatest dynamical effect is attained for $\phi = 45°$, in agreement with the observed concentration of aphelion points at mid-galactic latitudes (cf. Section 1).

There is some question about the best value of $\rho$. From the comparison of different gravitational potential models of the Galaxy with velocity dispersions of tracer stars, Bahcall (1984) derived $\rho = 0.185 M_\odot$ pc$^{-3}$, while Kuijken and Gilmore (1989) obtained a lower value of $\rho = 0.10 M_\odot$ pc$^{-3}$. Matese *et al.* (1995) used a density $\rho = 0.25 M_\odot$ pc$^{-3}$ at the most recent plane crossing if dark matter is present, but it could be as low as $0.13 M_\odot$ pc$^{-3}$ in a no-dark-matter model. Moreover, they found a quasiperiodic variation of the galactic disk density between $\sim 0.05 M_\odot$ and $0.15 M_\odot$ pc$^{-3}$ as the Solar System circles the galactic center at varying galactocentric distances. We adopt in the following an average value of $\rho = 0.15 M_\odot$ pc$^{-3}$.

If we assume that the comet remains more or less with the same $a$ during $N$ revolutions, the total change will add linearly (assuming also that the orientation of the comet's apsidal line and the vertical distance to the galactic midplane do not change significantly during $N$ revolutions), so we have

$$\left(\frac{\Delta q}{q}\right)_N = \left(\frac{\Delta q}{q}\right)_1 \times N. \tag{9}$$

Substituting $N$ by Eq. (1) and $(\Delta q/q)_1$ by Eq. (8) and introducing numerical values for the averages $\langle \cos\alpha \rangle = 2/\pi$ and $\langle \sin 2\phi \rangle = 2/3$, we finally obtain

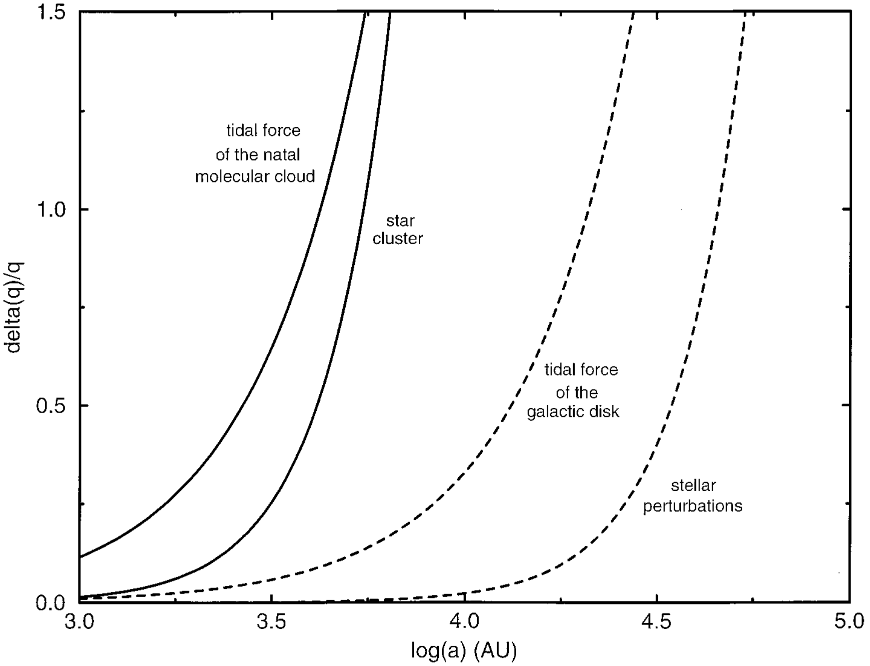

**FIG. 2.** Relative change in the perihelion distance of a comet as a function of its semimajor axis for different external perturbers. Dashed curves are for perturbers from the present galactic environment. Solid curves are for assumed perturbers in an early galactic environment.

$$\left(\frac{\Delta q}{q}\right)_{N,\mathrm{tide}} = 0.329\left(\frac{\varepsilon_{\mathrm{t}}}{2.25\times10^{-5}\,\mathrm{AU}^{-1}}\right)^{-2}\left(\frac{q}{30\,\mathrm{AU}}\right)^{-1/2}\left(\frac{a}{10^{4}\,\mathrm{AU}}\right)^{3/2}. \tag{10}$$

The error committed by averaging sine and cosine factors in the above equation fortunately has only little influence on the computed values of $a$. For instance, changes by about 50% in the product $\cos\alpha\sin 2\phi$ would lead to changes of only ~30% in the computed $a$.

The dashed curves of Fig. 2 show the change $\Delta q/q$ as a function of the semimajor axis $a$ for stellar perturbations [Eq. (7)] and for the tidal force of the galactic disk in the present solar neighborhood [Eq. (10)]. From the plots we see that changes $\Delta q \sim 0.5q$ due to the tidal force of the galactic disk are reached for a semimajor axis $a \sim 1.3\times10^4$ AU. The effect of stellar perturbations is much smaller; the condition $\Delta q \sim 0.5q$ is reached only for $a \sim 3.4\times10^4$ AU. Therefore, the tidal force of the galactic disk plays, at present, the major role in injecting comets into the planetary region, which confirms previous results (e.g., Heisler and Tremaine 1986, Morris and Mueller 1986) and is in good agreement with the observed maximum $1/a_0$ value of the spike of original reciprocal semimajor axes shown in Fig. 1.

If the early Solar System was within a galactic environment similar to the current one, icy planetesimals scattered by the jovian planets would have given rise to a loosely bound Oort cloud with an inner radius of $a \sim 1.3\times10^4$ AU. We note that the definition of an inner radius does not imply that no comets with smaller semimajor axes can be trapped in the Oort cloud. Since we introduced average values in Eq. (10), there will always be favorable circumstances to produce captures of comets with $a \lesssim 1.3\times10^4$ AU. Nevertheless, we should expect that the number of comets trapped in the Oort cloud falls off below that limit. From numerical experiments, Duncan *et al.* (1987) obtained a substantial fraction of Oort cloud comets with $a \sim$ 3000–13,000 AU, which amounts to about two-thirds of the total Oort cloud population in the range 3000–50,000 AU. Yet, this discrepancy with our computed inner radius cannot be considered to be very significant given the different procedures employed. Part of the discrepancy may arise from small differences in the adopted numerical values (for instance, the density of the galactic disk, the range of initial $q$ of the scattered comets). If we consider some extra effects, such as an enhanced role of Jupiter and Saturn in the scattering of bodies (cf. Section 5), the capture efficiency in the inner core may have decreased below the fraction estimated by Duncan *et al.* Therefore, we can conclude that under the current galactic conditions the fraction of comets trapped in the range 3000–13,000 AU would lie somewhere between a few percent and

~65%. The rest of the comet population would have been trapped in more loosely bound orbits with $a \gtrsim 13{,}000$ AU.

The picture of a loosely bound Oort cloud, however, presents some difficulties with which to deal. The first difficulty has to do with the disrupting effect of penetrating encounters with GMCs over the age of the Solar System (Napier and Staniucha 1982, Bailey 1983, Hut and Tremaine 1985). But there is a second important issue that we analyze below: No matter in which part of the planetary region the residual planetesimals were originally located, Jupiter and Saturn were, at the end, the planets that took control of the dynamical evolution of most bodies. And, as we discussed earlier, the probability that Jupiter and Saturn placed a comet in a weakly bound, Oort-type orbit is very low.

## 4. THE EARLY GALACTIC ENVIRONMENT OF THE SOLAR SYSTEM

Near-infrared imaging surveys of nearby GMCs have shed new light on the way stars form. Young stars appear embedded in dense cores of gas (mainly molecular hydrogen) and dust, which in itself is an indication that stars form within molecular clouds (Lada *et al.* 1993, Lada 1995). Furthermore, they do not seem to form in isolation, but in groups of different sizes and compactness, ranging from very poor clusters of a few members to very rich clusters of hundreds of stars. Kroupa (1995) raises the interesting issue of observations showing that the proportion of wide binaries (separations from a few AU to ~1800 AU) among pre-main-sequence stars is about 1.5 times larger than on the main sequence. From this finding Kroupa concludes that most galactic field stars may have formed as binary systems in clusters of best-fit parameters: 200 binary systems and half-mass radius of 0.8 pc. Perturbations among cluster binaries would lead to the dissolution of many pairs, leaving the fraction of binaries of about 60% observed in galactic field stars.

It is accordingly reasonable to propose that the Sun also formed within a molecular cloud and, perhaps, a star cluster (we will leave aside here the intriguing and very exciting possibility that the Sun had a primitive companion that escaped before the cluster dissolved). This primitive galactic environment could have lasted at most a few $10^7$ years, the time required for a GMC to dissipate in the galactic medium (Blitz 1993). If the Sun happened to form within a rich cluster, then the residence time could have extended to approximately a hundred million years, the average lifetime of open clusters (Lyngå 1982). Although a time span of a few tens of millions to one hundred of millions of years represents only a small fraction of the Solar System age, it may nevertheless cover key episodes of its history when Jupiter and Saturn probably formed (cf. Section 1), and Uranus and Neptune were probably well on the way to reaching their present sizes and locations. That was probably also the time when most of the residual solid matter in the accretion zones of Jupiter and Saturn and a significant fraction of the residual solid mass in the Uranus and Neptune zones were ejected (cf. Section 2).

Let us now analyze what would have been the consequences on the formation of the Oort cloud if the early Sun would have been within such a dense galactic environment. Let us assume first that the Sun was within a molecular cloud. The average density of a molecular cloud is about 50 $H_2$ molecules $\mathrm{cm}^{-3}$ (Blitz 1993), which corresponds to a mass density of $\rho_{\mathrm{mc}} \sim 2.5 M_\odot\ \mathrm{pc}^{-3}$. If we next assume that the Solar System formed at a distance $s(<R_{\mathrm{mc}})$ from the center of the cloud (assumed to be spherical of radius $R_{\mathrm{mc}}$ and of uniform density), the tidal force acting on a body at a radial distance $\Delta s$ from the Sun is given by

$$F = \frac{dF}{ds} \times \Delta s = \frac{2GM_s \Delta s}{s^3} = \frac{8}{3}\pi G \rho_{\mathrm{mc}} \Delta s, \qquad (11)$$

where $M_s$ is the mass enclosed within the sphere of radius $s$.

The rate of change of angular momentum of a comet at a distance $r$ from the Sun is given by

$$\frac{dH}{dt} = \mathbf{F}_t \times \mathbf{r} = \frac{1}{2}\left(\frac{dF}{ds}\right) r^2 \sin 2\eta \cos\gamma, \qquad (12)$$

where $F_t$ is the transverse component of the tidal force, $\eta$ is the angle between $\mathbf{r}$ and the direction from the Sun to the center of the natal molecular cloud, $\Delta s = r \times \cos\eta$, and $\gamma$ is the angle between the plane containing the radius vector $\mathbf{r}$ and the center of the molecular cloud and the comet's orbital plane.

We note that the drag force due to the comet's motion through the gas of the molecular cloud is negligible. For a comet nucleus of radius $R_c$ and density $\rho_c$, and assuming that Epstein's drag regime applies (i.e., that the mean free path of the gas molecules is large as compared with the dimensions of the body), we can define the "stopping time," $t_s$, i.e., the time required to reduce the comet's velocity by a factor $1/e$, as (see, e.g., Weidenschilling 1977)

$$t_s = \frac{\rho_c R_c}{\rho_{\mathrm{mc}} \bar{v}}, \qquad (13)$$

where $\bar{v}$ is the mean thermal velocity of the gas. If we introduce the numerical values $R_c = 10^5$ cm, $\rho_c = 0.5$ g $\mathrm{cm}^{-3}$ for a standard comet nucleus, $\rho_{\mathrm{mc}} = 2.5 M_\odot\ \mathrm{pc}^{-3}$ ($\simeq 1.7 \times 10^{-22}$ g $\mathrm{cm}^{-3}$), and $\bar{v} = 3.5 \times 10^4$ cm $\mathrm{sec}^{-1}$ (for a mean temperature of the molecular cloud of 10 K), we obtain $t_s = 8.3 \times 10^{21}$ sec ($= 2.6 \times 10^{14}$ years); i.e., $t_s$ is longer than the age of the known universe. Even if we consider the density of a core within the molecular cloud of $\sim 10^4$ $H_2$ cm$^{-3}$ we obtain a corresponding time $t_s = 1.3 \times 10^{12}$ years, still longer than the age of the universe. We can therefore neglect gas drag effects on the comet's motion with total confidence.

Taking into account that

$$dH = \left(\frac{GM_\odot q}{2}\right)^{1/2} \frac{dq}{q}, \tag{14}$$

and considering again that the tidal force of the natal molecular cloud acts during a period $N \times P$, where $P$ is the comet's orbital period and $N$ is given by Eq. (1), then after substituting these expressions into Eq. (12), we obtain for the change in the perihelion distance over $N$ revolutions the expression

$$\left(\frac{\Delta q}{q}\right)_{N,\mathrm{mc}} = \frac{4}{3} \frac{\sqrt{2}\pi G \rho_{\mathrm{mc}} r^2 N P \cos\gamma \sin 2\eta}{(GM_\odot q)^{1/2}}. \tag{15}$$

Substituting by the appropiate numerical values and considering averages $\langle \cos \gamma \rangle = 2/\pi$ and $\langle \sin 2\eta \rangle = 2/3$ we finally obtain

$$\left(\frac{\Delta q}{q}\right)_{N,\mathrm{mc}} = 3.65 \left(\frac{\varepsilon_t}{2.25 \times 10^{-5}\ \mathrm{AU}^{-1}}\right)^{-2} \left(\frac{q}{30\ \mathrm{AU}}\right)^{-1/2} \left(\frac{a}{10^4\ \mathrm{AU}}\right)^{3/2}. \tag{16}$$

From Eq. (16) we find that the tidal force of the natal molecular cloud can remove comets from the planetary region for semimajor axes as small as a few $10^3$ AU. The results are plotted in Fig. 2.

Therefore, a galactic environment much more crowded than the present one might have had dramatic consequences in the buildup of the Oort cloud. A tightly bound Oort cloud with a radius of a few thousand AU might be a consequence of such an early environment where the Sun possibly formed. Since most stars tend to form in clusters within molecular clouds, we consider this not to be an ad hoc assumption, but based on strong observational grounds. We can further speculate that had the Solar System formed in a galactic environment like the current one, far fewer comets in the Oort cloud would have survived until the present epoch.

Let us now assume that the Solar System formed within a cluster of stellar density $\nu_{\mathrm{cl}} \sim 15$ pc$^{-3}$, which is within the range observed in open clusters (Lyngå 1982). For a cluster in virial equilibrium we find a rms relative velocity of $V_{\mathrm{cl}} \sim 1$ km sec$^{-1}$. Therefore the stellar flux in the primitive Sun's neighborhood would have been $n_{\mathrm{cl}} = \nu_{\mathrm{cl}} \times V_{\mathrm{cl}} \sim 15$ stars pc$^{-2}$ myr$^{-1}$.

We can make use of Eqs. (3) and (4) for stellar encounters. Even in an open cluster like the one assumed here, the interstar distances will generally be much greater than the comet's semimajor axis at which perturbations by cluster stars can decouple the orbit from the planetary region, provided that the considered time scale is not longer than $\sim 3 \times 10^7$ years, the average lifetime of a comet with $a$ of a few thousand AU under the gravitational control of Neptune. The mean separation between cluster stars is $d \simeq (1/\nu_{\mathrm{cl}})^{1/3} \simeq 8.4 \times 10^4$ AU, whereas the closest approach to the Sun expected during $\tau = 3 \times 10^7$ years is $D_m = (2\nu_{\mathrm{cl}}\tau)^{-1/2} \simeq 6.9 \times 10^3$ AU. Therefore, very few star passages will be expected at distances smaller than the comet's distance, so we can still use Eq. (3) for distant encounters (actually, if we consider the very close stellar encounters, the computed change $\Delta v_c$ will be larger, so our result should be considered as a lower limit). It may be argued that the impulse approximation described by Eq. (3), which assumes the comet to be at rest during the star's passage, breaks down for the low encounter velocities of cluster stars; however, Brunini and Fernández (1996) have found that the impulse formula is a good approximation, even in the cases in which the encounter time is on the order of the comet's orbital period. We accordingly use Eq. (3) for the time being to obtain order-of-magnitude estimates, though admitting that more accurate numerical integrations will be a more appropriate way to address this problem in a follow-up study.

By introducing the numerical values discussed before in Eqs. (3) and (4), we obtain

$$\left(\frac{\Delta q}{q}\right)_{N,\mathrm{cluster}} = 4.528 \left(\frac{\varepsilon_t}{2.25 \times 10^{-5}\ \mathrm{AU}^{-1}}\right)^{-1} \left(\frac{q}{30\ \mathrm{AU}}\right)^{-1/2} \left(\frac{a}{10^4\ \mathrm{AU}}\right)^{5/2}. \tag{17}$$

Since the relative velocities within open clusters are about 30 times smaller than in the Sun's neighborhood at present, the dynamical effect will be much stronger, which is confirmed by Eq. (17). According to these results, if the Sun would have been a member of an open cluster like the one described here, the strong perturbations of other cluster stars would have decoupled comets from the planetary region for $a$ of a few thousand AU (see Fig. 2).

## 5. THE CONTRIBUTION OF THE JOVIAN PLANETS TO THE OORT CLOUD: A REASSESSMENT OF THE ROLE PLAYED BY JUPITER AND SATURN

It has long been argued that the Uranus–Neptune region was the source of Oort cloud comets and that Neptune's perturbations, and to a lesser degree Uranus's perturbations, were the main driving force in transferring comets from near-circular orbits within the planetary region to near-parabolic orbits (Safronov 1969, Fernández 1978). The reason for this is that the typical energy change per perihelion passage that a low-inclination comet experiences under the gravitational control of Neptune ($\sim 2 \times 10^{-5}$ AU$^{-1}$) is somewhat smaller than the binding energies of Oort cloud comets ($\sim$3–6 $\times 10^{-5}$ AU$^{-1}$). Therefore, a comet random walking in the energy space under the gravitational control of Neptune (or Uranus) is very likely to fall in the energy range of the Oort cloud before being ejected. Conversely, Jupiter's perturbations are so strong ($\sim 1.5 \times 10^{-3}$ AU$^{-1}$) that comets under its gravitational influence will very likely overshoot the Oort energy range to a hyperbolic orbit. We now deem it necessary to reconsider some aspects of this scenario.

As residual planetesimals of Neptune's zone are scattered, there is a statistical increase in the encounter velocity $u$ due to Fermi's acceleration mechanism (Arnold 1965), and also due to secular perturbations by the other planets. A body can be ejected in a parabolic orbit if the encounter velocity reaches the value $u = (\sqrt{2} - 1)v_{\rm cir}$, where $v_{\rm cir}$ is the (circular) orbital velocity at Neptune's distance. Now, before that happens the body's perihelion can go down to Uranus's orbit. The minimum perihelion distance $q_{\rm min}$ a body can reach is

$$q_{\rm min} = \frac{(1-U)^2}{1+2U-U^2}, \tag{18}$$

where $U = u/v_{\rm cir}$. Equation (18) shows us that for velocities $U \sim 0.3$, i.e., significantly smaller than that required for escape, the body can reach Uranus's zone.

Once the body reaches Uranus' zone, it can be subject to strong perturbations by both Neptune and Uranus. Even though close encounters with Neptune could be more probable at the beginning, because one of the nodes of the body's orbit should be close to Neptune's orbit, secular perturbations by the planets will change the orientation of the nodes and apsidal line of the body's orbit, so close interactions with either Uranus or Neptune can occur. The probabilities of close interactions with one of the planets can be expressed by Öpik's (1951) equation

$$p = \frac{\tau^2 U}{\pi \sin i |U_x|}, \tag{19}$$

where $\tau$ is the radius of the cross section for strong interactions and $U_x$ is the component of the encounter velocity in the radial direction. $\tau$ is proportional to the gravitational radius for collision expressed in units of the radius of the planet's heliocentric orbit (assumed to be circular). Therefore, $p$ will rapidly increase for smaller heliocentric distances and larger planet masses, the largest $p$ being for Jupiter.

TABLE I
Probability That a Given Jovian Planet Will Control the Dynamical Evolution of a Body Starting in Neptune's Accretion Zone

| Planet | $p_1$ |
|---|---|
| Jupiter | 0.60 |
| Saturn | 0.24 |
| Uranus | 0.06 |
| Neptune | 0.10 |

Numerical simulations show that bodies starting at Neptune's zone indeed evolve in such a way that most of them end up ejected by Jupiter. For instance, numerical simulations by Duncan *et al.* (1995) show that about one-third of objects starting in Neptune's zone end up as visible Jupiter family comets. Fernández and Gallardo (1997) have repeated these calculations using Öpik's two-body algorithm and found very similar results. In particular, their results show that almost 50% of the sample falls under the gravitational control of Jupiter and is eventually ejected by this planet, unless a collision with a planet or the Sun occurs first. No more than 15–20% of the bodies starting in Neptune's influence zone continue under its control until they are ejected. And these are results for the current Solar System: If we assume early conditions where Jupiter and Saturn were already formed while Uranus and Neptune were still accreting material, the contribution of the two outermost planets turns out to be somewhat lower (Fernández and Ip 1981). Furthermore, if the birthplaces of Uranus and Neptune were closer to the Sun, and therefore to Jupiter and Saturn, as the numerical experiments of Fernández and Ip (1984, 1996) show, a larger fraction of residual bodies of their accretion zones would fall under the gravitational control of their closer giant neighbors Jupiter and Saturn. The probability $p_1$ that a body starting in a low-inclination, low-eccentricity orbit in the accretion zone of Neptune falls under the dynamical control of a given jovian planet is given in Table I. The computed probabilities are average values for the different scenarios described above. They have been derived from different results obtained analytically and numerically by Fernández (1978), Fernández and Ip (1981, 1984, 1996), and some new numerical experiments by means of Öpik's two-body code. The scatter in the average probabilities is about 20%.

For bodies starting in Uranus' zone we obtained results similar to the previous ones for Neptune's zone.

As mentioned, comets scattered outward can be trapped in the Oort cloud. Let $p_2$ be the probability that a comet random walking in the energy space falls in the narrow

**TABLE II**
**Typical Energy Changes of Near-Parabolic Comets in Low-Inclination Orbits**

| Planet | $\varepsilon_t(\mathrm{AU}^{-1})$ |
|---|---|
| Jupiter | $1.50 \times 10^{-3}$ |
| Saturn | $3.49 \times 10^{-4}$ |
| Uranus | $3.67 \times 10^{-5}$ |
| Neptune | $2.25 \times 10^{-5}$ |

energy range $\Delta E$ of Oort cloud comets. If we assume that the distribution of energy changes per perihelion passage of near-parabolic orbits follows a Gaussian distribution (Kerr 1961), the probability $p_2$ is approximately given by

$$p_2 = \frac{1}{2\pi} \int_0^{\Delta E} e^{-z^2/2}\, dz, \tag{20}$$

where $z = \sqrt{3/2} \times \varepsilon/\varepsilon_t$ (Fernández 1981), $\varepsilon$ is the energy change per perihelion passage, and $\varepsilon_t$ is the standard deviation of the Gaussian energy distribution (that we adopted as the typical energy change). The adopted values of $\varepsilon_t$ for near-parabolic comets in low-inclination orbits (random inclinations in the range $0 < i < 30°$) and perihelia close to the jovian planet controlling the dynamical evolution are listed in Table II. They are taken from Fernández (1981).

The values quoted in Table II do not take into account close encounters; however, Fernández (1981) showed that close encounters played a very important role in the ejection process, mainly when low-inclination orbits are considered. The distribution of energy changes takes the form of a Gaussian distribution with long tails corresponding to strong perturbations (Everhart 1968). Fernández showed that in this case typical energy changes are about three to four times larger than the values quoted in Table II. To make allowance for close encounters, we computed $p_2$ from Eq. (20) taken as the standard deviation $\varepsilon_t^* = 3.5 \times \varepsilon_t$. We should bear in mind that this is a rough approximation, since the $\varepsilon$ distribution departs now from a Gaussian one because of the long tails. Nevertheless, our results show a fairly good agreement with those found numerically by Fernández and Ip (1981), so we do not expect variations by more than a factor 2 to 3 in more detailed studies (though we deem it extremely interesting to do this in the near future).

The probability that a given jovian planet will place a body coming from Neptune's accretion zone in the Oort cloud is expressed as

$$p_{\mathrm{oort}} = p_1 \times p_2. \tag{21}$$

The energy width can be approximately expressed as $\Delta E = (1/a)_{\mathrm{par}} + (1/a)_{\mathrm{l}}$, where $(1/a)_{\mathrm{par}} = 0$ is the energy of a parabolic comet and $E_{\mathrm{l}} = -(1/a)_{\mathrm{l}}$ is the largest binding energy (minimum semimajor axis) of a scattered comet that has its perihelion decoupled from the planetary region before ejection by planetary perturbations. Therefore, $a_{\mathrm{l}} = 1/\Delta E$ is the minimum semimajor axis of Oort cloud comets, so comets diffusing to semimajor axes $a > a_{\mathrm{l}}$ will be incorporated into the Oort cloud (since we work with average values, $a_{\mathrm{l}}$ cannot be taken as a sharp boundary; in actuality we should expect to have a transition region between no captures and full captures).

Results of $p_{\mathrm{oort}}$ as a function of the minimum semimajor axis $a_{\mathrm{l}}$ are shown in Fig. 3. We can see that for the classical Oort cloud, whose observed width is $\Delta E \sim 6 \times 10^{-5}$ AU$^{-1}$ ($a_{\mathrm{l}} \sim 17{,}000$ AU) (cf. Section 3), Neptune is clearly the main driving force in placing bodies there, in agreement with previous results (Safronov 1969, Fernández 1978). This is because even though about 60% of the planetesimals of Neptune's accretion zone fall under the gravitational control of Jupiter (cf. Table 1), the latter planet has a very low probability of placing bodies in the Oort cloud (less than 2%). The situation changes when we move to more tightly bound models of the Oort cloud, which means a widening of $\Delta E$. For instance, for $a \sim 4000$ AU Saturn, and to a lesser degree Jupiter, places in the Oort cloud a significant fraction of the total mass (about 30%). For extremely compact models of the Oort cloud ($a \sim 10^3$ AU), Saturn and in second place Jupiter become the main contributors of bodies to the Oort cloud. This was pointed out earlier by Weissman (1994), who suggested that a wider energy range for the Oort cloud would result in a greater efficiency of trapping comets there as compared with ejection, in particular for the case of Saturn. According to Weissman, if this greater trapping efficiency were also applied to other solar systems, it would help to explain the seeming scarcity of interstellar comets.

## 6. DISCUSSION

As mentioned, one of the problems with the existence of a loosely bound Oort cloud is its survival during billions of years (e.g., Napier and Staniucha 1982, Bailey 1983). Hut and Tremaine (1985) have found a half-life of $3 \times 10^9$ years for a comet with $a = 25{,}000$ AU, which is a less stringent constraint. Yet this still leaves little energy range for building up a comet cloud, since comets must have $a \gtrsim 17{,}000$ AU or $E \gtrsim -6 \times 10^{-5}$ AU$^{-1}$ to be effectively decoupled from the planetary region before ejection by planetary perturbations (cf. Fig. 1). But, on the other hand, for $a \gtrsim 25{,}000$ AU or $E \gtrsim -4 \times 10^{-5}$, only ~20% of the comets will survive throughout the Solar System lifetime. Therefore, the storage of comets in the Oort cloud will be much more efficient for the energy range $-6 \times 10^{-5} \lesssim E \lesssim -4 \times 10^{-5}$ AU$^{-1}$, i.e., for a narrow energy width

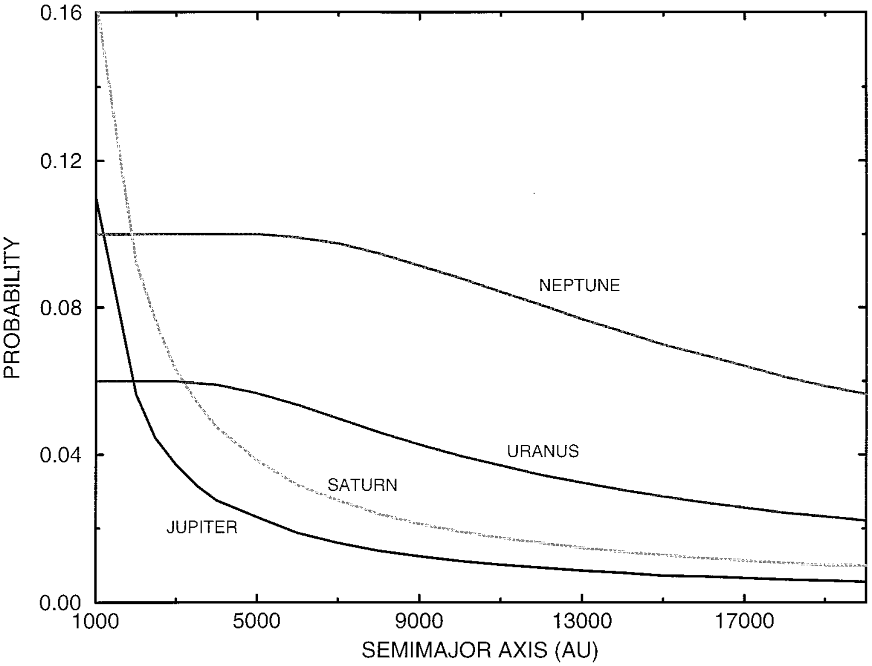

**FIG. 3.** Probability of placing a body coming from Neptune's accretion zone in the Oort cloud by a given jovian planet, as a function of the minimum semimajor axis of the Oort cloud reservoir (the smaller the minimum semimajor axis, the wider the energy range of the Oort cloud reservoir).

$\Delta E \sim 2 \times 10^{-5}$ AU$^{-1}$, of the order of Neptune's typical energy change. To overcome this difficulty, the existence of an inner core of the Oort cloud has been postulated as an additional reservoir (Hills 1981, Bailey 1983, Duncan *et al.* 1987). As comets with smaller binding energies are ejected when the Solar System meets a strong perturber (for instance, a GMC), other comets from the inner core gain energy (i.e., they are pumped up to occupy more loosely bound orbits), so there is continuous replenishment of the outer (or classical) Oort cloud. This is not quite a steady-state process since the inner core will also be depleted with time, though its dynamical lifetime may substantially exceed the age of the Solar System.

We next analyze how a massive inner core could form. *In situ* formation (e.g., Biermann and Michel 1978) encounters the difficulty of the extremely low density of the nebula medium at such large heliocentric distances. Grains are not expected to agglomerate in comet-sized bodies at distances greater than a few hundred AU (Fernández and Gallardo 1997). Cameron (1973) tried to explain the formation of comets in satellite nebulae of the solar nebula moving in highly elliptic orbits, while Hills (1982) considered that grains might have coagulated into comets at distances 1–5 × $10^3$ AU under the combined action of radiation pressure from the proto-Sun and neighboring protostars. Bailey (1987) tried to address the problem of the low density of the nebular material at such distances, arguing that comets could form at the shock front produced when the powerful stellar wind coming from the forming star meets the surrounding envelope. Yet the formed comets would have escape velocities, so this procedure would produce interstellar comets rather than a bound core or shell of comets. Duncan *et al.* (1987) did obtain a substantial inner Oort cloud population with semimajor axes in the range ~3000–20,000 AU (about 80% of the total population), though their results might somewhat depend on the initial conditions of the comets scattered to the Oort cloud (cf. Section 3). For instance, if the initial perihelion distances were concentrated around 5–10 AU, as discussed in Section 5, then the fraction of comets placed in the Oort region with $a \sim 3000$–20,000 AU would drop drastically; however, our proposal for the formation of an inner core appears as a natural by-product of the formation of the Solar System within a dense galactic environment.

Gaidos (1995) also considered the formation of a tightly bound Oort cloud at $a \sim 3000$ AU in a dense galactic environment. But he argued that the same strong forces that formed the comet cloud (either the tidal force of the natal molecular cloud or cluster stars) disrupted it very quickly; however, because of the short lifetime of a dense galactic environment, it is very likely that the core of tightly bound comets will survive throughout this early stage. External perturbers will tend to thermalize the comet cloud population, so the probability of lowering the cometary perihelia back to planetary distances will decrease to a very small value; for instance, for a thermalized comet population the probability that the perihelion distance decreases to $q < q_L$, where $q_L$ is the radius of the planetary region, is $\sim 2q_L/a$ (Hills 1981). Comets in the core can also gain energy to positive values (hyperbolic orbits). If we assume that the Solar System remained within a star cluster during $\Delta T = 10^8$ years, the condition for escape is that the rms change in the comet's velocity, $\Delta v_*$ [cf. eq. (4)] reaches the value

$$\Delta v_* \sim v_{\mathrm{esc}} = \left(\frac{2GM_\odot}{r}\right)^{1/2}, \tag{22}$$

where $v_{\mathrm{esc}}$ is the escape velocity at distance $r$. Again, if we take an average $\langle r \rangle = 1.5a$, we find that the above condition is fulfilled for $a \sim 5800$ AU. Therefore, comets in an inner core with $a \lesssim 5000$ AU would probably have survived during the residence time in an open cluster. The condition for survival in the natal molecular cloud is less stringent. For instance, if the Solar System remained there for 30 myr, the total energy change would be $\Delta(1/a) \sim 5 \times 10^{-6}$ AU$^{-1}$ (see Appendix), which is considerably smaller than the binding energy of the comets ($\sim 10^{-4}$ AU$^{-1}$).

We should bear in mind that the scenario described in this paper is only one among a wide range of possible scenarios, of which the formation of the comet cloud around an isolated Sun constitutes only an extreme case. The Solar System could well have formed in a molecular cloud more or less dense than the one adopted here, as well as in a more compact star cluster or in near isolation. We have tried to describe average conditions derived from observations of star-forming regions. This discussion opens up new possibilities not foreseen until now. After finishing this manuscript, I received a preprint from Eggers *et al.* (1997) discussing the capture of intracluster comets by the early Sun during a stage in which the Sun was assumed to be within an open cluster.

## 7. CONCLUDING REMARKS

In building a new scenario for the formation of a more tightly bound comet cloud, several key questions arise related to the conditions of formation of the Oort cloud and the primitive galactic environment of the Solar System:

1. Did the Solar System form in a molecular cloud and/or an open cluster? As seen before, observations tend to favor this formation scenario as the most common one, since molecular clouds are observed to be star factories, and protostars and young stars usually appear in clumps that lead to open clusters and associations.

2. Did the buildup of the Oort cloud take place while the Sun was still within the natal molecular cloud? As mentioned, molecular clouds have an average lifetime of a few tens of millions of years, while open clusters can have lifetimes significantly longer, perhaps on the order of a few hundreds of millions of years. Therefore, to answer this question we have to know the time scales of formation of the jovian planets, since the massive scattering of residual planetesimals accompanied the latest stages of their formation. The gaseous composition of Jupiter and Saturn strongly suggests a short formation time scale, probably significantly shorter than the dissolution time of the natal molecular cloud. With respect to Uranus and Neptune, the answer is more uncertain. Their non-negligible content of hydrogen and helium suggests that they were able to grow into massive objects on a short time scale, so they could start to scatter bodies while the Sun was still within the natal molecular cloud.

3. Since stronger external perturbers widen the energy range of the Oort region, did Jupiter and Saturn play a more significant role in the buildup of the Oort cloud than thought before? As shown, the answer may be positive; in particular, Saturn might have been a greater contributor than Jupiter.

4. Did Saturn and Jupiter place in the Oort cloud a significant fraction of residual planetesimals from their own accretion zones? The answer to this question also depends on how efficient the process of accretion of solid matter of these mostly gaseous planets was. Models of their internal structure show that Jupiter and Saturn may possess inner cores composed of silicates and ices of about $15M_\oplus$ each (Hubbard 1989), so most of the accreted material was gaseous hydrogen and helium. The probable presence of extended gaseous envelopes might have increased the efficiency of capture of planetesimals by these two planets, via gas drag, fragmentation, and dissolution of bodies crossing through their envelopes (Pollack *et al.* 1986). Still, it is probable that a significant fraction of the interacting bodies were finally ejected by the powerful gravitational interactions of Jupiter and Saturn. If Jupiter and Saturn were able to place a large number of bodies from their own accretion zones in a more tightly bound Oort cloud, this would imply a significant mixing of bodies from different parts of the planetary region, thus providing a physically heterogeneous population of Oort cloud comets, as bodies formed closer to the Sun would tend to have different proportions of volatiles and rock (in a sense, Oort's original idea that the asteroid belt was the source of comets might now be partially vindicated if bodies from the accretion zone of Jupiter were stored in a very compact Oort cloud).

Future observations of the chemical nature of new comets will be very relevant to determining their birthplaces in the planetary region. If we could find new comets that we are able to show, from their chemical composition, were formed in the Jupiter–Saturn region, then important aspects of the galactic environment that surrounded the early Solar System would be highlighted. Comets become, once more, important probes in learning how the Solar System formed.

## APPENDIX: ENERGY CHANGE OF A COMET ASSUMING THE SUN TO BE WITHIN A MOLECULAR CLOUD

Let us assume the Sun to be within a molecular cloud of radius $R_{\rm mc}$ and uniform density $\rho_{\rm mc}$. For simplicity let us also assume that the molecular cloud has a spherical shape and the Sun is at a distance $s(<R_{\rm mc})$ from the center. A comet of semimajor axis $a$ and eccentricity $e$ will experience a change $d(1/a)/dt$ given by the Gauss equation

$$\frac{d(1/a)}{dt} = -2a^{-3/2}\mu^{-1/2}\left(R\,\frac{ae\sin f}{\sqrt{1-e^2}} + B\,\frac{a^2\sqrt{1-e^2}}{r}\right), \tag{23}$$

where $\mu = GM_\odot$, $R$ and $B$ are the radial and tranverse components of the perturbing force, and $f$ and $r$ are the true anomaly and the heliocentric distance of the comet, respectively. The tidal force acting on the comet will be $\mathbf{F} = 8/3\pi G\rho_{\rm mc} r \cos\eta(\mathbf{s}/s)$, so we have $R = F\cos\eta$ and $B = F\sin\eta\cos\gamma$, where, as before (cf. Section 4), $\eta$ is the angle between $\mathbf{F}$ and $\mathbf{r}$, and $\gamma$ is the angle between the plane formed by $\mathbf{r}$ and $\mathbf{F}$ and the comet's orbital plane.

For a quasiparabolic orbit we have $\sqrt{1-e^2} \sim \sqrt{2q/a}$. If we average $d(1/a)/dt$ over the comet's orbital period $P$, the first term on the right side of Eq. (23) vanishes (the energy changes in the outgoing and incoming leg of the orbit cancel out), so Eq. (23) reduces to

$$\left\langle\frac{d(1/a)}{dt}\right\rangle_{\rm P} = -2\sqrt{2}\mu^{-1/2}\sqrt{q}\,\frac{1}{P}\int_0^P \frac{B}{r}\,dt. \tag{24}$$

Making the appropriate substitutions in Eq. (24) we obtain

$$\left\langle\frac{d(1/a)}{dt}\right\rangle_{\rm P} = -\frac{8}{3}\sqrt{2}\pi G\mu^{-1/2}q^{1/2}\rho_{\rm mc}\sin 2\eta\cos\gamma. \tag{25}$$

Taking averages $\langle\sin 2\eta\rangle = \pm 2/3$ and $\langle\cos\gamma\rangle = 2/\pi$, a density $\rho_{\rm mc} = 2.5M_\odot\ {\rm pc}^{-3}$, and $q = 30$ AU, we finally obtain for the energy change $\Delta(1/a)$ during $\Delta T(\gg {\rm P})$

$$\Delta(1/a) = \pm 5.0\times 10^{-6}\left(\frac{\Delta T}{30\ {\rm myr}}\right){\rm AU}^{-1}. \tag{26}$$

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