Oort Cloud Formation and Dynamics

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ABSTRACT

The Oort cloud is the primary reservoir of the “nearly isotropic” comets, which include new and returning long-period comets and Halley-type comets. We focus on the following topics: (1) The population, mass, and structure of the Oort cloud. (2) The fraction of Oort cloud comets that survive to the present, and the timescale for building the Oort cloud. (3) The relative importance of different regions of the protoplanetary disk in populating the Oort cloud. (4) The perihelion distribution of Oort cloud comets, and their impact rate on the giant planets.

1. Introduction

Recorded observations of comets stretch back more than 2,000 years. For example, Yau et al. (1994) showed that a comet noted in Chinese records in the year 69 BC was 109P/Swift-Tuttle, which most recently passed perihelion in 1992. However, it is only in the last 400 years that comets have been generally accepted as astronomical, as opposed to atmospheric, phenomena (Bailey et al. 1990, Yeomans 1991). Even so, learned opinion until the 20th century was divided on whether comets were interlopers from interstellar space (Kepler, Laplace) or members of the solar system (Halley, Kant).

By the mid-19th century, it was well-established that most comets have orbits larger than the orbits of the known planets. Lardner (1853) states “…we are in possession of the elements of the motions of 207 comets….it appears that 40 move in ellipses, 7 in hyperbolas, and 160 in parabolas.” Lardner further divides the comets on elliptical orbits into three categories that roughly correspond to what we would now call Jupiter-family, Halley-type, and “external” long-period comets (Levison 1996). The hyperbolic and
parabolic orbits, in turn, represent “new” long-period comets. (Levison 1996). Lardner also noted that, with the exception of Jupiter-family comets, there were roughly equal numbers of objects that revolved prograde (in the same direction as the planets) and retrograde around the Sun. Levison (1996) introduced the term “Nearly Isotropic Comets” (NICs) to encompass the Halley-type and long-period comets (HTCs and LPCs, respectively).

Newton (1891) and van Woerkom (1948) studied the effects of gravitational perturbations by Jupiter on cometary orbits. In particular, van Woerkom showed in detail that the observed distribution of cometary orbital energies was inconsistent with an interstellar origin for comets. It then fell to Oort, who had supervised the latter stages of van Woerkom’s thesis work (Blaauw and Schmidt 1993), to put the picture together. In his classic 1950 paper, Oort wrote

“There is no reasonable escape, I believe, from the conclusion that the comets have always belonged to the solar system. They must then form a huge cloud, extending . . . to distances of at least 150,000 A.U., and possibly still further.”

Interestingly, speculations by Halley (1705) in his famous Synopsis of the Astronomy of Comets could be interpreted as inferring a distant comet cloud. Halley was only able to fit parabolic elements to the 24 comet orbits he derived, but he argued that the orbits would prove to be elliptical, writing,

“For so their Number will be determinate and, perhaps, not so very great. Besides, the Space between the Sun and the fix’d Stars is so immense that there is Room enough for a Comet to revolve, tho’ the Period of its Revolution be vastly long.”

The rest of this review will discuss what the observed cometary orbital distribution reveals about the structure of the spherical cloud of comets which now bears Oort’s name. In §2 we review studies of the population and dynamics of the Oort cloud. In §3 we discuss
the hypothetical inner Oort cloud, which has been proposed to contain more comets than
the classical Oort cloud, and “comet showers” that might result from a stellar passage
through the inner cloud. In §4 we focus on modern studies of the formation of the Oort
cloud, assuming that comets started as planetesimals within the planetary region. In §5 we
estimate the rate at which Oort cloud comets impact the giant planets. §6 summarizes our
conclusions.

2. Population and Dynamics of the Oort Cloud

2.1. Observed Orbital Distribution

Figure 1 illustrates the orbital distribution of the single-apparition long-period comets
whose energies are given in the 2003 Catalogue of Cometary Orbits. (The catalogue contains
386 such comets, which only represents about half the known apparitions of long-period
comets. For the other half, the data were inadequate to solve for the comet’s energy, so the
orbit was assumed to be parabolic.) We first introduce some terminology and notation. The
symbol \( a \) represents the semi-major axis of a comet, measured with respect to the center of
mass of the solar system. The quantity actually determined in orbit fits is \( E \equiv 1/a \), which
has units of AU\(^{-1}\). \( E \), which we will informally refer to as “energy,” is a measure of how
strongly a comet is held by the Sun. (Note that a comet’s orbital energy per unit mass is
\(-\frac{GM_\odot}{2a}\), so the sign convention for \( E \) is the opposite of that used for orbital energy.) We
distinguish three values of \( E \), which we denote \( E_n \), \( E_o \), and \( E_f \). These denote, respectively,
the osculating (i.e., instantaneous) value of the comet’s \( 1/a \) value when it is passing through
the planetary region; the comet’s original \( 1/a \) before it passed through the planetary region;
and the comet’s future \( 1/a \) after it passes outside the planetary region. A comet with
\( E > 0 \) is bound to the Sun, i.e., it follows an elliptical orbit. A comet with \( E_f < 0 \) is
on a hyperbolic orbit and will escape the solar system on its current orbit; colloquially,
such a comet is called “ejected”. We will also use the symbols $q$ and $i$ to denote a comet’s perihelion distance and orbital inclination to the ecliptic, respectively.

Osculating (i.e., instantaneous) orbits of long-period comets passing through the planetary region (Figure 1a) indicated that many of the orbits were slightly hyperbolic, suggesting that those comets were approaching the solar system from interstellar space. Van Woerkom (1948) had shown that distant perturbations from Jupiter and the other giant planets could capture comets on near-parabolic orbits to more tightly bound orbits. Subsequently the comets would random walk in orbital energy to more tightly bound orbits (a few to eventually become “short-period” comets with orbital periods less than 200 years) or to escape the solar system.

However, when the orbits were integrated backward in time to well before the comets entered the planetary system, yielding the original inverse semi-major axis (denoted as $E_o$), the distribution changed radically (Figure 1b). The $E_o$ distribution is marked by a sharp “spike” of comets at near-zero but bound energies, representing orbits with semi-major axes exceeding $10^4$ AU; a low, continuous distribution of more tightly bound orbits; and a few apparently hyperbolic orbits. This is clearly not a random distribution.

In Figure 1b, about 30% (111 of 386) of the comets occupy the bins with $0 < E_o \leq 10^{-4}$. This region, which corresponds to semi-major axes $> 10^4$ AU, is the spike that led Oort to postulate the existence of the Oort cloud. Another 14 of the comets have $1 \times 10^{-4} < E_o \leq 2 \times 10^{-4}$, with 229 comets off-scale to the right. 32 of the comets have $E_o < 0$; most are visible in panel (b), with only 6 off-scale. Taken at face value, these orbits are slightly hyperbolic, so in principle these comets could be interlopers just passing through the Solar System. It is more likely, however, that most or all of these comets actually follow elliptical orbits, and that the “hyperbolic” orbits are a consequence of observational errors and/or inexact modeling of non-gravitational forces (Królikowska 2001). If the comets with
Fig. 1.— Distribution of cometary energies, $E \equiv 1/a$, where $a$ is the comet’s orbital semi-major axis in AU, from the 2003 Catalogue of Cometary Orbits. Only comets with $|E| < 0.0002$ AU are shown, i.e., only comets whose orbits are apparently weakly unbound ($E < 0$) or weakly bound to the solar system ($a > 5000$ AU).

Panel (a): Osculating value of $E$. (b) Original value of $E$. Panel (c): Future value of $E$. 

Cometary $1/a$ (AU$^{-1}$)
$E_o < 0$ were interstellar in origin, they would likely have speeds at "infinity" of order 30 km/s, which implies $E_o \sim -1$, a factor of $\sim 1000$ larger than the most negative value of $E_o$ measured for any comet (Wiegert and Tremaine 1999). Figure 1c shows the "future" orbits of the comets; more than half are slightly hyperbolic, indicating that they have been ejected from the solar system.

Oort recognized that the spike had to be the source of the long-period (LP) comets, a vast, spherical cloud of comets at distances greater than $10^4$ AU from the Sun, but still gravitationally bound to it$^1$. Oort showed that comets in the cloud are so far from the Sun that perturbations from random passing stars can change their orbits and occasionally send some comets back into the planetary system. On their first pass through the planetary system, Jupiter’s distant, random perturbation ejects roughly half of the “new” comets to interstellar space, while capturing the other half to more tightly bound, less eccentric orbits. Only about 5% of the new comets are returned to Oort cloud distances (Weissman 1979). On subsequent returns the comets continue to random walk in orbital energy until they are ejected, captured to a short-period orbit, collide with a planet or the Sun, or are destroyed by one of several poorly understood physical mechanisms. The few “hyperbolic” comets in Figure 1b are most likely the result of small errors in their orbit determinations, or unmodeled nongravitational forces resulting from jetting of volatiles on the surfaces of

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$^1$Some researchers have noted that Ópik (1932) anticipated Oort’s work by studying the effects of stellar perturbations on distant meteoroid and comet orbits, 18 years earlier. Ópik suggested that stellar perturbations would raise the perihelia of comets, resulting in a cloud of objects surrounding the solar system. However, he specifically rejected the idea that comets in the cloud could ever be observed, because he did not recognize that stellar perturbations would also cause some orbits to diffuse back into the planetary region. Ópik concluded that the observed LP comets came from aphelion distances of only 1,500 to 2,000 AU. Though Ópik’s 1932 paper was a pioneering work on stellar perturbations, it did not identify the cometary cloud as the source of the LP comets or relate the observed orbits to the dynamical theory.
the cometary nuclei. Non-gravitational forces make the orbits appear more eccentric than they actually are (Marsden et al. 1973).

Oort’s accomplishment in defining the source of the LP comets is even more impressive when one considers that it was based on only 19 well determined cometary orbits, compared with the 386 high-quality orbits in the 2003 catalogue. Further analysis of the observed orbits by Marsden et al. (1978) showed that the average “dynamically new” LP comet entering the planetary system from the Oort cloud comes from an aphelion distance of $\sim 4.3 \times 10^4$ AU, or $a \sim 2.15 \times 10^4$ AU.

In Figure 2 we show the comets with $E_o > 10^{-5}$ on a logarithmic scale in $a$. This plot indicates that the “original” semi-major axis distribution of long-period comets is bimodal, with one peak comprised of comets with $a$ of order hundreds or thousands of AU, and another containing comets with $a$ tens of thousands of AU. (The median semi-major axes of these two populations are 550 and 27,000 AU, respectively.) Those with $a < 10^4$ AU are conventionally called “returning” comets; those with $a > 10^4$ AU are called “new” comets. The reason for this terminology is as follows. The median value of $E_o$ for the new comets is $1/27,000 = 3.7 \times 10^{-5}$. The magnitude of the median energy change, $|\Delta E|$, which these comets undergo in one perihelion passage is $4 \times 10^{-4}$. These energy changes are caused by (generally distant) perturbations by Jupiter and Saturn, and are typically of order $\mu/A$, where $\mu$ is the perturbing planet’s mass in solar masses and $A$ is the planet’s semi-major axis in AU (Everhart 1968). Positive and negative energy changes have nearly equal likelihood. Since $|\Delta E| \gg E_o$, about half the comets have $E_f \sim -\Delta E$ and the other half have $E_f \sim +\Delta E$. The former are ejected from the Solar System; the other half are scattered onto more tightly bound orbits with $a \sim 1/\Delta E$, i.e., semi-major axes of a few thousand AU. Thus comets with original values of $a > 10^4$ AU are unlikely to have passed within 10 AU of the Sun in their recent past. This is only a rough criterion; Dybczyński (2001)
gives a detailed analysis of the past histories of long-period comets with well-determined orbits. Some 56% of the new comets have $E_f < 0$ and will not return. Only 7% of the returning comets are ejected on their current apparition; since most have recently orbited through the planetary region a number of times, they typically have $E_o \gg |\Delta E|$ because they (Quinn et al. 1990, Wiegert and Tremaine 1999). The most tightly bound comet in the plot has $a = 40.7$ AU and an orbital period $40.7^{3/2} = 260$ years. Conventionally, long-period comets have been taken to be those with orbital periods greater than 200 years, since until the discovery of Comet C/2002 C1 Ikeya-Zhang = C/1661 C1, apparitions of a comet with $P > 200$ years had never been successfully linked.

Figure 3 shows the distribution of perihelion distances, $q$, and inclination to the ecliptic, $i$, for all 386 comets. The perihelion distribution is peaked near $q = 1$ AU because comets that closely approach the Sun or the Earth are brighter and therefore easier to discover. Historically, comets have only been discovered if they passed well within the orbit of Jupiter (5.2 AU), since the onset of water sublimation occurs about 3 AU from the Sun. For example, all 57 comets with well-determined orbits in the Catalogue of Cometary Orbits that were discovered in the 19th century had $q < 2.3$ AU. Even now, the form of the perihelion distribution beyond $q \sim 2$ AU is not well-constrained because of severe observational incompleteness. However, the advent of electronic detectors and Near-Earth Object surveys has recently led to the discovery of a few long-period comets with larger perihelion distances. The 2003 Catalogue lists six comets on the list with $q > 7$ AU; all have been discovered since 1999, and the comet with the largest perihelion distance (11.4 AU), C/2003 A2, is the most recent entry in the catalogue. As we discuss below, the perihelion distribution is expected to be flat or rising with $q$. Thus, if all comets that have recently passed within 11 AU of the Sun were being detected, at least $(11-7)/11 = 36\%$ of them should have $q > 7$ AU. Since only 6 of 386 (1.6%) of the long-period comets known have $q > 7$, we conclude that we are missing at least 20 comets with $q < 11$ AU for each one that
Fig. 2.— Distribution of original semi-major axes, $a_o$. Comets show a bimodal distribution of $a_o$, with “new” comets having $a_o < 10,000$ AU, and “returning” comets having smaller orbits.
we discover. Figure 3b shows the inclination distribution of the comets, which is similar to an isotropic distribution (solid curve). This indicates that the observable Oort cloud is roughly spherical.

2.2. Cometary Fading and Disruption

Oort already recognized in his 1950 paper that the number of returning comets in the low continuous distribution decayed at larger values of $E$. That is, as comets random walked away from the Oort cloud spike, the height of the low continuous distribution declined more rapidly than could be explained by a purely dynamical model using planetary and stellar perturbations. This problem is commonly referred to as “cometary fading,” though “fading” is a misnomer as it seems to imply a gradual decline of activity. In fact, it is still not clear what the exact mechanism for fading is; for example, spontaneous, catastrophic disruption of comets could be the dominant loss mechanism. In any case, the fading mechanism must be a physical one; the missing comets cannot be removed by dynamical processes alone.

Oort handled fading by introducing a factor, $k$, where $k$ is “the probability that a comet is disrupted during a perihelion passage”. (Note that Oort specifically called this ”disruption” rather than “fading”.) Oort noted that Yamamoto (1936) had reported 11 observations of split comets since 1600 out of 576 observed comets in the same time period, yielding a value of $k = 0.019$, or 0.017 if “short-period” comets with orbital periods $< 50$ years were omitted. However, Oort found that this value removed comets too rapidly from the system, and thus suggested a slightly lower value of $k = 0.014$.

Whipple (1962) treated the problem somewhat differently, modeling the expected cumulative “lifetime” distribution of the LP comets as a power law, $L^{-\kappa}$ where $L$ is the number of returns that the comet makes. Whipple found that $\kappa = 0.7$ with an upper limit
Fig. 3.— Distribution of perihelion distances and inclinations to the ecliptic for the 386 single-apparition comets for which $E_o$ is tabulated in the 2003 Catalogue of Cometary Orbits.
of order $10^4$ returns gave the best fit to the observed orbital data.

Weissman (1979) was the first to use a Monte Carlo simulation to derive the expected cometary energy distribution, including realistic models of the expected loss rate due to a variety of physical destruction mechanisms (Weissman 1980a). In Weissman’s simulations the comets were perturbed by Jupiter and Saturn, random passing stars, and nongravitational forces, and removed by collisions, random disruption (splitting), and loss of volatiles (sublimation of ices). A fairly good match to the observed $E_o$ distribution in Figure 1(b) can be obtained. By tuning such a model to improve the fit, some insight into the possible physical and dynamical loss mechanisms can be obtained.

As a result of such modeling, Weissman found that 65% of the LP comets are dynamically ejected from the solar system on hyperbolic orbits, 27% are randomly disrupted – 10% on the first perihelion passage – and the remainder are lost by a variety of processes such as loss of all volatiles and collision with the Sun or a planet. The average hyperbolic ejection velocity is 0.6 km s$^{-1}$. Some comets may become unobservable due to the formation of nonvolatile lag deposits, or “crusts,” on their surfaces (Brin & Mendis 1979; Fanale & Salvail 1984), which would cut off further cometary activity. The average LP comet with perihelion $< 4$ AU makes 5 passages through the planetary region before arriving at one of the physical or dynamical end-states, with a mean lifetime of $6 \times 10^5$ years between the first and last passages.

Wiegert and Tremaine (1999; cf. Bailey 1984) investigated the fading problem by means of direct numerical integrations that included the gravitational effects of the Sun, the four giant planets and the “disk” component of the galactic tide (see below). They also examined the effects of non-gravitational forces on comets, as well as the gravitational forces from a hypothetical solar companion or circumsolar disk 100 to 1000 AU from the Sun. Like previous authors, Wiegert and Tremaine found that the observed $E_o$ distribution
could only be explained if some physical loss process was invoked. They found that they could match the observed $E_o$ distribution if the fraction of comets remaining observable after $L$ passages was proportional $L^{-0.6\pm0.1}$, consistent with the fading law proposed by Whipple 1962, or if $\sim95\%$ of LP comets live for only $\sim6$ returns and the remainder last indefinitely.

Historically, most comets have been discovered by amateurs. In recent years, telescopic surveys that primarily discover asteroids have discovered both active comets and inactive objects on comet-like orbits. For example, NEAT discovered 1996 PW, which has $a = 287$ AU, $q = 2.5$ AU, and $i = 30^\circ$ (Weissman and Levison 1997). Using statistical models of dormant comet discoveries by surveys (Jedicke et al. 2003), Levison et al. (2002) calculated the number of dormant, nearly isotropic Oort cloud comets (NICs) that should be present in the inner Solar System. This study used orbital distribution models from Wiegert and Tremaine (1999) and Levison et al. (2001) that assumed no disruption of comets. Levison et al. then compared the model results to the 11 candidate dormant NICs that had been discovered. Dynamical models that assume that comets merely stop outgassing predict that surveys should have discovered $\sim100$ times more dormant NICs than are actually seen. Thus, as comets evolve inward from the Oort cloud, $99\%$ of them become unobservable, presumably by breaking into much smaller pieces.

The fading problem is a complex one. Oort cloud comets on their first perihelion passage are often anomalously bright at large heliocentric distances (Oort & Schmidt 1951, Donn 1977, Whipple 1978), and thus their probability of discovery is considerably enhanced. Suggested mechanisms for this effect include a veneer of volatiles accreted from the interstellar medium and lost on the first perihelion passage near the Sun (Whipple 1978), blow-off of a primordial cosmic ray processed nucleus crust (Johnson et al. 1987), or the amorphous-to-crystalline water ice phase transformation that occurs at about 5 AU.
inbound on the first perihelion passage (Prialnik & Bar-Nun 1987).

### 2.3. Population and Mass of the Oort Cloud

To account for the observed flux of dynamically new LP comets, which he assumed to be about 1 per year within 1.5 AU of the Sun, Oort estimated that the population of the cometary cloud was $1.9 \times 10^{11}$ objects. More recent dynamical models (Heisler 1990; Weissman 1990a) have produced somewhat higher estimates, by up to an order of magnitude. These result in part from higher estimates of the flux of LP comets through the planetary system, and in part from a recognition of the role of the giant planets in blocking the diffusion of cometary orbits back into the planetary region (Weissman 1985). Comets perturbed inward to perihelia near the orbits of Jupiter and Saturn will likely be ejected from the solar system before they can diffuse to smaller perihelia where they can be observed. Thus, the terrestrial planets region is undersupplied in LP comets as compared with the outer planets region. This effect is known as the “Jupiter barrier.” We return to this topic in §5.

Heisler (1990) performed a sophisticated Monte Carlo simulation of the evolution of the Oort cloud, assuming it had formed with the centrally condensed density profile found by Duncan et al. 1987 (henceforth DQT87; see §4). Assuming a new comet flux of 2.1 comets/year with $q < 1$ AU, Heisler infers that the present-day Oort cloud contains $5 \times 10^{11}$ comets with $a > 20,000$ AU. This estimate refers to comets with “absolute magnitude” $H_{10} < 11$. Weissman (1996) relates $H_{10}$, which is a measure of a comet’s total brightness (generally dominated by coma) to cometary masses, using 1P/Halley to calibrate the relation. According to Weissman, the diameter of a comet with $H_{10} = 11$ is 2.3 km, the mass of a comet with $H_{10} = 11$ is $4 \times 10^{15}$ g, and the average mass of a comet is $4 \times 10^{16}$ g. Using Heisler’s inferred population, this implies a present-day mass of $2 \times 10^{28}$ g or $3.3M_{\oplus}$.
in comets with $a > 20,000$ AU. Weissman (1996) estimates that there are $1 \times 10^{12}$ comets with $a > 20,000$ AU, giving a mass for the outer OC of $7 \text{M}_\oplus$. Weissman then assumes, based upon DQT87, that the inner OC contains about 5 times as much mass as the outer OC, giving a total present-day OC mass of $38 \text{M}_\oplus$. However, this estimate is based upon a formation model and not on observations, since (a) comets from the hypothetical inner Oort cloud ($a \lesssim 20,000$ AU) are not perturbed into the planetary region except during strong comet showers, which only occur some 2% of the time (Heisler 1990) and (b) we are not presently undergoing a strong comet shower (Weissman 1993). We further discuss the population of the inner Oort cloud in §3 and §4.

### 2.4. Oort Cloud Perturbers

Since first proposed in 1950, Oort’s vision of a cometary cloud gently stirred by perturbations from distant passing stars has evolved considerably. Additional perturbers have been recognized: giant molecular clouds (GMCs) in the galaxy, which were unknown before 1970 (Biermann 1978; Clube & Napier 1982), and the galactic gravitational field itself, in particular the tidal field of the galactic disk (Byl 1983; Heisler & Tremaine 1986). GMC encounters are rare, occurring with a mean interval of perhaps $3-4 \times 10^8$ years, but can result in major perturbations on the orbits of comets in the Oort cloud. Hut & Tremaine (1985) showed that the integrated effect of GMC encounters over the history of the solar system is roughly equal to the integrated effects of all stellar passages. The galactic field sets the limits on the outer dimensions of the Oort cloud. The cloud can be roughly described as a prolate spheroid with the long axis oriented toward the galactic center (Antonov & Latyshev 1972; Smoluchowski & Torbett 1984, Torbett 1986). Maximum semi-major axes are about $1 \times 10^5$ AU (i.e., 0.5 pc, or almost 40% the distance to the nearest star) for direct orbits in the galactic plane, decreasing to about $8 \times 10^4$ AU for orbits
perpendicular to the galactic plane, and increasing to almost $1.2 \times 10^5$ AU for retrograde orbits (opposite to galactic rotation).

In addition, stars will occasionally pass directly through the Oort cloud, ejecting some comets and severely perturbing the orbits of others (Hills 1981). A star passage drills a narrow tunnel through the Oort cloud, ejecting all comets within a radius of $\sim 450$ AU, for a 1 M$_\odot$ star passing at a velocity of 20 km s$^{-1}$ (Weissman 1980b). Over the history of the solar system, Weissman estimates that passing stars have ejected about 10% of the Oort cloud population. The ejected comets will all be positioned close to the path of the perturbing star, as well as many of the comets which are thrown into the planetary system in a “cometary shower” (Weissman 1980b, Dybczyński 2002a,b).

Garcia-Sánchez et al. (1999, 2001; also see Frogel & Gould 1998) used Hipparcos and ground-based data to search for stars which have encountered or will encounter the solar system during a 20 Myr interval centered on the present. Correcting for incompleteness, Garcia-Sánchez et al. (2001) infer $11.7 \pm 1.3$ stellar systems pass within 1 pc of the Sun per Myr, so that some 50,000 such encounters should have occurred in the age of the solar system if the Sun had always occupied its current galactic orbit and environment. 73% of these encounters are with M dwarfs, which have masses less than 0.4 M$_\odot$.

It is now recognized that the galactic disk is the major perturber of the Oort cloud, though stars and probably GMCs still play an important role in randomizing the cometary orbits. Galactic tidal perturbations peak for orbits with their line of apsides at galactic latitudes of $\pm 45^\circ$ and go to zero at the galactic equator and poles. Delsemme (1987) showed that the distribution of galactic latitudes of the aphelion directions of the observed LP comets mimics that dependence. Although a lack of comet discoveries near the galactic equator could be the result of observational selection effects (e.g., confusion with galactic nebulae), the lack of comets near the poles appears to confirm the importance of the
galactic tidal field on the Oort cloud.

The galactic tide causes the cometary perihelia to oscillate on timescales of billions of years, in contrast to the random walk nature of stellar perturbations. Thus the tide results in comets being brought into the observable region more efficiently, making it somewhat easier to overcome the dynamical barrier that Jupiter and Saturn present to cometary diffusion into the inner planets region.

As a result of this better understanding of the roles of Oort cloud perturbers, it is now estimated that the mean dynamical lifetime of comets in the cloud is only about 60% the age of the solar system (Hut & Tremaine 1985), though some authors have estimated even shorter lifetimes (Bailey 1986). This led to suggestions that the observable, “outer” Oort cloud must be replenished, for example by capture of comets from interstellar space, as suggested by Clube & Napier (1984). However, cometary capture is an unlikely process because a three-body gravitational interaction is required to dissipate the excess hyperbolic energy. Valtonen & Innanen (1982) and Valtonen (1983) showed that the probability of capture is proportional to $V_\infty^{-7}$, where $V_\infty$ is the hyperbolic excess velocity. Capture is possible at encounter velocities $\leq 1$ km s$^{-1}$, but is highly unlikely at the Sun’s velocity of 16.5 km s$^{-1}$ relative to the Local Standard of Rest.

More plausibly, the outer Oort cloud could be replenished from an inner Oort cloud reservoir, i.e., comets in orbits closer to the Sun (Hills 1981, Bailey 1983) that are pumped up to replace the lost comets. However, the effects of molecular clouds on the Oort cloud are still highly uncertain, since molecular clouds are part of a “fractal” or “multifractal” continuum of structure in the interstellar medium (Chappell & Scalo 2001). The resulting spatial and temporal correlations in interstellar gas density will result in a much different spectrum of gravitational potential fluctuations experienced by the Oort cloud, compared to an interstellar model that has clouds distributed independently and randomly (John...
Scalo, personal communication, 2003). Thus, it would be premature to conclude that the outer Oort cloud has been so strongly depleted during its lifetime that a massive inner Oort cloud is required to replenish the outer cloud. We now turn to a more detailed discussion of the hypothetical inner cloud.

3. The Inner Oort Cloud and Comet Showers

In Oort’s original model, the density profile \( n(r) \) in the Oort Cloud (OC) is given by

\[
n(r) \propto \left( \frac{R_0}{r} - 1 \right)^{3/2},
\]

where \( R_0 \) is the distance to the outer edge of the OC (e.g., Bailey 1983, Bailey et al. 1990). For \( r \ll R_0 \), \( n(r) \propto r^{-\gamma} \), with \( \gamma \approx 1.5 \). Density distributions with \( \gamma < 3 \) have most of the mass in the outer regions of the cloud, so Oort’s model predicts that there should be few comets with \( r \ll R_0 \), i.e., the population of the inner Oort cloud should be small. To derive this density profile, Oort assumed an isotropic velocity distribution in the cloud; this may not be valid in the inner parts of the cloud. For instance, if the orbits are predominantly radial, \( \gamma \) should be \( \sim 3.5 \), implying a centrally condensed cloud.

Hills (1981) showed that the apparent inner edge of the Oort Cloud at a semi-major axis \( a = a_I \approx (1-2) \times 10^4 \) AU could be a selection effect due to the rarity of close stellar passages capable of perturbing comets with \( a < a_I \). Hills speculated that \( \gamma \gtrsim 4 \), so that many comets (and perhaps the great majority of comets) might reside in the unseen inner OC at semi-major axes of a few thousand AU. Besides its possible role as a reservoir which could replenish the outer cloud after it was stripped by a GMC (Clube and Napier 1984), inner Oort cloud comets might be an important source of impactors on the giant planets and their satellites (Shoemaker and Wolfe 1984, Bailey and Stagg 1988; also see Weissman 1986 and §5). However, the density profile of the Oort cloud is not known \( a priori \), but depends upon the formation process.
During rare passages of stars through the inner Oort cloud, comet showers could result (Hills 1981, Heisler et al. 1987, Fernández 1992, Dybczyński 2002a,b). Heisler (1990) simulated the LP comet flux from the Oort cloud into the planetary region, under the influence of stellar perturbations and a constant galactic tide. She found that the flux is constant within the statistical limits of her dynamical model, except when a major perturbation of the cometary orbits occurs as a result of a penetrating stellar passage. A hypothetical example of the flux versus time into the terrestrial planets region (q < 2 AU) from Heisler (1990) is shown in Figure 4.

The extreme increases in the cometary flux caused by a penetrating stellar passage through the inner Oort cloud are of particular interest. Hut et al. (1987) used a Monte Carlo simulation to show that a 1 M⊙ star passage at 20 km s⁻¹ at 3 × 10³ AU from the Sun would perturb a shower of \( \sim 5 \times 10^8 \) comets into Earth-crossing orbits, raising the expected impact rate by a factor of 300 or more, and lasting 2–3 × 10⁶ years (this model assumed a massive inner Oort cloud with a population five times that of the outer cloud, as in DQT87). Comets from the inner Oort cloud make an average of 8.5 returns each during a major cometary shower. The flux is very high, in part, because the shower comets from the inner Oort cloud start from shorter period orbits than outer Oort cloud comets, with typical periods in the inner cloud of 2–5 \( \times 10^5 \) years versus 3–5 \( \times 10^6 \) years in the outer cloud. Returning comets tend to be perturbed to even shorter period orbits, \( \sim 10^3 \) to \( 10^5 \) years. They thus make many returns in a relatively short period of time. The temporal profile and fraction of surviving comets for a major cometary shower as found by Hut et al. (1987) is shown in Figure 5. The dynamical evolution of cometary showers was also modeled by Fernández & Ip (1987). Farley et al. (1998) presented evidence that the flux to Earth of extraterrestrial \(^3\)He, a tracer of interplanetary dust, increased for 2.5 Myr, centered near the time of the large Popigai and Chesapeake Bay impacts some 36 Myr ago. This work provides the best evidence to date that comet showers have occurred in the past,
Fig. 4. — Number of new long-period comets from the Oort cloud entering the terrestrial planets region, $q < 2$ AU, versus time, based on a Monte Carlo simulation that included random passing stars and galactic tidal perturbations. The large spikes are comet showers due to random stars penetrating the Oort cloud. From Heisler (1990).
although some another mechanism (e.g., an “asteroid shower” following the catastrophic disruption of a main-belt asteroid, Zappalà et al. 1998) also might have produced the signature detected by Farley et al. (1998).

Fortunately, major cometary showers as a result of deep ($q \lesssim 3 \times 10^3$ AU), penetrating stellar encounters are rare, occurring perhaps once every $4 \times 10^8$ years. Cometary showers should also occur with a similar frequency due to random encounters with GMCs, but with possibly an order of magnitude less total flux into the planetary region (Morris & Muller 1987). Lesser showers from more distant, but still penetrating stellar passages at heliocentric distances $\sim 10^4$ AU occur more frequently, on the order of every $4 \times 10^7$ years (Dybczyński 2002a,b). If there is a massive inner Oort cloud, random cometary showers may actually dominate the LP cometary flux contribution through the planetary region (Weissman 1990b).

The suggestion that both biological extinction events (Raup & Sepkoski 1984) and impact craters (Alvarez & Muller 1984) on the Earth repeat with a period of approximately 26 Myr led to several hypotheses that invoked cometary showers as the cause of the extinctions. These hypotheses involved: (1) a dwarf companion star to the Sun in a distant, eccentric, 26 Myr period (corresponding to $a \sim 90,000$ AU) orbit with its perihelion deep in the Oort cloud (Whitmire & Jackson 1984; Davis et al. 1984); (2) a tenth planet circulating in a highly inclined orbit at about 150 AU from the Sun with a precession period of 26 Myr, so that it periodically passed through a trans-Neptunian disk of small bodies (Whitmire & Matese 1985); or 3) the solar system’s epicyclic motion above and below the galactic plane with a half-period of $32-34 \times 10^6$ years, with GMC encounters at galactic plane crossings (Rampino & Stothers 1984). The apparent coincidence between galactic plane crossings by the solar system and terrestrial extinction boundaries was originally pointed out by Innanen et al. (1978). The Sun’s galactic motion was also suggested as the clock
Fig. 5.— Dynamical evolution of a shower of comets from the inner Oort cloud due to a close, penetrating stellar passage at 20 km s\(^{-1}\) at 3 \(\times\) 10\(^3\) AU from the Sun. The solid histogram is the relative number of comets crossing the Earth’s orbit versus time; the dashed curve is the fraction of the original shower comets still evolving in the system. On the order of 5 \(\times\) 10\(^8\) comets brighter than \(H_{10} = 11\) are expected to be thrown into Earth-crossing orbits by the 1M\(_\odot\) star’s passage. From Hut et al. (1987).
mechanism by Schwartz & James (1984), though they only speculated about the underlying physical mechanism leading to the extinctions.

A variety of dynamical problems have been identified with each of these hypotheses, and no evidence in support of any of them has been found. As a result, periodic comet shower hypotheses have not gained wide acceptance and are generally discounted today. More detailed discussions of the relevant issues can be found in Shoemaker & Wolfe (1986), Tremaine (1986), and Weissman (1986b). Questions have also been raised about the reality of the periodicity in the fossil extinction record. Criticism has been made of the statistical techniques used to claim that the periodicity is significant (Hoffman 1985; Heisler & Tremaine 1989; Jetsu & Pelt 2000, Yabushita 2002), and of the accuracy of the dated tie-points in the geologic record, particularly prior to 140 Myr ago (Shoemaker & Wolfe 1986).

Variations in the cometary flux into the planetary region are also expected as a result of variation in the galactic tidal field. For example, the solar system undergoes near-harmonic motion above and below the galactic plane (Matese et al. 1995, Nurmi et al. 2001). This motion currently carries the planetary system some 50–90 pc out of the plane, comparable to the scale height of the disk (Bahcall & Bahcall 1985). The period of the oscillation is $\sim$52–74 Myr. Matese et al. (1995) showed that this causes the cometary flux to vary sinusoidally by a factor of 2.5–4 over that period, with the maximum flux occurring just after passage through the galactic plane. However, the dynamical model of Matese et al. did not include stellar perturbations. It is not clear whether stellar perturbations would increase or decrease the amplitude of the variation in the cometary flux. The solar system has passed through the galactic plane in the last few million years, so the current steady-state flux is likely near a local maximum.
4. Simulations of the Formation of the Oort Cloud

In his 1950 paper, Oort did not consider the formation of the comet cloud in detail, but speculated

“It seems a reasonable hypothesis to assume that the comets originated together with the minor planets, and that those fragments whose orbits deviated so much from circles between the orbits of Mars and Jupiter that they became subject to large perturbations by the planets, were diffused away by these perturbations, and that, as a consequence of the added effect of the perturbations by stars, part of these fragments gave rise to the formation of the large cloud of comets which we observe today.”

Ever since Oort’s work, the roles of the four giant planets in populating the comet cloud have been debated. Kuiper (1951) proposed that Pluto, which was then thought to have a mass similar to that of Mars or the Earth, scattered comets that formed between 38 and 50 AU (i.e., in the Kuiper belt!) onto Neptune-crossing orbits, after which Neptune, and to a lesser extent the other giant planets, placed comets in the Oort cloud. Later work (Whipple 1963, Safronov 1972) indicated that Jupiter and Saturn tended to eject comets from the solar system, rather than placing them in the Oort cloud. The kinder, gentler perturbations by Neptune and Uranus were more effective in populating the cloud, although it was not clear in Safronov’s orderly accretion scenario whether these planets could even form in the age of the solar system. Nonetheless, by the time of the work of Fernández (1978, 1980), there was a general consensus that Neptune and Uranus were primarily responsible for placing comets in the Oort cloud.

Shoemaker and Wolfe (1984) performed an early Monte Carlo simulation to follow the ejection of Uranus-Neptune planetesimals to the Oort cloud, including the effects of stellar perturbations for orbits with aphelia > 500 AU. They found that ~9% of the original
population survived over the history of the solar system, with ~90% of those comets in orbits with semi-major axes between 500 and $2 \times 10^4$ AU; 85% of the latter group had semi-major axes < $10^4$ AU. Shoemaker & Wolfe also found that the perihelion distribution of the comets was peaked just outside the orbit of Neptune, and estimated a total cloud mass of 100 to 200 $M_\oplus$. Unfortunately, their work was published only in an extended abstract, so the details of their modeling are not known.

The first study using direct numerical integrations to model the formation of the Oort cloud was that of Duncan et al. (1987; DQT87). To save computing time, DQT87 began their simulations with comets on low-inclination, but highly eccentric, orbits in the region of the giant planets (initial semi-major axes, $a_0$, of 2000 AU and initial perihelion distances, $q_0$, between 5 and 35 AU). Gravitational perturbations due to the giant planets and the disk ($z$) component of the Galactic tide were included. A Monte Carlo scheme from Heisler et al. (1987) was used to simulate the effects of stellar encounters. Molecular clouds were not included.

DQT87’s main results included the following: (1) The OC has a sharp inner edge at $a \sim 3000$ AU. (2) For heliocentric distances $r$ in the range $3000$ AU $\lesssim r \lesssim 50000$ AU, the number density of the OC falls steeply with increasing $r$, going roughly as $r^{-3.5}$. Thus the OC is centrally condensed, with roughly 4–5 times as many comets in the inner OC ($a \lesssim 20000$ AU) as in the classical outer OC. (3) The present-day inclination distribution should be nearly isotropic in the outer Oort Cloud and most of the inner Oort Cloud. The innermost part of the inner OC may still be slightly flattened. (4) Comets with $q_0 \gtrsim 15$ AU are much more likely to reach the OC and survive for billions of years in the OC than are comets with smaller initial perihelia. For example, only 2% of the comets with $q_0 = 5$ AU should occupy the OC at present, while 24% of the comets with $q_0 = 15$ AU and 41% with $q_0 = 35$ AU do so. This result appeared to confirm that Neptune and Uranus, which have
semi-major axes of 30 and 19 AU, respectively, are primarily responsible for placing comets in the Oort cloud. However, this finding can be questioned, since the highly eccentric starting orbits had the consequence of pinning the perihelion distances of the comets at early stages. This, in turn, allows Neptune and Uranus to populate the OC efficiently because they cannot lose objects to the control of Jupiter and Saturn.

Hahn and Malhotra (1999) investigated the migration of the giant planets due to their interaction with a disk of planetesimals. Assuming an initial disk mass of $50 M_\oplus$, Hahn and Malhotra estimated that some $12 M_\oplus$ would be placed in the OC (which they defined by $a > 3000$ AU), of which some $4 M_\oplus$ would survive to the present. Most comets in the OC would derive from the Saturn–Neptune region.

Dones et al. (2003) repeated the study of DQT87, starting with “comets” with semi-major axes between 4 and 40 AU and initially small eccentricities and inclinations. These initial conditions are probably more realistic than the highly eccentric starting orbits assumed by DQT87. We integrated the orbits of 3000 “comets” for times up to 4 billion years under the gravitational influence of the Sun, the four giant planets, the “disk” and “radial” components of the galactic tide, and passing stars. These simulations did not include other perturbers such as molecular clouds, a possible early environment if the Sun formed in a cluster (Gaidos 1995, Fernández 1997), or the effects of gas drag. We intend to consider these effects in future work.

We performed two sets of runs with dynamically “cold” and “warm” initial conditions. The results were very similar, so here we will focus on the “cold” runs, which included 2000 particles with root-mean-square (rms) initial eccentricity, $e_0$, and inclination to the invariable plane, $i_0$, equal to 0.02 and 0.01 radians, respectively. We assumed that the Sun resided in its present galactic environment during the formation of the OC.

For the “cold” runs, the fraction of objects we integrated that currently occupy the
classical “outer” OC \((a \geq 20,000 \text{ AU})\) is only \(2.35 \pm 0.34\%\), about a factor of three smaller than found by DQT87. The fraction of objects in the inner OC \((2000 \text{ AU} \leq a < 20,000 \text{ AU})\) is \(2.25 \pm 0.34\%\), vastly smaller than predicted by Hills (1981) and about an order of magnitude smaller than calculated by DQT87. This result holds because most comets that begin in the Uranus–Neptune zone evolve inward and are ejected from the solar system by Jupiter or Saturn. A small fraction are placed in the Oort cloud, most often by Saturn. However, all four of the giant planets place comets in the OC. The OC is built in two distinct stages in our models. In the first few tens of Myr, the OC is built by Jupiter and Saturn, which deliver comets to the outer OC. After this time, the OC is built mainly by Neptune and Uranus, with the population peaking about 1 Gyr after the beginning of the simulation. Objects that enter the OC during this second phase typically first spend time in the “scattered disk” \((50 \text{ AU} \leq a < 2,000 \text{ AU};\) Duncan and Levison 1997) and then end up in the inner OC.

Figures 6 and 7 show the formation of the Oort cloud in terms of the orbital evolution in (semi-major axis, perihelion distance) and (semi-major axis, inclination to the invariable plane of the solar system). We show six “frames” from our integrations at various times in the calculations. (Animations showing these data every 1 Myr throughout the simulation can be viewed at http://www.boulder.swri.edu/~luke.) Points in these plots are color-coded by their formation location \(a_0\): Jupiter region comets \((a_0 \text{ between 4 and 8 AU})\) are magenta; Saturn region comets \((8–15 \text{ AU})\) are blue; Uranus region comets \((15–24 \text{ AU})\) are green; Neptune region comets \((24–35 \text{ AU})\) are red; Kuiper Belt comets \((35–40 \text{ AU})\) are black.

In Figure 6, panel (a) \([0 \text{ Myr}]\) shows that the particles start with very small eccentricities, as represented by the diagonal line that extends from \(~4\) to 40 AU. After 1 Myr (panel (b)), the giant planets, particularly Jupiter and Saturn, have scattered many
Fig. 6.— Scatter plot of osculating barycentric pericenter distance ($q$) vs. osculating barycentric semi-major axis ($a$) at various times in our “cold” simulation of the formation of the Oort Cloud. The points are color-coded to reflect the region in which the simulated comets formed. Panel (a): Initial conditions for the simulation [0 Myr]. Panel (b): 1 Myr into the simulation. Panel (c): 10 Myr into the simulation. Panel (d): 100 Myr into the simulation. Panel (e): 1000 Myr into the simulation. Panel (f): Final results for the simulation, at 4000 Myr, i.e., roughly the present time. Note that in panel (f), there is a nearly empty gap for semi-major axes between about 200 and 3000 AU. Objects with $a$ in this range evolve at nearly constant $q$, as discussed by DQT87. From Dones et al. (2003).
comets into very eccentric orbits with perihelia still in the region of the giant planets. These particles are somewhat like the Centaurs and scattered-disk objects in the present Solar System, but typically have much larger eccentricities. 76% of the test particles remain. Of the 24% lost in the first Myr, most were ejected from the solar system by Jupiter or Saturn.

At 10 Myr (panel (c)), we see the beginning of the formation of the Oort cloud. Some particles with \( a \gtrsim 30,000 \) AU have had their perihelia raised out of the planetary region by galactic tides and the effects of passing stars. In all, 48% of the particles remain. At 100 Myr (panel (d)), the Oort cloud has assumed approximately its current form. 27% of the particles remain; 4.1% are in the Oort cloud. From 100 Myr to 1000 Myr (panel (e)), particles continue to enter the Oort cloud from the scattered disk. The total number of particles continues to decline – 15% remain – but the population in the Oort cloud peaks just before 1000 Myr. At 1000 Myr 7.05% of the comets are in the Oort cloud. Finally, at 4000 Myr (panel (f)), the structure of the Oort Cloud remains nearly the same as at 1000 Myr, but its population has declined slightly. In total, 10% of the particles we integrated remain. Of these, about half revolve on orbits in the planetary region (\( a < 45 \) AU), primarily in the Kuiper Belt, that have evolved little. The 101 “evolved” comets include 9 scattered-disk objects (50 AU \( \leq a < 2000 \) AU); 45 inner Oort cloud comets (2000 AU \( \leq a < 2000 \) AU); 46 outer Oort cloud comets (20,000 AU \( \leq a < 200,000 \) AU); and 1 escaping Oort cloud comet (\( a \geq 200,000 \) AU).

Figure 7 shows the evolution of the particles’ inclinations. Panel (a) [0 Myr] shows that the particles’ inclinations to the invariable plane are initially small. After 1 Myr [panel (b)], the planets have scattered the comets into moderately inclined orbits. After 10 Myr [panel (c)], the particles with \( a \gtrsim 30,000 \) AU have been perturbed by galactic tides and stars into a nearly isotropic distribution of inclinations. As time continues (panels [d]-[f]), tides affect the inclinations of particles closer to the Sun, so that at 4000 Myr inclinations
are clearly isotropic for $a \gtrsim 20,000$ AU.

We show a projection of the spatial distribution of comets in the Oort Cloud in galactic coordinates in Figure 8. In this figure the galactic plane is horizontal, so the invariable plane of the Solar System is inclined by about 60° to the horizontal. The circle has a radius of 20,000 AU and represents our chosen boundary between the inner and outer Oort clouds. By 100 Myr, the outer OC already has a nearly isotropic distribution of inclinations. By 4 Gyr, much of the inner Oort cloud also has a nearly isotropic distribution.

We now return to the issue of how centrally condensed the Oort Cloud is. Recall that DQT87 found a density profile $n(r) \propto r^{-\gamma}$ with $\gamma \sim 3.5$ for $3000$ AU < $r$ < $50,000$ AU, so that in their model most comets reside in the inner Oort cloud. If we fit the entire Oort cloud to a single power law, we find $\gamma \sim 2.8$, considerably shallower than the value found by DQT87. The shallow slope probably results because all the giant planets inject comets into the OC, even though most formed beyond 20 AU. Since $\gamma \sim 3$, the inner and outer Oort clouds contain comparable numbers of comets at present in our model. If we separately fit the inner and outer Oort cloud, we find $\gamma \sim 2.0$ and $\gamma \sim 3.5$, respectively.

Finally, in Fig. 9, we show the time evolution of the populations of the Oort cloud and scattered disk in our simulation. (To be considered an Oort cloud comet, a comet must have a semi-major axis of at least 2,000 AU and to have had a pericenter distance greater than 45 AU at some point in its history.) The scattered disk is initially populated by comets scattered by Jupiter and Saturn, and peaks in number at 20 Myr. After this time the population of the scattered disk declines with time $t$ approximately as a power law, $N(t) \propto t^{-\alpha}$, with $\alpha \sim 0.7$. At present, 0.35 ± 0.13% of the comets occupy the scattered disk.

Likewise, the Oort cloud grows rapidly in the first few tens of Myr due to comets injected by Jupiter and Saturn, and then undergoes a very prolonged period of growth, primarily due to Uranus and Neptune, with the peak population occurring at 970 Myr. The
Fig. 7.— Scatter plot of osculating inclination to the invariable plane vs. $a$ at various times in our “cold” simulation of the formation of the Oort Cloud. Panel (a): Initial conditions for the simulation [0 Myr]. Panel (b): 1 Myr. Panel (c): 10 Myr. Panel (d): 100 Myr. Panel (e): 1000 Myr. Panel (f): Final results for the simulation, at 4000 Myr. From Dones et al. (2003).
Fig. 8.— Locations of test particles in galactic \((y, z)\) coordinates. The plane \(z = 0\) is parallel to the galactic plane. The invariable plane of the Solar System is inclined to the galactic plane by about 60°. The scale of this plot is \(\pm 50,000\) AU. The dashed circle has a radius of 20,000 AU to show our adopted boundary between the inner and outer Oort clouds. This plot can be directly compared with Fig. 4 of Duncan, Quinn, and Tremaine (1987). Panel (a): 10 Myr into the simulation. Panel (b): 100 Myr into the simulation. Panel (c): 1000 Myr into the simulation. Panel (d): Final results for the simulation, at 4000 Myr. From Dones et al. (2003).
fraction of comets in the Oort cloud only declines from $7.1 \pm 0.6\%$ at 970 Myr to $4.7 \pm 0.5\%$ at 4 Gyr, \textit{i.e.}, $N(t) \propto t^{-0.2}$.

Figure 9 also shows the populations of the inner and outer Oort clouds separately. The population of the outer Oort cloud peaks at 600 Myr, and is presently declining as $t^{-0.6}$. The inner Oort cloud peaks at 1.8 Gyr, and is declining as $t^{-0.1}$. Because of the faster decline of the outer Oort cloud, the ratio of numbers of inner to outer Oort cloud comets has increased from 0.6 at 1 Gyr to 1.0 at present. Nonetheless, this ratio is much small than found by DQT87, who found 4–5 times more comets in the inner OC than in the outer OC. At 4 Gyr, 2 external returning comets, 45 inner Oort cloud comets, 46 outer Oort cloud comets, and 1 escaping comet remain in the Oort cloud, for a total of 94 Oort cloud comets. Only 2.3\% of the comets we integrated occupy the outer Oort cloud at 4 Gyr.

At face value, the low efficiency of OC formation in our model implies a massive primordial protoplanetary disk. Assuming an outer OC population of $5 \times 10^{11}–10^{12}$ comets (Heisler 1990, Weissman 1996) and an average cometary mass of $4 \times 10^{16}$ g, the original mass in planetesimals between 4 and 40 AU was $\sim 150–300 M_\oplus$, some 3 to 6 times the mass in solids in a “minimum-mass” solar nebula. This amount of mass likely would have produced excessive migration of the giant planets and/or formation of additional giant planets (Hahn and Malhotra 1999; Thommes \textit{et al.} 2002). Furthermore, the somewhat flattened orbital distribution of Halley-type comets appears to require a massive inner OC as a source region (Levison \textit{et al.} 2001). Finally, the population of the scattered disk that our model predicts, of order 10\% the population of the Oort cloud, is much larger than the inferred population of the scattered disk (Trujillo \textit{et al.} 2000).

These discrepancies suggest some deficiency in our model. This is not surprising, given that our assumptions are highly idealized. Most importantly, the formation of the Oort cloud needs to be studied in the context of a realistic model for planet formation. That is,
In our simulations the outer Oort cloud, which is originally populated by comets injected by Jupiter and Saturn, forms more rapidly than the inner Oort cloud, which is primarily populated by comets injected by Uranus and Neptune. Our model predicts that at present, the populations of the inner and outer Oort clouds are comparable. From Dones et al. (2003).
the planets were still forming at least during the early stages of the formation of the Oort cloud. Planetary migration in the early solar system appears to have been important in shaping the Kuiper Belt (Malhotra 1997; Gomes 2003; Levison & Morbidelli 2003), and the same is likely true for the Oort cloud. Uranus and Neptune may even have formed in the Jupiter-Saturn region (Thommes et al. 1999, 2002). Tremaine (1993), Gaidos (1995), Fernández (1997), Eggers et al. (1997, 1998), and Fernández and Brunini (2000) have discussed star formation in different galactic environments. Most of these papers point out that the Sun may have formed in a denser environment than it now occupies (i.e., in a molecular cloud or star cluster), and found that a more tightly bound OC would form. If the Sun remained in such a dense environment for too long, the resulting OC might not be stable, however (Gaidos 1995, Adams and Laughlin 2001). Drag due to residual gas from the solar nebula may have been important in the formation of the Oort cloud (de la Fuente Marcos and de la Fuente Marcos 2002, Higuchi et al. 2002). Collisions may have been important in determining which regions of the protoplanetary disk could populate the Oort cloud (Stern & Weissman 2001, Charnoz & Morbidelli 2003).

4.1. Perihelion Distribution and Impact Rates

Ecliptic comets appear to dominate impacts with the giant planets and their satellites (Zahnle et al. 1998, 2003). However, comets from the inner Oort cloud could contribute significantly to impacts in the saturnian, uranian and neptunian systems and on Pluto/Charon because these planets are not subject to the “Jupiter barrier” (Bailey and Stagg 1988, Weissman and Stern 1994).

The probability per orbit $p$ that a comet will collide with a planet of radius $R$ on a
circular orbit of semi-major axis $a$ is

$$p = \mathcal{F} \left( \frac{R}{a} \right)^2 \frac{U}{|U_x|} \frac{1}{\pi \sin i}.$$ 

This expression assumes that the orbits cross, and represents an average over a precession cycle. $\mathcal{F} = 1 + (v_e/v_\infty)^2$ is a gravitational focusing factor and $U$, $U_x$ are the speed and radial component of the comet’s speed divided by the planet’s orbital speed $v_c$; $v_\infty = U v_c$; and $v_e$ is the planet’s surface escape speed (Opik 1951). The rate of impacts by long-period comets is

$$\mathcal{R} = \dot{N} \langle q < a \rangle \langle p \rangle,$$

where $\dot{N} \langle q < a \rangle$ is the number of comets that pass perihelion within the planet’s orbit per year, and $\langle p \rangle$ is the mean impact probability of the comets with the planet. If the comets’ orbital distribution is not pathological, and $\mathcal{F} \gg 1$ (which is true even for Oort cloud comets impacting the giant planets), $\mathcal{R}$ is of order $\mu_R R_a N \langle q < a \rangle$, where $\mu$ is the ratio of the planet’s mass to the solar mass.

The biggest uncertainty in determining impact rates is in the cumulative perihelion distribution, $N(q)$. Everhart (1967) attempted to correct for observational incompleteness of the discoveries of LP comets, and inferred that 63 active LP comets (new and returning) pass perihelion with $q < 4$ AU each year. (Only about 4% of these comets were actually observed, so this estimate is clearly uncertain.) Everhart’s estimate refers to comets with absolute magnitude $H_{10} < 11$. The perihelion distribution near Jupiter ($a = 5.2$ AU) is uncertain. If $N(q) \propto q^\alpha$, where $\alpha = 1$ for an isotropic distribution, $\alpha = 2$ was assumed by Zahnle et al. (2003), and we find $\alpha = 3.4$ from a fit of the region interior to 12 AU (Fig. 10), we have 82, 106, and 154 active comets with $H_{10} < 11$ crossing Jupiter’s orbit per year. If we use the calibration of Weissman (1996), in which $H_{10} = 11$ corresponds to a cometary diameter of 2.4 km, and assume a cumulative size distribution with index 2, we have $\dot{N}_J = 500, 600,$ and $900$ km-sized LP comets crossing Jupiter’s orbit per year. We will take $\dot{N}_J = 600$. From Zahnle et al. (2003), $\langle p \rangle = 1.5 \times 10^{-7}$ at Jupiter for $\alpha = 2$, so Zahnle et al. (and we) obtain $\mathcal{R}_J = \dot{N}_J \langle p \rangle = 9 \times 10^{-5}$/year, i.e., about one impact per
10,000 years. According to Zahnle et al. (2003), if $\alpha = 2$ throughout the planetary region, Saturn, Uranus, and Neptune experience impacts by km-sized long-period comets once per 20,000 years, 200,000 years, and 100,000 years, respectively. According to these estimates, km-sized LP comets impact the giant planets at less than 1% of the rate of impacts by ecliptic comets.

However, we find $N(q)$ to be a much more steeply rising function of $q$ than was assumed by Zahnle et al. (2003) in the Jupiter–Uranus region. We find that the relative numbers of LP comets crossing the orbits of Jupiter, Saturn, Uranus, and Neptune are 1:18:240:650, as compared with 1:3:14:34, the ratios for $\alpha = 2$. We infer that impacts by km-sized LPCs should occur on Saturn, Uranus, and Neptune every 4000, 9000, and 5000 years (i.e., more often than LPCs impact Jupiter). These rates are some 10–15% of the rate due to ecliptic comets. Furthermore, our estimates are scaled from the number of active comets within 4 AU of the Sun. Dynamical models (e.g., Wiegert and Tremaine 1999) predict that there should be some 10 extinct long-period comets for each inactive comet. Near-Earth Object surveys, which have discovered two objects that are apparently extinct LPCs, suggest that there are only $\sim 0.1$ (rather than 10) extinct LPCs for each active LPC with $q < 3$ AU (Levison et al. 2002). This result imply that some 99% of LPCs with $q < 3$ AU undergo catastrophic disruption. However, the physical mechanism for disruption is unknown. If most LPCs with perihelia beyond 10 AU do not undergo disruption, the impact rates on Saturn, Uranus, Neptune, Pluto, and their satellites could be higher still. The impact record of Pluto, Charon, and the satellites of the giant planets may one day be used to constrain the properties of the inner Oort cloud (Bailey & Stagg 1988).
Fig. 10.— Cumulative perihelion distribution of Oort cloud comets is far from linear, which it would be for an isotropic velocity distribution, because of the “Jupiter barrier”. From Dones et al. (2003).
5. Summary

Oort’s picture of a near-spherical cloud of comets at distances of tens of thousands of AU is still valid. However, the sample of new comets that reach the region of the terrestrial planets is biased to objects with $a > 20,000$ AU because of the “Jupiter barrier”. Thus the population of the inner Oort cloud, at distances of thousands of AU, remains uncertain. Ultimately, observations of comets at perihelion distances beyond 10 AU and studies of the cratering record of the solar system may provide our best means of constraining the inner cloud. Future models of Oort cloud formation will build upon recent advances in our understanding of the Kuiper belt to consider processes such as planetary migration and collisions (Morbidelli & Brown, this volume). Even though cometary nuclei may be dark, the future of dynamical studies of the Oort cloud is bright.
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