Oort Cloud Formation and Dynamics

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The Oort cloud is the primary source 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 orbital distribution of known comets and the cometary "fading" problem; (2) the population and mass of the Oort cloud, including the hypothetical inner Oort cloud; (3) the number of Oort cloud comets that survive from the origin of the solar system to the present time, and the timescale for building the Oort cloud; (4) the relative importance of different regions of the protoplanetary disk in populating the Oort cloud; and (5) current constraints on the structure of the Oort cloud and future prospects for learning more about its structure.

1. INTRODUCTION

"They have observed Ninety-three different Comets, and settled their Periods with great Exactness. If this be true, (and they affirm it with great Confidence) it is much to be wished that their Observations were made publick, whereby the Theory of Comets, which at present is very lame and defective, might be brought to the same Perfection with other Parts of Astronomy."

— Jonathan Swift, *Gulliver's Travels* (1726)

Recorded observations of comets stretch back more than 2000 years (*Kronk,* 1999). For example, *Yau et al.* (1994) showed that a comet noted in Chinese records in the year 69 B.C. 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 (e.g., *Bailey et al.,* 1990; *Yeomans,* 1991). Even so, learned opinion until the mid-twentieth century was divided on whether comets were interlopers from interstellar space (Kepler, Laplace, and Lyttleton) or members of the solar system (Halley, Kant, and Öpik).

By the mid-nineteenth century, it was well established that most comets have orbits larger than the orbits of the known planets. *Lardner* (1853) stated " . . . 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 divided the comets on elliptical orbits into three categories that roughly correspond to what we would now call Jupiter-family comets (JFCs), Halley-type comets (HTCs), and returning long-period comets (LPCs) (e.g., *Levison,* 1996). The hyperbolic and parabolic orbits, in turn, represent "new" long-period comets (*Oort,* 1950; *Levison,* 1996). Lardner also noted that, with the exception of JFCs, there were roughly equal numbers of objects that revolved prograde (in the same direction as the planets) and retrograde around the Sun. [Note that the traditional dividing line between JFCs and HTCs is an orbital period P of 20 yr, with JFCs having $P < 20$ yr (semimajor axes, a, less than 7.4 AU), and HTCs having 20 yr $\leq P <$ 200 yr (7.4 AU $\leq a \leq$ 34.2 AU). *Levison* (1996) introduced the term "nearly isotropic comets" (NICs), which he divided into HTCs, which he took to have semimajor axes $a < 40$ AU, and the LPCs, which he defined to have $a > 40$ AU. The upper limit on the semimajor axis of an HTC at 34.2 AU or 40 AU is somewhat arbitrary, but *Chambers* (1997) later showed that there *is* a dynamical basis for this upper limit. Chambers demonstrated that NICs with $a <$ 22.5–39.6 AU, with the upper limit depending upon orbital inclination, can be trapped in mean-motion resonances with Jupiter, while bodies with larger orbits generally cannot.]

Newton (1891) and *van Woerkom* (1948) performed early studies of 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* can 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."

This review will discuss what the observed cometary orbital distribution reveals about the structure of the spherical cloud of comets that now bears Oort's name, and the results of new dynamical simulations of the Oort cloud's formation and subsequent evolution. In section 2 we describe the Oort cloud hypothesis and the evidence for why we believe that there indeed is an Oort cloud. We then review studies of the population and dynamics of the Oort cloud. In section 3 we discuss the hypothetical inner Oort cloud, which has been proposed to possibly contain more comets than the classical Oort cloud, and "comet showers" that might result from a stellar passage through the inner cloud. In section 4 we focus on modern studies of the formation of the Oort cloud, assuming that comets started as planetesimals within the planetary region. In section 5 we discuss constraints on the Oort cloud based upon observations of comets and the impact record of the solar system, and describe future prospects for improving our understanding of the structure of the Oort cloud. Section 6 summarizes our conclusions. We refer the reader to other chapters in this book for discussions of related topics, particularly the overview by Rickman and the chapters by Weidenschilling, Rickman, Yeomans et al., Morbidelli and Brown, Duncan et al., Harmon et al., Boehnhardt, Weissman et al., and Jewitt.

2. POPULATION AND DYNAMICS OF THE OORT CLOUD

2.1. Oort Cloud Hypothesis

We first give an overview of how we believe that LPCs attained orbits at vast distances from the Sun, remained in such orbits for billions of years, and then came close enough to the Sun that they began to sublimate actively.

The early solar system is believed to have consisted of the planets, with their current masses and orbits, and a large number of remnant small solid bodies ("planetesimals") between and slightly beyond the orbits of the planets. We will assume there is no remaining gas in the solar nebula, and will only discuss planetesimals in the region of the giant planets, which we will take to be 4–40 AU, where the planetesimals were likely to contain volatiles such as water ice. Even if the small bodies started on orbits that did not cross the orbits of any of the planets, distant perturbations by the planets, particularly at resonances, would have excited most of the planetesimals onto planet-crossing orbits in 10 m.y. or less (*Gladman and Duncan,* 1990; *Holman and Wisdom,* 1993; *Levison and Duncan,* 1993; *Grazier et al.,* 1999a,b). The major exception to this rule is in the Kuiper belt, where some orbits remain stable for billions of years (*Holman and Wisdom,* 1993; *Duncan et al.,* 1995; *Kuchner et al.,* 2002). [Here, we define the Kuiper belt to encompass small bodies on low-eccentricity orbits with semimajor axes, a, greater than 35 AU. Long-term orbital integrations indicate that *some* small bodies on near-circular orbits with $a \geq 35$ AU are stable for the age of the solar system. For example, *Duncan et al.* (1995) found a stable region between 36 and 39 AU, while *Kuchner et al.* (2002) found that most objects with $a \geq 44$ AU are stable for 4 G.y. The stability of objects with a between 39 and 44 AU depends upon their initial eccentricities and inclinations. There are few stable orbits for small bodies with $a \leq 35$ AU, except for Trojans of Jupiter and Neptune (*Nesvorný and Dones,* 2002) and main-belt asteroids.] This quasistability explains the existence of the Kuiper belt and the low-inclination ("ecliptic") comets, which include the scattered disk, Centaurs, and JFCs (*Duncan et al.,* 2004).

The LPCs, by contrast, are thought to derive from the planetesimals that did *not* remain on stable orbits, but became planet-crossing. The first stage in placing a comet in the Oort cloud is that planetary perturbations pumped up the orbital energy (i.e., semimajor axis) of a planetesimal, while its perihelion distance q remained nearly constant. If the planets had been the only perturbers, this process would have continued, in general, until the planetesimal's orbit became so large that it became unbound from the solar system, and thereafter wandered interstellar space. However, the very reason that a comet's orbit becomes unbound at large distances — the presence of stars and other matter in the solar neighborhood that exert a gravitational force comparable to that from the Sun — provides a possible stabilizing mechanism. *Öpik* (1932) and *Oort* (1950) pointed out that once the comet's orbit becomes large enough, passing stars affect it. (As we describe below, gas in the solar neighborhood now appears to be a slightly stronger perturber of the Oort cloud than stars.) In fractional terms, stars change cometary perihelion distances much more than they change the overall size of the orbit. (This is a consequence of the long lever arm and slow speed of comets on highly eccentric orbits near aphelion.) If passing stars can lift a comet's perihelion out of the planetary region before the planets can eject it from the solar system, the comet will attain an orbit in the Oort cloud. The characteristic size of the Oort cloud is set by the condition that the timescale for changes in the cometary semimajor axis is comparable to the timescale for changes in perihelion distance due to passing stars. In essence, the comet must be perturbed to a semimajor axis large enough that the orbit is significantly perturbed by passing stars, but not so large that the orbit is too weakly bound to the solar system and the comet escapes. This condition yields a cloud of comets with semimajor axes on the order of 10,000 to 100,000 AU (*Tremaine,* 1993; see also *Heisler and Tremaine,* 1986; and *Duncan et al.,* 1987). The trajectories of the stars are randomly oriented in space, so stellar perturbations eventually cause the comets to attain a nearly isotropic velocity distribution, with a median inclination to the ecliptic of 90° and a median eccentricity of 0.7. Subsequently, passing stars *reduce* the perihelion distances of a small fraction of these comets so that they reenter the planetary region and potentially become observable.

The above description is similar to Oort's vision of the comet cloud. However, less than half the local galactic mass density is provided by stars, the rest being in gas, brown dwarfs, and possibly a small amount of "dark matter" (*Holmberg and Flynn,* 2000). We thus now recognize that the smooth long-term effect of the total amount of nearby galactic matter, i.e., the "galactic tide," perturbs comets somewhat more strongly than do passing stars. The galactic tide causes cometary perihelion distances to cycle outward from the planetary region and back inward again on timescales as long as billions of years (*Heisler and Tremaine,* 1986). In addition, rare, but large, perturbers such as giant molecular clouds (GMCs) may be important for the long-term stability of the Oort cloud.

Dynamically "new" comets typically come from distances of tens of thousands of AU, thereby giving the appearance of an inner edge to the Oort cloud. *Hills* (1981) showed that this apparent inner edge could result from an observational selection effect. The magnitude of the change in perihelion distance per orbit, Δq, of a comet due to either galactic tides or passing stars is a strong function of semimajor axis (a), proportional to $a^{7/2}$. A dynamically new comet with perihelion interior to Jupiter's orbit must have had q ≳ 10 AU on its previous orbit; otherwise, during the comet's last passage through perihelion, Jupiter and/or Saturn would have likely given it a large energy kick (typically much larger than the comet's orbital binding energy) that would either capture it to a much shorter period orbit or eject it to interstellar space.

If we assume that a comet must come within 3 AU of the Sun to become active and thus observable, Δq must be at least ~10 – 3 AU = 7 AU. It can be shown that, because of the steep dependence of Δq on a, this condition implies that a ≳ 28,000 AU (*Levison et al.,* 2001). Comets with semimajor axes of a few thousand AU could, in principle, be much more numerous than comets from tens of thousands of AU, but they normally would not pass within the orbits of Jupiter and Saturn because of the "Jupiter barrier." Such "inner Oort cloud" comets would only enter the inner solar system following an unusually strong perturbation, such as a close stellar passage. Determining the population of the hypothetical inner Oort cloud is a major goal of modern studies of the formation of the cometary cloud. We now turn to a more detailed discussion of what is known about the orbits of LPCs.

2.2. Observed Orbital Distribution

Figure 1 illustrates the orbital distribution of the 386 single-apparition LPCs whose energies are given in the 2003 *Catalogue of Cometary Orbits* (*Marsden and Williams,* 2003). [The catalog contains 1516 single-apparition comets. Of these, only 386, or about one-quarter of the total, had observations that enable one to solve for the comet's energy. For the other comets, the fits assume a parabolic orbit.] We first introduce some terminology and notation. The symbol a represents the semimajor axis of a comet. The quantity actually determined in orbit solutions is E ≡ 1/a, which has units of AU^{-1}. (We will assume these units implicitly in the discussion below.) E, which we will informally refer to as "energy," is a measure of how strongly a comet is held by the Sun. We distinguish three values of E, which we denote E_i, E_o, and E_f. [For "original" and "future" orbits of LPCs (see below), a is computed with respect to the center or mass, or barycenter, of the solar system, while "osculating" orbits of objects in the inner solar system are computed with respect to the Sun.] These de-

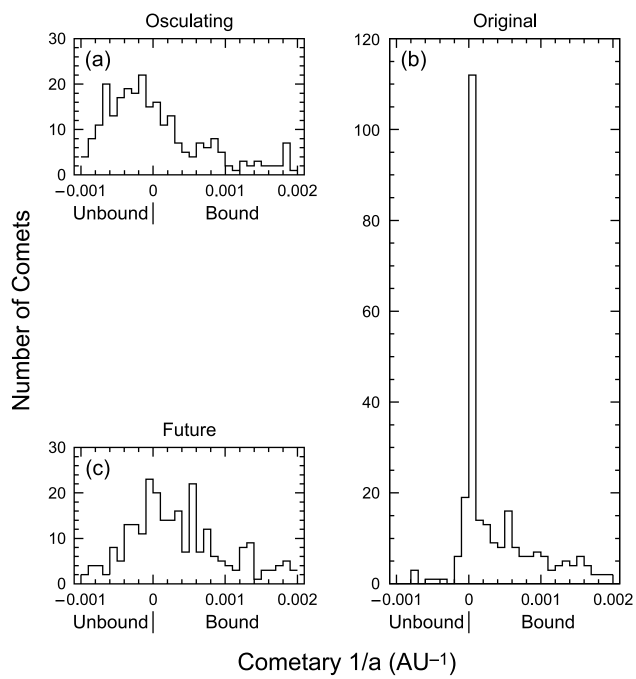

Fig. 1. Distribution of cometary orbital energies, E ≡ 1/a, where a is the comet's orbital semimajor axis in AU, from the 2003 *Catalogue of Cometary Orbits*. Only comets with –0.001 AU < E ≤ 0.002 AU are shown, i.e., only comets whose orbits are apparently weakly unbound (E < 0) or weakly bound to the solar system (a ≥ 500 AU). The catalog contains 386 "single-apparition" LPCs for which the orbital energy could be determined. Of these, 268, 254, and 251 occupy the bins shown in **(a)**, **(b)**, and **(c)**, respectively. All panels have the same horizontal and vertical scales. **(a)** Osculating value of "energy," E_i. **(b)** Original value of energy, E_o. **(c)** Future value of energy, E_f. The Oort cloud spike is not evident when the histogram is plotted in terms of the orbital energies during or after the comets' passages through the planetary region [**(a)** and **(c)**]. However, when planetary perturbations are "removed" by calculating the comet's orbit before it entered the planetary region, a spike of comets with a > 10,000 AU is evident [**(b)**]. The median semimajor axis of the comets shown in the spike is 27,000 AU. See text for further discussion.

note, 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 entered the planetary region (as determined by orbital integration); 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 $E < 0$ is on a hyperbolic orbit and will escape the solar system on its current orbit; colloquially, such a comet is called "ejected." (Note that a comet's orbital energy per unit mass is $-GM_\odot/2a$, so the sign convention for E is the opposite of that used for orbital energy.) We will also use the symbols q and i to denote a comet's perihelion distance and orbital inclination to the ecliptic, respectively.

Osculating orbits of LPCs passing through the planetary region (Fig. 1a) indicated that many of the orbits were slightly hyperbolic, suggesting that those comets were approaching the solar system from interstellar space. However, when the orbits were integrated backward in time to well before the comets entered the planetary system, yielding the original inverse semimajor axis (denoted as E_o), the distribution changed radically (Fig. 1b). The E_o distribution is marked by a sharp "spike" of comets at near-zero but bound energies, representing orbits with semimajor 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.

Oort recognized that the spike had to be the source of the LPCs, a vast, roughly spherical cloud of comets at distances greater than 10^4 AU from the Sun, but still gravitationally bound to it. [Some researchers have noted that *Öpik* (1932) anticipated Oort's work by studying the effects of stellar perturbations on distant meteoroid and comet orbits, 18 years earlier. Öpik 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, even indirectly, because he did not recognize that stellar perturbations would also cause some orbits to diffuse back into the planetary region. Öpik concluded that the observed LPCs came from aphelion distances of only 1500–2000 AU. Though *Öpik*'s (1932) paper was a pioneering work on stellar perturbations, it did not identify the cometary cloud as the source of the LPCs or relate the observed orbits to the dynamical theory.] 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. Oort's accomplishment in defining the source of the LPCs is particularly 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 catalog.

In Fig. 1b, about 30% (112) of all 386 comets have $0 \le E_o \le 10^{-4}$. [Another 87 of the comets have $1 \times 10^{-4} < E_o \le 2 \times 10^{-3}$, with 132 comets off-scale to the right (i.e., with semimajor axes <500 AU); see Fig. 2.] This region, which corresponds to semimajor axes $>10^4$ AU, is the spike that led Oort to postulate the existence of the Oort cloud. Oort suggested that most new comets have aphelion distances of 50,000–150,000 AU, i.e., semimajor axes of 25,000–75,000 AU. More recent determinations give values about half as large for the typical semimajor axes of new comets. The median semimajor axis of the 143 comets in the 2003 *Catalogue of Cometary Orbits* with $E_o \le 10^{-4}$ (including those with E_o slightly less than 0, see below) is 36,000 AU, and is 27,000 AU for the 112 comets with $0 \le E_o \le 10^{-4}$. Even these estimates of the typical value of the semimajor axes may be too large, since these orbit fits do not take into account nongravitational forces.

Thirty-one comets shown in Fig. 1b have $E_o < 0$. Taken at face value, these comets could be intruders just passing through the solar system. It is more likely 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 nongravitational forces. [If the comets with $E_o < 0$ were interstellar in origin, they would likely have speeds at "infinity" comparable to the velocity dispersion of disk stars, or tens of kilometers per second (Fig. 1 in *McGlynn and Chapman,* 1989). Such a velocity would imply $E_o \sim -1$, much larger than the most negative value of E_o measured for any comet (*Wiegert,* 1996).]

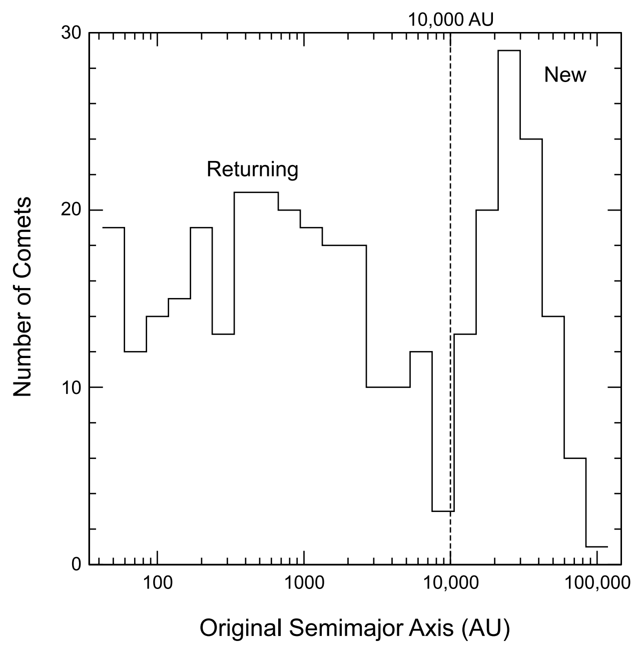

Fig. 2. Distribution of original semimajor axes, a_o. Comets are sometimes classified as "new" or "returning," depending on whether a_o is greater than or less than 10,000 AU, respectively. However, this classification is crude. To determine whether a particular comet is "new," it must be integrated backward one orbit, under the influence of the Sun and planets, galactic tides, and possibly nongravitational forces and nearby stars (*Dybczyński,* 2001).

Nongravitational forces make orbits (both "hyperbolic" and elliptical) appear more eccentric (i.e., larger) than they actually are (*Marsden et al.,* 1973, 1978; *Królikowska,* 2001). *Marsden et al.* (1973) estimate that if nongravitational forces were correctly accounted for, the average E_o value of a comet would increase by 2×10^{-5}. [This correction is up to 100 times larger for some "hyperbolic" comets (*Królikowska,* 2001).] If this correction applied for all new comets, a comet with a nominal E_o value of 1×10^{-5}, corresponding to a semimajor axis of 100,000 AU, would actually have a semimajor axis of 33,000 AU, and a comet with a nominal a_o of 20,000 AU would have a true semimajor axis of 14,000 AU.

In addition, *Marsden et al.* (1978) showed that orbital fits that neglect nongravitational forces give systematically larger "original" semimajor axes for comets with smaller perihelion distances, for which nongravitational forces are typically more important. They derived an empirical relation $\langle E_o \rangle = (4.63–2.37/q) \times 10^{-5}$ for the average original semimajor axis for new comets with a perihelion distance of q measured in AU. In the limit of large q, for which nongravitational forces are less important, this relation gives an average original semimajor axis $a_{ave} = 1/4.63 \times 10^{-5}$ = 21,600 AU. Since new comets have e ~ 1, this implies a typical aphelion distance of 43,200 AU and a time-averaged distance a_{ave} $(1 + \frac{1}{2}e^2)$ ~ 32,000 AU. Thus a typical Oort cloud comet resides some 30,000 AU from the Sun, which it circles once every 3 m.y.

Simulations by *Heisler* (1990) predict that during times of low comet flux, the energies of new comets should be peaked near $E_o = 3.5 \times 10^{-5}$, i.e., at a semimajor axis near 29,000 AU. Heisler assumed a local mass density of 0.185 $M_\odot/pc^3$. If the currently accepted value of 0.1 $M_\odot/pc^3$ is assumed instead (see discussion in *Levison et al.,* 2001), the peak semimajor axis should be near 34,000 AU. Thus Heisler's model predicts a semimajor axis that is larger than the inferred location of the peak. This discrepancy could result from errors in orbit determination, contamination of the "new" comet population with dynamically old comets with a > 10^4 AU, or, as Heisler proposed, could indicate that we are presently undergoing a weak comet shower (section 3). Neither the models nor data are yet adequate to determine which explanation is correct.

Figure 1c shows the "future" orbits of the comets; 96 of 386 (25%) are slightly hyperbolic, indicating that they will not return to the planetary region again and will leave the solar system. On their first pass through the planetary system, the distant, random perturbations by Jupiter and the other giant planets eject roughly half the "new" comets to interstellar space, while capturing the other half to smaller, more tightly bound, less-eccentric orbits (*van Woerkom,* 1948); see below. Only about 5% of the new comets are returned to Oort cloud distances of 10^4–10^5 AU (*Weissman,* 1979). On subsequent returns the comets continue to random-walk in orbital energy until they are ejected, are destroyed by one of several poorly understood physical mechanisms (see section 2.3), are captured to a "short-period" orbit with a revolution period less than 200 yr, or collide with the Sun or a planet. [There are two classes of short-period comets, HTCs and JFCs. The HTCs encompass 41 known objects with a median orbital period of 70.5 yr and a median inclination of 64°. Some or most HTCs may originate in the Oort cloud (*Levison et al.,* 2001). The JFCs include 236 known comets with a median orbital period of 7.5 yr and an median inclination of 11°. By contrast with HTCs, most JFCs probably do not originate in the Oort cloud. The small inclinations of the JFCs argued for the existence of a low-inclination source region, i.e., the Kuiper belt (*Joss,* 1973; *Fernández,* 1980a; *Duncan et al.,* 1988, *Quinn et al.,* 1990; *Fernández and Gallardo,* 1994), but it now appears likely that most JFCs arise from the related structure called the scattered disk (*Duncan et al.,* 2004). The numerical data listed here were derived from the tables of HTCs and JFCs in the Web page of Y. Fernández (http://www.ifa.hawaii.edu/~yan/cometlist.html).]

In Fig. 2 we show the bound comets with a < 10^5 AU on a logarithmic scale. This plot indicates that there are about twice as many comets with "original" semimajor axes (a) ranging from tens to thousands of AU, compared to the number with a > 10^4 AU. Those with a < 10^4 AU are often called "returning" comets; those with a > 10^4 AU are called dynamically "new" comets. The reason for this terminology is as follows. The median value of E_o for the new comets is 1/27,000 = 3.7×10^{-5}. The magnitude of the typical energy change, $|\Delta E|$, which these comets undergo in one perihelion passage is ~10^{-3}, i.e., more than an order of magnitude larger (*Marsden and Williams,* 2003; cf. *van Woerkom,* 1948; *Everhart,* 1968; *Everhart and Raghavan,* 1970). Since $|\Delta E| \gg E_o$, about half the comets have $E_f = E_o - \Delta E \sim -\Delta E$ and the other half have $E_f = E_o + \Delta E \sim +\Delta E$. The former are ejected from the solar system; the other half are captured onto more tightly bound orbits with a ~ $1/\Delta E$, i.e., semimajor axes of a few thousand AU.

Thus comets with original values of a > 10^4 AU are unlikely to have passed within the orbits of Jupiter and Saturn, that is, within 10 AU of the Sun, in their recent past. (By contrast, the perturbations due to Uranus and Neptune are much smaller. Typical energy perturbations are proportional to M_p/a_p, where M_p is the planet's mass and a_p is its semimajor axis.) The condition that a > 10^4 AU is only a rough criterion for a "new" comet, since the distribution of energy changes is broad and centered on zero. *Dybczyński* (2001) gives a detailed analysis of the past histories of LPCs with well-determined orbits. Some 55% of the observed new comets (statistically consistent with the expected 50%) have $E_f < 0$ and will not return. Only 7% of the returning comets are ejected on their current apparition; since most have recently traversed the planetary region a number of times, they typically have $E_o > |\Delta E|$ (*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 yr. (Conventionally, LPCs have been taken to be those with orbital periods greater than 200 yr, since until the discovery of Comet 153P = C/2002 C1 Ikeya-Zhang = C/1661

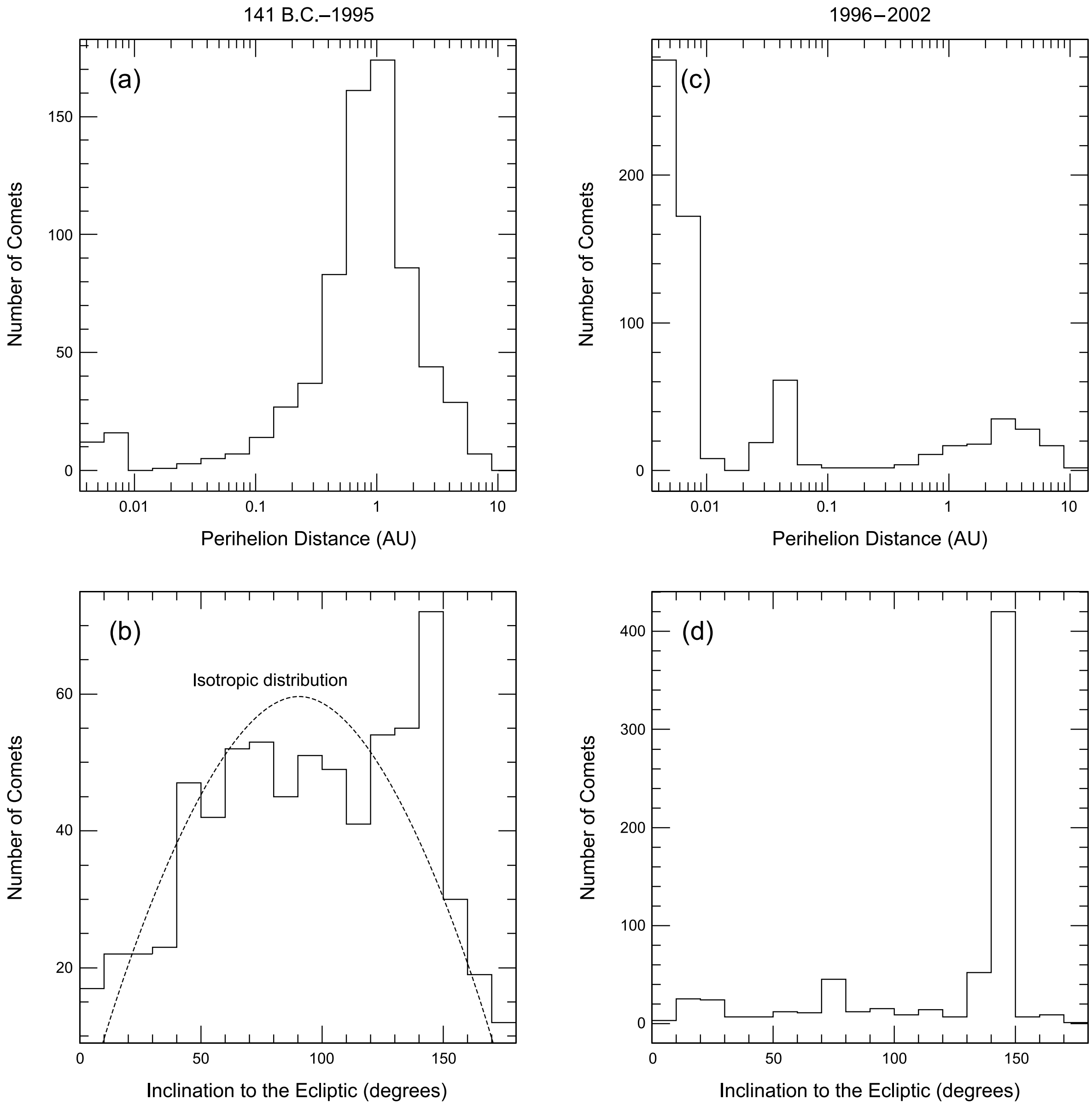

Fig. 3. Distribution of perihelion distances and inclinations to the ecliptic for the 706 historical (i.e., through 1995) single-apparition comets (left panels) and the 680 recent (1996–February 2003) single-apparition comets (right panels) from the 2003 *Catalogue of Cometary Orbits*. (**b**) shows a fit to an isotropic distribution for the non-Sun-grazers. The righthand panels are labeled 1996–2002 because the 2003 *Catalogue* is only complete through 2002, although it does include a few comets discovered early in 2003. The differences between the left and right panels reflect observational selection effects in the discovery of comets. There was a distinct change in the way comets were discovered in the mid-1990s because of (1) the discovery of numerous small Sun-grazing comets by the SOHO spacecraft, which was launched in December 1995, and (2) increased numbers of discoveries of all classes of comets by the automated searches for near-Earth objects begun around the same time.

C1 Hevelius, apparitions of a comet with P > 200 yr had never been definitively linked.)

Figure 3 shows the distribution of perihelion distances, q, and inclination to the ecliptic, i, for the 1386 "single-apparition" LPCs tabulated by *Marsden and Williams* (2003). The lefthand panels plot 706 "historical" comets, starting with C/-146 P1 and ending with C/1995 Y1. The righthand panels show 680 recent comets, starting with C/1996 A2 and ending with C/2003 B1. First consider the historical comets. The observed perihelion distribution (Fig. 3a) is peaked near q = 1 AU because of two factors with opposite dependences on heliocentric distance. First, historically, comets have only been discovered if they passed well within the orbit of Jupiter (5.2 AU), since water sublimes more readily (and hence cometary activity is more vigorous) when comets are closer to the Sun (*Marsden et al.,* 1973). For comets with q ≤ 3 AU, the total brightness of an "average" comet typically scales as $R^{-4}\Delta^{-2}$, as compared with $R^{-2}\Delta^{-2}$ for a bare nucleus, where R is the comet's distance from the Sun and Δ is its distance from Earth. Thus comets that closely approach the Sun or Earth are brighter and therefore easier to discover (*Everhart,* 1967a). Second, dynamical models suggest that the intrinsic number of comets per unit perihelion distance probably increases with increasing q throughout the entire planetary region (*Weissman,* 1985; *Dones et al.,* 2004).

Figure 3a also shows a smaller peak of comets with perihelion distances ≲0.01 AU (i.e., less than or approximately twice the radius of the Sun). These are Sun-grazing comets that have likely been driven onto small-q orbits by the secular perturbations of the planets (*Bailey et al.,* 1992). Most of these comets are members of the Kreutz family, which may be the remnants of a comet that broke up near perihelion (*Marsden,* 1967, 1989).

Figure 3b shows the inclination distribution of the historical comets, which roughly resembles an isotropic distribution (dashed curve). *Everhart* (1967b) showed that the departures from an isotropic distribution due to observational selection effects are small, with a ~ 10% preference for discovery of retrograde comets. This indicates that the observable Oort cloud is roughly spherical. The excess of comets with 140° ≤ i ≤ 150° is primarily due to the Kreutz Sun-grazers.

Figure 3c shows the perihelion distribution of comets discovered since 1996. About two-thirds of the comets are Sun-grazers (q < 0.01 AU), with a secondary peak centered near 0.04 AU due to the Meyer, Marsden, and Kracht "near Sun" groups (*Marsden and Meyer,* 2002) [see the Web pages of M. Meyer (http://www.comethunter.de/groups.html), J. Shanklin (http://www.ast.cam.ac.uk/~jds/kreutz.htm), and the U.S. Naval Research Laboratory (http://ares.nrl.navy.mil/sungrazer/)]. Almost all these comets have been discovered by the Solar and Heliospheric Observatory (SOHO) spacecraft (*Biesecker et al.,* 2002). From their apparent failure to survive perihelion passage, the SOHO Sun-grazers must be ≲0.1 km in diameter (*Weissman,* 1983; *Iseli et al.,* 2002).

In contrast to the historical discoveries, the distribution of recently discovered comets with q > 0.1 AU peaks not near 1 AU, but rather about 3 AU from the Sun. The outward march of this peak indicates that discovery of LPCs with large perihelia is still severely incomplete. For example, *Hughes* (2001) concludes that LPCs are still being missed beyond 2.5 AU. The advent of electronic detectors and automated near-Earth object surveys has recently led to the discovery of a few LPCs with the largest perihelion distances ever found, including C/1999 J2 Skiff (LONEOS survey, q = 7.11 AU), C/2000 A1 Montani (Spacewatch, q = 9.74 AU), and C/2003 A2 Gleason (Spacewatch, q = 11.43 AU). (See http://www.ifa.hawaii.edu/~yan/cometlist.html for a list of comets with q > 5 AU.) Inferring the true perihelion distribution for active comets at large q would require correcting for observational biases in comet discoveries. Performing this correction is difficult (and has not yet been attempted) because dynamically new comets are often anomalously bright at large heliocentric distances (*Oort and Schmidt,* 1951) on the inbound leg of their orbits, possibly because of sublimation of some type of ice such as CO that is more volatile than water ice.

Finally, Figure 3d shows the inclination distribution of the recently discovered comets. The peaks centered near 20, 75, and 145° are due to the Marsden/Kracht, Meyer, and Kreutz groups of Sun-grazers, respectively.

2.3. Cometary Fading and Disruption

Oort pointed out in his 1950 paper that the number of returning comets in the low continuous distribution (the "returning" comets) 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. [In a simple model that considers only the effects of planetary perturbations, and in which comets survive for an infinite length of time, the energy distribution of returning comets should be a constant for energies large compared to the magnitude of a typical energy perturbation (see *Oort,* 1950; *Lyttleton and Hammersley,* 1964) (Fig. 4).] This problem is commonly referred to as "cometary fading," although "fading" is a misnomer as it implies a gradual decline of activity. In fact, it is still not clear what the exact mechanism for fading is. Three physical mechanisms have been proposed to explain the failure to observe as many returning comets as are expected (*Weissman,* 1980a; *Weissman et al.,* 2002). These include (1) random disruption or splitting due to, e.g., thermal stresses, rotational bursting, impacts by other small bodies, or tidal disruption (*Boehnhardt,* 2002, 2004); (2) loss of all volatiles; and (3) formation of a nonvolatile crust or mantle on the nucleus surface (*Whipple,* 1950; *Brin and Mendis,* 1979; *Fanale and Salvail,* 1984). In these three cases, the comet is referred to as, respectively, "disrupted," "extinct," or "dormant." Recently, *Levison et al.* (2002) argued that spontaneous, catastrophic disruption of comets was the dominant physical loss mechanism for returning comets. In any case, the "fading" mechanism must be a physical one; the missing comets cannot be removed by currently known dynamical processes alone (*Weissman,* 1979, 1982; *Wiegert and Tremaine,* 1999).

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 adopted a value of k = 0.019, or 0.017 if "short-period" comets with orbital periods <50 yr 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.

In Fig. 4 we show the distribution of original energies, E_o, for the 386 LPCs with the best-determined orbits. If there were no "fading" (section 2.3), the distribution of E_o should be approximately constant for $E_o \gg 10^{-4}$ (dotted line). The actual distribution (solid line) lies far below the expected distribution, implying that many of the comets must have "faded." Models in which surviving comets have

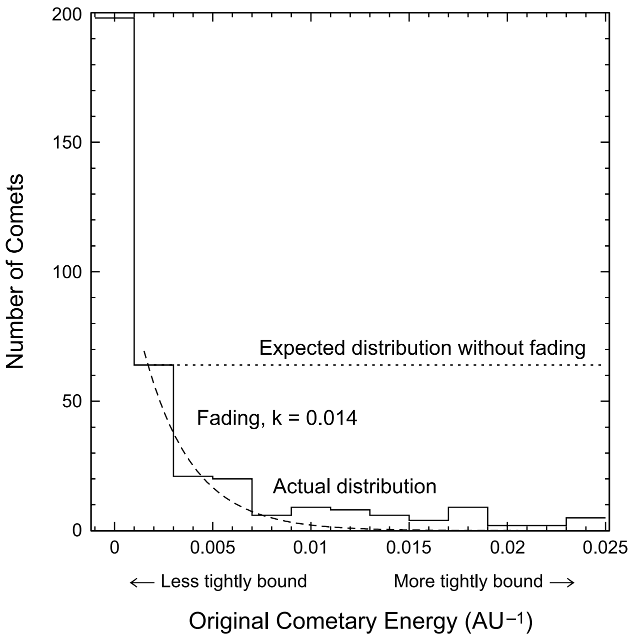

Fig. 4. Distribution of original cometary orbital energy for all 386 comets in the 2003 *Catalogue of Cometary Orbits* with well-determined energies. The histogram represents the observed distribution. The dashed curves give theoretical distributions with and without cometary "fading." *Oort* (1950) developed a simple model in which the number of "old" comets passing perihelion in a given period of time with energy E is proportional to $e^{-\alpha E}$ in the limit of large E. In this expression $\alpha = \sqrt{\frac{4k}{\pi(1-k)}}$; the unit of E is the mean magnitude of the energy perturbation per orbit produced by the planets, which we have taken to be 3.3×10^{-4} AU^{-1}; and k is the probability of disruption per orbit, which we have taken to be either 0 (flat curve) or 0.014 (declining curve). If no fading is assumed, the observed curve is far below the prediction of the model, while when a finite probability of fading is assumed, the model agrees somewhat better with observations. More elaborate fading models (*Weissman,* 1979, 1980a; *Wiegert and Tremaine,* 1999) are in good agreement with the observations, but the results are not necessarily unique. Although many authors have modeled the fading problem, there is still not a definitive physical explanation for fading. See section 2.3 for further discussion.

a constant probability of disruption per perihelion passage (dashed curve) or in which the number decays as a power law in the number of apparitions provide reasonable fits to the actual distribution.

*Whipple (*1962) treated the problem somewhat differently, modeling the expected cumulative "lifetime" distribution of the LPCs 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 on the order of 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 orbital energy distribution, including realistic models of the expected loss rate due to a variety of physical destruction mechanisms (*Weissman,* 1980a). Weissman's simulations contained a parameterization that accounted for cometary perturbations by Jupiter and Saturn, and comets were also perturbed by random passing stars and nongravitational forces. Comets were removed by collisions, random disruption (splitting), and loss of volatiles (sublimation of ices). A fairly good match to the observed E_o distribution in Figs. 1b and 4 was obtained. By tuning such a model to improve the fit, some insight into the possible physical and dynamical loss mechanisms was obtained. Weissman's best fit was with a model in which 10% of dynamically new comets randomly disrupted on their first return and 4% of returning comets disrupted on each subsequent return, with 15% of all comets being immune to disruption.

Wiegert and Tremaine (1999) (see also *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 carefully examined the effects of nongravitational forces on comets, as well as the gravitational forces from a hypothetical solar companion or circumsolar disk 100–1000 AU from the Sun. However, 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 to $L^{-0.6 \pm 0.1}$, consistent with the fading law proposed by *Whipple* (1962), or if ~95% of LPCs remain active for only ~6 returns and the remainder last indefinitely.

Historically, most comets have been discovered by amateurs. Determining the true population of comets requires a detailed understanding of observational bias, i.e., the probability that a comet with a specified brightness and orbit will be discovered. Many sources of bias have been identified, but have generally not been modeled in detail (*Everhart,* 1967a,b; *Kresák,* 1982; *Horner and Evans,* 2002; *Jupp et al.,* 2003). In recent years, telescopic surveys that primarily discover asteroids have discovered both active comets and inactive objects on comet-like orbits, which are sometimes called Damocloids. For example, the Near Earth Asteroid Tracking (NEAT) system discovered 1996 PW (*Helin et al.,* 1996), an object of asteroidal appearance that has a = 287 AU, q = 2.5 AU, and i = 30° (*Weissman and Levison,* 1997a). Discoveries by surveys are much better characterized than discoveries by amateurs, particularly for bodies that show little or no cometary activity. Using statistical models of discoveries of inactive (extinct or dormant) comets by surveys (*Jedicke et al.,* 2003), *Levison et al.* (2002) calculated the number of inactive, nearly isotropic comets (NICs) that should be present in the inner solar system. Their study used orbital distribution models from *Wiegert and Tremaine* (1999) and *Levison et al.* (2001) that assumed no disruption of comets. *Levison et al.* (2002) then compared the model results to the 11 candidate dormant NICs (mostly HTCs) that had been discovered as of December 3, 2001. Dynamical models that assume that comets merely stop outgassing predict that surveys should have discovered ~100 times more inactive 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 that rapidly dissipate.

A complication in modeling fading arises because Oort cloud comets on their first perihelion passage are often anomalously bright at large heliocentric distances compared to missing "returning" comets (*Oort and 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 and Bar-Nun,* 1987). When these Oort cloud comets return, they are generally not observed unless they come within about 3 AU of the Sun, where water ice can begin to sublimate at a sufficient rate to produce an easily visible coma (*Marsden and Sekanina,* 1973). This is illustrated in Fig. 5. The failure to observe many returning LPCs with q > 3 AU is likely to be an observational selection effect, as there is no known physical and/or dynamical mechanism for preferentially removing them. Thus, in comparing the heights of the E_o spike and low distribution, one should only consider comets with q < 3 AU. Considering only comets with q < 3 AU slightly alleviates the fading problem; the ratio of the number of returning to new comets is now 2.5, compared with 1.7 when all 386 high-quality orbits are used. Nonetheless, a returning-to-new ratio of 2.5 is still more than 10 times smaller than predicted by models without fading (*Wiegert and Tremaine,* 1999).

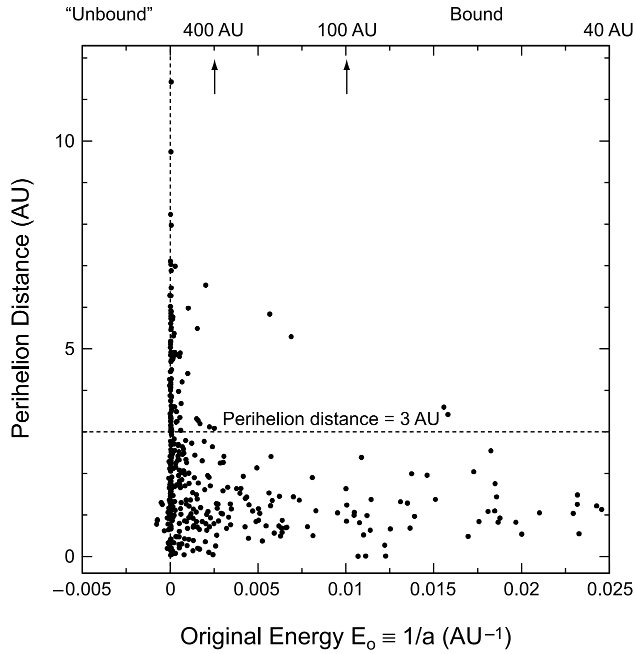

Fig. 5. Scatter diagram in original orbital energy and perihelion distance for the observed LPCs. The vertical band of comets at near-zero E_o is comets making their first perihelion passage from the Oort cloud. Comets diffuse left and right in the diagram as a result of planetary perturbations, primarily by Jupiter (in general, planetary perturbations do not significantly alter either the perihelion distance or the inclination of LPC orbits). Comets perturbed to negative values of E_o escape the solar system. Note the low number of LPCs with perihelion distances q > 3 AU and values of $E_o > 10^{-4}$. This deficit is likely an observational selection effect due to the inability of these comets to generate visible comae through water ice sublimation. Water ice sublimates poorly beyond 3 AU from the Sun. Data from *Marsden and Williams* (2003).

2.4. Population and Mass of the Oort Cloud

To account for the observed flux of dynamically new LPCs, 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 1.9×10^{11} objects. Oort stated that a "plausible estimate . . . of the average mass of a comet . . . is perhaps about 10^{16} g . . . uncertain by one or two factors of 10." For an assumed density of 0.6 g/cm^3, a cometary mass of 10^{16} g corresponds to a diameter of 3.2 km. More recent dynamical models (*Heisler,* 1990; *Weissman,* 1990a) have produced somewhat higher estimates of the number of comets in the Oort cloud, by up to an order of magnitude. These larger numbers come about in part from higher estimates of the flux of LPCs throughout 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 LPCs as compared with the outer planets region. This effect is known as the "Jupiter barrier." We return to this topic in section 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) (hereafter *DQT87*; see section 4). Assuming a new comet flux of 2.1 comets/year with q < 1 AU and "absolute magnitude" $H_{10} < 11$, *Heisler* (1990) inferred that the present-day Oort cloud contains 5×10^{11} comets with a > 20,000 AU and $H_{10} < 11$. *Weissman* (1996) relates H_{10}, which is a measure of a comet's total brightness that is generally dominated by coma, to cometary masses, using 1P/Halley to calibrate the relation (see also *Harmon et al.,* 2004). According to *Weissman* (1996), the diameter and mass of a comet with $H_{10} = 11$ are 2.3 km and 4×10^{15} g respectively. Assuming a broken power-law cometary size distribution from *Everhart* (1967b) (see also *Weissman and Levison,* 1997b), and assuming that a comet's luminosity at a standard distance is proportional to its mass, *Weissman*

(1996) infers that the average mass of a comet is 4×10^{16} g. Using *Heisler*'s (1990) modeled population, this implies a present-day mass of 2×10^{28} g or 3.3 $M_\oplus$ in comets with a > 20,000 AU. *Weissman* (1996) estimated that there are 1×10^{12} comets with a > 20,000 AU and $H_{10} < 11$, giving a mass for the outer Oort cloud (comets with a > 20,000 AU) of 7 $M_\oplus$. Weissman then assumed, based on *DQT87*, that the inner Oort cloud (a < 20,000 AU) contains about 5 times as much mass as the outer Oort cloud, giving a total present-day Oort cloud mass of 38 $M_\oplus$. However, this estimate is based upon a formation model and not on observations, since (1) comets from the hypothetical inner Oort cloud are not perturbed into the planetary region except during strong comet showers, which only occur some 2% of the time (*Heisler,* 1990), and (2) we are not presently undergoing a strong comet shower (*Weissman,* 1993). We further discuss the population of the inner Oort cloud in sections 3 and 4.

2.5. 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: GMCs in the galaxy, which were unknown before 1970 (*Biermann,* 1978; *Clube and Napier,*1982), and the galactic gravitational field itself, in particular the tidal field of the galactic disk (*Byl,* 1983, 1986; *Harrington,* 1985; *Heisler and Tremaine,* 1986). GMC encounters are rare, occurring with a mean interval of perhaps 3–4 × 10^8 yr, but can result in major perturbations on the orbits of comets in the Oort cloud. *Hut and Tremaine* (1985) showed that the integrated effect of molecular clouds on the Oort cloud over the history of the solar system is roughly equal to the integrated effects of all stellar passages. Atomic clouds have much smaller effects on the Oort cloud than do stars or molecular clouds (*Hut and Tremaine,* 1985).

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 and Latyshev,* 1972; *Smoluchowski and Torbett,* 1984). Maximum semimajor axes are about 1×10^5 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 8×10^4 AU for orbits perpendicular to the galactic plane, and increasing to almost 1.2×10^5 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 ~450 AU, for a 1 $M_\odot$ star passing at a speed of 20 km s^{-1} (*Weissman,* 1980b). Over the history of the solar system, Weissman estimated 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 will be many of the comets that are thrown into the planetary system in a "cometary shower" (*Weissman,* 1980b; *Dybczyński,* 2002a,b). An extremely close stellar encounter (interior to the inner edge of the Oort cloud) can, in principle, eject a large fraction of the comets in the entire cloud, because the star pulls the Sun away from the cloud (*Heisler et al.,* 1987). Such drastic encounters have probably not occurred in the past 4 b.y., but may have taken place in the early solar system if the Sun formed in a cluster.

García-Sánchez et al. (1999, 2001; see also *Frogel and Gould,* 1998) used Hipparcos and groundbased data to search for stars that have encountered or will encounter the solar system during a 20-m.y. interval centered on the present. Correcting for incompleteness, *García-Sánchez et al.* (2001) estimate that 11.7 ± 1.3 stellar systems pass within 1 pc (~200,000 AU) of the Sun per million years, so that ~50,000 such encounters should have occurred over the history of the solar system if the Sun had always occupied its current galactic orbit and environment. However, 73% of these encounters are with M dwarfs, which have masses less than 0.4 $M_\odot$. Strong comet showers are generally caused by stars with masses ~1 $M_\odot$. Passages through the Oort cloud by M dwarfs and brown dwarfs typically produce little change in the cometary influx to the planetary region (*Heisler et al.,* 1987).

It is now established that the galactic disk is the major perturber of the Oort cloud at most times (*Harrington,* 1985; *Byl,* 1986; *Heisler and Tremaine,* 1986; *Delsemme,* 1987), though stars and probably GMCs still play an important role in repeatedly randomizing the cometary orbits. Galactic tidal perturbations peak for orbits with their line of apsides at galactic latitudes of ±45° 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 LPCs 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 on the order of 1 b.y. (*Heisler and Tremaine,* 1986; *DQT87*). In general, the effect of the tide is stronger than that of passing stars because (1) the typical magnitude of galactic tidal perturbations is greater than the perturbation from stars for comets at a particular semimajor axis; and (2) the tide produces a regular stepping inward of cometary perihelia, in contrast to the random-walk nature of stellar perturbations. As a result, tides bring comets 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.

Hut and Tremaine (1985) estimated that the dynamical half-life of comets in the Oort cloud due to the effects of passing stars is about 3 G.y. at 25,000 AU and about 1 G.y. at 50,000 AU (see also *Weinberg et al.,* 1987). *Hut and Tremaine* (1985) estimated that the effects of GMCs on the Oort cloud are comparable to those of stars, though there are many uncertainties in how to treat clouds. Thus, due to stellar perturbations, only about 5% of the comets should survive at 50,000 AU for 4.5 G.y., while 5% should survive at 30,000 AU if the effects of clouds are included. Some authors have estimated even shorter lifetimes (e.g., *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 and Napier* (1984). However, cometary capture is an unlikely process because a three-body gravitational interaction is required to dissipate the excess hyperbolic energy. *Valtonen and Innanen* (1982) and *Valtonen* (1983) showed that the probability of capture is proportional to V_∞^{-7} for $V_\infty \geq 1$ km/s, where V_∞ is the hyperbolic excess velocity. Capture is possible at encounter velocities ≤1 km s^{-1}, but is highly unlikely at the Sun's velocity of ~20 km s^{-1} relative to the local standard of rest (*Mignard,* 2000).

More plausibly, the outer Oort cloud could be resupplied from an inner Oort cloud reservoir, i.e., comets in orbits closer to the Sun (*Hills,* 1981; *Bailey,* 1983) that are pumped up by passing stars to replace the lost comets. However, due to uncertainties in cloud parameters and the history of the solar orbit, it may 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. In particular, existing models of the effect of molecular clouds on the Oort cloud make highly idealized assumptions about the structure of molecular clouds, and are sensitive to assumptions about the history of the Sun's orbit (e.g., the extent of its motion out of the galactic plane). Finally, molecular clouds are part of a "fractal" or "multifractal" continuum of structure in the interstellar medium (*Chappell and 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 (J. Scalo, personal communication, 2003). We now turn to a more detailed discussion of the hypothetical inner cloud.

3. INNER OORT CLOUD AND COMET SHOWERS

In Oort's original model, he assumed that the velocity distribution of comets in the Oort cloud is given by an isotropic distribution of the form $f(v) = 3v^2/v_{max}^3$ for $v < v_{max}$ and $f(v) = 0$ for $v > v_{max}$. The velocity v_{max} is a function of distance from the Sun, r, determined by an assumed outer edge of the cloud at distance R_0. Specifically,

$$v_{max} = \sqrt{\frac{2GM_\odot}{R_0}\left(\frac{R_0}{r} - 1\right)}$$

with limiting cases

$$v_{max} \rightarrow \sqrt{2GM_\odot/r}$$

(i.e., the local escape velocity) for $r \ll R_0$ and $v_{max} \rightarrow 0$ for $r \rightarrow R_0$. Assuming that the Oort cloud is in equilibrium (i.e., the "pressure" due to the random motions of the comets balances the inward attraction due to solar gravity), this assumed velocity distribution determines the density profile n(r) (comets/AU^3) in the Oort cloud (see, e.g., *Spitzer,* 1987; *Binney and Tremaine,* 1987). Oort's profile is given by $n(r) \propto (R_0/r - 1)^{3/2}$ (*Oort,* 1950; *Bailey,* 1983; *Bailey et al.,* 1990). For $r \ll R_0$, $n(r) \propto r^{-\gamma}$, with $\gamma \approx 1.5$. (The median cometary distance in this model is 0.35 R_0; at this distance, the effective value of γ is ~1.7.) 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. However, Oort's assumption of an isotropic velocity distribution may not be valid in the inner parts of the cloud. For instance, if the orbits are predominantly radial (i.e., orbital eccentricities ~1), γ should be ~3.5, implying a centrally condensed cloud.

Hills (1981) showed that the apparent inner edge of the Oort cloud at a semimajor axis $a = a_I \approx (1\text{–}2) \times 10^4$ 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 $\gamma \geq 4$, so that many comets (and perhaps the great majority of comets) might reside in the unseen inner Oort cloud at semimajor axes of a few thousand AU. Besides its possible role as a reservoir that 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; see also *Weissman,* 1986, and section 5). However, the density profile of the Oort cloud is not known *a priori*, but depends in large part 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 LPC 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 vs. time into the terrestrial planets region (q < 2 AU) from *Heisler* (1990) is shown in Fig. 6.

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 $M_\odot$ star passage at 20 km s^{-1} at 3000 AU from the Sun would perturb a shower of ~5 × 10^8 comets into Earth-crossing orbits, raising the expected impact rate by a factor of 300 or more, and lasting 2–3 × 10^6 yr (this model assumed a massive inner Oort cloud with a population five times that of the outer cloud, as predicted by *DQT87*). Comets from the inner Oort cloud make an average of 8.5 returns each (allowing for disruption) 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 × 10^5 yr vs.

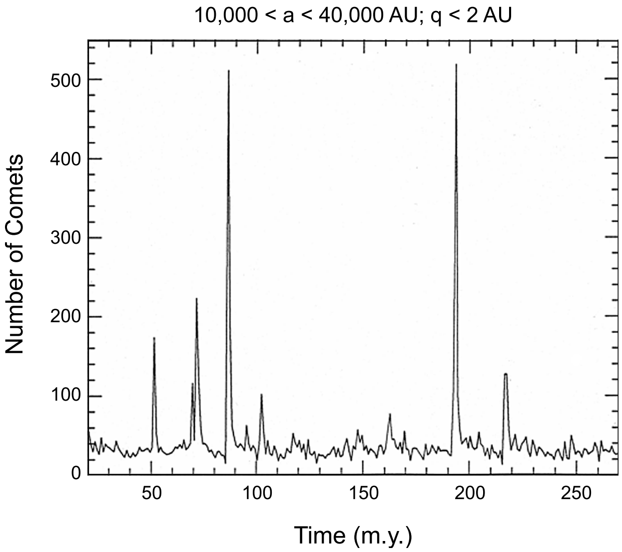

Fig. 6. Number of new LPCs from the Oort cloud entering the terrestrial planets region, q < 2 AU, vs. time, based on a Monte Carlo simulation that included random passing stars and galactic tidal perturbations. The large spikes are comet showers due to random stars penetrating the Oort cloud. From *Heisler* (1990).

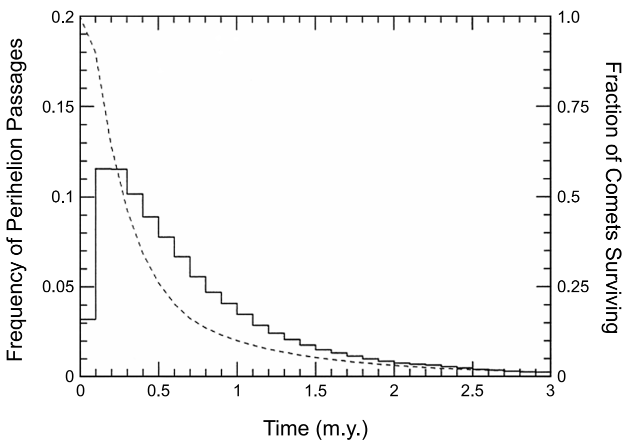

Fig. 7. Dynamical evolution of a shower of comets from the inner Oort cloud due to a close, penetrating stellar passage at 20 km s^{-1} at 3000 AU from the Sun. The solid histogram is the number of comets (arbitrary units) crossing Earth's orbit vs. time; the dashed curve is the fraction of the original shower comets still evolving in the system. On the order of 5×10^8 comets brighter than $H_{10} = 11$ are expected to be thrown into Earth-crossing orbits by the 1 $M_\odot$ star's passage. Roughly 10 of these comets would be expected to strike Earth. From *Hut et al.* (1987).

$3–5 \times 10^6$ yr in the outer cloud. Returning comets tend to be perturbed to even shorter period orbits, ~10^3–10^5 yr. 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) are shown in Fig. 7. The dynamical evolution of cometary showers was also modeled by *Fernández and Ip* (1987). *Farley et al.* (1998) presented the best evidence to date that at least one comet shower has occurred in the past. Specifically, they showed that the flux to Earth of extraterrestrial ^{3}He, a tracer of interplanetary dust, increased for 2.5 m.y., centered near the time of the large Popigai and Chesapeake Bay impacts some 36 m.y. ago and the late Eocene extinction event. However, it is possible that some other mechanism [e.g., an "asteroid shower" following the catastrophic disruption of a main-belt asteroid (*Zappalá 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 4×10^8 yr. 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 and Muller,* 1986). Lesser showers from more distant, but still penetrating stellar passages at heliocentric distances ~10^4 AU occur more frequently, on the order of every 4×10^7 yr (*Dybczyński,* 2002a,b; *Matese and Lissauer,* 2002). If there is a massive inner Oort cloud, random cometary showers may actually dominate the time-averaged LPC flux through the planetary region (*Weissman,* 1990b).

The suggestion that both biological extinction events (*Raup and Sepkoski,* 1984) and impact craters (*Alvarez and Muller,* 1984) on the Earth repeat with a period of approximately 26 m.y. led to several hypotheses that invoked periodic cometary showers as the cause of the extinctions. These hypotheses involved (1) a dwarf companion star to the Sun ("Nemesis") in a distant, eccentric, 26-m.y. period orbit (corresponding to a ~ 90,000 AU) with its perihelion deep in the Oort cloud (*Whitmire and 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 m.y., so that it periodically passed through a transneptunian disk of small bodies (*Whitmire and Matese,* 1985); or (3) the solar system's epicyclic motion above and below the galactic plane. In this last scenario, GMC encounters would occur near the times of galactic plane crossings (*Rampino and Stothers,* 1984), which occur every 26–37 m.y. (*Bahcall and Bahcall,* 1985). 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 mechanism by *Schwartz and James* (1984), although 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, although *Muller* (2002) recently proposed a modified version of the Nemesis companion-star hypothesis. More detailed discussions of the relevant issues can be found in *Shoemaker and Wolfe* (1986), *Tremaine* (1986), and *Weissman* (1986). 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 and Tremaine,* 1989; *Jetsu and Pelt,* 2000), and of the accuracy of the dated tie-points in the geologic record, particularly prior to 140 m.y. ago (*Shoemaker and Wolfe,* 1986).

Variations in the cometary flux into the planetary region as the Sun revolves around its galactic orbit are still the subject of research. For example, the solar system undergoes a 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 and Bahcall,* 1985). The full period of the oscillation is ~52–74 m.y. *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. 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."

Oort proposed the asteroid belt as the source region for the LPCs on the grounds that (1) asteroids and cometary nuclei are fundamentally similar in nature and (2) the asteroid belt was the only stable reservoir of small bodies in the planetary region known at that time. *Kuiper* (1951) was the first to propose that the icy nature of comets required that they be from a more distant part of the solar system, among the orbits of the giant planets. Thus, ever since Oort and Kuiper'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. [*Stern and Weissman* (2001) have recently argued that the primordial Kuiper belt at heliocentric distances <35 AU might have been an important source of Oort cloud comets. The *Dones et al.* (2004) simulations bear out this conclusion. However, in these models, perturbations due to Pluto are not important.]

Later work (*Whipple,* 1964; *Safronov,* 1969, 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 (if these planets were assumed to be fully formed) thus appeared to be more effective in populating the cloud. However, their role was unclear because the ice giants took a very long time to form in Safronov's orderly accretion scenario. *Fernández* (1978) used a Monte Carlo, Öpik-type code, which assumes that close encounters with planets dominate the orbital evolution of a small body, to calculate the probability that a comet would collide with a planet, be ejected from the solar system, or reach a near-parabolic orbit (i.e., an orbit of a body that might end up in the Oort cloud). He suggested that "Neptune, and perhaps Uranus, could have supplied an important fraction of the total mass of the cometary cloud." *Fernández* (1980b) extended this work by following the subsequent evolution of comets on plausible near-parabolic orbits for bodies that had formed in the Uranus-Neptune region ($5000 \leq a \leq 50,000$ AU; 20 AU $\leq q \leq 30$ AU; $i \leq 20°$). He included the effects of passing stars using an impulse approximation and included perturbations by the four giant planets by direct integration for comets that passed within 50 AU of the Sun. Fernández concluded that about 10% of the bodies scattered by Uranus and Neptune would occupy the Oort cloud at present, and that the implied amount of mass scattered by the ice giants was cosmogonically reasonable.

Shoemaker and Wolfe (1984) performed an Öpik-type 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 semimajor axes between 500 and 20,000 AU; 85% of the latter group had semimajor axes <10,000 AU. Shoemaker and 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; hereafter *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 semimajor axes, a_0, of 2000 AU and initial perihelion distances, q_0, uniformly distributed between 5 and 35 AU). Gravitational perturbations due to the giant planets and the disk (z) component of the Galactic tide were included (see below). 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 Oort cloud has a sharp inner edge at a heliocentric distance r ~ 3000 AU. (2) For 3000 AU ≤ r ≤ 50,000 AU, the number density of the Oort cloud falls steeply with increasing r, going roughly as $r^{-3.5}$. Thus the Oort cloud is centrally condensed, with roughly 4–5 times as many comets in the inner Oort cloud (a ≤ 20,000 AU) as in the classical outer Oort cloud. (3) The present-day inclination distribution should be approximately isotropic in the outer Oort cloud and most of the inner Oort cloud. The innermost part of the inner Oort cloud, interior to 6000 AU, may still be slightly flattened. (4) Comets with $q_0 \geq 15$ AU are much more likely to reach the Oort cloud and survive for billions of years than are comets with smaller initial perihelia. For example, only 2% of the comets with $q_0 = 5$ AU should occupy the Oort cloud at present, while 24% of the comets with $q_0 = 15$ AU and 41% with $q_0 = 35$ AU should do so. This result appeared to confirm that Neptune and Uranus, which have semimajor 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, allowed Neptune and Uranus to populate the Oort cloud efficiently because they could not lose objects to the control of Jupiter and Saturn.

Dones et al. (2004; hereafter *DLDW*) repeated the study of *DQT87*, starting with "comets" with semimajor axes between 4 and 40 AU and initially small eccentricities and inclinations. These initial conditions are more realistic than the highly eccentric starting orbits assumed by *DQT87*. *DLDW* integrated the orbits of 3000 comets for times up to 4 b.y. under the gravitational influence of the Sun, the four giant planets, the galaxy, and random passing stars. Their model of the galaxy included both the "disk" and "radial" components of the galactic tide. The disk tide is proportional to the local density of matter in the solar neighborhood and exerts a force perpendicular to the galactic plane, while the radial tide exerts a force within the galactic plane. These simulations did not include other perturbers such as molecular clouds, a possible dense early environment if the Sun formed in a cluster (*Gaidos,* 1995; *Fernández,* 1997), or the effects of gas drag (*de la Fuente Marcos and de la Fuente Marcos,* 2002; *Higuchi et al.,* 2002).

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

We will take the results of these calculations at 4 G.y. to refer to the present time. For a comet to be considered a member of the Oort cloud, we require that its perihelion distance exceeded 45 AU at some point in the calculation. For the "cold" runs, the percentage of objects that were integrated that currently occupy the classical "outer" Oort cloud (20,000 AU ≤ a < 200,000 AU) is only 2.5%, about a factor of 3 smaller than found by *DQT87*. The percentage of objects in the inner Oort cloud (2000 AU ≤ a < 20,000 AU) is 2.7%, almost 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 Oort cloud. The Oort cloud is built in two distinct stages in the *DLDW* model. In the first few tens of millions of years, the Oort cloud is built by Jupiter and Saturn, which deliver comets to the outer Oort cloud. After this time, the Oort cloud is built mainly by Neptune and Uranus, with the population peaking about 800 m.y. after the beginning of the simulation (Fig. 8). Objects that enter the Oort cloud during this second phase typically first spend time in the "scattered disk" [45 AU ≤ a < 2000 AU, with perihelion distance <45 AU at all times (*Duncan and Levison,* 1997)] and then end up in the inner Oort cloud.

Plates 5 and 6 show the formation of the Oort cloud in terms of the orbital evolution in semimajor axis as a func-

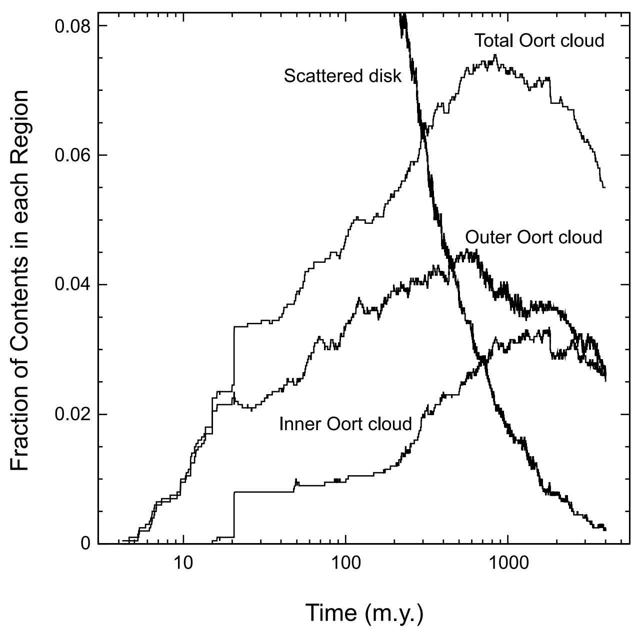

Fig. 8. Fraction of original cometary population placed in the inner and outer Oort clouds and in the scattered disk in the *DLDW* simulation. In these simulations the outer Oort cloud, which is originally populated by comets injected by Jupiter and Saturn, forms more rapidly than the inner Oort cloud, which is primarily populated by comets injected by Uranus and Neptune. The simulation predicts that at present, the populations of the inner and outer Oort clouds are comparable.

tion of perihelion distance and inclination to the invariable plane of the solar system, respectively. We show six "frames" from the *DLDW* integrations at various times in the calculations. (Animations showing these data every 1 m.y. 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 between 4 and 8 AU) are magenta triangles; Saturn region comets (8–15 AU) are blue triangles; Uranus region comets (15–24 AU) are green circles; Neptune region comets (24–35 AU) are red circles; Kuiper belt comets (35–40 AU) are black circles.

Plate 5a (0 m.y.) shows that the particles start with very small eccentricities, as represented by the diagonal line of particles that extends from ~4 to 40 AU. After 1 m.y. (Plate 5b), the giant planets, particularly Jupiter and Saturn, have scattered many comets into very eccentric orbits with perihelia still in the region of the giant planets. After 1 m.y., 76% of the test particles remain. Of the 24% lost in the first million years, most were ejected from the solar system by Jupiter or Saturn.

At 10 m.y. (Plate 5c), 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 m.y. (Plate 5d), the Oort cloud has begun to assume its current form. Twenty-eight percent of the particles remain; 4.7% are in the Oort cloud, with the rest in the planetary region or scattered disk. From 100 m.y. to 1000 m.y. (Plate 5e), 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 around 835 m.y. At 1000 m.y., 7.3% of the comets are in the Oort cloud. Finally, at 4000 m.y. (Plate 5f), the structure of the Oort cloud remains nearly the same as at 1000 m.y., but its population has declined slightly. In total, 11% of the particles that *DLDW* integrated remain. Of these, about half revolve on orbits in the planetary region (i.e., $a < 45$ AU), primarily in the Kuiper belt, that have changed little. Most of the other survivors reside in the Oort cloud, with nearly equal numbers of comets in the inner and outer clouds.

Plate 6 shows the evolution of the particles' inclinations. Plate 6a (0 m.y.) shows that the particles' inclinations to the invariable plane are initially small. After 1 m.y. (Plate 6b), the planets have scattered the comets into moderately inclined orbits. After 10 m.y. (Plate 6c), 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 (Plates 6d–6f), tides affect the inclinations of particles closer to the Sun, so that at 4000 m.y. inclinations are clearly isotropic for $a \gtrsim 7000$ AU.

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 (normally unobservable) inner Oort cloud. If we fit the entire Oort cloud at 4 G.y. in the *DLDW* model to a single power law, we find $\gamma \sim 3$, shallower than the value found by *DQT87*. The shallow slope probably results because all the giant planets inject comets into the Oort cloud, even though most *formed* beyond 20 AU. A value of $\gamma \sim 3$ implies that the inner and outer Oort clouds contain comparable numbers of comets at present in this model.

Finally, Fig. 8 shows the time evolution of the populations of the Oort cloud and scattered disk in the simulation. The scattered disk is initially populated by comets scattered by Jupiter and Saturn, and peaks in number at 10 m.y. (off-scale on the plot). The predicted population of the scattered disk in this model at the present time is roughly 10% the population of the Oort cloud.

Likewise, the Oort cloud grows rapidly in the first few tens of millions of years 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 around 800 m.y. From 150 m.y. to 4000 m.y., the fraction of comets in the Oort cloud ranges between 5% and 7.6%.

Figure 8 also shows the populations of the inner and outer Oort clouds individually. The population of the outer Oort cloud peaks around 600 m.y. The inner Oort cloud peaks around 1.8 G.y. Because of the faster decline of the outer Oort cloud, the ratio of numbers of inner to outer Oort cloud comets increases with time, to 1.1 at present. Nonetheless, this ratio is much smaller than was given by *DQT87*, who found 4–5 times more comets in the inner Oort cloud than in the outer Oort cloud. Only 2.5% of the comets that were initially in the simulation occupy the outer Oort cloud at 4 G.y.

At face value, the low efficiency of Oort cloud formation in the *DLDW* simulation implies a massive primordial protoplanetary disk. Assuming an outer Oort cloud population of 5×10^{11}–1×10^{12} comets (*Heisler,* 1990; *Weissman,* 1996) and an average cometary mass of 4×10^{16} g (section 2.4), the original mass in planetesimals between 4 and 40 AU was ~150–300 $M_\oplus$, some 3–6 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 et al.,* 2002; *Gomes et al.,* 2004). Since cometary masses are not well determined, it is not yet clear whether the large disk mass inferred by *DLDW* presents a real problem.

The results of the *DLDW* simulations appear inconsistent with observations in another way. The population of the scattered disk that *DLDW* predict, on the order of 10% of the population of the Oort cloud, is much larger than the inferred actual population of the scattered disk (*Trujillo et al.,* 2000). Finally, the *DLDW* model of the Oort cloud appears to be inconsistent with a model of the orbital distribution of the HTCs by *Levison et al.* (2001). Although the class of HTCs includes some objects on retrograde orbits, such as Halley itself, the observed HTCs with perihelia <1.3 AU have a median inclination i_{med} of only 58°. *Levison et al.* (2001), who took i_{med} = 45°, using the data available at that time, showed that the HTCs must originate in a somewhat flattened source region. Since the outer Oort cloud is known to be roughly isotropic, *Levison et al.* (2001) assumed that most HTCs must come from a flattened *inner* Oort cloud. However, because of the "Jupiter barrier" (section 5), the inner Oort cloud must contain many more comets than the outer Oort cloud to provide enough HTCs. By contrast, in the models of *DLDW*, the inner Oort cloud does not contain such a large population, nor is it particularly flattened. This discrepancy suggests some deficiency in one of the models. For example, the inner Oort cloud may not be the source of the HTCs, or the *DLDW* model may not be realistic enough because it neglects processes that were important in the early solar system.

The assumptions of the *DLDW* model 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, the planets were still forming during at least the early stages of the formation of the Oort cloud. Planetary migration in the early solar system (*Fernández and Ip,* 1984) appears to have been important in shaping the Kuiper belt (*Malhotra,* 1995; *Gomes,* 2003; *Levison and Morbidelli,* 2003; *Gomes et al.,* 2004), 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), likely changing the fraction of comets that ended up in the Oort cloud (see section 2).

Tremaine (1993), *Gaidos* (1995), *Fernández* (1997), *Eggers et al.* (1997, 1998), *Eggers* (1999), and *Fernández and Brunini* (2000) have discussed star formation in different galactic environments. These authors 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 Oort cloud would form. For example, *Eggers* (1999) modeled the formation of the Oort cloud, assuming that the Sun spent its first 20 m.y. in a star cluster with an initial density of 1000 or 10 stars/pc^3, as compared to the current density of ~0.1 stars/pc^3. The resulting cloud is produced primarily by Jupiter and Saturn, and its density peaks at a heliocentric distance of 6000–7000 AU in the 10 stars/pc^3 case or at <1000 AU in the 1000 stars/pc^3 case. After the cluster dispersed, Uranus and Neptune would have placed comets in the cloud in more or less the same way as they do with the Sun in its current environment.

If the Sun remained in a dense environment for too long, the resulting Oort cloud might not be stable, and the orbits of Uranus and Neptune would have become eccentric and/or inclined (*Gaidos,* 1995; *Ida et al.,* 2000; *Adams and Laughlin,* 2001; *Levison et al.,* 2004). 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 and Weissman,* 2001; *Stern,* 2003; *Charnoz and Morbidelli,* 2003).

5. CONSTRAINTS ON THE STRUCTURE OF THE OORT CLOUD

Barely one decade after the discovery of the first Kuiper belt object (besides Pluto), the number of known KBOs is comparable to the number of LPCs that have been discovered in recorded history. Full-sky surveys will likely tilt the balance decisively in favor of the Kuiper belt in the near future (*Jewitt,* 2004). This disparity is, of course, a consequence of the much greater distance to the Oort cloud and the r^{-4} heliocentric brightness dependence for distant bodies seen in reflected light. Thus a 200-km-diameter body with an apparent magnitude of 23 in the Kuiper belt at 40 AU would have a magnitude of 42 in the inner Oort cloud at 3000 AU, and a more typical 2-km comet at 20,000 AU, assuming an albedo of 0.04, would have a magnitude of 60. Thus direct imaging of comets at Oort cloud distances will not be possible in the foreseeable future.

There is no substitute for just counting comets in the Oort cloud. In principle, comets, especially in the inner cloud, could be detected when they occult stars (*Bailey,* 1976). G- or K-type main-sequence stars at a distance of 1 kpc (roughly twice the distance to the stars in Orion's belt) have visual magnitudes of ~15–17. If the brightness of a million such stars (about 10% of the number within 1 kpc) can be monitored, occultations by 30-km comets at a distance of 3000 AU can be detected in principle (e.g., *Axelrod et al.,* 1992; *Brown and Webster,* 1997). The Taiwan-America Occultation Survey (TAOS) project, which will search for occultations by KBOs, will soon come online (*Roques and Moncuquet,* 2000; *Cooray and Farmer,* 2003; *Cooray,* 2003), and detections of Oort cloud comets remain a long-term goal for occultation surveys (C. Alcock, personal communication, 2003).

For the present, our best hope is to try to infer the structure of the Oort cloud from the orbital distribution of known comets. This is a difficult exercise because of the numerous biases affecting discovery (section 2.2), and most importantly, because the "Jupiter barrier" severely limits the number of new comets from the inner Oort cloud that come within about 10 AU of the Sun (section 3).

Bailey (1983) finds that for a ≳ 28,000 AU, the Oort cloud has a density profile $n(a) \propto a^{-\gamma}$, with $\gamma = 2.4 \pm 0.2$. This assumes that the probability of discovery per year for a comet with a perihelion distance q well interior to Jupiter's orbit goes inversely as the comet's orbital period, which is plausible. However, Bailey's fits are based on only 37 "new" comets, a subset of those discussed by *Marsden et al.* (1978), with well-determined ("Class I") orbits and q > 2 AU. (The condition on perihelion distance is imposed in order to minimize unmodeled nongravitational effects.) At face value, Bailey's result implies an outer Oort cloud that is more centrally condensed than in Oort's original model (γ ~

1.5) and less centrally condensed than in *DQT87* or *DLDW*, both of whom find $\gamma \sim 3.5$ in the outer cloud. However, since systematic effects due to nongravitational forces, even for comets with q > 2 AU, and unknown observational biases might be important, it will be important to reevaluate Bailey's result by using a more homogeneous dataset.

To better constrain the Oort cloud, we need well-defined surveys that detect a large number of dynamically new LPCs with perihelia beyond Saturn, i.e., with $q \gtrsim 10$ AU. (By "comets," we mean bodies in highly eccentric long-period orbits. Such bodies may or may not be active.) The typical energy perturbations produced on comets by Uranus and Neptune are 10–100 times smaller than those produced by Jupiter and Saturn (*Everhart,* 1968; *Fernández,* 1981; *Weissman,* 1985; *Duncan et al.,* 1987), so comets with $q \gtrsim 10$ AU suffer no "Uranus barrier" or "Neptune barrier" to produce a bias against comets from the inner Oort cloud.

A key aspect of surveys is having a long enough observational arc to be certain that an object *is* a long-period comet. At present, there is only one known LPC with q > 10 AU, comet C/2003 A2 (Gleason), which was discovered during Spacewatch observations taken in January 2003. At the time of discovery the comet's magnitude was 20 and its heliocentric distance was 11.5 AU, a record. The IAU Circular reporting the discovery noted that the comet's inclination was only 8°, and stated "It seems likely that the object is a Centaur, showing cometary activity as (2060) = 95P/Chiron has shown near perihelion" (*Gleason et al.,* 2003). However, a later fit incorporating prediscovery observations indicated that C/2003 A2 is apparently a bona fide dynamically new comet (*Green,* 2003).

Planned surveys should discover many LPCs with perihelia beyond 10 AU. The Large Synoptic Survey Telescope (LSST) was endorsed as a recommended "major initiative" by the most recent U.S. Decadal Survey in Astronomy and Astrophysics (*National Research Council Astrophysics Survey Committee,* 2001). This 6–8-m optical telescope would survey much of the visible sky weekly down to 24th magnitude, beginning about one decade from now. Its objectives include studies of small bodies in the solar system (*Tyson,* 2002). In the shorter term, Pan-STARRS, a system consisting of four 1.8-m telescopes, is planning to begin operations by 2007. *Jewitt* (2004) estimates that Pan-STARRS will discover at least 400 comets per year (albeit mostly ecliptic comets), including many with large perihelia. It also may provide interesting constraints on the number of interstellar comets passing through the solar system. *Horner and Evans* (2002) note that the GAIA astrometric satellite, which is scheduled to be launched in 2010, is expected to cover about 200 LPCs each year.

The final approach we will discuss for constraining the population of the Oort cloud involves the impact history of the planets and their satellites. At present, ecliptic comets appear to dominate impacts with the giant planets and their inner satellites (*Zahnle et al.,* 1998, 2003), while asteroids dominate on Earth and the other terrestrial planets (*Shoemaker,* 1983; *Bailey and Stagg,* 1988; *Shoemaker et al.,* 1990; *Weissman,* 1990b; *McKinnon et al.,* 1997; *Levison et al.,* 2002; *Morbidelli et al.,* 2002; cf. *Rickman et al.,* 2001). *Zahnle et al.* (2003) estimate that ~1% of the impacts on Jupiter are produced by NICs, including both active and dormant cometary impactors. However, this percentage is higher for distant satellites, because the NICs experience less gravitational focusing than do ecliptic comets. For example, *Zahnle et al.* (2003) suggest that NICs produce about 30% of the 10-km craters on Jupiter's prograde irregular satellite Himalia.

The rate of impacts on a planet by LPCs is $\mathcal{R} = \dot{N}(q)\langle p \rangle$, where $\dot{N}(q)$ is the number of comets that pass perihelion within distance q of the Sun per year, and $\langle p \rangle$ is the mean impact probability of the comets with the planet per orbit of the comet. The biggest uncertainty in determining impact rates is in the cumulative perihelion distribution, $\dot{N}(q)$. The perihelion distribution is only well-constrained for $0.5 \text{ AU} \leq q \leq 2.5$ AU; over this range the number of comets per AU rises with q. *Zahnle et al.* (2003) assumed $\dot{N}(q) \propto q^2$ throughout the region of the giant planets. However, because they are partly or entirely exterior to the "Jupiter barrier," the saturnian, uranian, neptunian, and Pluto/Charon systems are also subject to impacts by comets that originate in the inner Oort cloud (*Bailey and Stagg,* 1988; *Weissman and Stern,* 1994). *DLDW* find $\dot{N}(q) \propto q^3$ in the giant planets region (also see *Fernández,* 1982; *Weissman,* 1985). As a result of this steeper dependence on q, *DLDW* estimate that LPCs could contribute some 10% of the present-day impacts on Saturn, Uranus, and Neptune, and could dominate the impact rate by comets on the irregular satellites of these planets. [For some irregular satellites, collisions with other such satellites probably dominate the current rates (*Nesvorný et al.,* 2003, 2004).]

Unfortunately, it is not straightforward to place limits on the population of the Oort cloud with the observed impact record. However, the existence of distant irregular satellites of the giant planets, with sizes as small as 1 km, does constrain the population of impactors that have traversed the planetary systems since the irregulars formed. Small satellites are easier to disrupt, and their orbital periods are so long that they cannot reaccrete after a catastrophic disruption event. *Nesvorný et al.* (2004) have used arguments of this sort to rule out some combinations of total mass and size distribution for the residual disk of planetesimals that remained after the giant planets formed.

Finally, if a very strong comet shower takes place due to the passage of a solar-mass star through the inner Oort cloud, the Jupiter barrier is temporarily eliminated, and a large flux of comets will enter the entire solar system, including the region of the terrestrial planets. The number of comets expected to strike Earth during such a shower is proportional to the number of comets in the inner Oort cloud, so the cratering record of Earth can be used to constrain the population of the inner cloud. During the Phanerozoic (the last 543 m.y.), about one or two major showers would be expected, given the known frequency at which stars pass near the Sun (section 3). If the population of the inner cloud were greater than about 100 times the population of the outer cloud, even a single very strong shower would produce more craters than Earth's record allows (*Shoemaker,* 1983; *Grieve and Shoemaker,* 1994; *Hughes,* 2000), and most of the known craters on Earth would have formed during a period lasting only a few million years. This constraint refers to craters tens of kilometers in diameter. There is some evidence that LPC nuclei have a flatter (i.e., more top-heavy) size distribution than do asteroids (*Shoemaker et al.,* 1990; *Levison et al.,* 2002; *Weissman and Lowry,* 2003), so considering only the largest known craters during the last half-billion years on Earth might yield a tighter constraint. As we noted in section 3, the Popigai and Chesapeake Bay craters (~100 km and 85 km in diameter, respectively), do seem to be associated with a comet shower 36 m.y. ago (*Farley et al.,* 1998).

6. SUMMARY

Oort's picture of a near-spherical cloud of comets at distances of tens of thousands of AU is still valid. An Oort cloud of about this size is a natural consequence of the interplay between scattering of planetesimals by the giant planets and tidal torquing by the galaxy and random passing stars. The formation of the Oort cloud is likely to be a protracted process, with the population peaking about 1 b.y. after the planets formed. The observed orbital energy distribution of LPCs requires that comets "fade," perhaps by undergoing spontaneous, catastrophic disruption. The best estimate of the current number of comets in the "outer" Oort cloud (a > 20,000 AU) is 5×10^{11}–1×10^{12} (*Heisler,* 1990; *Weissman,* 1991). Nominally, this estimate refers to comets with diameters and masses greater than 2.3 km and 4×10^{15} g, respectively. However, the relation between cometary brightness and mass is not well understood. Thus the total mass of even the outer Oort cloud is not well-determined.

The sample of new comets that reach the region of the terrestrial planets is biased to objects with a ≳ 20,000–30,000 AU because of the "Jupiter barrier." Thus the population of the inner Oort cloud, at distances of thousands of AU, remains uncertain. Recent simulations suggest that the population of the inner Oort cloud is comparable to that of the outer Oort cloud (*Dones et al.,* 2004), but more realistic simulations are needed. Rare passages of solar-type stars through the inner Oort cloud produce comet showers on all the planets. One such shower appears to have taken place 36 m.y. ago (*Farley et al.,* 1998).

Our present knowledge of the Oort cloud is much like the highly incomplete picture of the Kuiper belt we had one decade ago, after only a few objects had been discovered in the belt. In the next few decades, optical discoveries of comets at distances beyond 10 AU and direct detections by stellar occultations will provide a much better understanding of 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, growth, and collisions (*Morbidelli and Brown,* 2004). Most of the planetesimals that once orbited the Sun were probably ejected from the solar system. If most stars form comet clouds in the same way the Sun did, detection of bona fide interstellar comets is likely in the near future (*McGlynn and Chapman,* 1989; *Sen and Rama,* 1993). Millennia after mankind first wondered what comets were, we are on the verge of glimpsing their home.

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