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THE KUIPER BELT

Paul R. Weissman

Earth and Space Sciences Division, Jet Propulsion Laboratory, Pasadena, California 91109

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ABSTRACT

The Kuiper belt is a ring of icy planetesimals, i.e. comets, beyond the orbit of Neptune, a remnant of the formation of the solar system. These volatile-rich bodies never accreted into a planet because of the decreasing surface density of the solar nebula accretion disk and the increasingly long orbital periods at large heliocentric distances. The inner region of the Kuiper belt, between 34 and 45 AU, is dynamically active with an estimated population of $\sim 6 \times 10^9$ objects, and it is likely the source of the Jupiter-family short-period comets. The dynamically inactive region beyond 45 AU may extend out to 10^3 AU or more and may contain up to several times 10^{13} objects with a total mass of several hundred Earth masses. Observational searches have so far discovered 18 objects in the Kuiper belt, ranging in diameter from ~90 to 360 km. *IRAS* dust disks around nearby stars are likely similar, comet belt structures.

1. INTRODUCTION

Comets have long been recognized as a very different type of solar system body. Unlike the planets, which are all in low eccentricity, nearly coplanar orbits that do not intersect (with one minor exception: Pluto), cometary orbits are often highly eccentric, typically cross the orbits of many of the planets, and tend to be randomly oriented on the celestial sphere. Gravitational encounters with the major planets result in comets being transient members of the planetary system, with typical lifetimes of less than 10^6 years (Wetherill 1975, Weissman 1979, Levison & Duncan 1994). Thus, one of the most fundamental questions about comets has always been, where do they come from?

The comets observed passing through the planetary region are traditionally divided into two classes: long-period (LP) comets with orbital periods $P > 200$

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years and short-period (SP) comets with periods $P < 200$ years. The distinction is based largely on historical attempts to recognize returning comets and the fact that good orbit determinations only exist for about the past 300 years. The LP comets are typically in very eccentric orbits with semimajor axes up to 10^5 AU and orbital periods up to 10^7 years. In addition, their orbits are, to first order, randomly oriented on the celestial sphere. In contrast, the SP comets typically have more modest eccentricities with orbital periods mostly between 5 and 20 years, and are generally found in low inclination orbits, with $i < 35°$. The short-period comets also tend to be considerably fainter than their long-period counterparts and have steeper light curves as a function of heliocentric distance. An excellent review on the basic nature of comets is provided by Marsden & Roemer (1982).

The problem of the source of the long-period comets was solved by Oort (1950), who showed that they came from a vast spherical cloud of comets surrounding the planetary system and extending to interstellar distances. Comets in this cloud, now called the Oort cloud, are only weakly bound to the solar system and are easily perturbed by random passing stars, the Galactic tide (the nonisotropic gravitational field of the Galactic disk), and giant molecular clouds (GMCs). These perturbations scatter the comet orbits in angular momentum (and less so in energy) and cause some to diffuse into the planetary system, where they can be observed. The population of the Oort cloud is estimated to be $\sim 10^{12}$ comets (Weissman 1991), or possibly 10^{13} if a proposed but unseen inner core of comets in more tightly bound orbits is included (Hills 1981, Duncan et al 1987). The Oort cloud itself is believed to have been populated by icy planetesimals ejected from the outer planets zone during the formation of the planetary system, in particular by Uranus and Neptune. Informative reviews on the Oort cloud can be found in Weissman (1991) and Fernandez (1994).

It had generally been thought that the short-period comets were simply long-period comets that had diffused to short-period orbits by repeated planetary perturbations (Newton 1893, Everhart 1972). Oort cloud comets passing through the planetary region for the first time are scattered in orbital energy (proportional to $1/a$, where a is the semimajor axis of the orbit) by planetary perturbations, primarily by Jupiter. Comets scattered to larger (hyperbolic) semimajor axes achieve positive energy and are ejected to interstellar space. Comets scattered to smaller orbits return again to the planetary region and the perturbation process repeats. In this manner, some small fraction of the long-period comets, typically 10^{-3} to 10^{-4} can diffuse to short-period orbits after several hundred returns.

Two problems existed with this scenario. First, did it achieve the correct number of observed SP comets in the planetary region? Joss (1973) considered the dynamical mechanisms proposed at that time and estimated that there should only be 10^{-2} SP comets, clearly in conflict with the then known number of 73 SP comets. However, Delsemme (1973) used different, but still quite reasonable estimates for key parameters such as the cometary lifetime, and estimated a population of 84 SP comets, which was in good agreement with the observations. At present there are 174 known SP comets; 107 of them have been observed on more than one perihelion passage (Marsden & Williams 1993).

The second problem involved the very different inclination distributions of the LP and SP comets. Why were only low inclination LP comets captured to SP orbits? The proposed solution involved the fact that comets in low inclination, direct orbits can make low-velocity encounters with Jupiter and the other giant planets, resulting in major perturbations. It was believed that these very large perturbations led to the rapid evolution of low inclination LP comets into SP orbits, while higher inclination and retrograde comets with their much smaller planetary perturbations would not evolve far enough in $1/a$ during their limited physical lifetimes (Everhart 1972, 1974).

In the late 1970s cometary dynamicists were generally satisfied with this scenario, though there was still much debate about the details, and various researchers tried to model the process more precisely. However, a new possibility appeared in 1980 when Fernandez proposed that a far more efficient dynamical source for the SP comets was a belt of remnant icy planetesimals beyond the orbit of Neptune.[1] A distant comet belt at the edge of the planetary system was proposed in a classic paper by Gerard P Kuiper of the University of Chicago in 1951. Kuiper's paper dealt with the origin of the solar system, and he saw comets as a key to explaining much about the formation of the planetary system. He proposed that comets had formed as icy planetesimals in the outer planets region and had been ejected to the Oort cloud due to perturbations by Pluto (at that time Pluto was still believed to be a large planet with a mass of at least several Earth masses). This corrected Oort's earlier misconception that the comets had been ejected from the asteroid belt. Kuiper also proposed that no large planets had accreted beyond Pluto because the long orbital periods at those large solar distances led to very long formation times—greater than the age of the solar system. Thus, there would still be a belt of remnant icy planetesimals, i.e. comets, there.

Kuiper's suggestion prompted a number of investigations by others into the possibility of an outer planetary system comet belt. However, it was not until almost three decades later that attention would really focus on Kuiper's proposal, and then the attention would come from studies both within and outside the solar system, and on both theoretical and observational grounds. That attention has culminated in the past few years with the discovery of more than a dozen

[1] The idea of a comet belt beyond Neptune serving as a source of comets was first proposed in a little-noticed paper by Edgeworth (1949), but cometary dynamicists in the 1970s and 1980s were unaware of this work.

relatively large objects in orbits beyond Neptune, a region now called the Kuiper belt.

Because of its small mass, Pluto cannot significantly perturb the orbits of the icy planetesimals in its zone, and thus Neptune is effectively the outermost planet in the solar system. In fact, Pluto and its satellite Charon are often described as the largest icy planetesimals to have grown (and still be preserved) in the Kuiper belt. There is currently no evidence for a major planet beyond Pluto (Standish 1993).

This paper discusses the several different lines of evidence that came together in the past decade to focus attention on Kuiper's 1951 hypothesis, and the resulting observations and theoretical calculations that have largely confirmed it. Early follow-up on Kuiper's hypothesis is described in Section 2. The problem of the origin of the short-period comets, which provides key evidence for the existence of the Kuiper belt, is reviewed in Section 3. Section 4 discusses additional evidence that comes from studies of disk-like structures around protostars and the serendipitous discovery of dust disks around main sequence stars by the *IRAS* satellite. The observational searches that eventually led to the discovery of Kuiper belt objects, and the nature of the objects found to date, are described in Section 5. Dynamical studies of the stability of objects in the outer solar system and in orbits beyond Neptune are reviewed in Section 6. Finally, implications for future searches and other questions of interest are discussed in Section 7.

The course of events leading to the discovery of the Kuiper belt is presented chronologically, so as to demonstrate how ideas and concepts evolved with time, and how various developments influenced each other. It can be expected that these ideas will continue to evolve and to be refined in the future.

2. OUTER SOLAR SYSTEM PLANETESIMALS

Kuiper (1951) pointed out that the icy composition of comets, proposed the year before by Whipple (1950), could be explained if they formed in the outer solar system, beyond the orbit of Neptune where volatile ices could condense. He hypothesized that Pluto had ejected many of these small icy bodies to distant orbits, in contrast to Oort's (1950) suggestion that the distant comets had come originally from the asteroid belt. Kuiper pointed to the very different composition of comets and asteroids as evidence of their very different formation zones. Kuiper also proposed that planetesimals formed in the solar nebula beyond Pluto would not have been ejected and would still reside in a distant belt of comets, just beyond the planetary region.

In 1951 it was still thought that Pluto was a sizable planet, with a mass of at least several Earth masses. It was not until the discovery of Pluto's moon Charon in 1978 (Christy & Harrington 1978) that the mass of Pluto was finally measured and shown to be quite small, $\sim 2.1 \times 10^{-3}$ Earth masses ($M_\oplus$). Pluto is too small to eject or to significantly perturb the orbits of planetesimals in its own zone.

Interestingly, Kuiper was not the first to suggest the existence of a possible comet belt in the outer planets region. A lesser-known paper by Edgeworth (1949) also suggested the existence of a residual swarm of "clusters" of material beyond Neptune. By clusters, Edgeworth meant gravitationally bound swarms of particles, analogous to Lyttleton's (1948) "sandbank" model for cometary nuclei. Edgeworth even suggested that some of the clusters may occasionally detach themselves from the distant belt and be observed as comets. Unfortunately, Edgeworth's contribution was overlooked until recently, possibly because of its association with the unpopular (and now disproven) sandbank model.

In another study of solar system formation, Cameron (1962) proposed that the protosolar nebula had formed a massive central disk structure extending well beyond the planetary orbits, and that a large number of small bodies existed outside of the planetary system. Whipple (1964) was motivated by Cameron's work to examine the possible perturbative effects of a comet belt on the orbit of Neptune, and concluded that a comet belt totaling $\sim 10 M_\oplus$ at 40 AU, or $\sim 20 M_\oplus$ at 50 AU, could better explain the apparent discrepancies in Neptune's motion, than assuming a significant mass for Pluto. It is now recognized that the discrepancies in Neptune's motion are not real (Standish 1993), but this was not known in 1964. Whipple also suggested that material from the trans-Neptunian comet belt could serve as a source for the zodiacal dust cloud, with large grains spiraling into the inner solar system due to the Poynting-Robertson effect.

Whipple's work led Hamid et al (1968) to study the motion of seven short-period comets with large aphelion distances, in particular comet P/Halley. They concluded that the mass of the comet belt could not exceed $0.5 M_\oplus$ if the belt was at 40 AU, or $1.3 M_\oplus$ if it was at 50 AU. Similar results were obtained by Yeomans (1986) in his study of the motion of comet Halley. Anderson & Standish (1986) set an upper limit of $<5 M_\oplus$ on any possible cometary belt at 35 AU, beyond Neptune, based on tracking of the *Pioneer 10* spacecraft. More recently, Anderson et al (1995) have used *Pioneer* and *Voyager* tracking to set an upper limit of $<0.7 M_\oplus$ of unseen matter interior to the orbit of Neptune ($<0.17 M_\oplus$ interior to the orbit of Uranus), and less than "a few" $M_\oplus$ in a comet belt located 10 AU beyond Neptune.

Following on the work of Hamid et al (1968), Hogg et al (1991) simulated the perturbations on comet Halley by a hypothetical comet belt beyond Neptune, and then estimated what minimum mass might be detected with modern observations. Although they claimed a much tighter upper limit on the comet belt mass than did Hamid et al, their result was based on incorrect assumptions about the positional accuracy obtainable with current astrometric observations. In reality their limit is no better than those found by Hamid et al (1968) and Yeomans (1986).

Cameron (1978) considered the physics of a viscous accretion disk formed in the mid-plane of the protosolar nebula and suggested that the disk might grow to 10^3 AU in radius, or larger. He suggested that comets formed in the disk would spiral out to larger orbits as the disk lost mass, and could be pumped to very large orbits if the disk lost a significant fraction of its mass very rapidly. Although Cameron's emphasis was on finding an efficient means for populating the Oort cloud, he did recognize that material would accrete into comets at moderately large heliocentric distances beyond the planetary system.

3. ORIGIN OF THE SHORT-PERIOD COMETS

Everhart (1972) argued that the most likely source for the SP comets was LP comets in low inclination orbits with initial perihelia between 4 and 6 AU, close to Jupiter's orbit. Because such comets make frequent close approaches to Jupiter at low relative velocities, they receive particularly large perturbations in energy and can evolve fairly rapidly to short-period orbits. According to Everhart, after the LP comets had evolved to small semimajor axes, additional Jupiter perturbations would reduce their perihelion distances into the terrestrial planets region where they could be observed.

Comets with perihelia substantially interior or exterior to Jupiter's orbit receive lesser perturbations and evolve more slowly. The same is true for comets in high inclination and/or retrograde orbits. The small perihelion comets are also more prone to physical loss mechanisms such as sublimation and/or random disruption, both induced by solar heating (Weissman 1980), and thus might be destroyed before they could evolve to SP orbits.

Everhart (1974) also suggested that long-lived planetesimals formed inside the orbit of Neptune might serve as a source of SP comets. He thus anticipated, to some extent, the discussions of a distant comet belt that were to become prominent in the following decade. Everhart (1977) later concluded that the number of SP comets could be supplemented by capture of low inclination LP comets with perihelia near the other Jovian planets: Saturn, Uranus, and Neptune.

One problem with Everhart's work was that there did exist some known SP comets in high inclination orbits, such as P/Halley with $i = 162°$ and P/Swift-Tuttle with $i = 113°$. The high inclination SP comets tend to be in longer period orbits, with $20 < P < 200$ years, and are often referred to as "Halley-type" comets. In contrast, the low inclination SP comets with $P < 20$ years are often called "Jupiter family" comets. How were the high-inclination Halley-type comets captured to SP orbits, given their too small planetary perturbations?

Fernandez (1980) revived interest in Kuiper's (1951) paper by suggesting that a distant belt of remnant planetesimals, i.e. comets, beyond Neptune, might be the source of the SP comets. Fernandez estimated that a belt of comets between 35 and 50 AU would be ~350 times more dynamically efficient than direct capture of LP comets from the Oort cloud as described by Everhart. The high efficiency is the result of two factors: first, the smaller distance that the orbits had to diffuse in $1/a$ to appear as SP comets, and second, the fact that only a very small fraction of the LP comets, whose inclinations are distributed proportional to $\sin i$, are in low inclination orbits. Fernandez suggested that some larger objects, on the order of the mass of Ceres, $m \simeq 10^{24}$ g ($\sim 2 \times 10^{-4} M_{\oplus}$) had accreted in the distant comet belt, and that perturbations by these objects resulted in a slow diffusion of belt comets into Neptune-crossing orbits, where they could then begin the evolution to SP orbits.

A parallel development at the time was Hills' (1981) speculation on the possible existence of an unseen inner Oort cloud with a population perhaps 10 to 100 times that of the outer, dynamically active Oort cloud. This idea caught on rapidly and it was later shown (Duncan et al 1987) that a dense inner cloud was the natural by-product of the ejection of planetesimals from the Uranus-Neptune zone. Comets in the inner Oort cloud have semimajor axes of $\sim 10^3$–10^4 AU, vs 10^4–10^5 AU for comets in the outer Oort cloud. However, orbital eccentricities in both the inner and outer comet clouds are randomized with mean values of ~ 0.7, and so perihelia of comets extend over an even larger range of heliocentric distances.

During the mid-1980s the inner Oort cloud came to be identified also with the proposed comet belt beyond Neptune (Fernandez 1985a, Weissman 1985). It was believed that there existed a continuous distribution of comets, extending from just beyomd Neptune to 5×10^4 AU or more. The comet orbits just beyond Neptune were believed to be in the ecliptic plane, slowly increasing in mean inclination at larger heliocentric distances, with the inclinations becoming completely random beyond $\sim 10^4$ AU. However, Duncan et al (1987) showed that comets dynamically ejected from the Uranus-Neptune region were not "captured" into the inner Oort cloud until they had been pumped up to semimajor axes of $\sim 3 \times 10^3$ AU or more, where Galactic tidal perturbations could then detach their perihelia from the planetary region, i.e. perturb them to perihelia substantially greater than Neptune's semimajor axis. In contrast, the proposed Kuiper belt is a remnant population of icy planetesimals beyond Neptune that accreted in situ at their current locations in the ecliptic plane and have not been significantly perturbed over the history of the solar system. [However, Torbett & Smoluchowski (1990) showed that a fraction of the Kuiper belt population might be objects scattered outward from orbits near Neptune; see Section 6.] In addition, if we can apply the evidence from observations of protostellar disks and *IRAS* disks around main sequence stars (see Section 4), the Kuiper belt likely does not extend beyond about 1–2 $\times 10^3$ AU.

Critical support for Kuiper's (1951) hypothesis came from Duncan et al (1988), who investigated in detail the two possible dynamical sources for the SP comets: the Oort cloud and the trans-Neptunian comet belt. Duncan et al (1988) argued that as Oort cloud comets evolved inward toward SP orbits, they tended to preserve their random inclination distribution. In contrast to Everhart's (1972) earlier results, Duncan et al found that their dynamical integrations predicted a substantial number of high inclination and retrograde SP comets. Everhart's work apparently failed to produce high inclination SP comets because he did not carry his integrations long enough. Although high inclination and retrograde comets took more returns to evolve to SP orbits because of their smaller mean perturbations, they still would eventually reach small semimajor axes and provide a substantial steady-state population of high inclination and retrograde SP comets. These were not observed.

In contrast, when Duncan et al (1988) started comets from low inclination, low eccentricity orbits with perihelia near Neptune, they were able to reproduce the low inclination distribution of the observed SP comets, as well as other orbital elements including semimajor axis, aphelion distance, and argument of perihelion (see Figure 1). Duncan et al (1988) suggested that the trans-Neptunian comet belt would have a population of $\sim 4 \times 10^8$ comets in order to provide a SP comet resupply rate of 10^{-2} year^{-1} (Fernandez 1985b). Duncan et al also proposed that the trans-Neptunian comet belt should be called the "Kuiper belt."

Several counter-arguments and criticisms of Duncan et al (1988) have been proposed (e.g. Stagg & Bailey 1989). First, Duncan et al (1988) increased the planetary masses in their integrations by a factor of 40 to speed the dynamical evolution. Although this is a common technique in celestial mechanics, it can lead to spurious results. However, Quinn et al (1990) repeated the integrations with the planetary enhancement factor reduced to a factor of 10 and obtained similar results. In addition, both Wetherill (1991) and Ip & Fernandez (1991) obtained similar results, each using a simpler Öpik-type integrator and no enhancement of the planetary masses.

A second counter-argument involves physical loss mechanisms, which may preferentially destroy high inclination and retrograde LP comets during their longer, slower evolution inward from the Oort cloud. Possible loss mechanisms include collisions, sublimation, and random disruption (i.e. splitting). Collision rates are far too low to explain the discrepancy and are actually higher for direct orbits encountering Jupiter and Saturn because of the very large gravitational cross-sections of those planets at low encounter velocities. Nor is it likely that sublimation plays a significant role, because water ice sublimation rates are very low outside ~3 AU (Delsemme & Miller 1971) and SP comets do not approach distances inward of 3 AU until late in their dynamical evolution. Sublimation of more volatile ices like CO, HCN, and H_2CO, and the amorphous-crystalline ice phase transition, may provide mechanisms for cometary activity at larger heliocentric distances, but whether this can lead to nucleus destruction is doubtful. Random disruption is a poorly understood

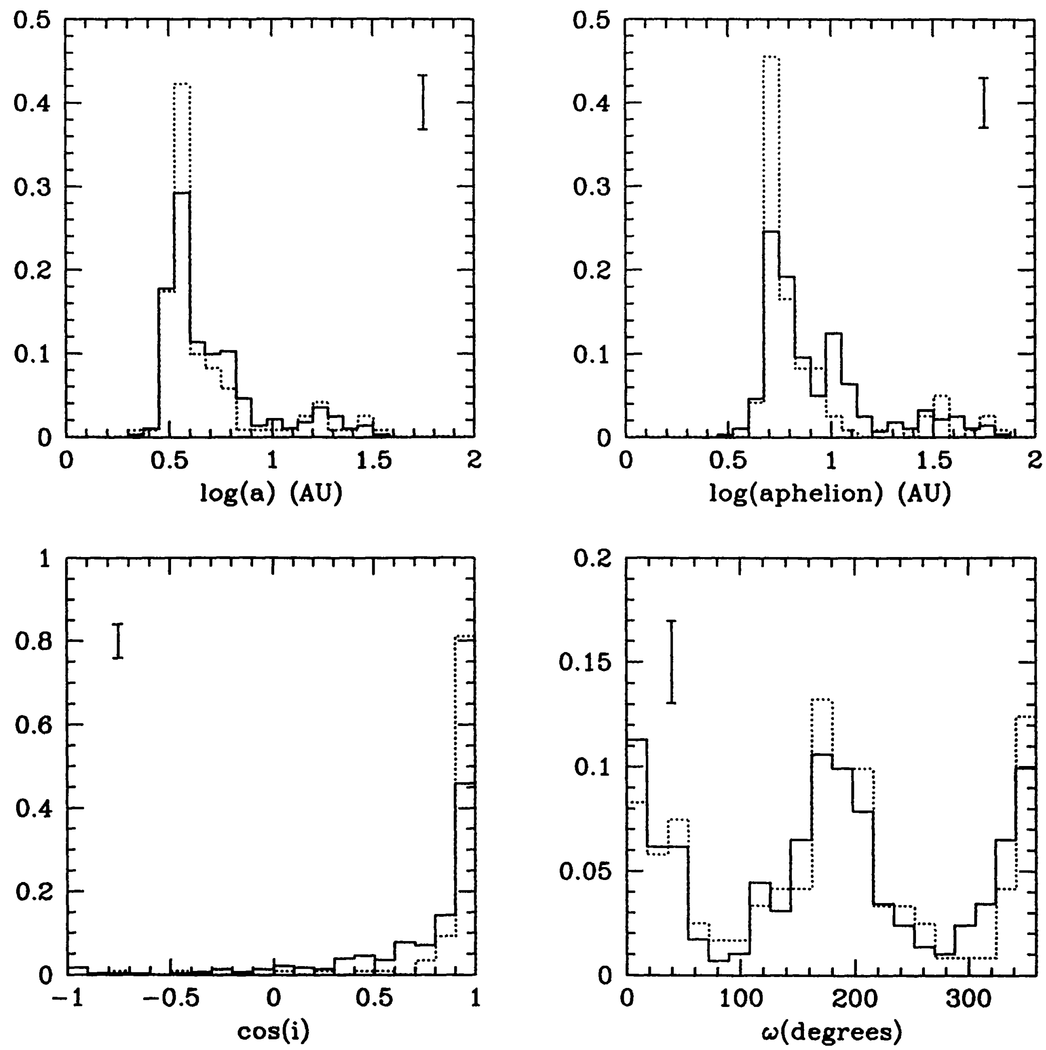
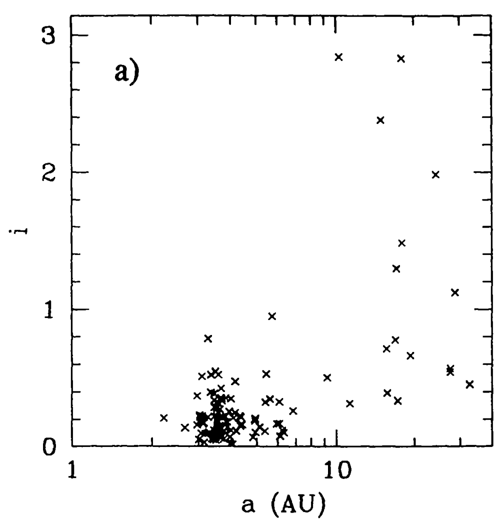


Figure 1 Distributions of semimajor axis, aphelion, cosine (inclination), and argument of perihelion for comets evolved to observable short-period orbits in dynamical simulations by Duncan et al (1988), assuming an origin in a flattened comet belt beyond Neptune. Solid curves are for 281 comets in the dynamical simulations; dashed curves are 121 observed short-period comets from Marsden's (1983) *Catalogue of Cometary Orbits.*

phenomenon (Weissman 1980, Sekanina 1982) but is thought to have something to do with heating of the comets as they approach the Sun, and thus, is again probably not applicable to this problem. In addition, Quinn et al (1990) showed that the Oort cloud still produced an excess of high inclination comets, even if a limiting physical lifetime of 500 or 1,000 returns was assumed for the evolving comets.

Stagg & Bailey (1989) also argued that the inclination distribution is not entirely preserved when LP comets are evolved to SP orbits. This is, in fact, visible in the results of Duncan et al (1988) and Quinn et al (1990), as shown in Figure 2, though an Oort cloud origin still predicts far too many high inclination and retrograde SP comets, in particular at $P < 20$ years ($a < 7.4$ AU). However, Stagg & Bailey (1989) failed to examine capture probabilities for inclinations greater than 27°, which is still comparable to the inclinations of the observed SP comets. Thus, their criticism is not supported by their own calculations.

Stagg & Bailey (1989) identified a third possible source of SP comets: comets from the inner Oort cloud that are thrown back into the planetary region by strong stellar or GMC encounters and allowed to diffuse down to SP orbits. Since the inner Oort cloud is partially randomized in inclination, the evolution of these comets would be similar to those from the dynamically active outer Oort cloud, and they would thus again produce an excess of high inclination and retrograde comets; this was demonstrated in simulations by Quinn et al (1990). However, this is a possible dynamical path for creating Halley-type comets and should not be ignored in future dynamical studies.



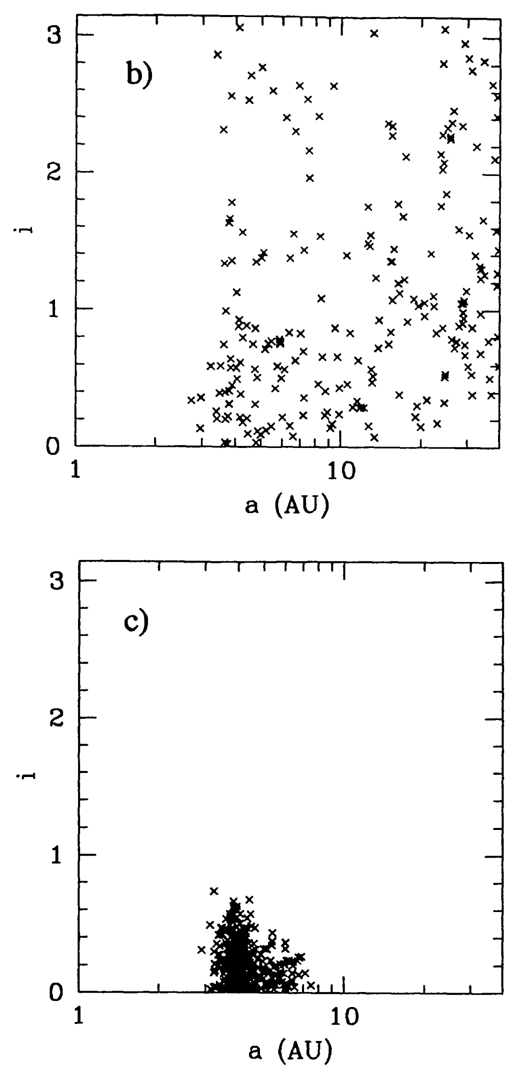


Figure 2 Scatter diagrams in semimajor axis and inclination for: (*a*) the observed short-period comets, (*b*) a dynamical simulation of comets captured to short-period orbits from the Oort cloud, and (*c*) a dynamical simulation of comets captured from a hypothetical comet belt beyond Neptune. (From Quinn et al 1990.)

Additional understanding of the dynamical evolution of SP comets was provided by Levison & Duncan (1994). They performed long-term integrations of the orbits of all the known SP comets and showed that a better parameter for denoting the difference between Jupiter family and Halley-type comets is the Tisserand parameter

$$T = a_J/a + 2\sqrt{(a/a_J)(1-e^2)}\cos i, \quad (1)$$

where a_J is the semimajor axis of Jupiter's orbit, and a, e, and i are the semimajor axis, eccentricity, and inclination of the comet's orbit, respectively. T is an approximate constant of the motion in the restricted 3-body problem (Sun-Jupiter-comet) and was devised to identify returning SP comets, even if their orbits had been significantly perturbed by Jupiter. Carusi & Valsecchi (1987) suggested that Jupiter family comets be defined as those with values of $T > 2$, and Halley-type comets as those with $T < 2$. Using this definition, Levison & Duncan (1994) showed that relatively few comets changed family or type during their dynamical evolution in the planetary system.

It is then possible to explain the Jupiter family and Halley-type comets if the observed SP comets are a mix of comets from the two dynamical reservoirs—the Oort cloud and the Kuiper belt. The low inclination, Jupiter-family SP comets with $T > 2$ come primarily from the low inclination Kuiper belt, while the high inclination Halley-type comets with $T < 2$ come primarily from the random inclination Oort cloud (Quinn et al 1990). Given the relative numbers in the two families, the Kuiper belt appears to be the dominant source of the observed SP comets. However, observational selection effects, primarily the less frequent perihelion passages due to their longer orbital periods, make it more difficult to find Halley-type comets. Thus, we cannot yet obtain the exact proportion between the two families.

However, there are still problems with the scenario outlined above. If one considers the distributions shown in Figure 2, it is not possible to add the distributions in Figure 2*b* (Oort cloud source) and Figure 2*c* (Kuiper belt source) to obtain the observed distribution for the short-period comets shown in Figure 2*a*. If one invokes an Oort cloud source to explain the high inclination, Halley-type comets, then one must also expect some number of Oort cloud comets in high inclination orbits evolving to smaller semimajor axes, $a < 10$ AU. These are not observed.

There are three possible explanations for this lack of small a, high inclination SP comets. First, it is possible that the comets are there but have been missed by observers, some of whom tend to focus their searches near the ecliptic (in particular, those looking for asteroids). Everhart (1967) studied observational biases in the discovery of LP comets and showed that a small fraction of comets with inclinations near 90° could be missed, but that comets with inclinations near 180° actually had higher discovery probabilities than LP comets in direct, low inclination orbits. Thus, observational biases alone cannot be invoked to explain the lack of such comets.

A second possibility is that the high inclination and retrograde comets are physically destroyed, either by exceeding their physical lifetimes as active comets or through some mechanism that hastens their physical demise. Bailey et al (1992) showed that secular perturbations can drive SP comets with inclinations near 90° to substantially smaller perihelion distances. Such orbits would result in higher sublimation rates on the cometary nuclei and more rapid physical aging. However, Levison & Duncan (1994) showed that this effect was not general for all high inclination SP comets and probably does not apply at all to retrograde SP comets with inclinations >140°. Unless further dynamical studies can demonstrate that the results of Bailey et al (1992) are more general, this mechanism does not provide a means for preferentially removing the Halley-type comets at small semimajor axes.

The final possibility is that the Duncan et al (1988) and Quinn et al (1990) integrations are in error and that they overestimate the number of LP comets diffusing to small semimajor axes as a result of the enhanced planetary masses in the integrations. This question can only be answered by further dynamical studies with no enhancement of the planetary masses in the integrations. Such studies are currently underway (H Levison, personal communication).

4. PROTOSTELLAR AND STELLAR DISKS

Evidence for a comet belt beyond Neptune came not only from solar system studies, but also from studies of nearby stellar systems and of star formation. One of the many surprising discoveries of the *Infrared Astronomical Satellite* (*IRAS*) mission was the detection of extended dust disks around main sequence stars, including Vega (α Lyrae), Fomalhaut (α Piscis Austrini), β Pictoris, and ϵ Eridani (Aumann et al 1984, Gillett 1986). The discovery was made quite by accident when the *IRAS* science team attempted to use Vega as a calibration source and discovered substantial infrared excesses at wavelengths of 25, 60, and 100 μm. Subsequent studies (Backman & Gillett 1987, Aumann & Good 1990) found infrared excesses around many main sequence stars, including solar-type stars.

In a few cases, analysis of *IRAS* data enabled resolution of the excess emission, showing it to have flattened or disk-like sources. The disk-like structure was dramatically illustrated by coronagraphic images of the β Pictoris disk, which is viewed nearly edge-on (Smith & Terrile 1984, 1987) and is shown in Figure 3. The disk brightness declines approximately as $r^{-1.7}$ and extends up to 1,100 AU from the central star. Estimates of the masses of the material in the disks range from a tiny fraction of an Earth mass, if all the material is just in micron-sized particles, to hundreds of Earth masses, if the material has a

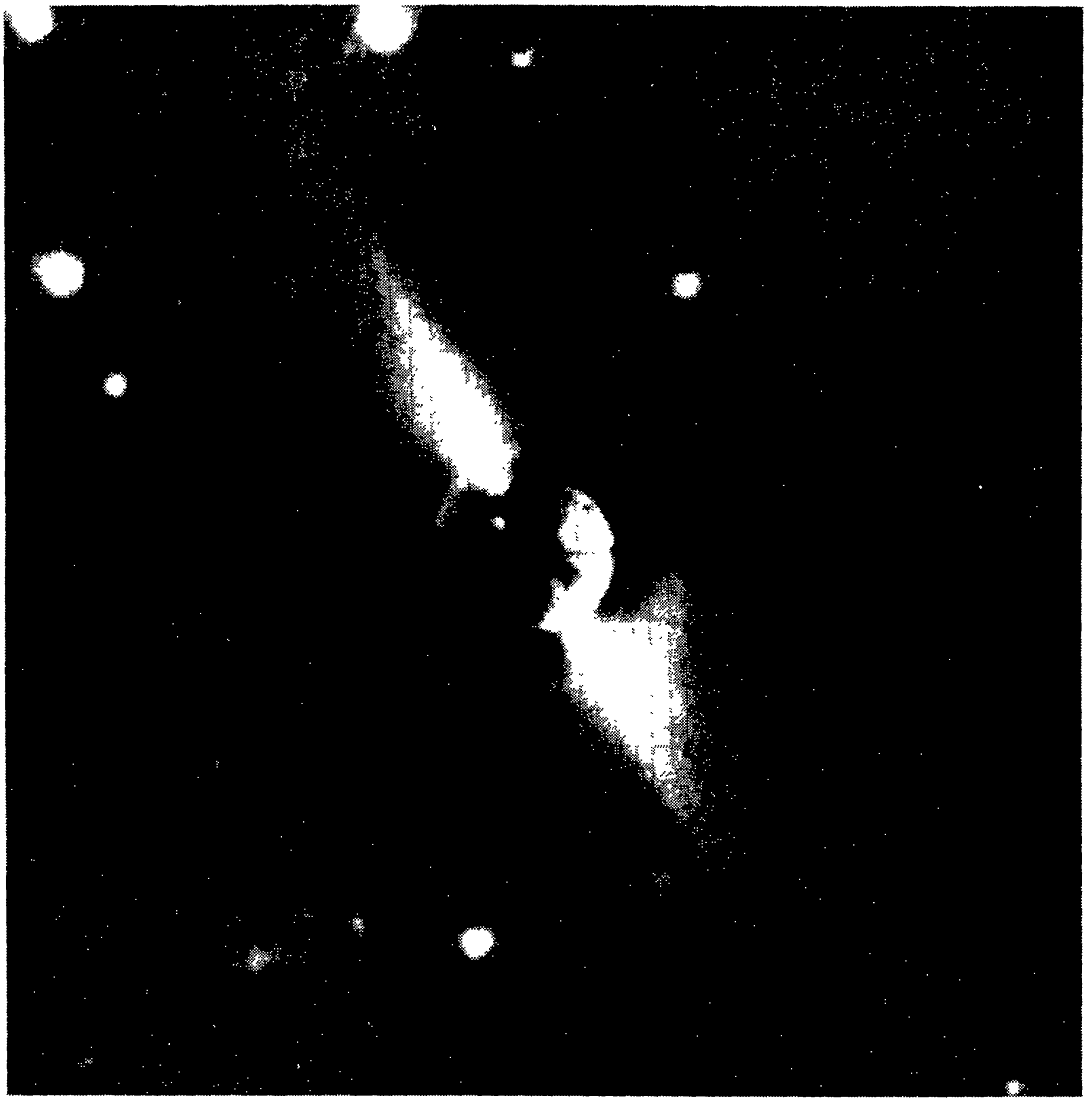


Figure 3 Coronagraphic photograph of the disk of material around the star β Pictoris, viewed edge-on (Smith & Terrile 1987). Disk material extends to 1,100 AU on either side of the star. The central star and the inner disk are occulted by the instrument. The disk was discovered by the *IRAS* satellite. Such disks appear to be common around main sequence stars.

typical asteroidal/meteoroid size distribution and extends up to bodies 10^3 km in diameter (Gillett 1986).

An interesting feature of the *IRAS* dust disks is that they do not extend all the way in to the central star. Maximum temperatures observed by *IRAS* show that the disks are cleared out to distances ranging from 20 to 70 AU around the four stars listed above. It was suggested that these clearings result from the material being swept up by planetary formation processes.

Another interesting feature is that the expected lifetimes of the dust in the disks is less than the probable age of any of the stars. Dust is removed by radiation pressure, the Poynting-Robertson effect, and collisions. Thus, there must be some mechanism replenishing the visible material in the dust disks.

Weissman (1984) and Harper et al (1984) first suggested that the *IRAS* dust disks were composed of comets, and that collisions and sublimation of volatile ices were continuously resupplying the fine material in the dust clouds. Weissman proposed that the disks were primordial inner Oort clouds that had not yet been dispersed to larger semimajor axes and random inclination orbits. Clearing times in excess of several times 10^8 years are expected for the Uranus-Neptune zone in our own solar system (Wetherill 1975), and are comparable to the main sequence ages of several of the *IRAS* excess stars. An additional link to comets was provided by observations of the β Pictoris disk by Telesco & Knacke (1991). They detected the 10 μm silicate emission feature that is also seen in cometary comae and in dense interstellar dust clouds.

Aumann & Good (1990) pointed out that since *IRAS* dust disks were common around G-type stars like the Sun, it would be unusual if the Sun did not possess a similar disk. They showed that if the solar system was surrounded by a disk as massive as that around β Pictoris, its presence could neither be confirmed nor ruled out by *IRAS* observations, which are dominated in the ecliptic by warm emission from the zodiacal dust cloud in the planetary region.

Observations of accretion disks around forming protostars provide a second astrophysical data source on the existence of circumstellar disks. Although such disks were long suspected on theoretical grounds (Lynden-Bell & Pringle 1974), their existence was not really established until the late 1980s when observational tools became good enough to detect them. Sargent & Beckwith (1987) mapped emission at millimeter wavelengths around the protostar HL Tau and showed it to be a disk-like structure extending out to 2,000 AU from the protostar and orbiting the protostar at Keplerian velocities. The mass of the disk was estimated at $\sim 0.1 M_\odot$. Since then, disk-like structures have been imaged at millimeter wavelengths around many protostars, with mass estimates between ~ 0.001 and $0.1 M_\odot$.

Another method for detecting protostar disks has been to look for infrared excesses in *IRAS* data. Surveys of the *IRAS* Point-Source Catalog (Cohen et al 1989, Kenyon et al 1990) showed disks around 25 to 50% of protostars. Millimeter surveys of many of the same stars showed that many had disk structures, even in cases where they had not been detected at infrared wavelengths (Beckwith et al 1990). This suggests that the particle size distribution in the disks may be evolving as fine material is either swept up or blown away.

Resolved images of disk-like structures around protostars in the Orion nebula were obtained at visual wavelengths for the first time by the *Hubble Space Telescope* (*HST*) (O'Dell & Wen 1994). Half of the 110 stars brighter than $V = 21$ in the *HST* images show evidence of circumstellar material, possibly in the form of flattened disks or envelopes.

5. OBSERVATIONAL SEARCHES OF THE OUTER SOLAR SYSTEM

Tombaugh (1961) performed the most complete areal search for trans-Neptunian objects, covering the entire sky north of $-30°$ declination to B magnitude 16 and succeeded in discovering Pluto in 1930. In addition, Tombaugh searched 1,530 square degrees of sky to a limiting V magnitude of 17.5: No outer solar system objects other than Pluto were found. Luu & Jewitt (1988) searched 200 deg^2 photographically with a Schmidt telescope to a limit of $V = 20$, and 0.34 deg^2 with a CCD camera to $R = 24$ ($V \simeq 24.5$), both with negative results. Levison & Duncan (1990) searched 4.9 deg^2 using a CCD to $V = 22.5$, again with negative results. Other negative searches include those by Cochran et al (1991) and Tyson et al (1992).

Kowal (1989) searched 6,400 deg^2 photographically to approximately $V = 20$, discovering the first outer solar system, planet-crossing object, 2060 Chiron (other than Pluto and recognized comets). Chiron is Saturn-crossing with a perihelion of 8.47 AU and an aphelion of 19.03 AU, just inside the orbit of Uranus. Its expected dynamical lifetime in this orbit is $\sim 1.2 \times 10^6$ years (Dones et al 1994), and there is a good possibility of it being perturbed into a typical SP comet orbit with a perihelion in the terrestrial planets region during its lifetime (Hahn & Bailey 1990). Chiron displays comet-like outbursts and coma (Meech & Belton 1989, Bus et al 1991). It was suggested early on that Chiron might be a surviving planetesimal from the Uranus-Neptune zone (Weissman 1985), where dynamical lifetimes are on the order of 10^8 years or more (Wetherill 1975). Duncan et al (1988) suggested that Chiron originated farther out, in the Kuiper belt.

A perplexing problem with Chiron is its albedo, which has been estimated at 0.11–0.20 (Campins et al 1994), implying a diameter of ~150–210 km. If Chiron is a comet-like object, possibly having originated in the Kuiper belt, why is its albedo so much higher than that of other cometary nuclei? (See Weissman & Campins 1993.) Chiron has been classified spectrally as C-type (carbonaceous), having a flat spectrum similar to that for carbonaceous asteroids in the main asteroid belt (similar spectra have been seen for some cometary nuclei, though comets are typically more red than gray). Conceivably, Chiron's surface may have been processed during closer approaches to the Sun in the past; this may account for its unusual albedo.

Three additional outer solar system, planet-crossing objects have been discovered: 5145 Pholus, 1993 HA_2, and 1994 TA (orbital data and estimated diameters are given in Table 1). All of these objects are in chaotic, unstable orbits—with the first two having aphelia beyond Neptune, and all have dynamical lifetimes of 10^6 to 10^8 years (Wetherill 1975, Dones et al 1994). These four objects—Chiron, Pholus, 1993 HA_2, and 1994 TA—must have come from some longer-lived dynamical reservoir. The maximum inclination among the four is 24.7° for 5145 Pholus, suggesting that their source reservoir is likely in the ecliptic plane and may be the same as that for the low inclination SP comets.

The first successful detection of an object beyond the orbit of Neptune (other than Pluto and Charon) was made by Jewitt & Luu (1992, 1993a). Using a CCD camera on the 2.2-meter University of Hawaii telescope, they searched ~1 deg^2 to $V = 25$ and found object 1992 QB_1 in August 1992. At the time of its discovery, 1992 QB_1 was at a heliocentric distance of 41.2 AU. The object was magnitude $R = 22.8$, reddish in color with $V - R = 0.7 \pm 0.2$, and stellar in appearance with no evidence of cometary coma. If the object has a typical cometary albedo of 0.04, then it is ~250 km in diameter. Subsequent observations allowed Marsden (1993a) to determine an orbit for 1992 QB_1 with $a = 43.82$ AU, $e = 0.088$, $i = 2.21°$, and $P = 290.2$ years. The perihelion distance of 39.99 AU is well beyond the orbit of Neptune; the aphelion of 47.67 AU is about 2 AU inside the aphelion distance of Pluto. Dynamical investigations (see next section) suggest that orbits like that of 1992 QB_1 are stable over the age of the solar system.

The second discovery of a trans-Neptunian object, designated 1993 FW, was made by Luu & Jewitt (1993a), who found the $R = 22.8$ magnitude object at 42.1 AU. The discovery image is shown in Figure 4. 1993 FW is similar in size to 1992 QB_1 (possibly slightly larger) but less red in color with $V - R = 0.4 \pm 0.1$, and again, stellar in appearance. A subsequent orbit solution by Marsden (1993b) found $a = 43.93$ AU, $e = 0.041$, $i = 7.74°$, and $P = 291.2$ years. Again, this orbit would be expected to be stable over the age of the solar system.

The next four objects discovered were significantly different in that their heliocentric distances were substantially closer to Neptune, in a region where the orbits cannot be stable unless protected by some dynamical mechanism. The four objects: 1993 RO (Jewitt & Luu 1993b), 1993 RP (Luu & Jewitt 1993b), 1993 SB, and 1993 SC (Williams et al 1993) were found at heliocentric distances ranging from 32.3 to 35.4 AU. Interestingly, all four objects were approximately 60° from Neptune in the sky, suggesting a possible Trojan-

Table 1 Outer solar system planet-crossing objects[a]

Designation	a (AU)	e	i (deg)	P (yr)	H (mag)	D^b (km)
2060 Chiron	13.73	0.384	6.93	50.85	6.0	190
5145 Pholus	20.36	0.573	24.70	91.85	7.3	120
1993 HA_2	24.78	0.523	15.63	123.38	9.5	44
1994 TA	17.5	0.393	5.43	73.0	11.5	17

[a]Listed in order of discovery. Data from discovery *IAU Circulars and Minor Planet Electronic Circulars.*
[b]Mean Chiron diameter measured by Campins et al (1994). Other diameters are estimated based on an assumed albedo of 0.10.

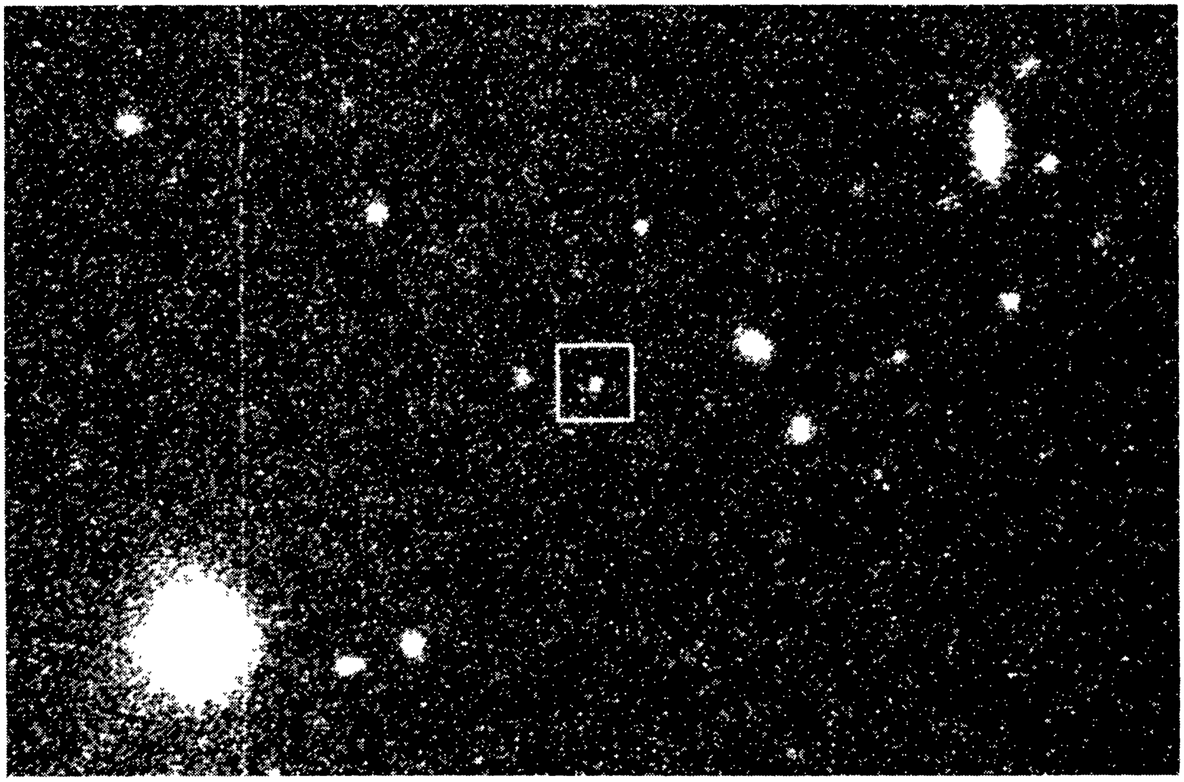


Figure 4 Discovery image of 1993 FW (inside the box) taken March 28, 1993 with the University of Hawaii 2.2-m telescope on Mauna Kea by Luu & Jewitt (1993). The comet is about *R* magnitude 23.3; the bright star at lower left is about magnitude 16. The vertical streak at the left is an artifact from the Tektronix 2048 × 2048 CCD. South is at the top; west is at the left.

type (1:1 resonance) dynamical relationship. However, Marsden (1994) has preferred an orbit solution for all four objects as being in a 3:2 mean-motion resonance with Neptune, similar to the motion of Pluto. A more recent orbital solution for 1993 SC (Marsden 1995a) clearly shows that it is in the 3:2 resonance. Malhotra (1994) has shown that the sweeping of dynamical resonances by Neptune during the formation of the planetary system would capture trans-Neptunian objects into mean-motion resonances with that planet, in particular the 3:2 and the 5:3 resonances. For the moment, such orbital solutions should be considered as tentative, as there are insufficient observations to clearly define the motion of these objects (except for 1993 SC). Assuming a cometary albedo, these four trans-Neptunian objects range between ~90 and ~290 km in diameter.

Continued searches have now found a total of 21 trans-Neptunian objects, which are listed in Table 2, in order of discovery. The columns in the table are the heliocentric distance at discovery, the semimajor axis and eccentricity (if a suitable orbit solution exists), the orbital inclination, the orbital period, the *R* magnitude at discovery, and an estimated diameter, based on an assumed cometary albedo of 0.04. Nine of the discovered objects are at heliocentric distances where they might make close approaches to Neptune, unless protected by some dynamical mechanism. The other 12 objects are well beyond the orbit of Neptune, though the eccentricity of their orbits are only well determined in six cases so far.

Of particular interest in Table 2 are two of the most recent discoveries, 1995 DA_2 and 1995 DB_2. Marsden (1995b,c) has suggested that these objects may be in the 2:1 resonance with Neptune. This is a very tentative suggestion and can only be confirmed or refuted by future observations. 1995 DA_2 is located at 33.1 AU, at a distance where its orbit would not be stable unless protected by some dynamical resonance. 1995 DB_2 is considerably farther from the Sun at 40.3 AU and could be in a stable, nonresonant orbit, though not a circular one (see Section 6). All of the other objects in Table 2 at heliocentric distances greater than 40 AU are likely to be stable over the history of the solar system.

The largest objects appear to be 1994 VK_8 and 1995 DC_2, each with a diameter of ~360 km, with 1993 FW, 1993 SC, 1994 JQ_1, 1994 TB, and 1995 DB_2 somewhat smaller at ~270–290 km diameter each (assuming an albedo of 0.04). The smallest object is 1993 RP at ~90 km. The cumulative absolute

Table 2 Kuiper belt objects[a]

Designation	r (AU)	a (AU)	e	i (deg)	P (yr)	H (mag)	D^b (km)
1992 QB_1	41.2	43.83	0.088	2.21	290.2	22.8	250
1993 FW	42.4	43.93	0.041	7.74	291.2	22.8	270
1993 RO	32.3	39.70[b]	0.205[b]	3.72	250.1	23	140
1993 RP	35.4			2.79		24.5	90
1993 SB	33.1	39.42[b]	0.321[b]	2.28	247.5	22.7	170
1993 SC	34.4	39.47	0.180	5.16	248.0	21.7	290
1994 ES_2	46.2	45.93	0.125	1.05	311.3	24.3	160
1994 EV_3	44.8	43.07	0.038	1.68	282.6	23.3	240
1994 GV_9	42.2	43.39	0.042	0.547	285.8	23.1	230
1994 JS	36.6			1.54		22.4	240
1994 JV	35.2			18.1		22.4	210
1994 JQ_1	43.4	44.31	0.027	3.73	295.0	22.9	270
1994 JR_1	35.2	39.76[b]	0.130[b]	3.80	250.7	22.5	210
1994 TB	31.7	39.56[b]	0.375[b]	12.2	248.9	21.5	270
1994 TG	42.2			6.76		23	240
1994 TH	40.9			16.1		23	230
1994 TG_2	42.4			2.25		24	150
1994 VK_8	43.4			1.43		22.3	360
1995 DA_2	33.1	47.56[c]	0.304[c]	5.38	328.1	23.0	150
1995 DB_2	40.3	47.62[c]	0.154[c]	3.20	328.6	22.5	280
1995 DC_2	45.4			0.884		22.5	360

[a]Listed in order of discovery. Data from discovery *IAU Circulars*, Minor Planet Electronic Circulars, and B Marsden (personal communication).
[b]Tentative orbit. Forced 3:2 resonance solution.
[c]Tentative orbit. Forced 2:1 resonance solution.

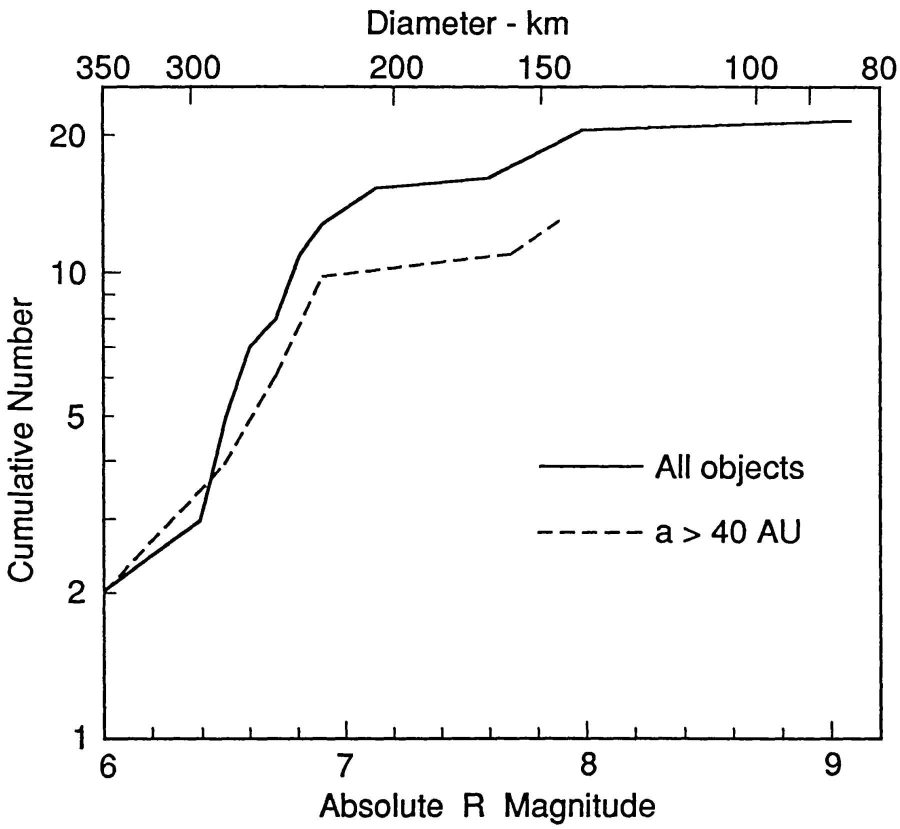


Figure 5 Cumulative absolute R magnitude distribution for the 21 discovered Kuiper belt comets (*solid curve*), and for just the 13 objects discovered with $a > 40$ AU (*dashed curve*). The diameter scale assumes a cometary albedo of 0.04.

magnitude distribution of the 21 objects is shown in Figure 5. The steep slope of the distribution between absolute R magnitude 6.0 and 7.0 is greater than that observed for the collisionally evolved main asteroid belt at similar sizes and may be indicative of an upper size limit in the growth of bodies by accretion in the Kuiper belt. However, given the modest number of bodies discovered at this time, this cannot be considered a very robust conclusion. The low slope of the distribution at diameters less than 200 km (absolute magnitude >7.2) is indicative of observational incompleteness at the fainter magnitudes.

Jewitt & Luu (1995) estimated that there are 3.5×10^4 objects in the Kuiper belt larger than 100 km diameter, based on the discovery of their first seven objects after searching a total of $\sim$1.2 deg^2, and assuming the belt to be confined to orbital inclinations less than $\sim 8°$. Because Kuiper belt objects have now been found in orbits inclined up to 18°, Jewitt & Luu's estimate is likely only a lower limit. If each of the objects is 100 km in diameter with a density of 1.0 g cm^{-3}, then the minimum mass of the Kuiper belt is $\sim 1.8 \times 10^{25}$ g, or $\sim 0.003 M_{\oplus}$. Jewitt & Luu (1995) also noted that past observational searches set an upper diameter limit of 600 km on comets between 30 and 50 AU.

6. DYNAMICAL STABILITY IN THE OUTER PLANETS REGION

Study of the long-term dynamical evolution of orbits in the outer planetary region has been made possible in the past decade as a result of improved integration codes developed to study the problem and the availability of high-speed, low-cost computer workstations that can be dedicated for periods of weeks or months to a single dynamical investigation. The first detailed study of the stability of orbits in the Kuiper belt was by Torbett (1989), who showed that low inclination orbits beyond Neptune would be chaotic and could become Neptune-crossing if their perihelion distances were between 30 and 45 AU. Torbett also estimated that the population of the Kuiper belt must be on the order of 10^9 comets to provide a resupply rate of short-period comets of 10^{-2} year^{-1} (Fernandez 1985b). Torbett & Smoluchowski (1990) showed that the chaotic motion induced by planetary perturbations could also scatter Kuiper belt comets to larger perihelia and semimajor axes.

Gladman & Duncan (1990) followed the evolution of test particles in initially near-circular orbits throughout the outer planets region for 2.2×10^7 years. They showed that most orbits between the four giant planets and out to semimajor axes of ~34 AU become planet-crossing in 10^5 to 10^7 years. Once the orbits are planet-crossing, they will fairly rapidly (~10^6 years) be ejected from the planetary region. However, Gladman & Duncan found that orbits beyond $a =$ 34 AU were stable for the duration of their integrations.

Holman & Wisdom (1993) performed similar integrations but for a duration of up to 8×10^8 years for test particles between the giant planets and 2×10^8 years for particles beyond Neptune. Their results are illustrated in Figure 6. Particularly long-lived objects near the semimajor axes of each of the giant planets are 1:1 Trojan-type librators near the L_4 and L_5 Lagrange points, 60° ahead and behind each planet in its orbit. Long-lived stable regions in the Kuiper belt were found between 37 and 39 AU and also beyond ~42 AU.

Even longer simulations were performed by Levison & Duncan (1993), who integrated the orbits of test particles in low eccentricity orbits between 30 and 50 AU for 10^9 years. For initially near-circular orbits ($e = 0.01$), stable regions exist with semimajor axes as close as 34 AU from the Sun, though some objects were lost as far out as 40 AU. For modest eccentricity orbits ($e = 0.10$), the stable regions between 35 and 42 AU were considerably narrower, but most orbits beyond semimajor axes of 42 AU survived for the full 10^9 years of the integration. Some of the apparently stable regions between 34 and 40 AU may be associated with mean-motion and/or secular resonances with Neptune.

For yet higher eccentricities, up to $e = 0.2$, Levison & Duncan (1993) found that objects were lost from the Kuiper belt with semimajor axes as large as 46 AU. In addition, Levinson & Duncan determined that semimajor axes near

48 AU tended to be unstable; these orbits are close to the 2:1 mean-motion resonance with Neptune.

M Duncan, H Levison, and S Budd (personal communication) have now extended their integrations of Kuiper belt test particles to periods of 4×10^9 years—essentially the age of the solar system. Their results are shown in Figure 7. For low inclination orbits ($i = 1°$), stable orbits are generally found between semimajor axes of ~37 and 40 AU and beyond ~42 AU for $e = 0.01$; between ~38 and 39 AU and beyond ~43 AU for $e = 0.05$; beyond ~44 AU for $e = 0.10$; and beyond ~46 AU for $e = 0.15$ (except for orbits near the 2:1 resonance with Neptune). As seen in Figure 7, the detailed structure of the stable and unstable regions is quite complex. For orbits with initially higher inclinations, the structure is even more complex, though again, stable regions generally exist for semimajor axes greater than 43 AU for eccentricities <0.10.

Based on these integrations, the orbits of 1992 QB_1 and 1993 FW, described in the previous section, are likely to be stable over the age of the solar system. Also apparently in stable orbits are 1994 ES_2, 1994 EV_3, 1994 GV_9, and 1994

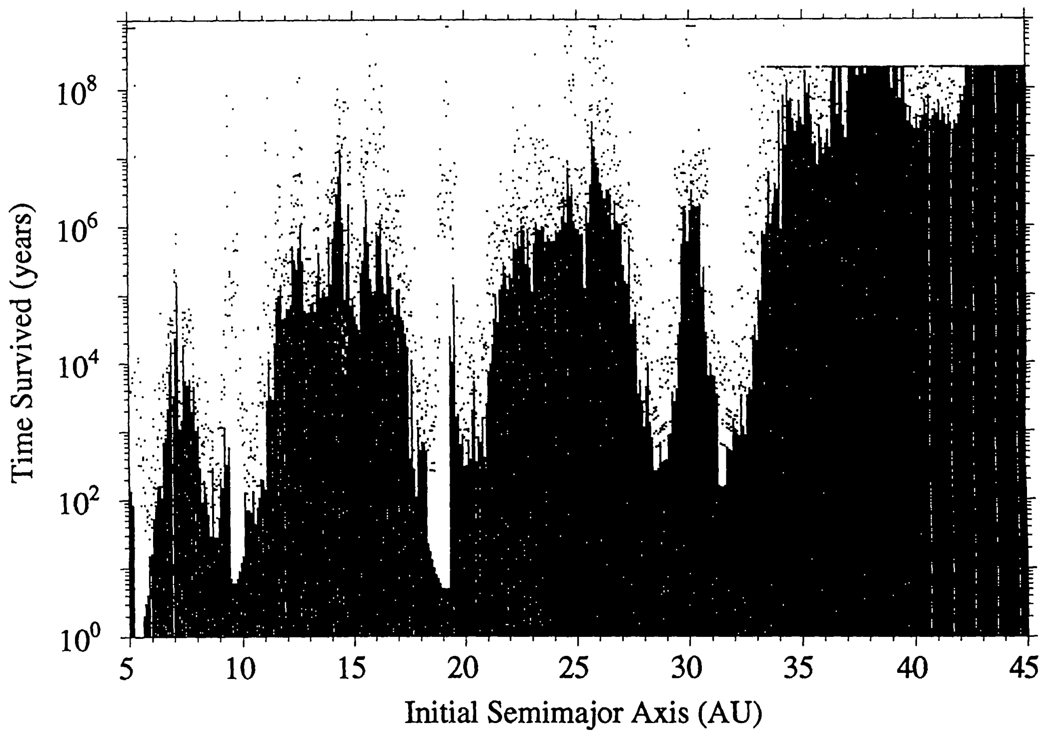


Figure 6 Time required for initially near-circular orbits to become planet-crossing as a function of initial semimajor axis for test particles in the outer planets region as found by Holman & Wisdom (1993). Vertical lines show the time of loss of the first (of 6) test particles at a particular semimajor axis; dots above the lines show the time of loss for the other particles. Particle orbits were integrated for 8×10^8 years between the planets and for 2×10^8 years for orbits beyond Neptune. Long-lived survivors at the semimajor axis values of each planet are Trojan-type librators around the L_4 and L_5 Lagrange points.

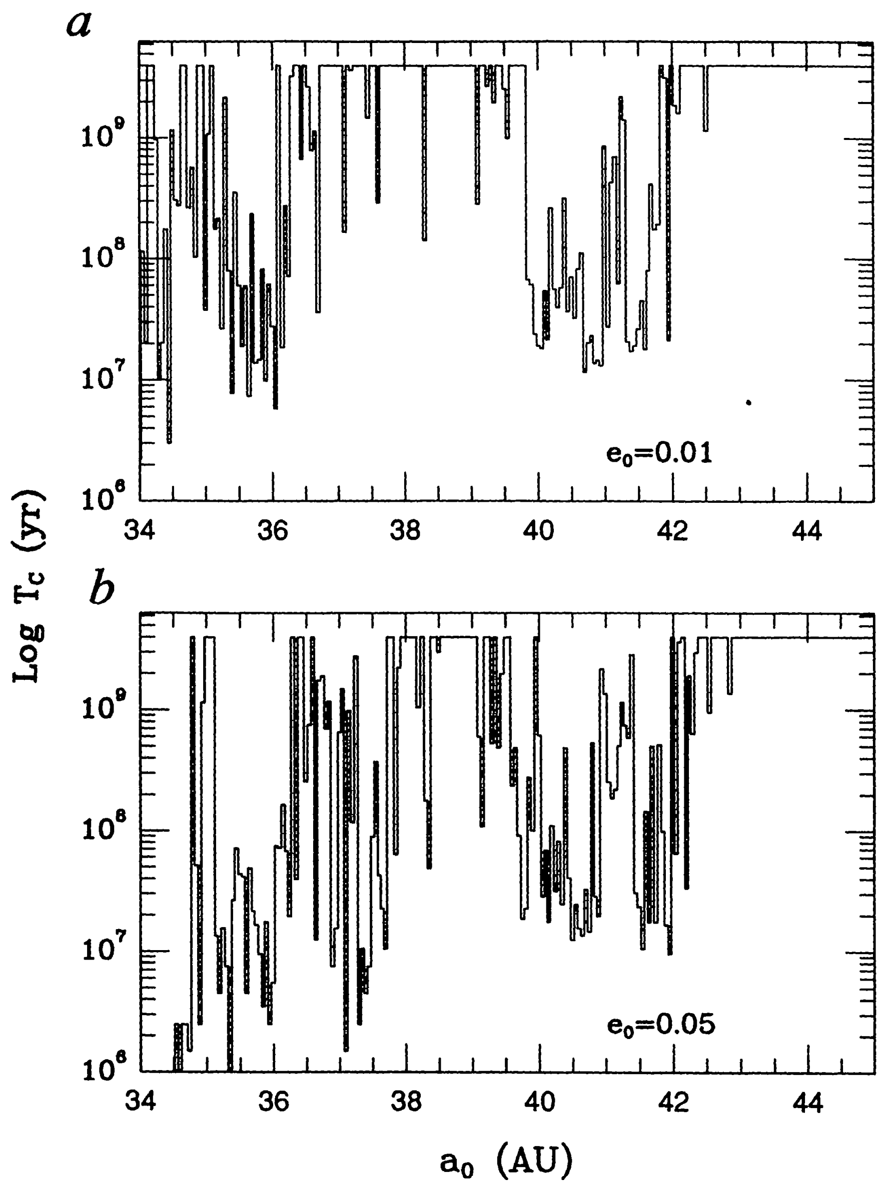


Figure 7 Planet-crossing times as a function of initial semimajor axis for test particles in the trans-Neptunian region over the age of the solar system (M Duncan, H Levison, and S Budd, personal communication). Particles were removed if they became Neptune-crossing or if they made a close approach to Neptune during the 4×10^9 year period of the numerical integrations: (a) initial eccentricity = 0.01; (b) initial eccentricity = 0.05; (c) initial eccentricity = 0.10; (d) initial eccentricity = 0.15. The initial inclination for all integrations was $i = 1°$.

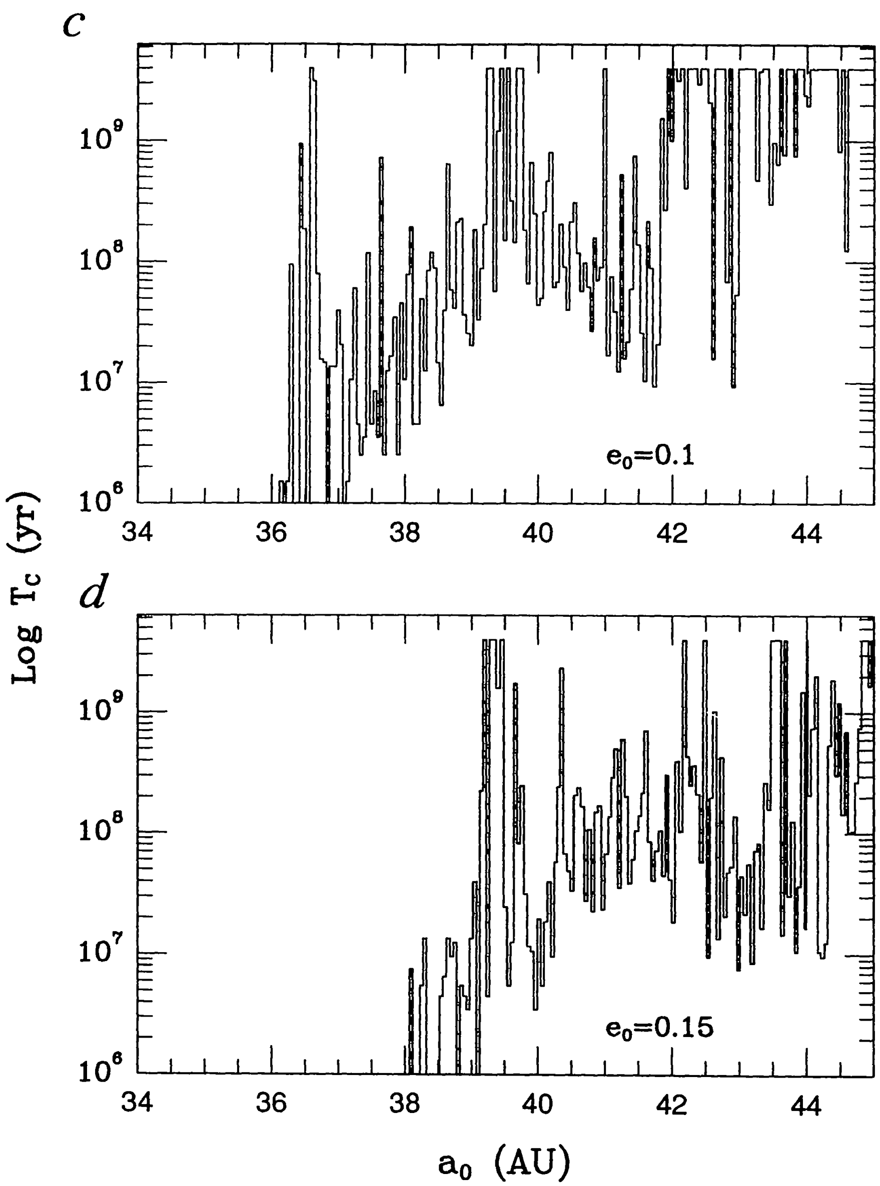


Figure 7 (*Continued*)

JQ_1. The long-term stability of the other objects at $r > 40$ AU will depend on their orbital eccentricities when they are determined; most will be stable if their orbital eccentricities are suitably low, i.e. <0.1. However, secular resonances may result in unstable orbits for specific (a, e, i) combinations.

Presumably, the region beyond Neptune was once populated by a continuous distribution of icy planetesimals. That region has now been shaped dynamically by Neptune perturbations, so as to give a complex structure similar to that seen in the main asteroid belt, where secular and mean-motion resonances have played a major role in clearing specific areas of (a, e, i) space. The overall result is shown in Figure 8 (M Duncan, H Levison, and S Budd, personal communication), which gives the radial distribution of comets in the Kuiper belt after 4×10^9 years. The initial distribution of objects is given by a $1/r^2$ surface density distribution in the protosolar nebula, and an initial eccentricity of 0.05 is assumed. The trans-Neptunian region is largely depleted at $r < 35$ AU, whereas the Kuiper belt population is relatively untouched at $r > 46$ AU. According to Levison & Duncan, 38% of the comets originally formed between 34 and 45 AU have survived over the history of the solar system.

Levison & Duncan (1994) showed that the resupply rate of SP comets must be $\sim$0.06 year^{-1} to maintain the current steady-state population; this is somewhat higher than Fernandez's (1985b) earlier estimate of 0.01 year^{-1}. New studies of the rate of comets currently leaving the Kuiper belt for Neptune-crossing orbits give a loss rate of 6×10^{-11} year^{-1} (M Duncan, H Levison, and S Budd, personal communication), of which $\sim$17% are expected to successfully evolve to visible SP comets (Duncan et al 1988). This then suggests a current population of

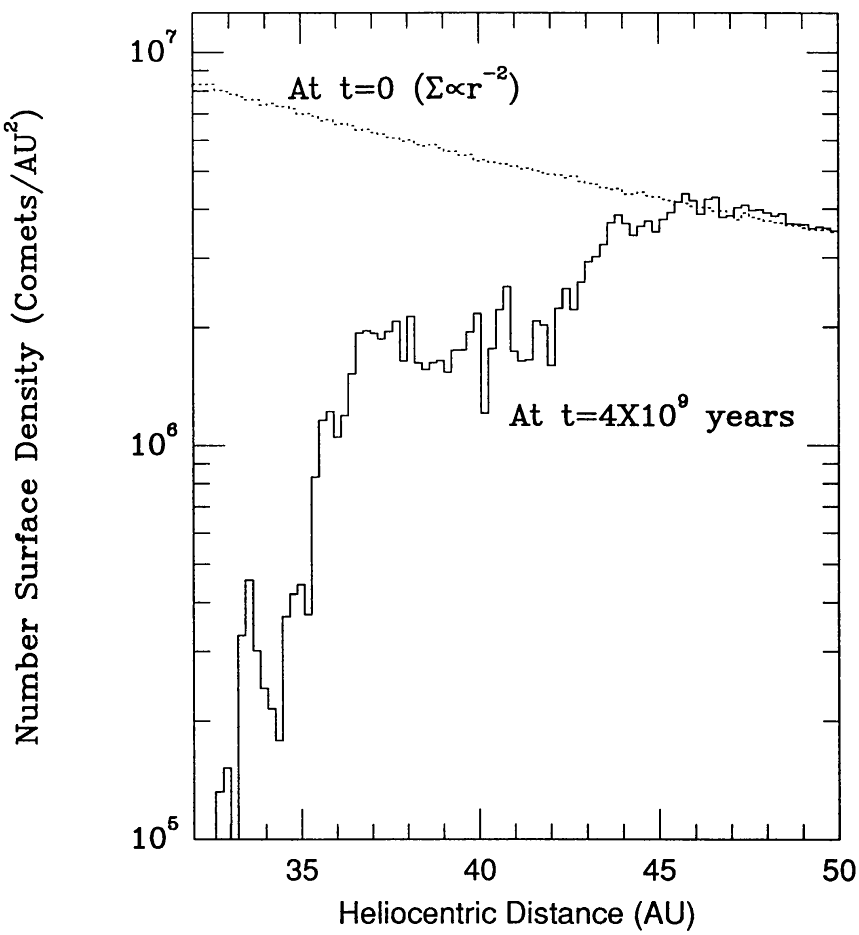


Figure 8 Surface density Σ vs heliocentric distance of test particles in the Kuiper belt after a 4×10^9 year integration (M Duncan, H Levison, and S Budd, personal communication). The initial radial distribution assumes a surface density of planetesimals in the protosolar nebula proportional to $1/r^2$. An initial eccentricity of 0.05 and inclination of 0° are assumed.

6×10^9 comets for the dynamically active region of the Kuiper belt between 34 and 45 AU. If these comets have a typical mass equivalent to the mean mass of 3.8×10^{16} g estimated by Weissman (1990), then the total mass of the dynamically active region of the Kuiper belt is 2.3×10^{26} g or 0.04 $M_\oplus$. This is consistent with the mass limits noted in Section 2.

At heliocentric distances greater than 45 AU, the Kuiper belt consists of a population of icy planetesimals that have orbited essentially undisturbed since the origin of the planetary system. If the r^{-2} surface density dependence holds to larger distances, then there are $\sim 4 \times 10^{10}$ comets between 45 and 100 AU, $\sim 9 \times 10^{10}$ comets between 100 and 500 AU, and 4×10^{10} comets between 500 and 1000 AU. The total mass between 45 and 1,000 AU would be $\sim 1.1 M_\oplus$. Considerably more mass may exist in the Kuiper belt if the surface density distribution in the solar nebula is shallower than $1/r^2$. Observations of the β Pictoris disk suggest a total of tens to hundreds of $M_\oplus$ of material, suggesting a population of between 10^{13} and 10^{14} comets. Thus, if the Kuiper belt is similar, it may contain even more comets than the Oort cloud.

7. DISCUSSION

The past two decades have brought about a remarkable convergence of theory and observations, both within our solar system and of nearby stars and protostars, which suggests that disks of planetesimals extending out hundreds to thousands of AU from the central star are ubiquitous. The total mass in each disk may amount to tens or hundreds of Earth masses—a significant fraction of the total mass of the known planetary system, which is $447 M_\oplus$.

The evidence for the existence of the Kuiper belt is compelling. It has been shown that the orbital element distributions of the Jupiter family comets can only be explained if they come from a highly flattened source in the ecliptic plane. Although legitimate questions were raised concerning Duncan et al's (1988) original results, most of those objections were answered by Quinn et al (1990). In addition, new integrations by M Duncan, H Levison, and S Budd (personal communication) are now underway and are again confirming the results of Duncan et al (1988) and Quinn et al (1990), with no enhancement of the planetary masses.

Observations of dust disks around protostars and main sequence stars demonstrate that structures like the Kuiper belt are a common feature of star formation. It is somewhat amusing that we can observe these disks around other stellar systems but not yet around our own—a case of not being able to see the forest for the trees. However, future infrared surveys hold the potential of much greater sensitivity and offer the capability to look for the Kuiper belt, now that we know that it is there.

The discovery of comets beyond Neptune in orbits where they are likely stable over the lifetime of the solar system is further confirmation of the existence of the

Kuiper belt. Given the small area searched to date, and the limiting magnitudes of the surveys, it can be expected that future searches will be increasingly successful at finding more Kuiper belt objects.

The discovery of objects at trans-Neptunian distances appears to be accelerating, with 1 found in 1992, 5 found in 1993, 12 in 1994, and 3 in the first 10 weeks of 1995. When the first asteroid, Ceres, was discovered in 1801, it was followed by three discoveries in the next six years, but then none for 38 years until the introduction of improved star charts, and later, astronomical photography. As with the asteroids, the discovery of Kuiper belt objects appears to be closely associated with an enabling technology: the application of large-area CCDs to astronomical searches. Further developments such as arrayed CCD focal planes and automated search programs should further accelerate the discovery rate in the near future.

Current ground-based limits on the searches for Kuiper belt objects have been reported to be R magnitude 24.5 (Jewitt & Luu 1995), though some other search programs may not go fainter than $R = 23$. However, only two objects have been discovered at $R > 24$, and only five at $R > 23$. The majority of the discoveries have come in a fairly narrow range of magnitudes, between $R = 21.5$ and 23. This is dramatically illustrated by the steep slope in Figure 5. If searches did really extend to R magnitude 24.5, we would expect the discovery of far more objects in the 70–200 km diameter range, unless the size distribution of Kuiper belt comets were unusually flat in that diameter range. Thus, the practical limit of the ground-based searches at present is closer to $R = 23$, except for a few fortunate fainter discoveries. Four of the five comets fainter than $R = 23$ have been found by Jewitt and his collaborators, so their survey seems to have a somewhat better capability for achieving fainter detections.

The existence of a large number of fainter comets in the Kuiper belt seems inescapable. Modeling of the accretion of icy planetesimals in the Neptune zone by Greenberg et al (1984) showed that large bodies would accrete up to dimensions of 250–1000 km, with a few bodies undergoing runaway accretion to larger sizes, including one that would form the core of Neptune. Greenberg et al (1984) found that the slope of the expected size distribution at diameters larger than 16 km was quite steep, qualitatively similar to that in Figure 5, but more modest at smaller sizes.

A similar dual-slope power-law distribution was found by Everhart (1967), who determined the intrinsic brightness distribution for LP comets as a function of their absolute total magnitude (including coma), including correction for observational selection effects. Weissman (1990) scaled Everhart's results to obtain a dual-slope power-law mass distribution for cometary nuclei. This distribution has the interesting property that the majority of the integrated mass of the distribution comes from the comets at the junction of the two slopes, at diameters between 4 and 32 km.

It is expected that the size distribution of long-period comets formed in the Uranus-Neptune zone and that of Kuiper belt comets formed just beyond this zone are similar. Accretion of LP comets into larger bodies would proceed more rapidly at the shorter orbital periods in the Uranus-Neptune zone, but that process would be truncated by their ejection to the Oort cloud. Kuiper belt comets would accrete more slowly in their more distant orbits, but would have the entire history of the solar system to achieve their current size distribution. Unfortunately, detailed direct measurements of the sizes of LP and SP comet nuclei are not yet sufficient to determine their respective size distributions or to discriminate between the two dynamical types.

The accretion of even larger objects in the Uranus-Neptune zone and in the Kuiper belt has been speculated on by Stern (1991) who suggested that 10^2 to 10^3 1000-km diameter (or larger) objects may have accreted. The Pluto-Charon binary and Neptune's retrograde satellite Triton are proposed as members of this class of objects still resident in the planetary system. Other large objects may have been ejected to the Oort cloud or may be resident in the stable regions of the Kuiper belt at $a > 46$ AU. However, if several of these objects did exist as close as 50 AU, it is surprising that none were detected by the extensive photographic searches by Tombaugh (1961) and Kowal (1989).

Limits placed on the sky density of Kuiper belt objects versus magnitude by the various searches to date are shown in Figure 9 (H Levison, personal communication), along with a star indicative of the sky density of six Kuiper belt objects greater than 100 km diameter per square degree, found by Jewitt & Luu (1995) based on their first seven discoveries. The dashed lines are dual-slope power-law fits to the diameters of Kuiper belt objects. Main belt asteroids have a typical slope parameter, $b = 3.5$, which puts most of the mass in the largest bodies. However, the surveys of Kowal (1989) and Cochran et al (1991) appear to rule out such a slope, and suggest that a steeper slope, possibly $b = 5$, might be a better fit. Alternatively, a sharp cut-off in the size distribution may occur at a diameter of ~500 km. However, the discussion above with regard to the real effective magnitude limits of the searches to date, suggests that some if not all of the points in Figure 9 should be shifted to the left to lower magnitudes, which would then still leave considerable uncertainty about the actual size distribution of the Kuiper belt objects.

In addition to ground-based searches of the outer solar system, the repaired *Hubble Space Telescope* is now also being used to look for Kuiper belt objects. Search fields were exposed and are now undergoing analysis by A Cochran and colleagues (personal communication). It is anticipated that the *HST* images with the new WFPC 2 camera can reach magnitude 28.5, equivalent to a 20 km diameter comet at 40 AU, or a 30 km diameter at 50 AU, assuming an albedo of 0.04 (solid circle in Figure 9).

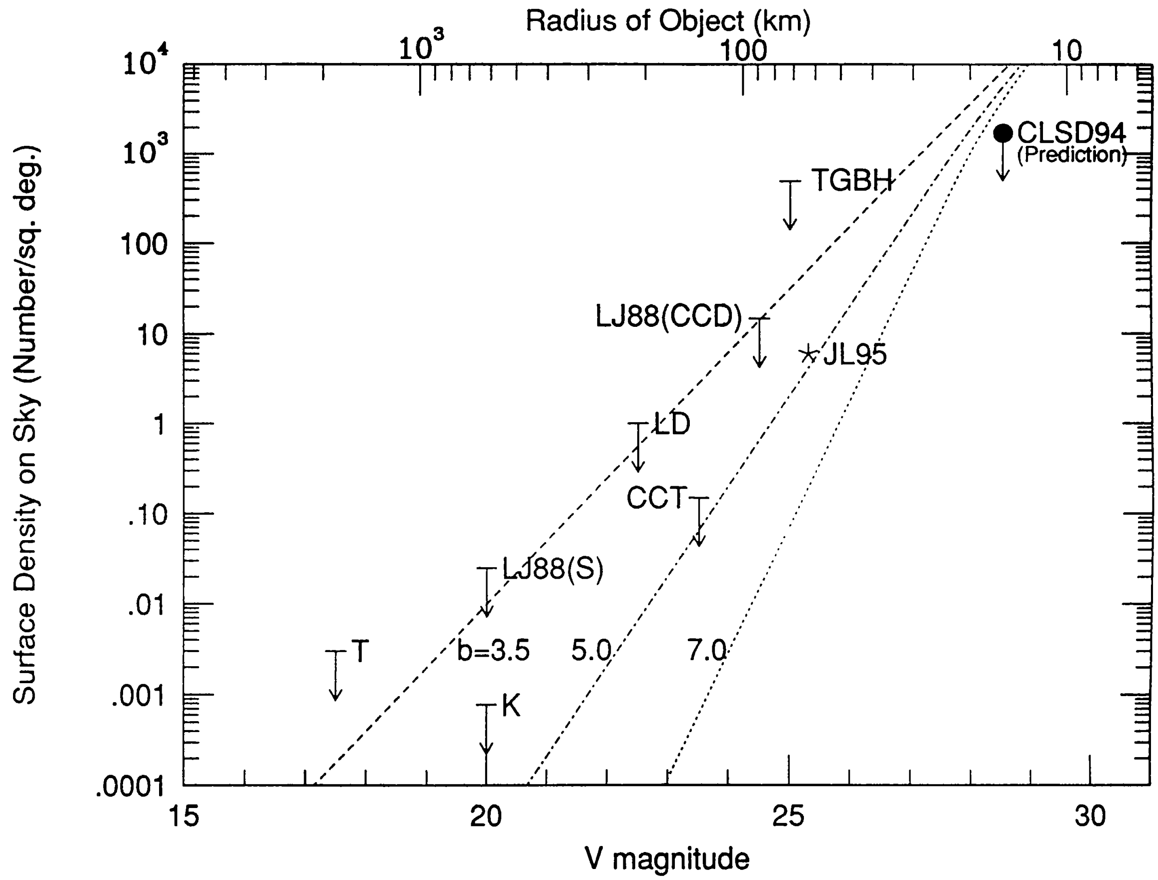


Figure 9 Upper limits on the sky density of Kuiper belt objects as set by various searches (*arrows*), and the first seven discoveries by Jewitt and colleagues (*star*). The searches are: T, Tombaugh (1961); K, Kowal (1989), LJ88, Luu & Jewitt (1988) with Schmidt telescope (S) and CCD (CCD), respectively; LD, Levison & Duncan (1990); CCT, Cochran et al (1991); TGBH, Tyson et al 1992; and JL95, Jewitt & Luu (1995). The solid circle and arrow at upper right is a predicted limit based on a planned search in 1994 with the *Hubble Space Telescope* by A Cochran, H Levison, SA Stern, and M Duncan (personal communication). The dashed lines are power-law fits to various model size distributions (see text).

An alternative means of searching for the Kuiper belt is to look for the possible gravitational effects on spacecraft transiting the region. The *Voyager 1* and *2*, and *Pioneer 10* and *11* spacecraft are currently at heliocentric distances between ~38 and 60 AU, ranging from the inner edge of the dynamically active Kuiper belt to the dynamically stable region. The spacecraft are moving outward at rates of 2.5 to 3.5 AU year^{-1}. However, the trajectories are generally not in the ecliptic plane. In addition, the *Voyager* spacecraft use thrusters to maintain attitude control, which degrades their ability to measure small gravitational accelerations.

A possible preliminary gravitational hint of the Kuiper belt is given by Anderson et al (1995) who used *Voyager* and *Pioneer* tracking to set an upper limit on the unobserved mass interior to Neptune's orbit of $-0.7 \pm 0.6 M_{\oplus}$.

They suggest that the negative sign of the upper limit may be indicative of a nonsymmetric mass distribution beyond Neptune's orbit. Thus, it will be very interesting to see what additional results are obtained from tracking of these spacecraft as they proceed through the proposed Kuiper belt region. The *Voyager 1* and *2* spacecraft could conceivably operate until about the year 2018, when they would be at heliocentric distances of 139 and 116 AU, respectively.

It is not yet clear whether the difference in the heliocentric distances of the formation zones for the LP and SP comets would manifest itself in recognizable compositional and/or physical differences in the LP and SP comets. The temperature gradient in the solar nebula can be expected to vary slowly, approximately as $r^{-1/2}$. Current maximum blackbody temperatures are 88 K at 20 AU, versus 63 K at 40 AU. This difference may be reflected in the volatile ices such as CO, HCN, H_2CO, CH_4, and NH_3 frozen into the cometary nuclei. Systematic depletions of some comets in C_2 have been described by Schleicher (1994). Interestingly, most of the comets showing these depletions are SP comets of the Jupiter family. However, it is not clear if these depletions are some intrinsic property of these comets, or if they are the result of physical evolution and aging during their many perihelion passages close to the Sun.

There is an ongoing debate whether the objects in the Kuiper belt should be regarded as comets or asteroids (or perhaps be given some new classification). Because the objects have not displayed any evidence of cometary activity at discovery, in particular a cometary dust coma, they have been given asteroidal designations. On the other hand, given their location in the outer solar system and the likely fact that they formed at those large solar distances, the objects almost certainly contain large quantities of water and other volatile ices. In addition, given their relatively small sizes, they probably are largely unprocessed solar nebula condensates. If these objects were brought to small heliocentric distances, their ices would sublimate and they would appear as comets. In fact, that is precisely the conclusion that has been reached with regard to the Kuiper belt; it is the source of a substantial fraction of the observed SP comets. Thus, the objects in the Kuiper belt are comets, and probably should be given cometary designations.

The very slow heliocentric motion of comets in the Kuiper belt requires repeated astrometric observations over a period of many years to establish good orbital solutions for each object. Observers are encouraged to support such programs so that the radial distribution and orbital statistics of the Kuiper belt can be established, and in order to discriminate between different possible dynamical resonances with Neptune.

Another question concerns whether Kuiper should share credit for the suggestion of the belt's existence with KE Edgeworth. Both scientists clearly suggested the existence of small objects orbiting the Sun beyond the orbit of Neptune, and Edgeworth (1949) went a step farther in suggesting that these objects may occasionally appear as visible comets. It would seem that credit should be shared. However, the term "Kuiper belt" has already been in use for several years now, and it may be confusing to try and change it now. Nevertheless, Edgeworth's contribution deserves to be recognized.

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