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The Dynamical Structure of the Kuiper Belt

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ABSTRACT

In the last few years, the astronomical community has witnessed a revolution in the understanding of the deep, outer regions of our planetary system. This revolution started with the discovery of the object 1992 QB_1, which was the first of over 30 Kuiper Belt objects with radii $\sim$ 100–200 km that have now been discovered by groundbased observations. When 1992 QB_1 was discovered, the Kuiper Belt was instantly transformed from a theoretical construct used to explain the orbital element distribution of short-period comets to a bona fide component of the solar system.

Since the Kuiper Belt was discovered in 1992, the amount of data, both theoretical and observational, concerning it has mushroomed. Among the new results that are discussed are: *i*) Billion year numerical integrations have lead to an understanding of the dynamical structure of the Kuiper Belt. However, the observed Kuiper belt orbital element distribution is not consistent with an initially uniform population of bodies perturbed by the planets in their current configuration. Thus, the observed distribution is supplying us with clues about the formation and early evolution of the outer solar system. *ii*) Theoretical arguments have strongly suggested that the Kuiper Belt was initially much more massive than we see today. This result may put important constraints on the structure of the solar nebula in the outer solar system.

INTRODUCTION

Since its discovery in 1929, Pluto has been traditionally viewed as the last vestige of the planetary system; a lonely outpost at the edge of the solar system. During the past few years, there has been a growing realization that Pluto and Charon and, perhaps, Triton may be among the largest bodies of a population of objects that formed in the region beyond Uranus, and that a substantial population of smaller trans-Neptunian bodies still exists in what has come to be known as the Kuiper belt.

Although speculation on the existence of a trans-Neptunian comet belt dates back almost 50 years (Edgeworth 1949; Kuiper 1951), serious work on the topic did not start until Fernández (1980) invoked it as a possible source reservoir for the short-period comets (those with orbital periods < 200 years). Dynamical simulations by Duncan et al. (1988) and Quinn et al. (1990) showed that a comet belt beyond Neptune is the most plausible source for the low inclination, Jupiter-family comets (see Levison 1996 for a recent review). Duncan et al. (1988) suggested the name 'Kuiper belt' for this population, in recognition of Kuiper's 1951 paper suggesting it. The first Kuiper belt object to be found, 1992 QB_1, was discovered in 1992. Since then a total of 39 trans-Neptunian objects with radii $\gtrsim 50$ km have been found by ground-based searches (as of October 1996: e.g., Jewitt & Luu 1995; Williams et al. 1995; Irwin et al. 1995), and ~ 30 Halley-sized objects have been detected using the Hubble Space Telescope (HST, Cochran et al. 1995).

Since the study of the Kuiper belt is still young, some of what we discuss in the following sections is speculative, and much of it is likely to change rapidly in the coming years (or even months) as this field matures and more data become available. Nonetheless, researchers have made significant progress understanding it from both the point of view of the observational searches, and the computational studies of the bodies in this region. Due to the limited space available here and that complete reviews of the Kuiper belt are available elsewhere (for example see Weissman & Levison 1996), we will concentrate on the dynamical structure of the Kuiper belt and the implications that this structure has for the formation of the outer solar system.

THE OBSERVED DYNAMICAL STRUCTURE OF THE KUIPER BELT

The first successful detection of an object beyond the orbit of Neptune (other than Pluto and Charon) was by Jewitt & Luu (1992, 1993a) in August 1992. 1992 QB_1 was at a heliocentric distance of $41.2\,AU$ at the time of discovery and has a radius of $\sim 130\,km$, assuming a typical cometary albedo of 0.04. Subsequent observations allowed Marsden (1994) to determine an orbit for 1992 QB_1 with semimajor axis of $44.0\,AU$, eccentricity of 0.071, inclination of 2°, and orbital period of 292 years. The second discovery of a trans-Neptunian object, was of 1993 FW. A subsequent orbit solution by Marsden (1995) found $a = 43.8\,AU$, $e = 0.051$, $i = 7.7°$, and $P = 290$ years. Both of these objects have perihelion distances well beyond the orbit of Neptune.

The next four objects discovered were significantly different in that their heliocentric distances at discovery were substantially closer to Neptune, in a region where the orbits cannot be stable unless protected by some dynamical mechanism (see below). The four objects: 1993 RO (Jewitt & Luu 1993b), 1993 RP (Luu & Jewitt 1993b), 1993 SB & 1993 SC (Williams et al. 1995), were found at heliocentric distances ranging from 32.3 to $35.4\,AU$. Marsden (1996) has orbit solutions for all these objects but 1993 RP (for which there are insufficient observations) that show that are in the 2:3 resonance with Neptune.

Continued ground-based searches have now discovered a total of 39 trans-Neptunian objects, as of the middle of October, 1996. Twenty one of the 39 Kuiper belt objects have been observed at two or more oppositions, and thus have reasonably good orbits determined for them. It should be emphasized that 'reasonably good' does not imply exact and that there are significant uncertainties in the published orbits. The green dots in Figure 1 show the eccentricities of these objects verse their semi-major axes. The blue lines in the figure show the locations of the mean motion resonances with Neptune. The known Kuiper belt objects appear to fall into two distinct classes. At heliocentric distances less than $\sim 41\,AU$, all the known Kuiper belt objects are in mean motion resonances with Neptune and have orbital eccentricities greater 0.1. Beyond $\sim 41\,AU$ the Kuiper belt objects tend not to be in mean motion resonances and most have eccentricities < 0.1. We return to this issue in the next section.

In addition to large objects, in 1994 and 1995 HST's WFPC2 imaged two fields in the Kuiper belt to search for comet-sized bodies. Cochran et al. (1995) have reported detecting approximately 30 objects in the first field with V magnitudes between 27.9 and 28.6 (radii between 5 and $10\,km$ assuming an albedo of 0.04). These objects had a very small signal-to-noise ratio ($\sim$ 2–3) and thus the argument for their detection is statistical. In essence, Cochran et al. found a total of 53 candidate objects that appear to be moving in prograde low-inclination orbits while finding only 24 that appear to be moving in retrograde orbits. The retrograde detections were assumed to be noise. A chi-square test indicates that there is less than a 1% chance that the difference between the prograde and retrograde sample is statistical. Therefore, at the 99% confidence level, the excess prograde candidates are real objects. This team failed to detect objects in the second field. However, the background in this field was brighter than in the first and thus the limiting magnitude in the second field was smaller ($V = 27.7$ compared to 28.6 in the first). Since the brightest objects that they discovered in the first field was $V = 27.9$, it is not surprising that they did not discover objects in the second. Thus, the lack of detections cannot in any way be construed to invalidate the detections in the first field. However, the detection is still controversial, and the issue will not be resolved until deeper HST observations are obtained (currently scheduled for the summer of 1997). Given the character of the observations in the first field, it was not possible to determine the orbits of any of these candidate objects. Therefore, we will not be able to make use of these observations in our discussion of the dynamical structure of the Kuiper belt in the following sections.

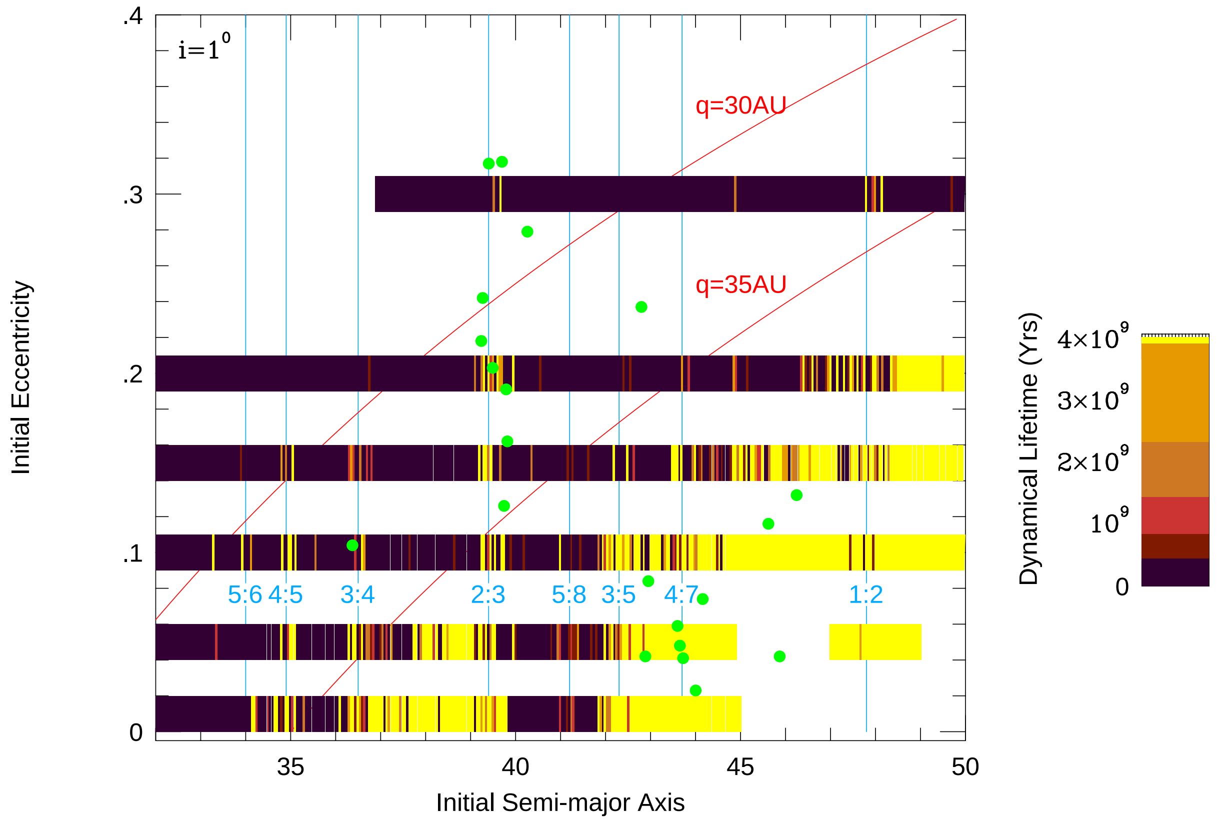


Figure 1 — The dynamical lifetime for test particles in the Kuiper belt derived from Duncan et al.'s (1995) 4×10^9 year integrations. Each particle is represented by a narrow vertical strip of color, the center of which is located at the particle's initial eccentricity and semimajor axis (initial inclination = 1°). The color of each strip represents the dynamical lifetime of the particle. Strips colored yellow represent objects that survive for the length of the integration, 4×10^9 years. Dark regions are particularly unstable on these timescales. The green dots represent the location of the orbits for the known Kuiper belt objects, as determined by Marsden. For reference, the locations of the important Neptune mean motion resonances are shown in blue and two curves of constant perihelion distance, q, are shown in red.

THE LONG-TERM STABILITY OF ORBITS IN THE KUIPER BELT

The first detailed studies of the stability of orbits in the Kuiper belt was by Torbett (1989) and Torbett & Smoluchowski (1990), who showed that low inclination orbits beyond Neptune are chaotic with Lyapunov times less than 10^6 years if their perihelion distances are between 30 and 45 AU. Gladman & Duncan (1990) integrated 20 particles initially on circular orbits between 30 and 40 AU for 2×10^7 years and showed that objects with $a \lesssim 34\,AU$ would become planet-crossers and thus leave the Kuiper belt. These integrations were modest by current standards. Moreover, Torbett and Smoluchowski assumed fixed orbits for the major planets.

Study of the dynamical evolution of orbits in the outer planetary region over longer periods has recently been made possible as a result of improved integration codes developed to study the problem (Wisdom & Holman 1991; Saha & Tremaine 1992; Levison & Duncan 1994), and the availability of high-speed, low-cost computer workstations which can be dedicated for periods of weeks or months to a single dynamical investigation. Since the initial studies noted above, numerical integrations of orbits in the Kuiper belt have been greatly extended and expanded. Levison & Duncan (1993) and Holman & Wisdom (1993) performed integrations for 10^9 and 2×10^8 years, respectively. In both papers, the authors studied the behavior of objects initially on low-inclination, nearly-circular orbits inside of 45 AU.

The most complete study of the long-term behavior of objects in the Kuiper belt has been performed by Duncan et al. (1995). They performed two sets of numerical integrations. In the first they followed the orbital evolution of 1,300 test particles on initial orbits with eccentricities between 0 and 0.3, and initial inclination of 1° within the Kuiper belt over a period of 4×10^9 years, essentially the age of the solar system. In the second, they followed the evolution of 3,000 particles with initial eccentricities between 0 and 0.15 and inclinations of 90° within the Kuiper belt for a period of 10^9 years. Each particle was followed until it suffered a close encounter with Neptune. Once comets can encounter Neptune, they will rapidly evolve ($\sim 10^7$–10^8 years) into the inner planets region, or be ejected to the Oort cloud or to interstellar space (Levison & Duncan 1996).

The results of Duncan et al.'s (1995) 4×10^9 year integrations are shown in Figure 1. The colored strips indicate the length of time required for a particle to become a Neptune-crosser as a function of its initial semimajor axis and eccentricity. Strips that are colored yellow represent objects that survive for the length of the integration. As can be seen in the figure, the Kuiper belt can be expected to have a complex structure, although the general trends are easily explained. Objects with perihelion distances less than $\sim 35\,AU$ (shown as a red curve) are unstable, unless they are near, and presumably librating about, a mean motion resonance with Neptune. Indeed, the results in Figure 1 show that many of the Neptunian mean motion resonances (shown in blue) are stable for the age of the solar system. Objects with semimajor axes between ~ 40 and 42 AU are unstable. This is due to the presence of three overlapping secular resonances that occur in this region of the solar system: two with Neptune and one with Uranus (Knežević et al. 1991).

Indeed, secular resonances appear to play a critical role in ejecting particles from the Kuiper belt. This can be seen in Figure 2, which shows some of the results of Duncan et al.'s (1995) 10^9 year integration. Here, the color strips show the length of time required for a particle to become a Neptune-crosser as a function of its initial semimajor axis and inclination. These particles all had initial eccentricities of 0.01. Also shown are the locations of the Neptune longitude of perihelion secular resonances (in red) and the Neptune longitude of the ascending node secular resonances (in yellow) as determined by Knežević et al. (1991). It is important to note that much of the clearing of the Kuiper belt occurs where these two resonances overlap. This includes the low inclination region between 40 and 42 AU. The Neptune mean motion resonances are also shown (in green). Much of the behavior observed by Duncan et al. (1995) has been independently explained using analytic methods in recent papers by Morbidelli et al. (1995) and Malhotra (1996).

It is interesting to compare Duncan et al.'s (1995) results to the current best orbital elements of the known Kuiper belt objects as determined by Marsden. This comparison is made in Figure 1. The locations of all the Kuiper belt objects with established orbits are shown as filled green circles in the figure. The main result of this comparison is that objects at heliocentric distances less than $\sim 42\,AU$ have sufficiently high eccentricities that they must be in Neptune mean motion resonances to be stable. Objects at larger distances appear to have lower eccentricities and are not in obvious mean motion resonances (though one object is in the 3:5). One interesting aspect of this distribution is that the boundary between the two classes appears to be near the location of the main secular resonances. In addition, there is a region ($36\,AU \lesssim a \lesssim\ \sim 39\,AU$ with $i \lesssim 15°$ and $e \lesssim 0.05$) which is dynamically stable for the age of the solar system. The observations to date indicate that this region is unpopulated. Therefore, there are clearly discrepancies between the observed orbital element distribution in the Kuiper belt and that predicted by dynamical erosion of the planets in their current configuration.

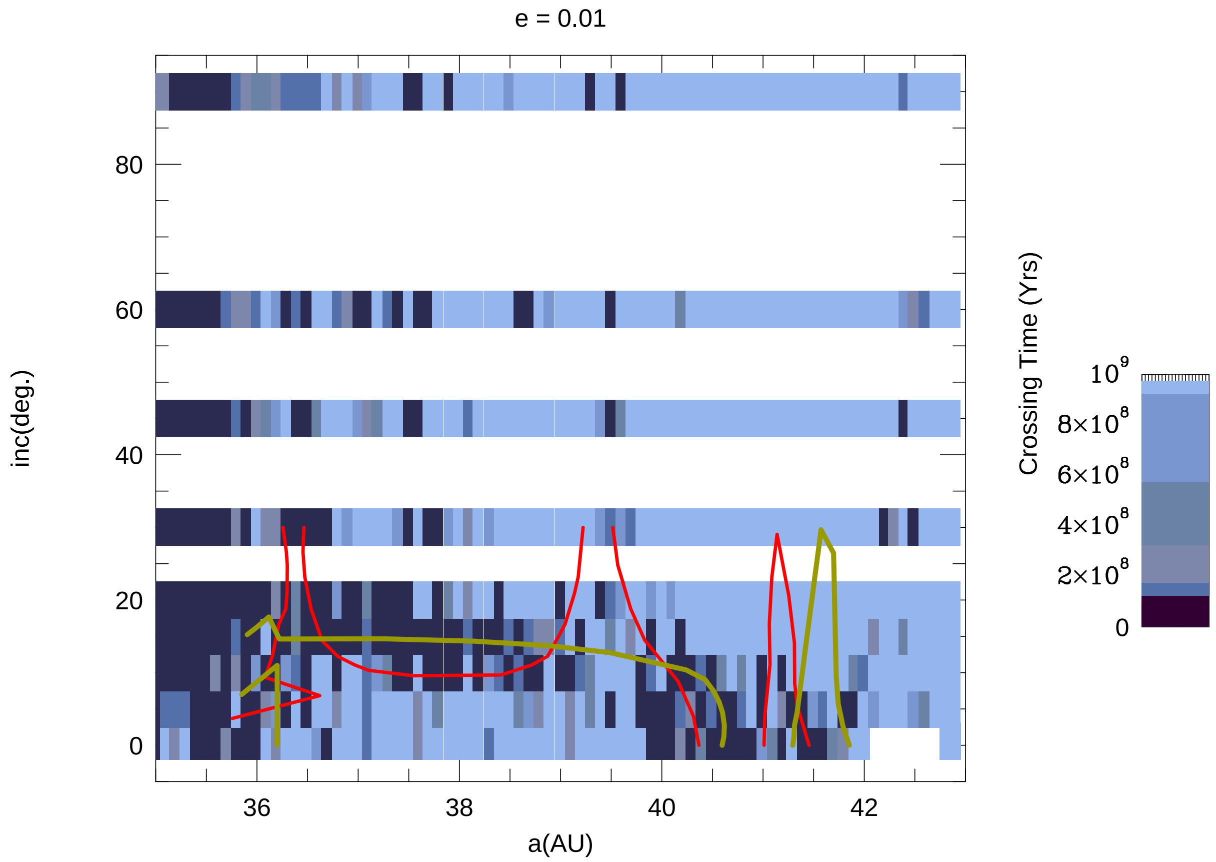


Figure 2 — The dynamical lifetime for test particles with initial eccentricity = 0.01 derived from Duncan et al.'s (1995) 10^9 year integrations. This plot is similar to Figure 1 except that a different color table was used for the solid bars. In addition, the red and yellow curves show the locations of Neptune longitude of perihelion secular resonances (ν_8) and the Neptune longitude of the ascending node secular resonances (ν_{18}), respectively, as determined by Knežević et al. (1991). The green lines show the location of the important Neptune mean motion resonances.

If these distinct classes of Kuiper belt orbits persist and the unpopulated region remains unpopulated as new objects are discovered and as better orbits are determined, then some mechanism other than the long-term gravitational effects of the outer planets in their current configuration must have created them. Three mechanisms that may have accomplished this come to mind:

- The hypothetical early outward migration of Neptune would cause its mean motion resonances to sweep through this region thereby capturing most objects into these resonances (Malhotra 1995, Holman 1995). The idea is based on the results of Fernandez & Ip (1981) that show that Uranus and Neptune most likely migrated outward as they dynamically dispersed the planetesimals surrounding them. Uranus and Neptune evolved outward because they were much more likely to scatter objects down to Jupiter and Saturn, which removed them from the planetary system, than eject them from the planetary system (also see Levison & Duncan 1996). Malhotra (1995) showed that Kuiper belt objects are likely to have been captured in the mean motion resonances with Neptune if their initial eccentricities were small. After capture, the eccentricities of the Kuiper belt objects increased as Neptune continued its outward migration. If this model is correct then Neptune initially had a semi-major axis of about $24\,AU$. This mechanism was first proposed to explain Pluto's current orbit (Malhotra 1993). It correctly predicts that almost all objects interior to $\sim 41\,AU$ should be in mean motion resonances, and that there should be some objects outside of $41\,AU$ that are on low eccentricity, non-resonant orbits (Figure 3a). It also predicts a large number of objects in the 1:2 mean motion resonance with Neptune with large eccentricities and small perihelion distances. As of yet, none of these objects have been discovered. This remains a possible problem for this mechanism.

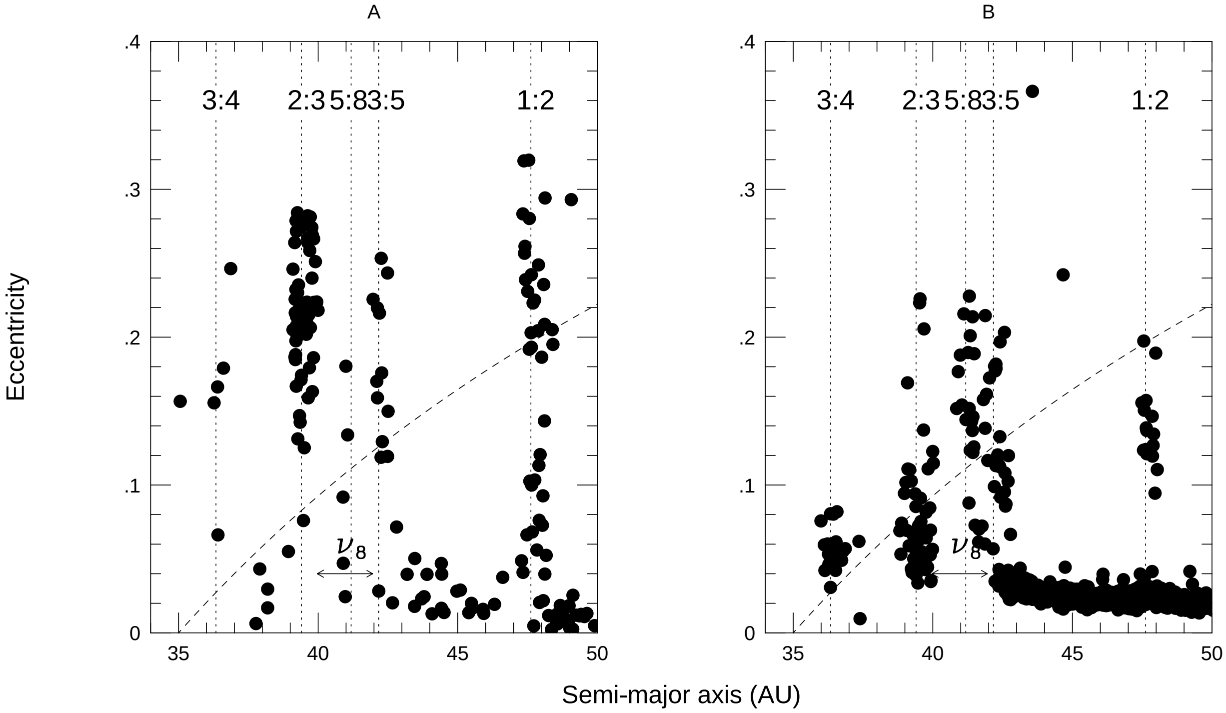


Figure 3 — A) The eccentricity, semi-major axis distribution for a hypothetical population of Kuiper belt objects that was created by planet migration as determined by Holman (1995). B) The eccentricity, semi-major axis distribution of test particles after the ν_8 secular resonance migrated as the mass of the Kuiper belt decreased. In both cases, the particles were initially uniformally distributed in semi-major axis. The locations of the mean motion resonances with Neptune are indicated by the dotted lines. The arrow shows the current location of the ν_8 secular resonance. The dashed curve shows the location of the perihelion distance equal to $35\,AU$.

- Some process may have pumped up the orbital eccentricities and inclinations of particles in this region to values greater than $e \approx 0.05$ and/or $i \gtrsim 10°$ where the dynamical lifetimes are short. One method for exciting random motion in a disk is by mutual gravitational encounters between objects in the disk. In this vein, it is interesting to note that the escape velocity of the largest known Kuiper belt object is approximately $200\,m/s$ (assuming a density of 2 g/cm^3), which is about 5% of its heliocentric orbital velocity. Thus, if there were initially enough of these objects for the Kuiper belt to be dynamically relaxed by mutual gravitational scattering, then Kuiper belt objects would have a typical eccentricity of a few percent, not quite enough to depopulate the region of interest. However, if there were larger perturbers in the Kuiper belt, they could produce higher eccentricities. For example, if the Kuiper belt initially had objects the size of Charon ($R = 600\,km$), then the typical eccentricity would be $= 0.1$. Indeed, there are arguments suggesting such a population in the past (Stern 1991). In this way, the region of interest may have been depopulated, except in the resonances where high eccentricity orbits are stable.

- Secular resonances can also excite the eccentricities of particles in the inner Kuiper belt. Levison et al. (1996) have shown that a massive Kuiper belt would tend to increase the precession rate of Neptune's perihelion, while decreasing the perihelion precession rates of particles in the disk. Thus, the ν_8 secular resonance would be closer to the Sun if the Kuiper belt were massive. Levison et al. (1996) performed a set a numerical integrations that followed the behavior of test particles in the Kuiper belt under the gravitational influence of the Sun, outer planets, and a massive disk that slowly dissipated. They found that particles inside of the current location of the ν_8 resonance were pumped to high eccentricities as the ν_8 resonance swept outward (see Figure 3b). These particles were removed from the Kuiper belt if they were not in a mean motion resonance with Neptune. Thus, this mechanism predicts that most objects inside the current location of the ν_8 resonance will be in Neptune mean motion resonances, while objects outside of the ν_8 will be in low eccentricity, non-resonant orbits. A possible problem with this mechanism is that it does not appear to produce objects with larger enough eccentricities in the mean motion resonances with Neptune. In addition, the issue of whether the Kuiper belt was massive in the past is still open to question (see next section).

These three explanations are not exhaustive. Physical collisions and gas drag may have also played an important role. Nonetheless, these three models make very different predictions about the distribution of objects in the Kuiper belt. It is hoped that further discoveries and better orbit determinations will help to resolve whether any of these mechanisms has played an important role.

THE EARLY EVOLUTION OF THE KUIPER BELT

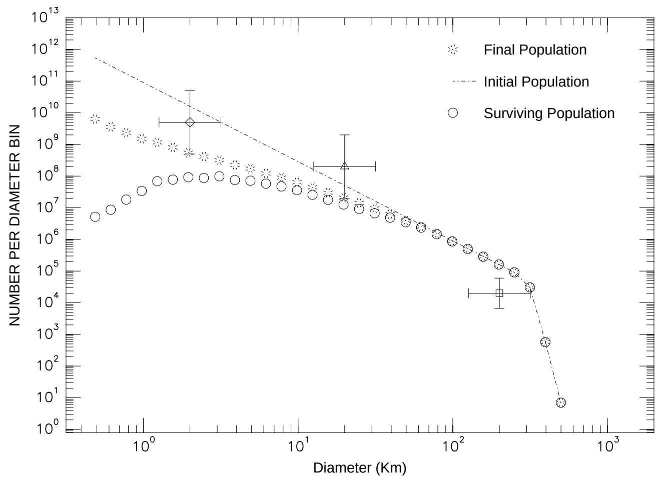
As discussed above, the current orbital element distribution in the Kuiper belt indicates that the primordial Kuiper belt was significantly different from what we see today. Indeed, over the last few years, evidence has mounted that supports the idea of a massive primordial Kuiper belt. (The best estimates are that there currently is only about $0.07\,M_\oplus$ between 30 and $50\,AU$ [Weissman & Levison 1996].)

Stern (1995) and Davis & Farinella (1996) have shown that the Kuiper belt is currently eroding away due to collisions. The model reported by Davis & Farinella is time dependent; thus it is possible for them to show that the Kuiper belt will lose a significant fraction of its mass in the next 10^9 years (see Figure 4). Since the Kuiper belt is currently losing mass due to collisional erosion, it clearly had to be more massive in the past.

Stern (1995) showed that it is not possible for objects with radii greater than about $30\,km$ to form in the current Kuiper belt, at least by two-body accretion, over the age of the solar system. The current surface density is too low to accrete bodies larger than this size. However, Stern (1996) showed that objects the size of $1992\,QB_1$ could have grown in a massive Kuiper belt if the mean eccentricities of the accreting objects were small, on the order of a few times 10^{-3}. This point is illustrated in Figure 5 which shows the accretion time for a 100 km radius object as a function of eccentricity and the total Kuiper belt mass within $50\,AU$ of the Sun. A Kuiper belt of at least several Earth masses is required in order for $100\,km$ sized objects to have formed. It is interesting to note that according to this model, the $100\,km$ sized objects had to have formed before Uranus and Neptune, because the presence of those planets would pump the eccentricities of the initial objects too high for QB_1-sized objects to accrete.

The idea of a historically massive Kuiper belt solves a small but puzzling aspect of the problem. Edgeworth's (1949) and Kuiper's (1951) original arguments for the existence of the Kuiper belt were based on the idea that it seemed unlikely that the disk of planetesimals that formed the planets would have abruptly ended at the current location of the outermost known planet. An extrapolation into the Kuiper belt of the current surface density of non-volatile material in the outer planetary region predicts that there should be about $30M_\oplus$ of material there. However, our best estimates are that there is only about $\sim 0.07M_\oplus$ between 30 and $50\,AU$. It would be ironic if the first arguments for the existence of the Kuiper belt are incorrect although the Kuiper belt itself does exist. If the early Kuiper belt were indeed massive, then the arguments by Edgeworth and Kuiper remain valid.

Finally, the idea of a historically massive Kuiper belt has important consequences for the early evolution of the Pluto-Charon system (cf. Levison & Stern 1995). A massive Kuiper belt could be responsible for trapping Pluto into the 2:3 mean motion and Kozai resonances (Levison & Stern 1995). In addition, it could help to explain how the Pluto-Charon binary formed by increasing the likelihood of a giant impact.



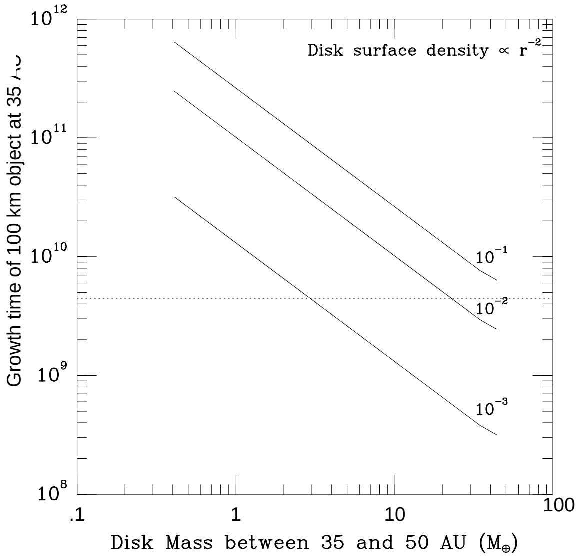


Figure 4 (LEFT) — The results of a collision calculation in the Kuiper belt by Davis & Farinella (1996, their Figure 3c). The number of objects in each size bin is plotted as a function of diameter. The initial size distribution is shown by the dot-dashed curve and follows a power law with $b = -3.5$ for objects smaller then 200 km. The final size distribution is shown by the asterisks. The number of objects that have not experienced catastrophic collisions and thus are primordial are shown by the open circles. Note that only a very small fraction of the comet-sized objects are primordial; most are fragments of a larger object. The data points with error bars represent the current observational constraints (also see Wiessman & Levison 1996).

Figure 5 (RIGHT) — Accretion times for a 100-km radius object as a function of the total mass of the Kuiper belt, as calculated by Stern (1996b). The solid curves represent three different values of the mean orbital eccentricity assumed for the accreting objects. All three curves are for objects at 35 AU from the Sun. The age of the solar system is shown by the dotted horizontal line. Note that the Kuiper belt must have been at least a few Earth masses in order for 100-km objects to have formed within the age of the solar system, and greater than 10 Earth masses if the 100-km objects formed in less than 10^9 years.

CONCLUDING REMARKS

With the arguments presented in the last section in mind, it is possible to build a strawman model of the Kuiper belt, which is depicted in Figure 6. Following Stern (1996), there are three distinct zones in the Kuiper belt. Region A is a zone where the dynamical perturbations of the outer planets have played an important role in the Kuiper belt's heliocentric structure. In this region the planets have tended to pump up the eccentricities of objects. About half of the objects in this region have been dynamically removed from the Kuiper belt (Duncan et al. 1995). The remaining objects have eccentricities that are large enough that accretion has stopped and erosion has become important. Thus, we expect that a significant fraction of the mass in region A has been removed by collisions. Indeed, the solid curve in this region of Figure 6 shows an estimate of the current Kuiper belt surface density from Duncan et al. (1995, reproduced from their Figure 7), while the dotted curve shows an estimate of the initial surface density, extrapolated from that of the outer planets. If these curves are at all representative of reality, the current surface density in this region has been depleted by a factor of $\sim 10^3$. The outer boundary of region A is at $\sim 50\,AU$ if the 1:2 mean motion resonance is not populated by objects in high eccentricity orbits ($52\,AU$ is the aphelion distance of objects in the 2:3 mean motion resonance with $e = 0.3$) and $\sim 65\,AU$ if the 1:2 is populated by objects in high eccentricity orbits.

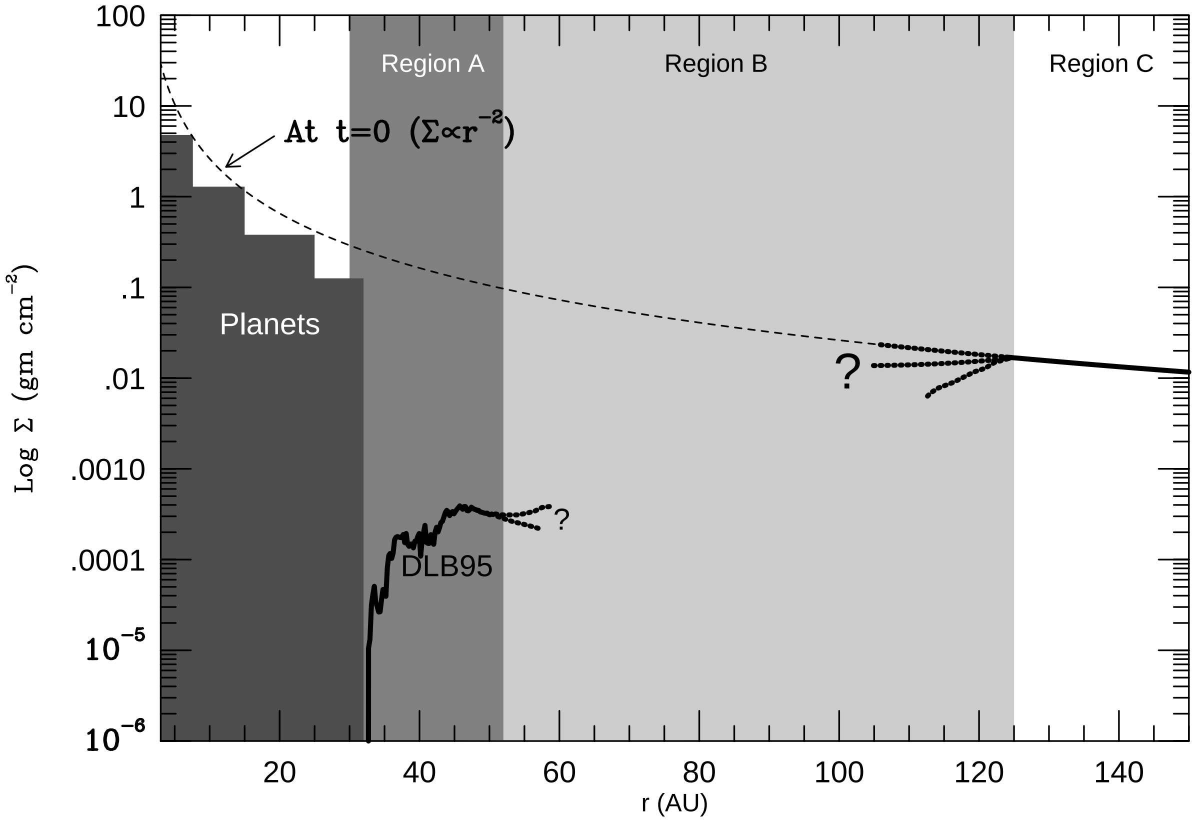


Figure 6 — A strawman model of the Kuiper belt. The dark area at left marked "Planets" shows the distribution of solid material in the outer planets region. The dashed curve is an extension into the Kuiper belt of the power law found for the outer planets and illustrates the likely initial surface density distribution of solid material in the Kuiper belt. The dashed curve has been scaled so that it is twice the surface density of the outer planets, under the assumption that planet formation was 50% efficient. The shadded areas show the location of the three regions of the Kuiper belt as described in the text. The solid curve shows a model of the mass distribution in Region A by Duncan et al. (1995, their Figure 7), scaled to an estimated population of 5×10^9 Kuiper belt objects between 30 and 50 AU.

Region B in Figure 6 is a zone where collisions are important in shaping the structure of the Kuiper belt, but the gravitational effects of the planets are not important. Without the effects of the planets, the orbital eccentricities of objects in this region will most likely be small enough that collisions lead to accretion of bodies, rather than erosion. Large objects could have formed here, so that the size distribution of objects may be significantly different than in the region immediately interior to it. However, the surface density may not have changed very much in this region over the age of the solar system. The outer boundary of Region B is very uncertain, but will likely be beyond $100\,AU$ (Stern, personal communication). Region C is a zone where collision rates are low enough that the surface density of the Kuiper belt and the size distribution of objects in it have remained virtually unchanged over the history of the solar system.

The strawman model presented above and the arguments for a massive primordial Kuiper belt presented in the last section are only speculative, at best. The only possible methods for testing these ideas and others discussed throughout this paper will rely on developing a good understanding of the current content of the Kuiper belt through observations. Of particular interest to the issues discussed here is the orbital element distribution of Kuiper belt objects. We point out that 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 strongly 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. Only 21 of the 39 Kuiper belt objects have been observed at multiple oppositions and at least 9 objects have not been recovered and are most likely lost (Marsden, this volume). Orbital solutions for even the well observed objects remain somewhat uncertain. If we are to ever understand the dynamical origin and evolution of the Kuiper belt, more observations, particularly followup observations on known objects, must be carried out.

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