DYNAMICS OF THE KUIPER BELT

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Our current knowledge of the dynamical structure of the Kuiper Belt is reviewed here. Numerical results on long-term orbital evolution and dynamical mechanisms underlying the transport of objects out of the Kuiper Belt are discussed. Scenarios about the origin of the highly nonuniform orbital distribution of Kuiper Belt objects are described, as well as the constraints these provide on the formation and long-term dynamical evolution of the outer solar system. Possible mechanisms include an early history of orbital migration of the outer planets, a mass loss phase in the outer solar system, and scattering by large planetesimals. The origin and dynamics of the scattered component of the Kuiper Belt are discussed. Inferences about the primordial mass distribution in the trans-Neptune region are reviewed. Outstanding questions about Kuiper Belt dynamics are listed.

1. INTRODUCTION

In the middle of this century, Edgeworth (1943) and Kuiper (1951) independently suggested that our planetary system is surrounded by a disk of material left over from the formation of planets. Both authors considered it unlikely that the protoplanetary disk was abruptly truncated at the orbit of Neptune. Each also suggested that the density in the solar nebula was too small beyond Neptune for a major planet to have accreted but that this region may be inhabited by a population of planetesimals. Edgeworth (1943) even suggested that bodies from this region might occasionally migrate inward and become visible as short-period comets. These ideas lay largely dormant until the 1980s, when dynamical simulations (Fernández 1980; Duncan et al. 1988; Quinn et al. 1990) suggested that a disk of transneptunian objects, now known as the Kuiper Belt, was a much more likely source of the Jupiter-family short-period comets than was the distant and isotropic Oort comet cloud.
II. LONG-TERM ORBITAL STABILITY IN THE OUTER SOLAR SYSTEM

A. Trans-Neptune Region

With the discovery of its first member in 1992 by Luu and Jewitt (1993), the Kuiper Belt was transformed from a theoretical construct to a bona fide component of the solar system. By now, on the order of 100 Kuiper Belt objects (KBOs) have been discovered, a sufficiently large number to permit first-order estimates about the mass and spatial distribution in the transneptunian region. A comparison of the observed orbital properties of these objects with theoretical studies provides tantalizing clues to the formation and evolution of the outer solar system. Other chapters in this volume describe the observed physical and orbital properties of KBOs (Jewitt and Luu) and their collisional evolution (Farinella et al.); here we focus on the dynamical structure of the transneptunian region and the dynamical evolution of bodies in it. The outline of this chapter is as follows: In section II we review numerical results on long-term dynamical stability of small bodies in the outer solar system; in section III we review our current understanding of the Kuiper Belt phase space structure and dynamics of orbital resonances and chaotic transport of KBOs; section IV provides a discussion of resonance sweeping and other mechanisms for the origin and properties of KBOs at Neptune’s mean motion resonances; the origin and dynamics of the “scattered disk” component of the Kuiper Belt is discussed in section V; current ideas about the primordial Kuiper Belt are described in section VI; we conclude in section VII with a summary of outstanding questions in Kuiper Belt dynamics.
evolving onto Neptune-encountering orbits, thereby potentially providing a source of Jupiter-family comets at the present epoch.

Duncan et al. (1995) performed integrations of thousands of particles for up to 4 Gyr in order to complete a dynamical survey of the transneptunian region. The main results can be seen in Color Plate 18 and include the following features:

1. For nearly circular, very low-inclination particles there is a relatively stable band between 36 and 40 AU, with essentially complete stability beyond 42 AU. The lack of observed KBOs in the region between 36 and 42 AU suggests that some mechanism besides the dynamical effects of the planets in their current configuration must be responsible for the orbital element distribution in the Kuiper Belt. This mechanism is almost certainly linked to the formation of the outer planets. Several possible mechanisms are described in later sections.

2. For higher eccentricities (but still very low inclinations) the region interior to 42 AU is largely unstable except for stable bands near mean-motion resonances with Neptune (e.g., the well-known 2:3 near 39.5 AU, within which lies Pluto). The boundaries of the stable regions for each resonance have been computed independently by Morbidelli et al. (1995) and Malhotra (1996) and are in good agreement with the results shown in Color Plate 18. The dynamics within the mean-motion resonances are discussed in detail in section III.

3. The dark vertical bands between 35–36 AU and 40–42 AU are particularly unstable regions in which the particles’ eccentricities are driven to sufficiently high values that they encounter Neptune. These regions match very well the locations of the \( \nu_1 \) (see section IV.B) and \( \nu_5 \) secular resonances as computed analytically by Knezevic et al. (1991): the test particles precess in these regions with frequencies very close to two of the characteristic secular frequencies of the planetary system.

4. A comparison of the observed orbits of KBOs with the phase space structure (Color Plate 18, Fig. 1) shows that virtually all of the bodies interior to 42 AU are on moderately eccentric orbits and located in mean-motion resonances, whereas most of those beyond 42 AU appear to be in nonresonant orbits of somewhat lower eccentricities. In addition, there is one observed object, 1996 TL\(_{66}\), with semimajor axis \( \approx 80 \) AU, beyond the range of Color Plate 18 and Fig. 1. It is thought to be a member of a third class of KBOs representing a “scattered disk” (see section V). Attempts to understand the origin of these three broad classes of KBOs will occupy much of what follows in this chapter.

**B. Test Particle Stability between Uranus and Neptune**

Gladman and Duncan (1990) and Holman and Wisdom (1993) performed long-term integrations, up to several hundred million years’ duration, of the evolution of test particles on initially circular orbits in between the giant planets’ orbits. The majority of the test particles were perturbed
into a close approach to a planet on timescales of 0.01–100 Myr, suggesting that these regions should largely be clear of residual planetesimals. However, Holman (1997) has shown that there is a narrow region, 24–26 AU, lying between the orbits of Uranus and Neptune, in which roughly 1% of minor bodies could survive on very low-eccentricity and low-inclination orbits for the age of the solar system. He estimated that a belt of mass totaling roughly $10^{-3} \, M_\oplus$ cannot be ruled out by current observational surveys. This niche is, however, extremely fragile. Brunini and Melita (1998) have shown that any one of several likely perturbations (e.g., mutual scattering, planetary migration, and Pluto-sized perturbers) would have largely eliminated such a primordial population. We note also that there are similarly stable (possibly even less “fragile”), but apparently unpopulated dynamical niches in the outer asteroid belt (Duncan 1994) and the inner Kuiper Belt (Duncan et al. 1995).

C. Neptune Trojans

The only observational survey of which we are aware specifically designed to search for Trojans of planets other than Jupiter covered 20 square degrees of sky to limiting magnitude $V = 22.7$ (Chen et al. 1997). Although 93 jovian Trojans were found, no Trojans of Saturn, Uranus, or Neptune were discovered. Although this survey represents the state of the art, it lacks the sensitivity and areal coverage to reject the possibility that Neptune holds Trojan swarms similar in magnitude to those of Jupiter (D. Jewitt, personal communication, 1998). Further searches clearly need to be done.
Several numerical studies of orbital stability in Neptune’s Trojan regions have been published. Mikkola and Innanen (1992) studied the behavior of 11 test particles initially near the Neptune Trojan points for $2 \times 10^6$ years. Holman and Wisdom (1993) performed a $2 \times 10^7$-year integration of test particles initially in near-circular orbits near the Lagrange points of all the outer planets. Most recently, Weissman and Levison (1997) integrated the orbits of 70 test particles in the L4 Neptune Trojan zone for 4 Gyr. In all these studies, some Neptune Trojan orbits were found to be stable. Weissman and Levison (1997) found that stable Neptune Trojans must have libration amplitudes $D \lesssim 60^\circ$ and proper eccentricities $e_p \lesssim 0.05$. It is interesting to note that this range for $D$ is similar to that Levison et al. (1997) found for the Jupiter Trojans, but the maximum stable $e_p$ for the Neptune regions is a factor of 3 smaller than that of the Jupiter regions. Holman and Wisdom (1993) reported a curious asymmetric displacement of the L4 and L5 Trojan libration centers of Neptune whose cause remains unknown.

III. RESONANCE DYNAMICS AND CHAOTIC DIFFUSION

It is evident from the numerical analysis of test particle stability in the transneptunian region that the timescales for orbital instability span several orders of magnitude and are very sensitive to orbital parameters. For example, the map of stability time (i.e., time to first encounter within a Hill sphere radius of Neptune) for initially circular orbits is very patchy, with short dynamical lifetimes interspersed among very stable regions (see Color Plate 18). Most particles that have a close approach to Neptune are removed from the Kuiper Belt shortly thereafter by means of a quick succession of close approaches to the giant planets. However, a small fraction evolve into anomalously long-lived chaotic orbits beyond Neptune that do not have a second close approach to the planet on timescales comparable to the age of the solar system (see section V). The nature and origin of the long-timescale instabilities (which are most relevant for understanding the origin of short-period comets from the Kuiper Belt) is not well understood at present.

In general, we understand that the mean-motion resonances of Neptune form a “skeleton” of the phase space (Fig. 1), with the perturbations of the other giant planets, including secular resonances, forming a web of superstructure on that skeleton. The phase space in the neighborhood of Neptune’s 3:2 mean-motion resonance is the best studied, following the discovery of Pluto and its myriad of resonances (cf. Malhotra and Williams 1997). Color Plate 19a shows the dynamical features that have been identified at the 3:2 resonance, in the $(a, e)$ plane. The boundary of this resonance, determined by means of a seminumerical analysis of the averaged perturbation potential of Neptune, is shown (dark solid lines) as well as the loci of the apsidal $\nu_8$ and nodal $\nu_{18}$ secular resonances (see
section IV.B) and the Kozai resonance in this neighborhood (Morbidelli 1997). The stable libration zone, determined from an inspection of many surfaces of section of the planar restricted three-body model of the Sun-Neptune-Plutino (Malhotra 1996), is indicated by the blue shaded region. The stable resonance libration boundary is significantly different from the formal perturbation theory result, because averaging is not a good approximation in the vicinity of the resonance separatrix: the separatrix broadens into a chaotic zone because of the interaction with neighboring mean-motion resonances. The width of the chaotic separatrix increases with eccentricity, eventually merging with the chaotic separatrices of neighboring mean-motion resonances. The $\nu_8$ secular resonance is mostly embedded in the chaotic zone, while the $\nu_{18}$ occurs at large libration amplitudes close to the chaotic separatrix; the Kozai resonance occurs at large libration amplitude for low-eccentricity orbits, and at smaller libration amplitude for eccentricities near 0.2–0.25.

Color Plate 19b shows a “map” of the diffusion speed of test particles determined by numerical integrations of up to 4 Gyr by Morbidelli (1997). It is clear that instability timescales in the vicinity of the 3:2 resonance range from less than a million years to longer than the age of the solar system. In general, within the resonance, higher-eccentricity orbits are less stable than those of lower eccentricities; the stability times are longest deep in the resonance and shorter near the boundaries. We note that the uncolored regions exterior and adjacent to the colored zones at eccentricities below $\sim 0.15$ are stable for the age of the solar system, but those above $\sim 0.15$ are actually chaotic on timescales shorter than the shortest indicated in the colored zones.

The short stability timescales in the most unstable zones are due to dynamical chaos generated by the interaction with neighboring mean-motion resonances; this can be directly visualized in surfaces of section of the planar restricted three-body model (Malhotra 1996). Test particles in these zones suffer large chaotic changes in semimajor axis and eccentricity on short timescales, $\mathcal{O}(10^5–7)$ yr, and are not protected from close encounters with Neptune. In a small zone near semimajor axis 39.5 AU, initially circular low-inclination orbits are excited to high eccentricity and high inclination on timescales of $\mathcal{O}(10^7)$ yr (Holman and Wisdom 1993; Levison and Stern 1995); this instability is possibly due to overlapping secondary resonances (Morbidelli 1997). The finite diffusion timescale, comparable to but shorter than the age of the solar system, in a large area (green zone) inside the resonance is not understood at all: possibly higher-order secondary resonances are the underlying cause. The numerical evolution of test particles in this region follows initially a slow diffusion in semimajor axis with nearly constant mean eccentricity and inclination, until the orbit eventually reaches a strongly chaotic zone (Morbidelli 1997). The diffusion timescales in this region are comparable to or only slightly less than the age of the solar system, so it is likely to be an active source region for short-period comets via purely dynamical instabilities.
The dynamical structure in the vicinity of other mean-motion resonances has not been obtained in as much detail as that of the 3:2. We expect differences in details (different profile of the libration zone, differing secular resonance effects, etc.) but generally similar qualitative features. We also note that because the orbital evolution obtained in nondissipative models of Kuiper Belt dynamics is time reversible, the transport of particles from strongly chaotic regions to weakly chaotic regions is also allowed. In the most general terms, this is the likely explanation for the putative scattered disk (section V).

IV. RESONANT KUIPER BELT OBJECTS

The origin of the great abundance of resonant KBOs and, equally importantly, their high orbital eccentricities is an interesting question whose understanding may lead to significant advances in our understanding of the early history of the solar system. In this section, we discuss current ideas pertinent to this class of KBOs.

A. Planet Migration and Resonance Sweeping

An outward orbital migration of Neptune in early solar system history provides an efficient mechanism for sweeping up large numbers of transneptunian objects into Neptune’s mean-motion resonances. We describe this scenario in some detail here; its importance stems from the linkage it provides between the detailed orbital distribution in the Kuiper Belt and the early orbital migration history of the outer planets. This theory, which was originally proposed for the origin of Pluto’s orbit (Malhotra 1993), supposes that Pluto formed in a common low-eccentricity, low-inclination orbit beyond the (initial) orbit of Neptune. It was captured into the 3:2 resonance with Neptune and had its eccentricity excited to its current Neptune-crossing value as Neptune’s orbit expanded outward as a result of angular momentum exchange with residual planetesimals. The theory predicts that resonance capture and eccentricity excitation would be a common fate of a large fraction of transneptunian objects (Malhotra 1995).

The process of orbital migration of Neptune (and, by self-consistency, migration of the other giant planets) invoked in this theory is as follows. Consider the late stages of planet formation, when the outer solar system had reached a configuration close to its present state, namely four giant planets in well-separated, near-circular, coplanar orbits; the nebular gas had already dispersed; the planets had accreted most of their mass; but there remained a residual population of icy planetesimals and possibly larger planetoids. The subsequent evolution consisted of the gravitational scattering and accretion of these small bodies. Circumstantial evidence for this exists in the obliquities of the planets (Lissauer and Safronov 1991; Dones and Tremaine 1993). Much of the Oort Cloud, the putative source of long-period comets, would have formed during this stage by the scattering of planetesimals to wide orbits by the giant planets and the subsequent
action of galactic tidal perturbations and perturbations from passing stars and giant molecular clouds (e.g., Fernández 1985; Duncan et al. 1987). During this era, the back reaction of planetesimal scattering on the planets could have caused significant changes in their orbital energy and angular momentum. Overall, there was a net loss of energy and angular momentum from the planetary orbits, but the loss was not extracted uniformly from the four giant planets. Jupiter, by far the most massive of the planets, likely provided all of the lost energy and angular momentum, and more; Saturn, Uranus, and Neptune actually gained orbital energy and angular momentum and their orbits expanded, while Jupiter’s orbit decayed sufficiently to balance the books. This was first pointed out by Fernández and Ip (1984), who noticed it in numerical simulations of the late stages of accretion of planetesimals by the proto-giant planets.

1. Migration of the Jovian Planets. The reasons for this rather non-intuitive result can be understood from the following heuristic picture of the clearing of a planetesimal swarm from the vicinity of Neptune. Suppose that the mean specific angular momentum of the swarm is initially equal to that of Neptune. A small fraction of planetesimals is accreted as a result of physical collisions. Of the remaining, there are approximately equal numbers of inward and outward scatterings. To first order, these cause no net change in Neptune’s orbit. However, the subsequent fate of the inward- and outward-scattered planetesimals is not symmetrical. Most of the inward-scattered objects enter the zones of influence of Uranus, Saturn, and Jupiter. Of those objects scattered outward, some are eventually lifted into wide, Oort Cloud orbits, while most return to be rescattered; a fraction of the latter is again rescattered inward, where the inner jovian planets, particularly Jupiter, control the dynamics. The massive Jupiter is very effective in causing a systematic loss of planetesimal mass by ejection into solar system escape orbits. As Jupiter preferentially removes the inward-scattered planetesimals from Neptune’s influence, the planetesimal population encountering Neptune at later times is increasingly biased toward objects with specific angular momentum and energy greater than Neptune’s. Encounters with this planetesimal population produce effectively a negative drag on Neptune, which increases its orbital radius. Uranus and Saturn, also being much less massive than and exterior to Jupiter, experience a similar orbital migration, but smaller in magnitude than that of Neptune. Thus, Jupiter is in effect the source of the angular momentum and energy needed for the orbital migration of the outer giant planets as well as for the planetesimal mass loss. However, owing to its large mass, its orbital radius decreases by only a small amount.

The magnitude and timescale of the radial migration of the jovian planets due to their interactions with residual planetesimals is difficult to determine without a full-scale N-body model. The work of Fernández and Ip (1984) is suggestive but not conclusive, on account of several limitations of their numerical model that produced highly stochastic results:
they modeled a small number of planetesimals, ~2000, and the masses of individual planetesimals were in the rather exaggerated range of 0.02–0.3 M$_\oplus$; and, perhaps most significantly, they neglected long-range gravitational forces. Current studies attempt to overcome these limitations by using the faster computers now available and more sophisticated integration algorithms (Hahn and Malhotra 1999). Still, fully self-consistent high-fidelity models remain a distant goal at this time. Remarkably, an estimate for the magnitude and timescale of Neptune’s outward migration is possible from an analysis of the orbital evolution of KBOs captured in Neptune’s mean-motion resonances.

2. Resonance Sweeping. Capture into resonance is a delicate process, difficult to analyze mathematically. Under certain simplifying assumptions, Malhotra (1993, 1995) showed that resonance capture is very efficient for adiabatic orbital evolution of KBOs whose initial orbital eccentricities were smaller than ~0.05. Resonance capture leads to an excitation of orbital eccentricity whose magnitude is related to the magnitude of orbital migration:

\[ \Delta e^2 = \frac{k}{j+k} \ln \frac{a_f}{a_i} = \frac{k}{j+k} \ln \frac{a_N}{a_{N,i}} \]  

(1)

where $a_i$ and $a_f$ are the initial and current semimajor axes of a KBO, $a_N$ is Neptune’s current semimajor axis, and $a_{N,i}$ is its value in the past at the time of resonance capture; $j$ and $k$ are positive integers defining a $j+k : j$ mean-motion resonance. From this equation and the observed eccentricities of Pluto and the Plutinos (see the chapter by Jewitt and Luu, this volume), it follows that Neptune’s orbit has expanded by ~9 AU.

Numerical simulations of resonance sweeping of the Kuiper Belt have been carried out assuming adiabatic giant-planet migration of specified magnitude and timescale. The orbital distribution of Kuiper Belt objects obtained in one such simulation is shown in Fig. 2. The main conclusions from such simulations are that (i) few KBOs remain in circular orbits of semimajor axis $a \approx 39$ AU, which marks the location of the 3:2 Neptune resonance; (ii) most KBOs in the region up to $a = 50$ AU are locked in mean-motion resonances; the 3:2 and 2:1 are the dominant resonances, but the 4:3 and 5:3 also capture noticeable numbers of KBOs; (iii) there is a significant paucity of low-eccentricity orbits in the 3:2 resonance; (iv) the maximum eccentricities in the resonances are in excess of Neptune-crossing values; (v) inclination excitation is not as efficient as eccentricity excitation; only a small fraction of resonant KBOs acquire inclinations in excess of $10^\circ$. Not shown in Fig. 2 are other dynamical features, such as the resonance libration amplitude and the argument-of-perihelion behavior (libration, as for Pluto, or circulation), which are also reflective of the planet migration/resonance sweeping process.

More detailed discussion of numerical results on resonance sweeping is given in Malhotra (1995, 1998a, 1999) and Holman (1995). Two
Figure 2. The distribution of orbital elements of transneptunian test particles after resonance sweeping, as obtained from a 200-Myr numerical simulation in which the jovian planets’ semimajor axes evolve according to $a(t) = a_i - \Delta a \exp(-t/\tau)$, with timescale $\tau = 4$ Myr and $\Delta a = \{-0.2, 0.8, 3.0, 7.0\}$ AU for Jupiter, Saturn, Uranus, and Neptune, respectively (Malhotra, 1999). The test particles were initially distributed smoothly in circular, zero-inclination orbits between 28 AU and 63 AU, as indicated by the dotted line in the lower panel. In the upper two panels, the larger filled circles represent particles that remain on stable orbits at the end of the simulation, and the smaller open circles represent the elements of those particles that had a close encounter with a planet and subsequently move on scattered chaotic orbits (“removed” from the simulation at the instant of encounter). Neptune’s mean-motion resonances are indicated at the top of the figure.

Additional points are worthy of note here. One is that, owing to the longer dynamical timescales associated with vertical resonances, the magnitude of inclination excitation of KBOs is sensitive to both the magnitude and the timescale of planetary migration; it is estimated that a timescale on the order of $1-3 \times 10^7$ yr would account for Pluto’s inclination (Malhotra 1998a). The second is that the total mass of residual planetesimals required for a $\sim 9$-AU migration of Neptune is estimated to be $\sim 50 \, M_\oplus$ (Malhotra...
1999); this estimate is supported by recent numerical simulations of planet migration (Hahn and Malhotra 1999).

An outstanding issue is the apparent paucity of KBOs at Neptune’s 2:1 mean-motion resonance in the observed sample (Fig. 1), whereas the planet migration/resonance sweeping theory predicts comparable populations in the 3:2 and 2:1 resonances (Fig. 2). Possible explanations are (i) observational incompleteness (cf. Gladman et al. 1998), (ii) significant leakage out of the 2:1 resonance on Gyr timescales by means of weak instabilities or perturbations by larger members of the Kuiper Belt, or (iii) that the planet migration/resonance sweeping did not occur as postulated. However, the success of the resonance sweeping mechanism in explaining the orbital eccentricity distribution of Plutinos, and the difficulty of explaining the distribution by other means, argues strongly in favor of this model. Further work is needed to refine the relationship between the orbital element distributions and the detailed characteristics of the planet migration process, including the overall efficiency of resonance capture and retention.

If such planet migration and resonance sweeping occurred, then it follows that the KBOs presently resident in Neptune’s mean-motion resonances formed closer to the sun than their current semimajor axes would suggest. If there were a significant compositional gradient in the primordial transneptunian planetesimal disk, it may be preserved in a rather subtle manner in the present orbital distribution. Because each resonant KBO retains memory of its initial orbital radius in its final orbital eccentricity [equation (1)], there would exist a compositional gradient with orbital eccentricity within each resonance; nonresonant KBOs in near-circular low-inclination orbits between 30 and 50 AU most likely formed at their present locations and would reflect the primordial conditions at those locations. However, if there were significant orbital mixing by processes other than resonance sweeping, these systematics would be diluted or erased.

B. Secular Resonance Sweeping

The combined, orbit-averaged perturbations of the planets on each other cause a slow precession of the direction of perihelion and of the pole of the orbit plane of each planet. Of particular importance to the long-term dynamics of the Kuiper Belt are the perihelion and orbit pole precession of Neptune, both of which have periods of about 2 Myr in the present planetary configuration. The perihelion direction and orbit pole orientation of the orbits of Kuiper Belt objects also precess slowly at rates that depend upon their orbital parameters. For certain ranges of orbital parameters, the perihelion precession rate matches that of Neptune; this condition is termed

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* In December 1998, while this article was in the review process, the Minor Planet Center reported new observations yielding revised orbits for 1997 SZ10 and 1996 TR66, identifying these as the first two KBOs in the 2:1 resonance with Neptune (Marsden 1998).
the \( \nu_8 \) secular resonance. Similarly, the 1:1 commensurability of the rate of precession of the orbit pole with that of Neptune’s orbit pole is called \( \nu_{18} \) secular resonance. (See Malhotra 1998b for an analytical model of secular resonance.) The \( \nu_8 \) and \( \nu_{18} \) secular resonances occur at several regions in the Kuiper Belt, where they cause strong perturbations of the orbital eccentricity and orbital inclination, respectively (cf. Color Plates 18 and 19).

The secular effects are sensitive to the mass distribution in the planetary system (see Ward 1981 and references therein). Levison et al. (1999) have noted that a primordial massive transneptunian disk would have significantly altered the locations of the \( \nu_8 \) and \( \nu_{18} \) secular resonances. From a suite of numerical simulations, they estimate that a \( \sim 10 \, M_\oplus \) primordial disk between 30 and 50 AU would have the \( \nu_8 \) secular resonance near \( a \approx 36 \) AU, and that it would have moved outward to its current location near 42 AU as the disk mass declined. Such sweeping by the \( \nu_8 \) secular resonance excites the orbital eccentricities of KBOs sufficiently to cause them to encounter Neptune and be removed from the Kuiper Belt. Only objects fortuitously trapped in Neptune’s mean-motion resonances remain stable. The simulations also find that the \( \nu_{18} \) secular resonance sweeps inward from well beyond its current location as the Kuiper Belt mass declines, thereby moderately increasing the inclinations (up to \( \sim 15 \) degrees) of KBOs beyond 42 AU. However, this mechanism does not produce orbital eccentricities in Neptune’s 2:3 mean-motion resonance as large as those observed. Furthermore, damping of the eccentricity and inclination by density waves is to be expected in a massive primordial disk (Ward and Hahn 1998) but has not yet been included in the simulations. We conclude that the sweeping of secular resonances has probably played some role in the excitation of the Kuiper Belt, but its quantitative effects remain to be determined.

**C. Stirring by Large Neptune-scattered Planetesimals**

A third mechanism to explain the observed orbital properties of KBOs is to invoke the orbital excitation produced by close encounters with large Neptune-scattered planetesimals on their way out of the solar system or to the Oort Cloud. The observed excitation in the Kuiper Belt requires the prior existence of planetesimals with masses \( \sim 1 \) Earth mass, according to Morbidelli and Valsecchi (1997). There is circumstantial evidence (e.g., the obliquity of Uranus’s spin axis) that a population of objects this massive might have formed in the region between Uranus and Neptune and are now gone (Safronov 1966; Stern 1991). Many of these objects must have spent some time orbiting through some parts of the Kuiper Belt. A much more massive initial belt might then have been sculpted to its presently observed structure because of the injection of most of the small bodies into dynamically unstable regions in the inner belt and the enhanced role of mutually catastrophic collisions among small planetesimals in the outer belt.
In this picture, then, the observed KBOs interior to \( \sim 42 \) AU are the lucky ones ending up in the small fraction of phase space (a few percent; see Fig. 1) protected from close encounters with Neptune by mean-motion resonances. This mechanism is similar to one involving large Jupiter-scattered planetesimals proposed earlier to explain the excitation of the asteroid belt (Ip 1987; Wetherill 1989).

Petit et al. (1998) have combined three-body integrations and semi-analytic estimates of scattering to model the effects of large planetesimals in the Kuiper Belt. They argue that the best reconstruction of the observed dynamical excitation of the Kuiper Belt requires the earlier existence of two large bodies. The first is a body of half an Earth mass on an orbit of large eccentricity with a dynamical lifetime of several times \( 10^8 \) yr. The second is a body of one Earth mass that evolves for \( \sim 25 \) Myr on a low-eccentricity orbit spanning the 30–40 AU range.

An attractive feature of this mechanism is that it yields an overall mass depletion in the inner Kuiper Belt and accounts for the fact that the outer Kuiper Belt (\( a > 42 \) AU) is moderately excited. It does not, however, appear to explain the lack of low-eccentricity objects in Neptune’s 2:3. In addition, the models performed to date require a specific set of very large objects, for which there is no direct evidence, to be at the right place for the right length of time. The presumed eventual removal of these objects by means of a final close encounter with Neptune would perturb Neptune’s orbit significantly and also jeopardize the stability of resonant KBOs; this is in conflict with the observed evidence.

V. THE SCATTERED DISK

As noted previously, the current renaissance in Kuiper Belt research was prompted by the suggestion that the Jupiter-family comets (JFCs) originated there (Fernández 1980; Duncan et al. 1988). Thus, as part of the research intended to understand the origin of these comets, a significant amount of effort has gone into understanding the dynamical behavior of objects that are on orbits that can encounter Neptune (Duncan et al. 1988; Quinn et al. 1990; Levison and Duncan 1997). It is somewhat ironic, therefore, that these studies have led to the realization that a structure known as the scattered comet disk, rather than the Kuiper Belt, could be the dominant source of the Jupiter-family comets.

For our purposes, scattered-disk objects are distinct from Kuiper Belt objects in that they evolved out of their primordial orbits beyond Uranus early in the history of the solar system. These objects were then dynamically scattered by Neptune into orbits with perihelion distances near Neptune but semimajor axes in the Kuiper Belt (Duncan and Levison 1997). Finally, some process, usually interactions with Neptune’s mean-motion resonances, raised their perihelion distances, thereby effectively storing the objects for the age of the solar system. Scattered-disk objects (hereafter
SDOs) occupy the same physical space as KBOs but can be distinguished from KBOs by their orbital elements. In particular, as we describe in more detail below, SDOs tend to be on much more eccentric orbits than KBOs.

Of the 60 or so Kuiper Belt objects thus far cataloged, only one, 1996 TL$_{66}$, is an obvious SDO. 1996 TL$_{66}$, discovered in October 1996 by Jane Luu and colleagues (Luu et al. 1997), is estimated to have a semi-major axis of 85 AU, a perihelion of 35 AU, an eccentricity of 0.59, and an inclination of 24°. Such a high-eccentricity orbit most likely resulted from gravitational scattering by a giant planet, in this case Neptune.

The idea of the existence of a scattered comet disk dates to Fernández and Ip (1989). Their numerical simulations indicated that some objects on eccentric orbits with perihelias inside the orbit of Neptune could remain on such orbits on gigayear timescales and hence might be present today. However, their simulations were based on an algorithm that incorporated only the effects of close gravitational encounters (Opik 1951) and hence severely overestimates the dynamical lifetimes of bodies such as those in their putative disk (Dones et al. 1998). As a result, the dynamics of their scattered disk bears little resemblance to the structure found in more recent direct integrations to be discussed below.

The only investigation of the scattered disk that uses modern direct numerical integrations is the one by Duncan and Levison (1997). This investigation was a followup to Levison and Duncan (1997), which was an investigation of the behavior of 2200 small, massless objects that initially were encountering Neptune. The latter’s focus was to model the evolution of these objects down to Jupiter-family comets and followed the system for only 1 Gyr. Duncan and Levison (1997) extended these integrations to 4 Gyr. Most objects that encounter Neptune have short dynamical lifetimes. Usually, they either (1) are ejected from the solar system, (2) hit the sun or a planet, or (3) are placed in the Oort Cloud, in less than $\sim 5 \times 10^7$ years. It was found, however, that 1% of the particles remained in orbits beyond Neptune after 4 Gyr. So, if at early times there was a significant amount of material from the region between Uranus and Neptune or the inner Kuiper Belt that evolved onto Neptune-crossing orbits, there could be a significant amount of this material remaining today. What is meant by “significant” is the main question when it comes to the current importance of the scattered comet disk.

Duncan and Levison (1997) found that some of the long-lived objects were scattered to very long-period orbits, where encounters with Neptune became infrequent. However, at any given time, the majority of them were interior to 100 AU. Their longevity is due in large part to their being temporarily trapped in or near mean-motion resonances with Neptune. The “stickiness” of the mean-motion resonances, which was mentioned by Holman and Wisdom (1993), leads to an overall distribution of semi-major axes for the particles that is peaked near the locations of many of the mean-motion resonances with Neptune. Occasionally, the longevity is enhanced by the presence of the Kozai resonance. In all long-lived cases,
particles had their perihelion distances increased so that close encounters with Neptune no longer occurred. Frequently, these increases in perihelion distance were associated with trapping in a mean-motion resonance, although in many cases it has not yet been possible to identify the exact process that was involved. On occasion, the perihelion distance can become large, but 81% of scattered-disk objects have perihelia between 32 and 36 AU.

Figure 3 shows the dynamical behavior of a typical particle. This object initially underwent a random walk in semimajor axis because of encounters with Neptune. At about $7 \times 10^7$ yr it was temporarily trapped in Neptune’s 3:13 mean-motion resonance for about $5 \times 10^7$ yr. It then performed a random walk in semimajor axis until about $3 \times 10^8$ years, when it was trapped in the 4:7 mean-motion resonance, where it remained for $3.4 \times 10^9$ years. Notice the increase in the perihelion distance near the time of capture. While trapped in this resonance, the particle’s eccentricity became as small as 0.04. After leaving the 4:7, it was trapped temporarily in Neptune’s 3:5 mean-motion resonance for $\sim 5 \times 10^9$ yr and then went through a random walk in semimajor axis for the remainder of the simulation.

Duncan and Levison (1997) estimated an upper limit on the number of possible SDOs by assuming that they are the sole source of the Jupiter-family comets. Duncan and Levison computed the simulated distribution

![Figure 3](image-url)

Figure 3. The temporal behavior of a long-lived member of the scattered disk. The black curve shows the behavior of the comet’s semimajor axis. The gray curve shows the perihelion distance. The three dotted curves show the location of the 3:13, 4:7, and 3:5 mean-motion resonances with Neptune.
of comets throughout the solar system at the current epoch (averaged over the last Gyr for better statistical accuracy). They found that the ratio of scattered-disk objects to visible Jupiter-family comets\(^6\) is \(1.3 \times 10^6\). There are currently estimated to be 500 visible JFCs (Levison and Duncan 1997), so there are \(\sim 6 \times 10^8\) comets in the scattered disk if it is the sole source of the JFCs. It is quite possible that the scattered disk could contain this much material. Figure 4 shows the spatial distribution for this model.

To review the above findings, \(\sim 1\%\) of the objects in the scattered disk remain after 4 Gyr, and \(6 \times 10^8\) comets are currently required to supply all of the Jupiter-family comets. Thus, a scattered comet disk requires an initial population of only \(6 \times 10^{10}\) comets (or \(\sim 0.4 \, M_\oplus\), Weissman 1990) on Neptune-encountering orbits. Because planet formation is unlikely to have been 100% efficient, the original disk could have resulted from the scattering of even a small fraction of the tens of Earth masses of cometary

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\( ^6\) We define a “visible” Jupiter-family comet as one with a perihelion distance less than 2.5 AU.

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Figure 4. The surface density of comets beyond Neptune for two different models of the source of Jupiter-family comets. The dotted curve is a model assuming that the Kuiper Belt is the current source (Levison and Duncan 1997). There are \(7 \times 10^9\) comets in this distribution between 30 and 50 AU. This curve ends at 50 AU because the models are unconstrained beyond this point, not because it is believed that there are no comets there. The solid curve is the model of Duncan and Levison (1997), assuming that the scattered disk is the sole source of the Jupiter-family comets. There are \(6 \times 10^8\) comets currently in this distribution.
material that must have populated the outer solar system in order to have formed Uranus and Neptune.

VI. THE PRIMORDIAL KUIPER BELT

As with many scientific endeavors, the discovery of new information tends to raise more questions than it answers. Such is the case with the Kuiper Belt. Even the original argument that suggested the Kuiper Belt is in doubt. Edgeworth’s (1949) and Kuiper’s (1951) speculations 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, Neptune. An extrapolation into the Kuiper Belt of the current surface density of nonvolatile material in the outer planetary region implies that there should be about 30 M\(_\odot\) of material there. However, the recent KBO observations indicate only a few \(\times 0.1\) M\(_\odot\) between 30 and 50 AU. Were Kuiper and Edgeworth wrong? Is there a sharp outer edge to the planetary system? One line of theoretical arguments suggests that the answer may be no to both questions; we discuss these below, but we note at the end some contrary arguments as well.

Over the last few years, several points have been made supporting the idea of a massive primordial Kuiper Belt; see the chapter by Farinella et al., this volume. Stern (1995) and Davis and Farinella (1997) have argued that the inner part of the Kuiper Belt (\(\leq 50\) AU) is currently eroding away due to collisions and therefore must have been more massive in the past. Stern (1995) also argued that the current surface density in the Kuiper Belt is too low to grow bodies larger than about 30 km in radius by means of two-body collisional accretion over the age of the solar system. The observed \(\sim 100\)-km-size KBOs could have grown in a more massive Kuiper Belt, of at least several Earth masses, if the mean eccentricities of the accreting objects were small, on the order of a few times \(10^{-3}\) or perhaps as large as \(10^{-2}\) (Stern 1996; Stern and Colwell 1997a; Kenyon and Luu 1998). Models of the collisional evolution of a massive Kuiper Belt suggest that 90% of the mass inside of \(\sim 50\) AU could have been lost through collisions over the age of the solar system (Stern and Colwell 1997b; Davis and Farinella 1998). Thus, it is possible for a massive primordial Kuiper Belt to grind itself down to the levels that we see today.

With these arguments, it is possible to build a “straw man” model of the Kuiper Belt, which is depicted in Fig. 5. Following Stern (1996), there are three distinct zones in the Kuiper Belt. Region A is a zone where the gravitational perturbations of the outer planets have played an important role, tending to pump up the eccentricities of objects. About half of the objects in this region could have been dynamically removed from the Kuiper Belt (Duncan et al. 1995). The remaining objects have eccentricities that are large enough that accretion has ceased and erosion is dominant. Thus, we expect that a significant fraction of the mass in region A has been removed by collisions. The dotted curve shows an estimate of the initial
Figure 5. A “straw man” model of the Kuiper Belt. The dark area at left marked “Planets” shows the distribution of solid material in the outer planets region; it follows a power law with a slope of about −2 in heliocentric distance. 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 solid curve shows a model of the mass distribution by Duncan et al. (1995, see Fig. 4), scaled to an estimated population of $5 \times 10^6$ Kuiper Belt objects between 30 and 50 AU. The Kuiper Belt is divided into three regions; see text for a description. The dotted curves illustrate the unknown shape of the surface density distribution in region B.

Surface density of solids, extrapolated from that of the outer planets, and the solid curve (marked DLB95) shows an estimate of the current Kuiper Belt surface density from Duncan et al. (1995, reproduced from their Fig. 7). Region B in Fig. 5 is a zone where collisions are important but the perturbations of the planets are not. The orbital eccentricities of objects in this region will most likely remain small enough that collisions lead to accretion of bodies, rather than erosion. Large objects could have formed here (see Stern and Colwell 1997a), but the surface density may not have changed very much in this region over the age of the solar system. Observational constraints based on Cosmic Background Explorer (COBE), Diffuse Infrared Background Experiment (DIRBE), data put the transition between regions A and B beyond 70 AU (Teplitz et al. 1999). The outer boundary of region B is very uncertain but will likely be beyond 100 AU (S. A. 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.

If the above model is correct, then the Kuiper Belt that we have so far observed may be a low-density region that lies inside a much more massive outer disk. In other words, we may now be seeing a “Kuiper Gap” (Stern and Colwell 1997b).

The idea of an increase in the surface density of the Kuiper Belt beyond 50 AU may explain a puzzling feature of the dynamics of the planets: Neptune’s small eccentricity. Ward and Hahn (1998) have shown that if the Kuiper Belt smoothly extends to a couple of hundred AU and if the eccentricities in the disk are smaller than ~0.05, then Neptune can excite apsidal waves in the disk that will carry away angular momentum from Neptune’s orbit and damp that planet’s eccentricity. They estimate an upper limit of ~2 M⊕ on the mass of material between 50 and 75 AU. This upper limit is marked WH98 in Fig. 5.

We note that Ward and Hahn (1998) estimate more mass than a simple extension of the Kuiper Belt’s observed surface density would imply (i.e., we are seeing a Kuiper Gap). However, their upper limit on the surface density is much less than that required by the accretion models to grow the observed KBOs. There are three possible resolutions to this problem:

1. It could be a matter of timing. As Stern and Colwell (1997a) describe, the KBOs must have been formed before Neptune in order for their eccentricities to be small enough for accretion. Conversely, the Ward and Hahn (1998) upper limit applies only after Uranus and Neptune have cleared away any local objects that could excite their eccentricities. Perhaps the surface density of the Kuiper Belt decreased significantly between these two times. For example, it could have decreased because of Neptune and Uranus injecting massive objects into the 50–100-AU region, stirring up the disk and greatly increasing the collisional erosion (Morbidelli and Valsecchi 1997).
2. The uncertainties in the models could be larger than the discrepancy between them. Stern and Colwell (1997a) make assumptions about the velocity evolution of their objects and the physics of the collisions. Ward and Hahn (1998) make assumptions about the shape of the surface density distribution and eccentricities. Perhaps when more detailed models are constructed, the discrepancy will vanish.
3. There really was an edge to the disk from which the planets formed, at about 50 AU. This would explain why no classical KBOs have been discovered beyond this point. Although the lack of discoveries may be due to observational incompleteness (Gladman et al. 1998), Monte Carlo simulations of the detection statistics of observational surveys are consistent with a Kuiper Belt edge at 50 AU (Jewitt et al. 1998). Clearly, more work needs to be done on this topic.
VII. CONCLUDING REMARKS

Studies of Kuiper Belt dynamics offer the exciting prospect of deriving constraints on dynamical processes in the late stages of planet formation that have hitherto been considered beyond observational constraint. Many questions have been raised by the intercomparisons between observations of the Kuiper Belt and theoretical studies of its dynamics; these outstanding issues are listed below.

1. It is likely that the Kuiper Belt defines an outer boundary condition for the primordial planetesimal disk and, by extension, for the primordial solar nebula. What new constraints does it provide on the solar nebula, its spatial extent and surface density, and on the timing and manner of formation of the outer planets Uranus and Neptune? How does the Kuiper Belt fit in with observed dusty disks around other sunlike stars, such as β Pictoris?

2. What is the spatial extent of the Kuiper Belt: its radial and inclination distribution? What are the relative populations in the scattered disk and the classical Kuiper Belt? What mechanisms have given rise to the large eccentricities and inclinations in the transneptunian region?

3. What are the relative proportions of the resonant and nonresonant KBOs and their eccentricity, inclination, and libration amplitude distributions? These provide constraints on the orbital migration history of the outer planets.

4. The phase space structure in the vicinity of Neptune’s mean motion resonances is reasonably well understood only for the 3:2 resonance. Similar studies of the other resonances are warranted.

5. Given the apparent highly nonuniform orbital distribution of KBOs, precisely what is the source region of short-period comets and Centaurs? What is the nature of the long-term instabilities that provide dynamical transport routes from the Kuiper Belt to the short-period comet and Centaur population?

6. Was the primordial Kuiper Belt much more massive than at present? What, if any, were the mass loss mechanisms (collisional grinding, dynamical stirring by large KBOs or lost planets)?

7. Is there a significant population of Neptune Trojans or a belt between Uranus and Neptune? What can we learn from its presence/absence about the dynamical history of Neptune?

8. What is the distribution of spins of KBOs? It may help constrain their collisional evolution.

9. What is the frequency of binaries in the Kuiper Belt? (How unique is the Pluto-Charon binary?)

10. What is the relationship between the Kuiper Belt and the Oort Cloud? How does the mass distribution in the Kuiper Belt relate to the formation of the Oort Cloud? Is there a continuum of small bodies spanning the two regions?
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Acknowledgments The authors acknowledge support from NASA's Planetary Geosciences and Origins of Solar Systems Research Programs. M. J. D. is also grateful for the continuing financial support of the Natural Science and Engineering Research Council of Canada. H. L. thanks P. Weissman and S. A. Stern for discussions. Part of the research reported here was done while R. M. was a Staff Scientist at the Lunar and Planetary Institute, which is operated by the Universities Space Research Association under contract no. NASW-4574 with the National Aeronautics and Space Administration. This paper is Lunar and Planetary Institute Contribution no. 959.

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