A BRIEF SUMMARY OF KUIPER BELT RESEARCH

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1. Historical background

Ideas about the contents of the Solar System beyond Neptune and Pluto can be traced back to at least Edgeworth (1943, 1949) and Kuiper (1951), who speculated on the existence of pre-planetary small bodies in the outer Solar System beyond the orbit of Neptune – remnants of the accretion process in the primordial Solar Nebula. The basis for the speculation was primarily the argument that the Solar Nebula was unlikely to have been abruptly truncated at the orbit of Neptune, and that in the trans-Neptunian accretion timescales were too long for bodies larger than about ~ 1000 km in radius to have formed in the 4.5 billion year age of the Solar System. Another important theoretical argument relevant to this region of the Solar System is related to the origin of short period comets. Fernández (1980) suggested that the short period comets may have an origin in a disk of small bodies beyond Neptune, rather than being "captured" from the population of long period comets originating in the Oort Cloud, the latter scenario having considerable difficulty reconciling the observed flux of short period comets with the exceedingly low efficiency of transfer of long period comet orbits to short period ones by means of the gravitational perturbations of the giant planets. The new scenario received further strength in the numerical work of Duncan et al. (1988) and Quinn et al. (1990) which showed that the relatively small orbital inclinations of the Jupiter-family short period comets were not consistent with a source in the isotropic Oort Cloud of comets but could be reproduced with a source in a low-inclination reservoir beyond Neptune's orbit. Duncan et al. named this hypothetical source the *Kuiper Belt*, and the name has come into common use in the last decade (although other names are also in use, e.g. Edgeworth–Kuiper Belt, and trans-Neptunian objects). A recent theoretical milestone was the work by Holman and Wisdom (1993) and Levison and Duncan (1993) on the long term stability of test particle orbits in the trans-Neptunian Solar System. This work showed that low-eccentricity, low-inclination orbits with semimajor axes in excess of about 43 AU are stable on billion year timescales, but that in the region between 35 AU and 43 AU orbital stability times range from 10^7 yr to more than 10^9 yr [see, for example, figure 1 in Holman (1995)]. Orbital instability in this intermediate region typically leads to a close encounter with Neptune which causes dramatic orbital changes, with the potential for subsequent transfer to the inner Solar System. Thus, this region could in principle serve as the reservoir of short period comets at the present epoch. However, the idea of a kinematically cold — i.e. low-eccentricity, low-inclination — population in this region is at odds with recent observations, and the question of the origin of short period comets remains unsettled at the present time.

On the observational side, published sky surveys relevant to the search for outer Solar System small bodies are listed in Table 1. The earliest is that of Clyde Tombaugh who carried out a search of the ecliptic sky in the 1930's from Lowell Observatory, a search that resulted in the discovery of Pluto. The most recent searches of David Jewitt and his students have used the new technology of CCDs to go to fainter magnitudes (but at the expense of covering only very small areas of the sky). The first Kuiper Belt object was discovered in 1992 by Jane Luu and David Jewitt, and given the designation *1992* QB_1. Several dozen detections have been made since then in ground-based observations. In addition, Cochran et al. (1995) reported on a detection of small, very faint members of the Kuiper Belt using the Hubble Space Telescope (HST). However, this claim is questionable as the noise characteristics of the data were improperly accounted for (Brown et al., 1997). The HST

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experiment is scheduled to be repeated in the autumn of 1997, using the improved instrumentation aboard the Space Telescope.

TABLE 1. Observational surveys of the outer Solar system

Author(s)	limiting magnitude, m_R	Sky area deg^2	number detected	notes
Tombaugh (1961)	16.8	1530	1	Pluto
Kowal (1989)	19.5	6400	1	2060 Chiron
Luu & Jewitt (1988)	20.0	297	0	
Levison & Duncan (1990)	22.0	4.9	0	
Jewitt & Luu (1995)	24.8	1.2	7	1992 QB1,...
Williams et al. (1995)	20.5–23.5	0.5	2	
Irwin et al. (1995)	23.5	0.7	2	
Cochran et al. (1995)	28.1	0.001	29(?)	
Jewitt et al. (1996)	24.2,23.2	3.9,4.4	17	
Gladman & Kavelaars (1997)	24.8	0.05	0	

2. Summary of observations

The current inventory (as of August 1997) of KBOs consists of 53 objects detected at heliocentric distances of 28 AU to 43 AU. The physical properties of KBOs remain poorly known, as summarized below.

Color: Colors appear to be reddish, but quite diverse (Luu and Jewitt, 1997; Tegler and Romanishin, 1997).

Albedo: No albedo information is available, although albedos are thought to be similar to those of short period comets, typically 0.04.

Size: Physical diameters of the observed KBOs are in the range 100–500 km (as inferred from the observed brightnesses and the assumption of a geometric albedo=0.04). Owing the rather narrow range of sizes observed so far, the size distribution is not highly constrained; it is consistent with an inverse power law with index near 3 (cf. Jewitt et al., 1996).

Population: Taking account of the characteristics of the small field CCD surveys that these objects were detected in, it is estimated that there are $\sim 10^5$ KBOs brighter than magnitude 24 (or diameter greater than 100 km, in the 30–to–100 AU heliocentric distance range). This may be compared with the asteroid population which consists of only 230 bodies larger than 100 km in diameter. The Kuiper Belt population dwarfs that of the asteroid belt by more than 2 orders of magnitude.

Total mass: Using plausible power-law size distributions, the total mass of the Kuiper Belt in the 30–100 AU region is estimated to be 0.2–0.6 Earth-masses (Jewitt et al., 1996), consistent with the upper limit estimated from the orbit of Halley's comet (Hamid et al., 1968). We note, however, that the larger number is quite insecure as it is based upon the orbital characteristics of only one object, namely the brightest observed KBO, 1996 TL$_{66}$ (Luu et al., 1997). The estimated Kuiper Belt mass is 1–to–2 orders of magnitude smaller than the primordial mass of solids in this region inferred from theoretical models of the Solar Nebula (cf. Tremaine 1990, Stern 1996).

Orbits: The orbital periods of KBOs are well in excess of 200 years. Therefore, observations over less than ~ 5 years allow only very limited accuracy for the fitted orbits, and only about half of the detected KBOs have been fitted to orbits of reasonable quality (Marsden 1997). Nevertheless, some patterns are already evident in the distribution of their orbital elements (Fig. 1): it is clear that the orbital distribution is rather peculiar, highly non-uniform in semimajor axis, with nearly 50% of all objects librating in orbital resonances with Neptune, primarily the 3:2 resonance. There is a noticeable paucity of objects at semimajor axes less than 39 AU and also in the range 40 AU to 42 AU. The orbital eccentricities of the 3:2 resonant objects are surprisingly large, with the largest eccentricity objects being on deeply Neptune-crossing orbits (but protected from catastrophic close

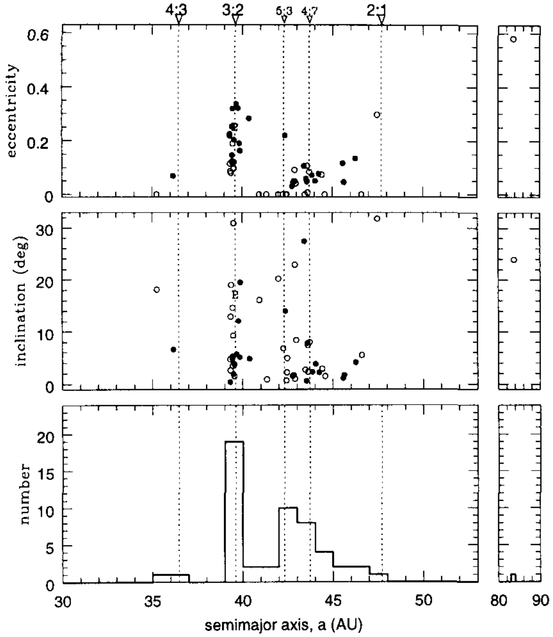

Figure 1. Orbital element distribution of detected KBOs (as of August 15, 1997). The open circles represent objects observed at only one opposition; filled circles those observed at multiple oppositions. The vertical dotted lines indicate the locations of Neptune's mean motion resonances.

encounters with that planet due to the resonance libration). Another surprise is the inclination distribution: inclinations range up to 31 degrees! Considering that ecliptic surveys are biased against high inclinations (cf. Jewitt et al. 1996), it appears that the Kuiper Belt is rather thick. It should be stated that there is possibly significant observational incompleteness in the distribution beyond $a \approx 42$ AU. Worthy of special note is the detection of one object, 1996 TL_{66}, on the most highly eccentric orbit which is also highly inclined and whose estimated semimajor axis is $\sim$ 83 AU, the largest known so far (Luu et al. 1997). This object is possibly a member of a "scattered disk" population, a remnant of those Uranus-Neptune zone and/or Kuiper Belt planetesimals that were placed on chaotic but dynamically long-lived orbits after a close encounter with Neptune in the early history of the Solar System (Duncan and Levison 1997).

3. Orbital dynamics

A very large fraction of KBOs – roughly 40% – have orbits similar to that of Pluto, namely, locked in the 3:2 orbital resonance with Neptune, and have been informally named "Plutinos". The 3:2 resonance lock provides a dynamical protection mechanism against close encounters with Neptune by causing a libration of the longitude of perihelion about a center 90° removed from Neptune's longitude. (The reader is referred to Malhotra and Williams (1997) for a detailed discussion of Pluto's resonance librations.) A two-dimensional view of the global structure of the phase space in the neighborhood of Neptune's mean motion resonances has been obtained by means of surfaces-of-section within the planar restricted three-body model (Malhotra 1996). In particular, these views show that the stable zone in Pluto's neighborhood is very narrow, and is surrounded by a large "chaotic sea". Generally, each low order exterior orbital resonance of Neptune has a similar phase space structure: a narrow zone where eccentric orbits can librate stably, surrounded by a large chaotic zone. In addition to the mean motion resonances, important dynamical effects arise from secular resonances as well. Numerical and semi-numerical analyses of these are given in Duncan et al. (1995), Morbidelli et al. (1995) and Morbidelli (1997).

The overabundance of KBOs in the 3:2 resonance is a remarkable feature in light of the very small volume of phase space represented by the libration zone relative to the neighboring non-resonant (generally chaotic) phase space. Such an overabundance was actually predicted by the "resonance sweeping" theory for the origin of Pluto's Neptune-crossing resonant orbit (Malhotra 1993, 1995). In this theory, it is proposed that during the late stages of accretion of the giant planets, as part of the process of gravitational scattering and removal of residual planetesimals (the same process which is believed to have formed the Oort Cloud), an exchange of energy and angular momentum amongst the planets and planetesimals caused the giant planets to migrate radially. In particular, Neptune's outward orbital migration caused the trans-Neptunian population of small bodies to be swept by Neptune's orbital resonances. As a consequence, there was great mass erosion in the region up to about 50 AUs; the majority of the surviving small bodies were captured into Neptune's mean motion resonances and had their orbital eccentricities pumped up to modestly large values.

The process of resonance capture is a very delicate one and difficult to analyze mathematically. However, under certain simplifying assumptions and idealizations, first order perturbation theory for mean motion resonance sweeping and resonance capture into a $j : j+k$ mean motion resonance provides a relationship between the eccentricity pumping and the magnitude of outward migration of Neptune's orbit (Malhotra 1995):

$$\Delta e^2 \simeq \frac{j}{j+k} \ln \frac{a_N}{a_{N,i}} \tag{1}$$

where a_N is Neptune's current orbital semimajor axis and $a_{N,i}$ is its value in the past at the time of resonance capture. Thus, from Pluto's current orbital eccentricity of 0.25, we can estimate that Neptune's orbit expanded by at least 5 AU. Furthermore, the observed KBOs in the 3:2 Neptune resonance have eccentricities up to 0.32; this increases the above estimate for Neptune's orbital expansion to 7 AU.

Numerical simulations of giant planet orbital migration and resonance sweeping of the trans-Neptunian region have corroborated the above picture (Malhotra 1995, 1997a; Holman 1995). These simulations also show that KBO orbital inclinations may also be excited to large values during resonance sweeping (Malhotra 1997b). However, we note that these simulations assumed an adiabatic, smooth process for planetary migration on timescales of a few million years, and treated KBOs as massless test particles, thereby possibly overestimating the resonance capture efficiency as well as neglecting the gravity and mutual scatterings or collisions of the KBOs and other bodies scattered by the giant planets.

Several additional suggestions have been made in the last year which are also relevant to understanding the origin of the dynamical structure of the Kuiper Belt. Levison et al. (1997) have pointed out the importance of the sweeping of secular resonances, particularly in the mass-loss phase of the primordial massive Kuiper Belt; and Morbidelli and Valsecchi (1997) have discussed the possible role of "large Neptune-scattered planetesimals" in causing a gravitational "stirring" of KBOs into unstable orbits, thereby depleting a large fraction of the primordial mass, and permitting only those objects that happened to fall into stable resonant niches to survive over the age of the Solar System.

4. Concluding remarks

Kuiper Belt research is in its infancy. This fact alone explains much of the excitement surrounding this field. But I think that the excitement is justified more substantively by the likelihood that the peculiar Kuiper Belt dynamical structure holds memory of the long term dynamical history of the outer Solar System. Indeed, it is possible to trace a detailed, quantitative trail from the present Kuiper Belt dynamical structure to dynamical processes in the early stages of planet formation, an era hitherto considered largely outside of observational constraint.

Observations to date have detected only the brightest and, hence, presumably the closest and largest KBOs. It is essential to obtain a more complete census of the KBO population, including its orbital and size distribution in order to make further progress in dynamical studies which will allow an elucidation of the relationship between these objects and Neptune, Triton, Pluto-Charon, the Centaur population, and the Oort Cloud, as well as the Jupiter-family short period comets, and the asteroids. It is also important to seek opportunities for physical studies of these objects, many of which are perhaps the least perturbed remnants of the planetesimal accretion process and may provide new constraints on conditions that existed in the primitive Solar Nebula.

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