The Outer Edge of the Kuiper Belt

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I. The Kuiper Belt

The orbit elements of Kuiper Belt Objects (KBOs) may be divided into 3 populations:

- The **Plutinos** are the KBOs orbiting at the 3:2 mean–motion resonance with Neptune. Plutinos have semimajor axes $a \simeq 40$ AU, eccentricities $0 \lesssim e \lesssim 0.3$, and high inclinations $i \sim 10^\circ$ (see Figs. 1–2).

- KBOs in the **Classical Disk** are at greater distances, $a \gtrsim 40$ AU, and have orbits that are moderately stirred with $e \sim \sin i \sim \mathcal{O}(0.1)$.

- Members of the **Scattered Disk** are high e and i KBOs having perihelia near Neptune, $q \sim 30$ AU. Scattered Objects likely formed near Neptune but were scattered outwards into wide orbits beyond $a \gtrsim 50$ AU orbits. They are easily identified in Fig. 1 since they usually reside near the Neptune–crossing curve.

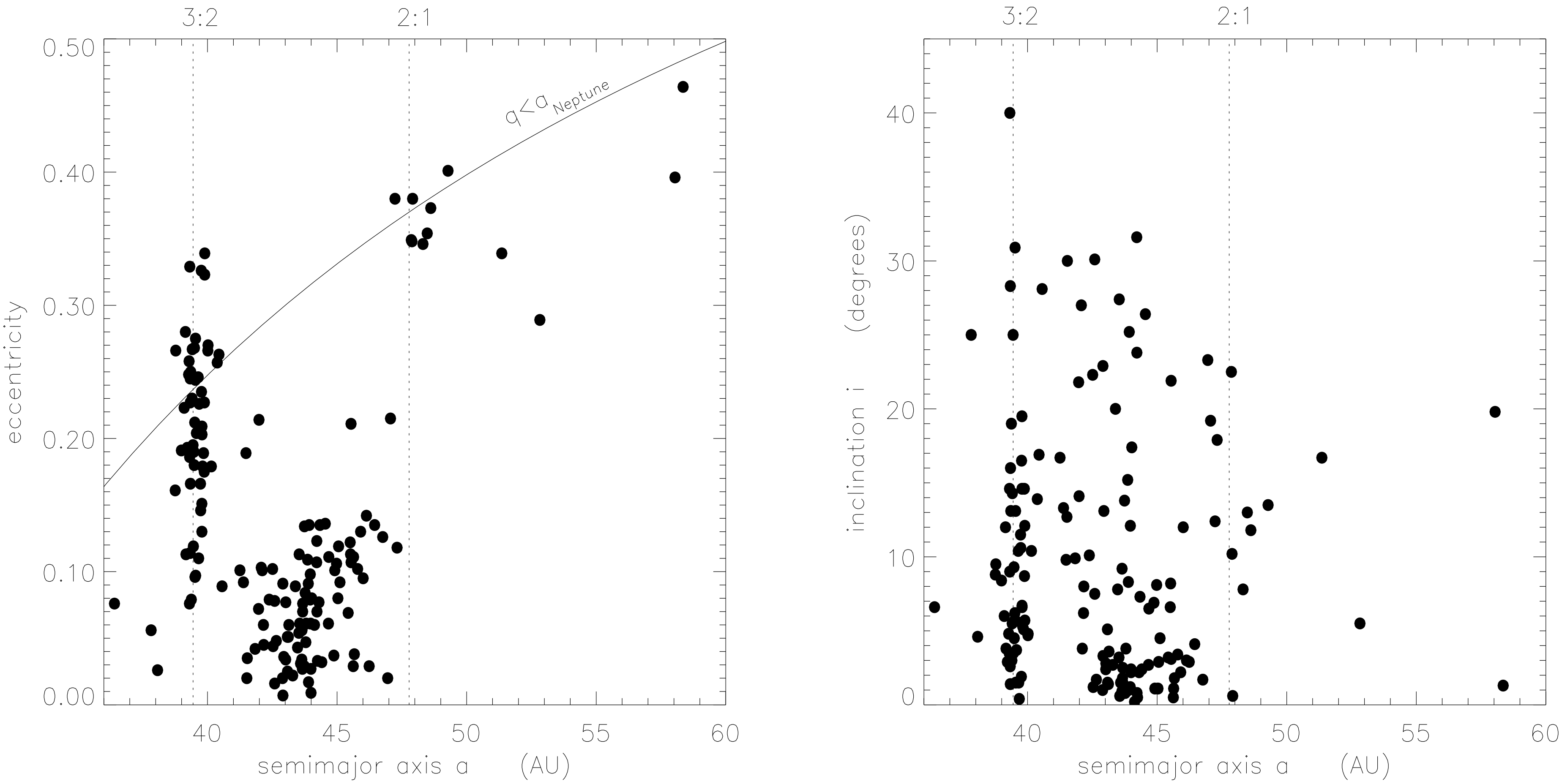

Figure 1. Eccentricity e and inclination i versus semimajor axis a for Kuiper Belt Objects. The dotted lines indicate the locations of Neptune's 3:2 and 2:1 mean–motion resonances, and KBOs above the solid curve lie on Neptune–crossing orbits. These data are obtained from the IAU Minor Planet Center.

II. Planet–Migration

The high abundance of eccentric KBOs at Neptune's 3:2 resonance is probably due to an early episode of planet–migration. Neptune will have accreted from a planetesimal disk that is also the progenitor of the Kuiper Belt. This recently–formed planet will gravitationally scatter neighboring planetesimals, and the ensuing angular momentum exchange drives Neptune outwards about 7 AU into the Kuiper Belt (Malhotra 1995, Hahn & Malhotra 1999). This slow and steady expansion of Neptune's orbit allows the planet to capture KBOs at its mean–motion resonances, which expands their orbits and pumps up their eccentricities.

Numerical simulations of planet–migration and resonance–capture have been performed, and the endstate of one run is shown in Fig. 2. Note the abundance of KBOs at Neptune's resonances, the stirred state of the Classical Disk, and the agreements as well as discrepancies with the observed endstate, Fig. 1. Note also that Neptune's gravitational reach ends at the 2:1 resonance at $r \simeq 48$ AU, and that more distant KBOs preserve their primordial e and i.

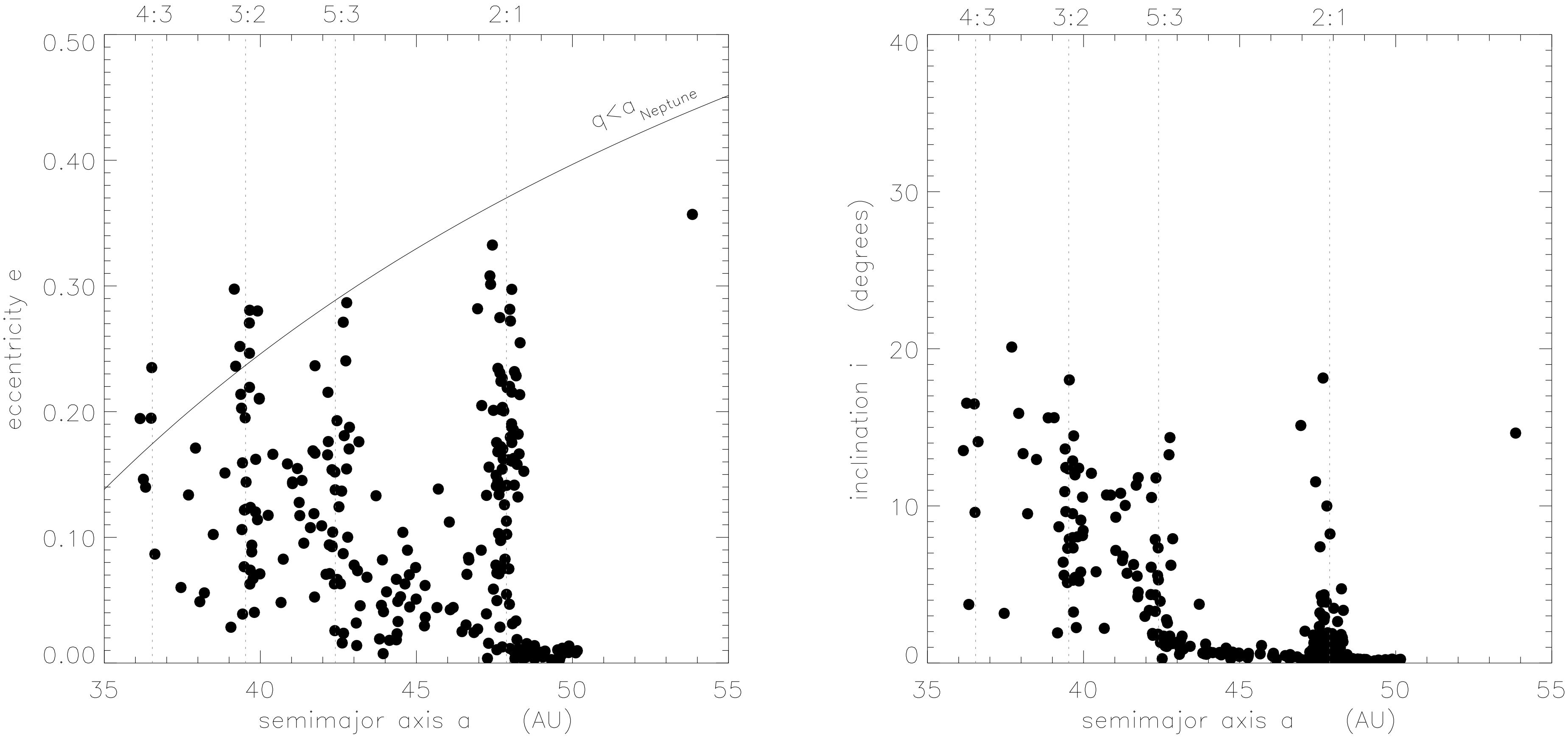

Figure 2. Results of an N–body simulation of a system of 4 migrating giant-planets and 500 massless test particles initially in nearly circular orbits exterior to Neptune. The system is evolved for $t = 3 \times 10^8$ years. Planet–migration is effected by applying a torque to each planet such that its semimajor axis a_i shifts by Δa_i over an exponential timescale $\tau = 3 \times 10^7$ years. Accounting for the $e \simeq 0.3$ Plutinos at Neptune's 3:2 resonance requires Neptune's orbit to expand $\Delta a_i \simeq 7$ AU. In order to simulate the stochastic scattering of planetesimals by Neptune, some random "jitter" is also added to the torque on Neptune. This reduces the trapping efficiency at the 2:1 resonance and results in some eccentricity–pumping as particles slip through the resonance. This "jitter" might be the cause of the e–excitation observed in the Classical Disk (see Fig. 1).

III. The Problem: Where are the Distant KBOs beyond $r > 50$ AU?

Gladman $et\ al.$ (1998) point out that if you assume that any KBOs orbiting beyond $r > 50$ AU have the same size distribution [e.g., $dN(R) \propto R^{\text{-3.6 or so}}$], the same radial distribution [$\sigma \propto r^{\text{-2 or so}}$] and the same inclinations [$i_{\text{apparent}} \sim 10^\circ$] as is observed in the inner $r < 50$ AU part of the Belt, then about 8% of all telescopic KBO detections should occur at distances beyond $r > 50$ AU, *regardless of the observer's limiting magnitude*.

- 243 KBOs have been detected, so one might expect to find a total of ~ 20 KBOs beyond $r > 50$ AU.

- However only 2 KBOs have been observed beyond $R > 50$ AU, and both are members of the Scattered Disk.

- This discrepancy suggests that some of the preceding assumptions are incorrect.

IV. Three Possible Solutions

- Perhaps the “Classical” Kuiper Belt ends at $r = 50$ AU. *This, however, is not a very compelling explanation since disks around other young stars are often hundreds of AU across.*

- The KBO size–distribution $dN(R)$ might vary with distance r, Specifically, the maximal KBO size $R_{\text{max}}(r)$ could decrease with distance r. *Although plausible, this explanation requires a very steep power–law,* $R_{\textit{max}}(r) \propto r^{\textit{-4 or faster}}$ *(Hahn and Brown 1999). This steep decrease in* $R_{\textit{max}}$ *with* r *is not supported by recent KBO accretion models (e.g., Davis* $et\ al.$ *1999).*

- The planet–migration scenario predicts that KBOs beyond Neptune’s 2:1 resonance at $r = 48$ AU should reside in undisturbed orbits (see Fig. 2). Such KBOs would appear to inhabit a very thin ring on the sky–plane. If this KBO ring is inclined from the ecliptic, where most KBO surveys take place, then it could have easily escaped detection.

V. Could Distant KBOs Inhabit a Dynamically Cold Disk?

- Figure 3 shows the ecliptic coordinates of the deep pencil–beam surveys, most of which are along the ecliptic.

- These pencil–beam surveys searched down to magnitude $m \simeq 25$ to 28, and could have detected KBOs of radii $R \simeq 20$ to 50 km at $r = 50$ AU. No such KBOs were found.

- Note that if this dynamically cold disk of KBOs were inclined by at least 0.5° from the ecliptic, it would have easily escaped detection.

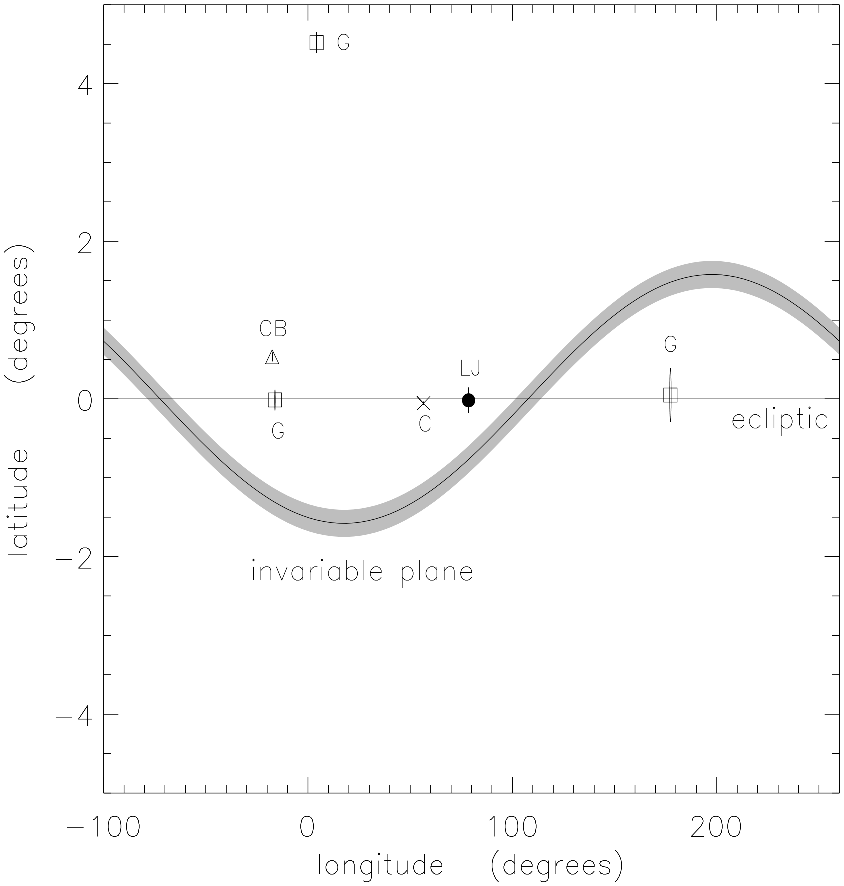

Figure 3. The ecliptic latitude and longitude of the deep pencil–beam surveys by G = Gladman *et al.* (1998), LJ = Luu and Jewitt (1998), CB = Chiang and Brown (1999), and C = Cochran *et al.* (1995). The vertical bars indicates the surveys' areal coverage which appear squashed due to the choice of axes. Also shown is the invariable plane which is inclined by $i = 1.6^\circ$ from the ecliptic. The half–width of the shaded region is 0.2° and corresponds to the maximum vertical velocities reported in the recent KBO accretion model of Kenyon and Luu (1999).

VI. Looking for Distant KBOs

- The natural place to look for a cold disk of KBOs is near the invariable plane, which is essentially the mean plane inhabited by the giant planets. This plane is inclined by 1.6° from the ecliptic (see Fig. 3).

- Later this year, Hermann Boehnhardt (ESO) and I will search for this hypothetical disk of KBOs by surveying down to magnitude $m \simeq 26$ along a vertical stripe running $\pm 4^\circ$ from the ecliptic using the ESO 2.2m telescope at La Silla, Chile.

VII. Distant KBOs and the History of the Outer Solar System

The detection of distant KBOs in a Classical Disk extending beyond Neptune's 2:1 resonance at $r = 48$ AU would provide valuable constraints on various models of the accretion and orbital evolution of the outer solar system.

A. For instance, the discovery of KBOs in a common orbital plane beyond $r > 48$ AU would support the planet–migration scenario described in II.

However there are alternate histories for the outer solar system:

B. Petit *et al.* (1999) suggest that the Classical Disk's stirred state (e.g., $e \sim \sin i \sim 0.1$) was due to scattering by other failed protoplanets that briefly roamed the outer solar system.

C. Thommes *et al.* (1999) propose that Uranus & Neptune where themselves scattered outwards by Jupiter & Saturn, and that dynamical friction with a massive Kuiper Belt subsequently circularized Uranus & Neptune's orbit. This can also stir up the Kuiper Belt.

D. And Ida *et al.* (200) suggest that the Kuiper Belt was instead stirred due to the close passage of another star.

VIII. What can be Inferred from Distant KBOs?

- If astronomers do find a dynamically cold Kuiper Belt beyond Neptune's 2:1 resonance, then we may conclude that a migrating Neptune (scenario A) was the dominant source of the perturbations that are recorded in the $r < 48$ AU part of the Classical Disk.

- But if KBOs beyond $r > 48$ AU do exhibit sizable eccentricities and inclinations, then we can conclude that additional perturbations (perhaps scenarios B, C, and/or D) were also responsible for stirring op the Classical Disk. However an episode of planet–migration is still required to account for the Plutinos at the 3:2 resonance.

IX. References

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