THE OUTER EDGE OF THE KUIPER BELT. J. M. Hahn, *Lunar and Planetary Institute, Houston TX 77058, USA, (hahn@lpi.usra.edu)*.

One of the more curious features of the Kuiper Belt is the apparent dearth of Kuiper Belt Objects (KBOs) orbiting the Sun beyond 50 AU with modest eccentricities and inclinations, e.g., with $e \sim \sin i \lesssim 0.3$. Their non–detection is not simply due to a selection effect since deep pencil–beam surveys can view the Kuiper Belt down to limiting magnitudes of $m \simeq 25.4$ to 28 [1, 2, 3]. These surveys could have detected KBOs having radii $R > 20$ to 50 km at $r = 50$ AU and an albedo $a > 0.04$. Note that KBOs of these sizes are plentiful at smaller heliocentric distances. One possible explanation for their absence at greater distances is that the solar nebula, which is the progenitor of the Kuiper Belt, was truncated at 50 AU. However this idea is not very compelling since disks around other stars have typical radii of a few hundred AU. Another possible explanation is that the maximum size of KBOs, $R_{\max}(r)$, *decreases* with heliocentric distance r, which could explain the absence of large distant KBOs from most surveys [4]. However the null result obtained by the deeper pencil–beam surveys requires $R_{\max}(r)$ to fall off faster than r^{-4}, a variation that is significantly faster than is reported in a recent KBO accretion model [5]. The following shall instead consider an alternative explanation, that the distant Kuiper Belt beyond 50 AU is dynamically cold and thus appears as a very thin disk when projected upon the sky. This configuration is quite plausible in light of the fact that small distant bodies can form only while in nearly circular orbits. It would also explain why the pencil–beam surveys have not yet detected these bodies; astronomers are probably not looking in the correct part of the sky.

Accretion models show that about 30 Earth–masses of dust starting in nearly circular orbiting between $30 < r < 50$ AU is necessary in order to produce at least one Pluto and the observed population of $\sim 10^5$ KBOs of radii $R > 50$ km [6]. This process occurs via runaway growth in about 40 million years, after which accretion stalls as the larger KBOs raise the swarm's random velocities. Subsequent collisions at higher velocities are thought to grind the $R \lesssim 1$ km bodies down to dust, which is presumably removed by radiation forces [6, 7]. However the anticipated eccentricities e and inclinations i of the larger survivors are still much smaller than the $e \sim \sin i \sim \mathcal{O}(0.2)$ that is currently observed among KBOs (Fig. 1). This excitation is evidently due to other perturbers.

Several scenarios have been suggested as the source of this excitation: (*i*) the formation of Neptune and its outward migration into the Kuiper Belt [8, 9], (*ii*) the scattering of Earth–mass planetesimals into the Kuiper Belt by Neptune [10], (*iii*) the scattering of a proto–Uranus and proto–Neptune into the Kuiper Belt by Jupiter and Saturn [11], and (*iv*) the close passage of another star to within $r \sim 150$ AU [12]. Although most of these scenarios can be tweaked and/or combined such that they produce the observed excitation (including the abundance of high–e KBOs at Neptune's mean–motion resonances seen in Fig. 1), they all make distinct predictions about the state of the Kuiper Belt beyond $r > 50$ AU. The detection and characterization of this part of the Belt, if it exists, would provide a critical test of these scenarios.

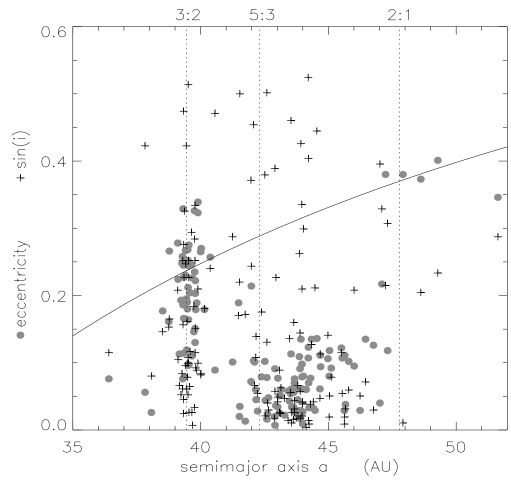

Figure 1: KBO eccentricities (●) and inclinations (+) versus semimajor axis a. The locations of Neptune's 2:1, 5:3, and 3:2 mean–motion resonances are also indicated. KBOs having eccentricities above the curve are on Neptune–crossing orbits.

According to scenario (*i*), Neptune forms after Pluto and the large KBOs have already accreted. The planet gravitationally scatters neighboring KBOs, and the ensuing angular momentum exchange drives Neptune outwards about 8 AU into the Kuiper Belt. This slow and steady expansion of Neptune's orbit allows the planet to capture KBOs at its mean–motion resonances, which pumps up eccentricities to the observed values[1]. However Neptune's gravitational influence ends at its 2:1 resonance, so the orbit elements of the undisturbed KBOs beyond $r > 50$ AU should reflect their primordial e and i.

The maximum angular thickness of this disk may be estimated by treating these distant KBOs as a swarm of particles having a single size R. When in equilibrium, the swarm will have random velocities comparable to their surface escape velocity, which yields inclinations of $\sin i \simeq \sqrt{2\rho r R^2/M_\odot} \sim 10^{-4}(R/1\text{ km})$, where ρ is the KBO bulk density and $M_\odot$ is the solar mass. It is noted that a shallow but wide–angle KBO survey examined 52 square degrees around the ecliptic to a limiting red magnitude of 22.5 and did not detect any $r > 50$ AU KBOs in the classical disk [13]. Since this survey is quite likely to have had the putative cold Kuiper Belt along

[1]It should be noted that the planet–migration scenario does not completely explain the observed distribution of KBO orbit elements, in particular, the high inclinations among KBOs orbiting beyond the vertical secular resonance at 41 AU, as well as the low abundance of KBOs that might be trapped at the 2:1. These issues are currently being investigated by the author.

its line–of–sight, it establishes an upper limit of $R \lesssim 200$ km on the size of KBOs at $r = 50$. This implies that the dynamically cold disk would have inclinations smaller than about 1°. But it is also likely that smaller, harder–to–see KBOs would also be abundant, in which case dynamical friction can reduce the larger bodies' random velocities by as much as an order of magnitude or more. Thus the largest and most visible KBOs beyond 50 AU might inhabit a narrow plane that would appear razor–thin on the sky.

Scenario (*ii*) attributes the observed KBO excitation to "Large Neptune–Scattered Planetesimals"; these are essentially failed protoplanetary cores of mass ~ 0.1 to 1 $M_\oplus$ that may have once roamed about the young Kuiper Belt. Since their disturbing influence would likely extend beyond Neptune's 2:1 resonance, the detection of eccentric, inclined KBOs with semimajor axes beyond 50 AU would support the notion that there were once fairly massive bodies at these heliocentric distances.

Scenario (*iii*), which is a radical variation of the preceding theme, suggests that Uranus and Neptune themselves are failed protoplanetary cores that initially formed in the vicinity of Jupiter and Saturn but were subsequently scattered outwards into wide eccentric orbits. Gravitational interactions with a very massive 100–200 $M_\oplus$ trans–saturnian Kuiper Belt (containing enough mass to assemble ~ 10 additional Neptunes!) subsequently circularize the planets' orbits at their present heliocentric distances. However simulations show that these planets' temporarily large aphelia allow them to stir the Kuiper Belt, sometimes out to great heliocentric distances.

Scenario (*iv*) suggests that the stirred state of the Kuiper Belt is due to the close passage of a solar–mass star to within $r \sim 100$–200 AU; this is most likely to have occurred early in the solar system's history when the Sun may still have been a member of a young stellar cluster. This scenario is unique in that it predicts KBO eccentricities and inclinations to *increase* with heliocentric distance.

These preceding scenarios all make distinct, testable predictions as to the state of the distant part of the Kuiper Belt beyond 50 AU. However it should be noted that the null result obtained by the pencil–beam surveys [1, 2, 3] places a tight constraint on the size and density of KBOs in a stirred disk beyond 50 AU. Specifically, there are no more than $\Sigma \sim 1$ KBOs per degree^2 of radius $R \gtrsim 50$ km in the vicinity of 50 AU; this surface–density limit is substantially smaller than the $\Sigma \sim 7$ KBOs per degree^2 reported by the shallower surveys for $R \gtrsim 50$ km bodies in the $r < 50$ AU zone [13].

Nonetheless this null result is quite consistent with the possibility of a distant, dynamically cold Kuiper Belt. Figure 2 shows the ecliptic coordinates of the published pencil–beam surveys. It is evident that if a thin Kuiper Belt is inclined by at least 0.5° from the ecliptic plane then it would have easily escaped detection. Although this hypothetical Belt has an unknown inclination and node, the first place one might look for it is near the invariable plane, which is essentially the mean plane inhabited by the giant planets (see Fig. 2). A search for this disk would require a deep survey at a fixed longitude that scans the Kuiper Belt over latitudes of perhaps $\pm 2^\circ$ from the ecliptic, preferably using a modern wide–field camera. The minimal experiment need only detect a handful of KBOs beyond 50 AU to demonstrate whether they inhabit a common plane on the sky; orbit determinations are not necessary. It should also be noted that about 5% of all KBOs are members of the Scattered Disk, which are KBOs that probably formed near Neptune but were scattered to greater heliocentric distances [14]. These high–inclination objects would also appear in this survey at similar abundances.

A telescopic search for a distant, dynamically cold Kuiper Belt is recommended since its presence, or absence, would place strong constraints on the various models that endeavor to explain both the orbital as well as the accretion histories of the Kuiper Belt and the giant planets Uranus and Neptune.

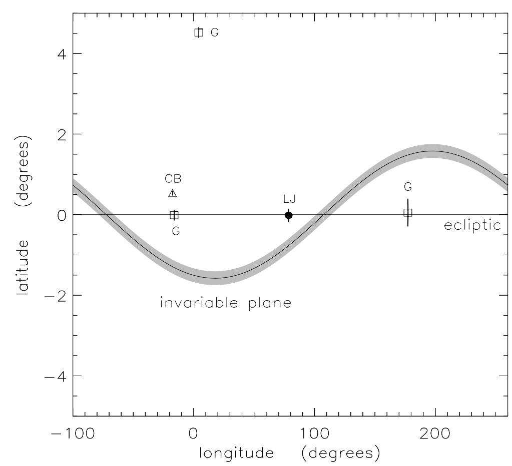

Figure 2: The ecliptic latitude and longitude of the deep pencil–beam surveys by G = Gladman *et al.* (1998), LJ = Luu and Jewitt (1998), and CB = Chiang and Brown (1999). The vertical bars indicates the surveys' areal coverage which appears squashed due to the choice of axes. The LJ survey did not report all if its lines–of–sight, so this figure is incomplete. Also shown is the invariable plane which is inclined by $i = 1.6^\circ$ from the ecliptic and has a node $\Omega = 107.6^\circ$ from the equinox. The half–width of the shaded region is 0.2° and corresponds to the maximum vertical velocities reported in a recent KBO accretion model [6].

References: [1] Gladman *et al.*, 1998, AJ, 116, 2042, [2] Luu and Jewitt, 1998, ApJ, 502, L91, [3] Chiang and Brown, 1999, AJ, 118, 1411, [4] Hahn and Brown, 1999, LPSC XXX, [5] Davis *et al.*, 1999, LPSC XXX, [6] Kenyon and Luu, 1999, AJ, 118, 1101, [7] Stern and Colwell, 1997, AJ, 114, 841, [8] Malhotra, 1995, AJ, 110, 420, [9] Hahn and Malhotra, 1999, AJ, 117, 3041, [10] Petit *et al*, 1999, Icarus, 141, 367, [11] Thommes *et al*, 1999, Nature, 402, 635, [12] Ida *et al*, 2000, ApJ, in press, [13] Jewitt *et al*, 1998, AJ, 115, 2125, [14] Duncan and Levison, 1997, Science, 276, 1670.