THE EDGE OF THE SOLAR SYSTEM

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ABSTRACT

We have surveyed for Kuiper Belt objects (KBOs) in six fields of the ecliptic (total sky area 1.5 deg\(^2\)) to limiting magnitudes between \(R = 24.9\) and \(R = 25.9\). This is deep enough to detect KBOs of diameter \(\geq 160\) km at a distance of 65 AU. We detected 24 objects. None of these objects, however, is beyond 53 AU. Our survey places a 95% CL upper limit of \(\Sigma < 5\) deg\(^{-2}\) on the surface density of KBOs larger than \(\sim 160\) km beyond 55 AU. This can be compared to the surface density of \(\sim 6\) deg\(^{-2}\) of \(\geq 160\) km KBOs at distances 30–50 AU determined from this survey and previous shallower surveys. The mean volume density of \(D > 160\) km KBOs in the 55–65 AU region is, at greater than 95% confidence, less than the mean density in the 30–50 AU region, and at most two-thirds of the mean density from 40 to 50 AU. Thus, a substantial density increase beyond 50 AU is excluded in this model-independent estimate. A dense primordial disk could be present beyond 50 AU if it contains only smaller objects or is sufficiently thin and inclined to have escaped detection in our six survey fields.

Subject headings: Kuiper Belt — minor planets, asteroids — solar system: formation

On-line material: color figure

1. INTRODUCTION

Our current general understanding of the formation of our solar system is consistent with the expectation that a large population of small bodies—leftovers from the primordial planetesimal disk in the solar nebula—exists at the present time beyond the orbits of Neptune and Pluto, where planetary accretion timescales exceed the current age of the solar system. Direct observational evidence for such a population (now known as the Kuiper Belt) was first obtained with the discovery of 1992 QB\(_1\) (Jewitt & Luu 1993) and has subsequently grown under contract NASW-4574 with the National Aeronautics and Space Administration.

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images are registered and summed (with σ-clipping rejection) to yield a deep template image of the fixed field. The template is then subtracted from each individual exposure after applying an algorithm to match the point-spread functions, thus efficiently removing all nonmoving objects from the images. These images are first searched for bright slow-moving objects. Then each field’s images are summed with displacements to track a potential KBO motion, and the sum image is searched for faint objects, an approach similar to that used in other deep KBO searches (Tyson et al. 1992; Cochran et al. 1995; Gladman et al. 1998; Luu & Jewitt 1998; Chiang & Brown 1999). This last step is repeated several thousand times to permit detection of KBOs in any bound orbit at distances 30–80 AU. Candidate KBOs were confirmed using data taken 6–8 days apart.

Effective areas and limiting magnitudes are determined by inserting several thousand artificial KBOs into the raw data at a variety of velocities and positions. We then search for these using the same methods used to detect real KBOs. The total area subtended by the six search fields is 1.5 deg², but bright stars, CCD defects, etc., limit the effective area of the search to 1.3 deg² for bright KBOs. This effective search area is simply the total area surveyed multiplied by the probability of detecting an object of particular magnitude. The effective area drops at fainter magnitudes because of noise but has minimal velocity dependence, since all the objects move appreciably over the two-night detection baseline.

The 1998 May observations used the Kron-Cousins R filter, and we find that the effective area of these three fields of the search is 0.51 deg² at bright magnitudes, dropping by 50% at R = 25.2. The 1999 May observations, using a wideband VR filter (Jewitt, Luu, & Chen 1996), reach 50% completeness for 25.7 R mag KBOs over effective area of 0.77 deg². VR magnitudes are converted to R as described in the notes of Table 2. Table 1 lists the fields observed for this survey and the total integration times, limiting magnitudes and effective areas for each. Several times more area is covered than for the largest previously published survey to this depth (Luu & Jewitt 1998).

Twenty-three KBOs and one Centaur were discovered in the survey. The observing scheme produces a 10 day arc for most of these objects. Orbital parameters and their uncertainties are determined using the software described in Bernstein & Khushalani (2000). Although the full orbital parameters are poorly constrained by such a short arc, the distance is determined fairly accurately. Recovery observations have been made for seven of the objects, and in all cases the refined orbits produce distances consistent with the 10 day estimates. Table 2 lists detected objects and their heliocentric distances, and Figure 1 plots their size versus distance under the assumption of a 4% albedo. Distances beyond 53 AU are ruled out at greater than the 3σ level for all of these objects, save the poorly determined 1999 KK17 and 1999 JJ132. Placing either of these objects beyond 53 AU would require them to be near aphelion of very eccentric orbits; hence, we can exclude the possibility that they are dynamically primitive objects outside 53 AU. Thus, over 1.3 deg², we likely have zero detections of objects beyond 53 AU, and certainly no objects on near-circular orbits beyond this distance, even though objects with diameters larger than 160 km would be visible to 65 AU over much of the field.

The diameter D of each KBO is estimated from its absolute magnitude H by assuming a geometric albedo of 0.04, as in Jewitt et al. (1998), and taking the phase correction to be insignificant. Henceforth, we will be concerned only with “large” KBOs, having H ≤ 7.7 and implied D ≥ 160 km. An upper limit to the density of large KBOs in the 55–65 AU range is as follows: at 55 AU, a magnitude of R = 25.1 is sufficient to detect objects with H ≤ 7.7, while, at 65 AU, the necessary depth is R = 25.8. The search efficiency is dropping in this magnitude interval, so an exact estimate of the effective search volume would require a model for the intrinsic KBO distance distribution. An approximation adequate for our purposes is to take the effective area to be that of an H = 7.7 object at the midpoint, 60 AU. This corresponds to a magnitude of R = 25.5, at which the effective search area is 0.57 deg². Since the effective areas at 55 and 65 AU are 0.97 and 0.29 deg², respectively, this is comparable to the average effective area as well. Our upper limit to the surface density of KBOs with D ≥ 160 km at distances 55 < r < 65 AU is therefore 5 deg⁻² (95% CL).

### 3. COMPARISON TO THE INNER KUIPER BELT

We test the hypothesis of inner belt depletion by comparing the volume density of KBOs inside 50 AU with that outside 50 AU. Because we have a faint limiting magnitude and we have determined the distances (and hence approximate size) for all our detected objects, we can proceed by constructing samples of objects of similar size in the two distance regimes, without any assumption about the KBO size distribution. The outer region is the 55 < R < 65 AU annulus quantified above.

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### Table 1: Field Information

| Field | Dates of Observation<sup>a</sup> | R.A. (J2000) | Decl. (J2000) | Ecliptic Coordinates | Invariable Latitude | Exposure Time | Filter | $A^<b>_0$ | $m^<b>_0$ |
|-------|---------------------------------|-------------|--------------|----------------------|-------------------|--------------|--------|-----------|-----------|
| A     | 1998 May 19                     | 11 37 20    | +2 13 20     | 174.0               | -0.19             | -1.63        | 12     | R         | ...       |
|       | 1998 May 28–29<sup>*</sup>      | 11 37 22    | +2 14 34     | 173.9               | -0.18             | -1.63        | 19     | R         | 0.178     | 24.9    |
| B     | 1998 May 19                     | 13 02 36    | -6 46 00     | 197.0               | -0.03             | -1.61        | 18     | R         | ...       |
|       | 1998 May 28–29<sup>*</sup>      | 13 02 00    | -6 42 26     | 196.9               | -0.09             | -1.67        | 24     | R         | 0.180     | 25.2    |
| D     | 1998 May 19                     | 20 27 52    | -19 20 00    | 304.6               | -0.02             | 0.24         | 18     | R         | ...       |
|       | 1998 May 28–29<sup>*</sup>      | 20 47 35    | -19 19 47    | 309.1               | -1.40             | 0.81         | 26     | R         | 0.147     | 25.4    |
| E     | 1999 May 10–11<sup>*</sup>      | 12 05 00    | -0 30 00     | 181.4               | 0.04              | -1.48        | 33     | VR        | 0.163     | 25.8    |
|       | 1999 May 18–19<sup>*</sup>      | 12 04 34    | -0 32 28     | 181.3               | -0.01             | -1.53        | 33     | VR        | 0.200     | 25.3    |
| F     | 1999 May 10–11<sup>*</sup>      | 14 00 00    | -12 12 00    | 212.2               | 0.03              | -1.50        | 30     | VR        | 0.196     | 25.9    |
|       | 1999 May 18–19<sup>*</sup>      | 13 59 21    | -12 15 15    | 212.1               | -0.08             | -1.61        | 33     | VR        | 0.200     | 25.8    |
| G     | 1999 May 10–11                  | 20 45 00    | -18 00 00    | 308.8               | 0.05              | 0.62         | 48     | VR        | ...       |
|       | 1999 May 18–19<sup>*</sup>      | 20 45 00    | -18 00 00    | 308.8               | 0.05              | 0.62         | 44     | VR        | 0.167     | 25.7    |

<sup>a</sup> Observations marked with asterisks were searched for KBOs; unmarked observations were used only for recovery.

<sup>b</sup> $m_0$ and $A_0$ are fitted to the effective area $A$ for detection of implanted KBOs using $A = (A_0/2) \operatorname{erfc}(m - m_0)/(2w)$. $A_0$ is the maximum effective area for each field, $m_0$ is the point where the effective area is 50% of $A_0$, and $w$ is a width parameter.
The absence of any objects in the outer sample region limits the volume completeness limits of the 1998 and 1999 survey fields. The two rectangular boxes denote lines of constant magnitude, corresponding to the 50% confidence level. 

\[
\text{V}_1 > 0.50 \quad \text{(each sample's volume of the outer region).}
\]

For our inner region, we select all KBOs with distances in the range 30–50 AU and again \( H \leq 7.7 \). Most known KBOs within 40 AU are in mean-motion resonance orbits or have likely been perturbed by a Neptune encounter, affecting the surface density of KBOs in an uncertain manner. For this reason, we will also compare our results with an inner region of 40–50 AU.

Denoting the mean volume density of \( H \leq 7.7 \) KBOs in the inner and outer regions as \( n_1 \) and \( n_2 \), respectively, we are interested in an upper bound to the density ratio \( f \equiv n_1/n_2 \). It is easily shown that, under a Bayesian analysis with a uniform prior on \( n_1 \), we can find the probability that \( f \) is above some value given \( N_1 \) detected objects in the inner region over an effective volume \( V_1 \) and \( N_2 = 0 \) objects detected in the effective volume \( V_2 \) of the outer region. In this case, the probability that \( f \) is above some value is

\[
P(>f) = (1 + fV_2/V_1)^{-N_1}.
\]

Our survey yields \( N_1 = 8 \) KBOs that have a distance between 30–50 AU and \( H \leq 7.7 \). These are all brighter than \( R = 24.1 \). The ratio of volumes between the 55–65 AU sample and the 30–50 AU sample, \( V_1/V_2 \), is 0.50 (each sample's volume is that subtended by its effective area). Equation (1) then gives \( f < 0.91 \) at 95% confidence. If only the seven KBOs in the inner region from 40–50 AU are considered, then we find \( f < 0.68 \) (95% CL). We can thus assert in a model-independent way that the density of KBOs in the 55–65 AU range is at least one-third lower than in the 40–50 AU range.

We could estimate the inner region density from other surveys...
with brighter magnitude limits than ours, though the comparison with our own brighter objects has the advantage of canceling any dependence on ecliptic latitude or longitude that may be present in the KBO density. Of the very few published wide-area KBO surveys, Jewitt et al. (1996, hereafter JLC) is the closest to ours in magnitude limits and area covered. The JLC survey covers 8.3 deg² to a limiting magnitude of R = 24.2. At this depth, KBOs must have H ≤ 7.3 (D ≥ 200 km) to be visible all the way to 50 AU. Out of 15 KBOs found by JLC, 11 have distances within 30–50 AU and H ≤ 7.3. Using JLC’s effective areas quoted at R = 23.2 and R = 24.2, a rough estimate for the effective area for all 11 KBOs is 6.1 deg². Our survey can detect H ≤ 7.3 objects to a distance of 67 AU, if the same R = 25.5 limit is used, so we may conservatively take the outer region in this case to be 55–67 AU across the 0.57 deg² effective area for R ≤ 25.5. This then yields a Bayesian limit of f < 2.44 (95% CL) for the ratio of outer to inner volume densities of H ≤ 7.3 objects.

Our failure to detect any scattered-disk objects beyond 50 AU does not invalidate our argument, since we claim only a fair sample of the population, not an exhaustive survey. We can test the fair-sample hypothesis by examining our detected population of H ≤ 7.7 objects; we claim that this population is complete to about 65 AU and that a majority of the population is within 55 AU, i.e., that we are capable of detecting most of the objects anywhere in their orbits. There should consequently be no bias toward finding objects at perihelion. Examining the nine objects with H ≤ 7.7 in Table 2, we see that four are closer to aphelion than perihelion (1998 KY₆₁, KC₆₂, K₉₆₃, and 1999 KR₆₃), one is nearer perihelion (1998 KS₆₃), and four have uncertain a (1999 JA₁₃₂, JB₁₃₂, JD₁₃₂, and JF₁₃₂). Our objects’ distance distribution is thus qualitatively consistent with an unbiased sampling of their own orbits. A quantitative comparison (K-S test) also demonstrates internal consistency. While this is a weak test, it is one that the full population of known KBOs fails miserably—there is an extremely strong bias toward objects near perihelion. Indeed, our 1999 KR₉₃ is the only known KBO of significant orbital eccentricity (e > 0.1) to be discovered near aphelion.

Our lack of detections beyond 55 AU is consistent with a density beyond 55 AU that is at most similar to that within 50 AU, and it is likely that we have observed an underdensity in the outer Kuiper Belt. The measurements are not consistent with a large increase in the surface density beyond 50 AU.

4. CONCLUSIONS

If planetary perturbations are solely responsible for the structure of the Kuiper Belt, a dense primordial disk would be expected beyond ~50 AU where these perturbations are insignificant. Our survey would have detected such a disk but did not. Possible reasons for this nondetection are:

1. KBOs in the outer Kuiper Belt could be fainter than expected, owing to a lower albedo or much redder color or much smaller sizes. To explain our survey results, this would require a change in the physical properties of KBOs beyond 50 AU.

2. The outer Kuiper Belt could have been dynamically excited early in the history of the solar system by a stellar encounter (Ida, Larwood, & Burkert 2001), or by perturbations from large Neptune-scattered planetesimals. Such excitation could have increased the orbital inclinations and eccentricities of the objects, lowering the apparent surface density on the sky and possibly decreasing the maximum size of objects through the cessation or reversal of the accretion process. More extreme excitation could have stripped away the outer Kuiper Belt.

3. The disk is actually present, but dynamically cold (Hahn 2000). It could have escaped our survey by simply not intersecting our fields, entirely possible if this disk is inclined to the ecliptic plane. The invariable plane (the angular momentum plane of the solar system), inclined to the ecliptic by 1°5′, would be a likely candidate for the location of such a cold, dense disk. Our field G is only 0°6′ from the invariable plane, so the scale height of the cold disk would have to be ≪1° to have escaped detection. This implies a very thin, extremely dense disk. Absence of KBOs beyond 50 AU in future deep survey fields would eliminate the possibility of a cold disk.

4. Another possibility is that a dense planetesimal disk never existed beyond ~50 AU. If the outer planets, Uranus and Neptune, formed much closer to the Sun than their present distances (cf. Malhotra 1993, 1995), then the primordial surface density beyond ~30 AU may have been very small initially. This would suggest that the larger KBOs actually formed interior to 30–40 AU and were displaced to their present orbits by a large-scale rearrangement of orbits in the outer solar system.

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