

*Letter to the Editor***Kuiper Belt searches from the Palomar 5-m telescope****Brett Gladman¹ and JJ Kavelaars²**¹ Dept. of Astronomy*, 406 Space Sciences Bldg., Cornell University, Ithaca, NY, 14853, USA² Dept. of Physics and Astronomy*, Queen's University, Kingston, ON, K7L 3N6, CANADA

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Abstract. Motivated by a desire to understand the size distribution of the Kuiper Belt, an observing program was conducted at the Mount Palomar 5-m telescope from 1994–1996. The observations consisted of follow-up observations of known objects (in order to improve their very indeterminate orbits), and deep exposures on a single field to search for small objects below the limiting magnitudes of other surveys. Eighteen object recoveries were successfully obtained over the course of the follow-up program. Data reduction of the deep fields consisted of a software recombination of many fields shifted at different angular rates in order to detect objects at differing heliocentric distances. We set an upper limit of < 1 object per 0.05 square degrees in the ecliptic brighter than magnitude $R \simeq 25$. The lack of detected objects in this work serves to help constrain the number density of Kuiper Belt comets.

Key words: Kuiper Belt – outer solar system – Trans-Neptunian objects

1. Introduction and Motivation

Observational searches for objects in the outer solar system, and especially in the trans-Neptunian region, began to produce consistent results beginning in 1992 with the discovery of the first so-called Kuiper Belt object 1992 QB1 (Jewitt and Luu 1993). Since then, approximately 3 dozen Kuiper Belt objects (KBOs hereafter) have been found (see Stern 1996 for a review), ranging in apparent magnitude from about 22 to 24.6 in R-band, and heliocentric distance from 30 – 45 AU. Assuming

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a comet-like albedo of $p = 0.04$, these objects have diameters ranging from 100 to 300 km, although it cannot be ruled that the brightness variation could be due to differing albedos rather than sizes.

The size distribution of KBOs is of great interest. Although originally it had been hoped that the population might be collisionless (and thus might hold the signature of the formation process), recent work (Stern 1995) has shown that the collisional effects cannot be neglected over 4.5 Byr. However, knowledge of the size distribution is still important for understanding the link between the Kuiper Belt and both the short-period comets (Levison and Duncan 1994) and Pluto (Stern 1996). After this Palomar search program was begun, the HST results of Cochran et al. (1995) provided another strong motivation (discussed below) by statistically detecting a very large population of Kuiper Belt comets.

The goal of this program was to find small KBOs rather than more objects with diameters of a few hundred kilometers. Instead of searching large areas of sky to limiting magnitudes of $R \simeq 23 - 23.5$, the intent was to concentrate on a single field (for each observing run) and integrate for 4–6 hours to reach a limiting magnitude of $R \simeq 26$. In essence, the hope was that a power law increase in the number of objects with decreasing magnitude would dominate the loss due to searching a single field.

Figure 1 shows a compilation of previous results, adapted from a figure from Irwin et al. (1995), whose assumptions we adopt below. The plot shows the number of outer solar system objects as a function of absolute H_R magnitude. The H_R magnitude is the apparent magnitude of the object if it were 1 AU from both the Sun and Earth; we can use $R = H_R + 10 \log r_{AU} \simeq H_R + 16$ for objects at 40 AU. The cumulative number $N(< H_R)$ of objects brighter than some specified H_R magnitude is computed from an estimated projected sky density by assuming a Kuiper belt of width $\pm 10^\circ$ extending uniformly around the ecliptic. Fig. 1 shows the results of direct searches in the Kuiper belt (solid symbols), and model-dependent limits (open symbols) based on the conversion of Kuiper Belt objects into Cen-

taurs. The data sets connected by lines on the left half of the figure are upper limits of various surveys described in Irwin et al. (1995). The Jewitt and Luu (JL) survey provides a direct detection of 6 objects per sq. degree, and model dependent limits on smaller objects through the non-detection of Centaurs. The Spacewatch program provides a model-dependent data point due to their observations of Centaurs; Kowal's discovery of Chiron provides another. The HST observations are best interpreted (Levison, 1996, private communication) as detecting 2:3 Neptune librators near their perihelia at ≈ 33 AU, which implies $N \sim 2 \times 10^8$ objects brighter than $H_R = 12.8$, as is plotted on Fig. 1.

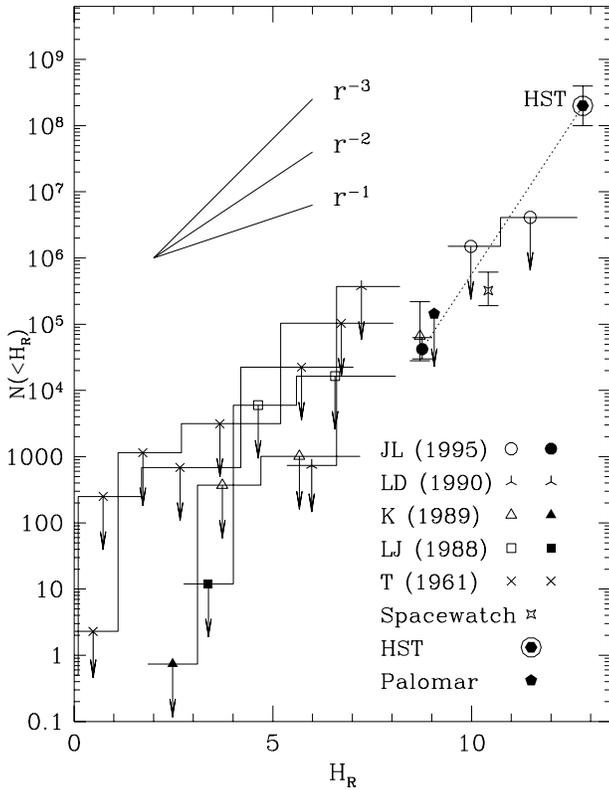


Fig. 1. Constraints on the Kuiper Belt luminosity function, adapted from Irwin et al. (1995). Filled symbols are direct observational constraints for objects in the Kuiper Belt; hollow symbols show model-dependent constraints related to the number of Centaurs interior to Neptune. Power-law indices indicate the slopes of various cumulative size distributions in the top center. The Palomar point indicates the result of the survey; the target magnitude was in fact $H_R = 10$.

Connecting the two positive searches of the Kuiper Belt (the JL and HST data points) yields a single power law slope which is reasonably consistent with all the data (including the upper limits on the left of the figure). If true, then there should be ~ 5 objects per $10' \times 10'$ field at $R \approx 26$ (the proposed depth of the Palomar observations). This pencil-beam survey should thus be able to determine the reality of this proposed power law, and a negative result would mean that either the HST result was spurious or that the size distribution must steepen rather

precipitously after $H_R = 10$, and cannot be fit by a single power law in the range $8 < H_R < 13$.

The orbital properties of the known KBOs are much less well constrained than may be generally realized. At the time of writing, of the 39 KBOs ever given provisional designations, 11 should be considered lost, 18 have been observed solely at one opposition, and only 11 have multi-opposition orbits of somewhat good quality (Marsden, 1996, private communication). Therefore, frequent follow-up observations of these objects are crucial to prevent them from being lost. Without good orbit determinations, dynamical studies are handicapped (see Duncan et al. 1995, Morbidelli et al. 1995). Thus, a second goal of this observation program was to recover as many known objects as possible to determine astrometric positions, which were then communicated to the Minor Planet Center.

2. Observational procedures

A 2048×2048 thinned Tektronix CCD was used at prime focus of the 5-m Hale telescope. The chip has high quantum efficiency (85 – 90% from 550 – 750 nm) and a fast readout (40 secs with binned pixels of $0.56''$). The square field of view is $9.7'$ on a side. Due to the bright sky at Palomar, the Gunn r filter was used for the majority of the observations (Thuan and Gunn 1976); this filter, designed to screen out specific night sky lines, is centered at 655 nm with a full-width of 90 nm.

Since KBOs at opposition have retrograde motions of 3–5''/hour, integration times were limited to 300 sec to prevent trailing losses with $0.56''$ pixels. For $2''$ seeing, 300 sec exposures produced a SNR of 4 for objects with $R \approx 23$, which is sufficient to recover most known KBOs, but is clearly insufficient to detect the faint objects we are searching for in the pencil-beam survey. For these objects, we needed to recombine a series of images in software, assuming a direction and rate for the retrograde motion; i.e., the same method used in the HST data reduction of Cochran et al. (1995). Fortunately, since our searches were done looking towards opposition, the predictable retrograde motion always dominates the sky rate, and recombinations at different orbital inclinations (Cochran et al. 1995) were found to be unnecessary. Therefore, each angular rate corresponds to first order to different heliocentric distances. By recombining the frames at a variety of rates, we can search for objects from 10–60 AU. Since there appear to be fewer Centaurs per sq. degree than KBOs (fainter than $H_R=8$), the most likely discovery is of new KBOs in the range 30–40 AU. Our 300 sec integration time was not optimized to detect Centaurs in any case, since trailing losses would occur inside Uranus (the poor seeing conditions obtained meant that trailing losses between 20 and 30 AU were not significant).

All images involved in the deep search were de-biased and flat-fielded as usual. Only the worst cosmic rays were removed, since automated routines might remove the objects we are looking for. The data analysis software consists of an IRAF¹ script which, given an angular rate and direction, recombines the im-

¹ The Image Reduction and Analysis Facility is distributed by the National Optical Astronomy Observatories, operated by the Associa-

Table 1. Summary of KBO follow-up observations, for all objects for which images were obtained at 2 or more times during the run. A number in () following an object indicates that the observation was the first recovery for that opposition. (C) indicates that 1993 HA2 is a Centaur, and (P) indicates the 1994 EV3 observation was not measured due to its poor quality and because it was simultaneously recovered at Mauna Kea. (N) indicates not found, despite a more than sufficient limiting magnitude.

Date	# nights	# open	KBO fields obtained, and results
Mar 1994	2	0	none
Dec 1994	3	2 hours	1993 SC (with CFHT help)
Feb 1995	2	6 fields	1993 FW (3), 1994 EV3(P), 1994 GV9, 1994 JQ1, 1994 JV(N)
Jun 1995	3	2	1993 HA2 (C), 1993 RO (3), 1994 JS, 1995 KJ1 (1), 1995 KK1(N), 1994 TB (2)
Jan 1996	4	2.5	1994 GV9(3), 1994 VK8, 1995 DA2, 1995 HM5(2), 1995 YY3(1) 1995 GA7(N), 1995 GJ(N), 1994 JV(N)
Apr 1996	1	3 fields	1994 GV9, 1995 DC2, 1995 HM5

ages by shifting their pixels and then co-adding them. The offsets are calculated from the time delay between the start of any given exposure and one chosen reference frame (usually the first). Thus, all stationary objects will elongate, trailing in the direction of recombination; only objects moving at the specified angular rate will have their signal constructively add into a single seeing disk. Experimentation with median filtering the frames before recombination in order to remove all stationary objects met with mixed success due to the problem of variable seeing (over the 4–6 hour integration) causing different point-spread functions. Since the deep-search fields were selected to have very few background stars, this refinement produced negligible improvement.

For object recovery, multiple images of the fields were simply blinked in software to detect the known KBOs. Astrometric positions were then calculated by computing a full plate solution using either the HST Guide star catalog, or the APM sky survey. Computed positions were generally accurate to sub-arcsecond, neglecting possible systematic errors in the catalogs. The positions were reported to the Minor Planet Center for orbit improvement.

3. Results

We first summarize the results of the recovery attempts (Table 1). This portion of the program was quite successful, as evidenced by the 18 follow-ups, even though the seeing conditions on most of the nights were poor (1.8'' at best). The February 1995 and April 1996 observations were conducted as service observing by Tyler Nordgren (Cornell University), and consisted of images of KBO fields acquired in the normal course of obtaining sky flats (a very productive use of this otherwise ‘dead time’). The KBO 1993 SC was recovered only in conjunction with observations conducted in early Jan. 1995 at the Canada France Hawaii Telescope (CFHT) by one of us (JJK). Considerable time was spent in Jan. 1996 attempting to recover 3 of the KBOs, but despite searches along long arcs to depths one magnitude fainter than the discovery brightness, 1995 GA7, 1995 GJ, and 1994

JV could not be found and should be considered lost (and are counted among the 11 so designated at the end of Sec. 1).

The deep search portion of the program was severely hampered by consistently poor seeing on those nights for which the dome could be opened. Seeing ranging from 1.9''–2.5'' was typical, thus decreasing the limiting magnitude of the deep search. Only 1 night was usable from the June 1995 run, and 2 nights (of a single field) were available from the Jan. 1996 observing run. Therefore, 0.05 square degrees of sky were searched in total. The limiting magnitude for SNR=4 objects in the June 1995 field was $R \simeq 24.8 \pm 0.2$ (the error being due to the night not being photometric). Although many faint main-belt asteroids were detected by the detection software, no objects with retrograde motions slower than 10''/hour were found.

To insure that the recombination software functioned correctly, it was decided to conduct the January 1996 search in the field containing 1995 DA2, so that at least 1 KBO would exist in the field to be detected. The two available nights in this run both suffered from seeing worse than 1.8'' and were not photometric. Nevertheless, we had no trouble in recovering 1995 DA2 ($R \approx 23.2$), which was at a SNR $\simeq 4$ on each 300 sec exposure and thus easily visible in blinked images. Fig. 2 shows that the detection algorithm also has no difficulty (as it should) in finding this object. The trails on this image are all stationary stars and galaxies, the point-like object is the KBO, which is the combined result of 36 images that have been shifted and added at -3.5''/hour (the object’s retrograde motion) in the ecliptic. 1995 DA2 has a SNR of 25 in the combined image, and any object moving at a similar angular rate with a magnitude $R \simeq 25.2 \pm 0.2$ should come up to a SNR of 4 in the combined image. The target magnitude of $R \simeq 26$ was not reached due to the poor seeing and the fact that this caused the deep field to be abandoned earlier in the night than was originally planned.

The frames were combined at angular rates between 2 and 11''/hour; experiments with artificially implanted objects showed that an accuracy of 0.5''/hour was sufficient to detect the objects, and then the actual shift rate could be fine-tuned to precisely match the object’s motion. These angular rates correspond to retrograde opposition motions for direct circular orbits in the ecliptic plane from 10 – 60 AU. A detected object on the

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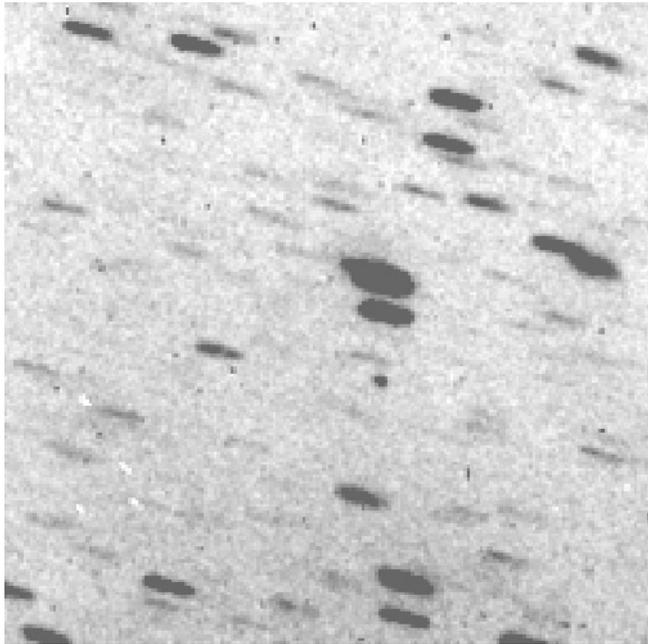


Fig. 2. An $\approx 2.5'$ portion of the Jan. 1996 deep field showing KBO 1995 DA2 (the point-like image near the center of the frame, below the two darkest streaks). Trails are images of stationary objects, which are smeared due to the recombination algorithm in this shifted and co-added image. The many obvious cosmic-rays can be easily rejected by their image profile.

first night of the June run could be recovered from the data from the second night, thus confirming its motion and allowing an orbit to be computed. No other (non-asteroidal) moving objects were found on the June fields however.

We thus are left with only an upper limit for the population of KBOs at this magnitude level. We choose to express this limit as there being <1 object per 0.05 square degrees brighter than $R = 25.0 \pm 0.3$, or, using the assumption of Irwin *et al.*, $N < 1.4 \times 10^5$ KBOs brighter than $H_R=9.0$, which is plotted on Fig. 1. The uncertainty in the upper limit is meant to reflect the facts that (1) none of the nights were photometric, (2) the two nights had different magnitude limits, and (3) objects weaker than $\text{SNR}=4$ have been recovered by us, and so this limit might be unnecessarily pessimistic. Poisson statistics imply <20 , <60 , and <120 objects per square degree at the 1, 2, and 3 σ levels, respectively.

The single limit thus produced can be seen to be entirely consistent with all other surveys. Unfortunately, our target of $H_R=10$ was not obtained due to poor seeing conditions. As can be seen from Fig. 1, if the same upper limit could be placed at $H_R=10$, then stiff constraints could be placed upon the size distribution. The negative result of this independent survey will help to constrain models of the luminosity function of the belt (Weissman and Levison 1996). A single night of good seeing would allow the magnitude limit to be improved dramatically.

4. Conclusions

We have attempted to address two major issues in Kuiper Belt research: (1) improving the orbits of known KBOs for dynamical studies, and (2) searching for fainter (and thus smaller) objects in order to improve knowledge of the size distribution. The objects recovered work have had their orbits constrained considerably, particularly for 1994 TB (Minor Planet Electronic Circular 1995-M07) and 1995 HM₅ (MPEC 1996-C05). The observations/orbits for first opposition objects can be found in Minor Planet Circulars 25494/25514 (1995 KJ₁) and 26660/26724 (1995 YY₃). An improved orbit for 1995 HM₅ from the April 1996 observations appears in MPC 27122. The upper limit on faint objects from the deep survey is consistent with previous surveys.

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References

- Cochran, A., Levison, H., Stern, S.A., Duncan, M., 1995, ApJ 455, 342
- Duncan M., Levison H., Budd M., 1995, AJ 110, 3073
- Jewitt D., Luu J., 1993, Nature 362, 730
- Jewitt D., Luu J., 1995, AJ 109, 1867
- Irwin M., Tremaine S., Zytlow A., 1995, AJ 110, 3082
- Levison H., Duncan M., 1994, Icarus 108, 18
- Morbidelli A., Thomas, F., Moons, M., 1995, Icarus 118, 322
- Stern S.A., 1995, AJ 110, 856
- Stern S.A., 1996, in: The Inventory of the Solar System, T.W. Rettig ed., ASP Conference Proceedings, to appear.
- Weissman P., Levison H., 1996, in: Pluto-Charon, University of Arizona Press, to appear.