Observational Limits on a Distant Cold Kuiper Belt

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\textbf{ABSTRACT}

Almost all of the > 600 known Kuiper belt objects (KBOs) have been discovered within 50 AU of the Sun. One possible explanation for the observed lack of KBOs beyond 50 AU is that the distant Kuiper belt is dynamically very cold, and thus thin enough on the sky to have slipped between previous deep survey fields. We have completed a survey designed to search for a dynamically cold distant Kuiper belt near the invariable plane of the Solar system. In 2.3 deg\textsuperscript{2} we have discovered a total of 33 KBOs and 1 Centaur, but no objects in circular orbits beyond 50 AU. We find that we can exclude at 95\% CL the existence of a distant disk inclined by $i \leq 1^\circ$ to the invariable plane and containing more than 1.2 times as many $D > 185$ km KBOs between 50 and 60 AU as the observed inner Kuiper belt, if the distant disk is thinner than $\sigma = 1^\circ.75$.

\textit{Subject headings:} Kuiper Belt—minor planets—solar system: formation

1. Introduction

More than 500 Kuiper belt Objects (KBOs) have been discovered since the first, 1992 QB1, was detected almost a decade ago. Nearly all of these are currently within 50 AU of the sun, and only one has been detected beyond 54 AU, despite surveys sensitive enough to detect 160 km-diameter KBOs to 60 AU. Such surveys have placed strong upper limits on the density of KBOs in an outer
Kuiper belt (Allen, Bernstein & Malhotra 2001; Trujillo et al. 2001; Jewitt, Luu, & Trujillo 1998; Gladman et al. 2001). There are several possible explanations for the observed absence of distant KBOs, each with distinctly different predictions for the Kuiper belt beyond 50 AU, and distinctly different implications for the history of the solar system.

In the simplest view of the Kuiper Belt, the region beyond 50 AU, where the gravitational perturbations of the giant planets become negligible, has remained dynamically cold, with KBOs moving on their primordial circular and coplanar orbits. It is inferred that the region inside 48 AU has been heavily depopulated, by a factor of 10-100 in mass, over the age of the solar system as a result of planetary perturbations and mutual collisions (Stern 1996; Stern & Colwell 1997; Levison & Duncan 1993; Duncan, Levison, & Budd 1995). In the absence of such perturbations, the outer disk is expected to be a factor of 5–100 times as dense as the presently observed inner Kuiper belt. However, as yet no discovered KBO has been determined to be in a circular orbit beyond 48 AU. Shallow surveys, with typical magnitude limits of \( R < 23.5 \), have searched for KBOs in more than 100 deg\(^2\) of sky, but objects at \( \geq 50 \) AU must be \( \geq 280 \) km in diameter to be detected in such surveys. (In quoting sizes of KBOs in this paper, we assume a 4% albedo.) It is desirable to search for smaller objects since the growth timescales for KBOs in the outer Kuiper belt, though highly uncertain, are likely longer than in the inner Kuiper belt. Only a few square degrees, however, have been surveyed to magnitudes \( R \gtrsim 24.5 \).

Hahn (2000) has pointed out that if the outer disk were dynamically very cold, thus restricted to a thin line on the sky, it could have easily slipped between the previous sparse deep survey fields. The most likely location for this distant cold disk would be the invariable plane, the plane normal to the total angular momentum of the solar system, which is inclined 1.6\(^\circ\) to the ecliptic (Allen 1976). Most deep KBO surveys, including our previously published results (Allen, Bernstein & Malhotra 2001)[ABM], have been conducted close to the ecliptic plane, possibly missing a thin disk near the invariable plane. We have therefore supplemented the ABM survey with four new fields that are strategically chosen on the sky to maximize the likelihood of detecting a thin trans-Neptunian disk near the invariable plane. We present here new limits on a putative cold disk beyond 50 AU that result from our observations in these new survey fields combined with previously published data.

2. Distant Disk Survey Observations

The new observations were taken with the KPNO Mayall 4-m telescope and Mosaic camera, during two consecutive nights in March 2001. The observation and reduction methodologies are identical to those of ABM. In brief: data were taken using a broad-band \( VR \) filter similar to that described in Jewitt, Luu, & Chen (1996). Each field is observed in a series of 7 to 9 exposures each night, each exposure 480 s long. The images were registered and then combined with a “digital tracking” technique to search for faint moving objects: after registration, the images from each night are summed (with sigma-clipping rejection) into a deep template. This template is then subtracted from each individual image in the opposing night, after matching the point spread functions. This
removes all stationary objects from each image, leaving only moving objects and cosmic rays. These blank images are searched individually for bright KBOs, then combined at potential KBO motion vectors to search for faint slow-moving objects. The images were combined tens of thousands of times to search all likely orbits between 30 and 100 AU.

As the observations were taken in fields very near opposition, the distance can be estimated to within 10% from the apparent velocity. Although we cannot determine orbits with the short (two-night) observational arc obtained here, a distance alone is usually sufficient to exclude the possibility of a distant circular orbit.

We discovered 10 new KBOs in this 2001 survey data, over an effective area of 1.0 deg$^2$. The effective area is simply the subtended survey area multiplied by the detection efficiency—the latter factor being probability of detecting a KBO at a particular magnitude. The effective area is determined by inserting hundreds of artificial moving objects into the data, then repeating the search process. In our 2001 survey, the detection efficiency drops by 50% at a magnitude of $R \sim 24.9$ due to noise, but has no dependence on velocity or distance as all KBOs within 200 AU will move appreciably in the two-night baseline. This limiting magnitude varies from field to field due to seeing and integration-time variations, while the peak detection efficiency varies primarily with stellar density and field overlap. Data for each field are listed in Table 1 and the details for each discovered object are listed in Table 2.

Also included in the Tables are details of the fields and detected objects from the 1998 and 1999 ABM data, which have an effective area of 1.3 square degrees with mean limiting magnitude of $R = 25.4$. Altogether, our surveys between 1998 and 2001 cover 2.3 square degrees and we discovered a total of 33 KBOs and 1 Centaur. The discovered objects were found at distances between 20 and 53 AU, but none of the objects beyond 48 AU are on circular orbits. In our 2001 survey, no KBOs were found beyond 46 AU. We have clearly detected no possible distant cold disk members, even though we could have detected KBOs larger than $D=185$ km to distances of 55 AU or greater over nearly the entire survey area with our stated magnitude limits.

Figure 1 shows in invariable-plane coordinates the extent of the ABM fields (A–G), the new fields (H–L), and other authors’ surveys. The heavy line is the ecliptic plane (the plane containing the orbit of the Earth), about which the previous surveys are clustered. Observing in the ecliptic rather than the invariable plane (the total angular momentum plane of the Solar System) has been the norm, as the difference between the two is not important when considering a thick disk such as the Kuiper belt inside 50 AU. It is only when searching for a disk with vertical dispersion $\sigma \lesssim 2^\circ$ that this difference becomes significant.

Deep KBO surveys conducted by other researchers (Chiang & Brown 1999; Gladman et al. 2001, 1998) generally cover too little area (on the order of a Keck field $\sim 0.01$ deg$^2$) to provide additional constraints on a thin disk. In the analysis described in the next section, we have included the KBO survey by Gladman et al. (2001), conducted with the Canada-France-Hawaii Telescope. This survey discovered 1999 DG8, for which a one-night arc suggests a distance of $\approx 60$ AU. This
is the only known object which could have a circular orbit beyond 50 AU, but the short arc means that the eccentricity of the orbit is completely indeterminate—it could easily be a scattered disk member. For the following analysis we must calculate the probability of cold disk models being consistent with the observations. We sum the probabilities of the model yielding 1 or 0 objects in the Gladman et al. (2001) CFHT field, since the nature of 1999 DG8 is indeterminate. This, along with the high latitude of the field [1.5 to 2 deg to the invariable plane], substantially weaken its ability to constrain a cold disk in the invariable plane.

3. Limits on a Distant Disk

We did not detect any KBOs beyond 50 AU in the primordial, circular orbits expected of objects in a distant cold disk. We wish to constrain the total number of KBOs which could be resident in such a disk. We will consider only KBOs with diameter \( D \geq 185 \) km, since such objects are detectable at > 50% efficiency in all our fields at a distance of 55 AU, assuming 4% albedo. We express the total population \( N_{\text{cold}} \) of \( D > 185 \) km objects between 50 and 60 AU as \( f N_{\text{CKBO}} \), where \( N_{\text{CKBO}} \) is the number of classical KBOs (CKBOs) larger than \( D = 185 \) km. Trujillo et al. (2001) determine \( N_{\text{CKBO}} \sim 3500 \). The cold disk is assumed to have some inclination \( i \) and ascending node \( \Omega \) relative to the invariable plane. The surface density of cold disk objects on the sky is assumed to have a Gaussian distribution in the vertical direction with dispersion \( \sigma \), and to be uniform with disk longitude. An exponential vertical distribution yields similar results for most disk widths.

We ask then what is the probability \( P(O|f, i, \Omega, \sigma) \) of a given disk model yielding the observations \( O \). For simplicity we assume that all the \( N_{\text{cold}} \) objects in the 50–60 AU range have the apparent magnitude \( m = 24.8 \) that a \( D = 185 \) km object would have at a distance of 55 AU. This is conservative in the sense that many of the objects would presumably be larger and brighter, but we do not want to assume any particular size distribution for the cold-disk members. Note that for \( f = 1 \), we may imagine taking the CKBO population, collapsing (cooling) it down to a thin disk, then moving the disk out from its present 38–48 AU annulus to a 50–60 AU annulus. If the “classical” belt is truly a depleted and excited inner portion of the full Kuiper Belt, then this is a lower bound to the expected distant disk.

For chosen disk parameters \( \{f, i, \Omega, \sigma\} \), we convolve the model sky surface density with the survey geometry and detection efficiencies specified in Table 1, yielding an expected number of detections. The expected number of detections for each field, \( N_i \), for each cold disk orientation is then

\[
N_i = 3550 \frac{E_i}{2} \frac{\Delta(\text{RA}) \cos(\text{dec})}{2\pi} \left| \text{erf} \left( \frac{|b_{i1}|}{\sqrt{2}\sigma} \right) - \text{erf} \left( \frac{|b_{i2}|}{\sqrt{2}\sigma} \right) \right|,
\]  

(1)

where \( E_i \) is the detection efficiency in each field, \( \Delta(\text{RA}) \) is the field width and \( b_{i1} \) and \( b_{i2} \) are the top and bottom field latitudes in the cold disk plane. Since the actual number of detections is zero (save possibly for 1999 DG8 in the CFHT field), \( P(O) \) is easily calculated from Poisson statistics. A given disk configuration is excluded at 95% confidence if \( \geq 3 \) detections are expected.
As an example, 74% of the nodes of a very thin disk ($\sigma = 0^\circ.5$) inclined at $i = 1^\circ.0$ to the invariable plane, are ruled out at the > 95% confidence level for $f = 1$. Most of the remaining un-excluded disks travel through our field H, due to its slightly brighter limiting magnitude. The $i = 1^\circ$, $\sigma = 0^\circ.5$ disks which are not ruled out by our deep fields are plotted in Figure 1.

To simplify the interpretation, we marginalize over the ascending node $\Omega$ by assuming a uniform prior distribution in the interval $0 < \Omega < 2\pi$:

$$P(O|f, i, \sigma) = \frac{1}{2\pi} \int_0^{2\pi} P(O|f, i, \Omega, \sigma) d\Omega.$$  \hfill (2)

Figure 2 plots the probability $P(O|f = 1, i, \sigma)$. As we allow the cold disk model to be more inclined to the invariable plane, our limits become weaker because these disks more easily dodge the surveyed fields. Our limits also become weaker as the model disks become thicker, at inclinations $\leq 1^\circ$, since the sky density of the KBOs drops in our fields. This situation reverses at higher inclinations, where the thicker disks ($\sigma > 0.5^\circ$) are more likely to be detected, as they are unable to slip between our fields and the inclination variation matters less.

If we assume that the distant cold disk must be located in the invariable plane, then we can place further limits on how many objects larger than 185 km could exist between 50–60 AU without being detected in our survey. Figure 3 plots the value of $f$ at which $P(O|f, i = 0^\circ, \sigma) = 0.05$, as a function of disk thickness $\sigma$. A thin disk ($\sigma = 0.22^\circ$) must have less than half as many $D > 185$ km KBOs as the classical Kuiper belt ($f < 0.5$ at 95% CL). An $i = 0^\circ$ distant disk with the same number of objects as the inner belt must have $\sigma > 1.85^\circ$ to have a $> 5\%$ chance of escaping detection in the surveys to date. The apparent width of the classical Kuiper belt is $\approx 5^\circ$ (Trujillo et al. 2001). If the outer disk has the same width instead of being dynamically colder, an increase of factor $f > 2.36$ over the classical belt population is ruled out at the 95% CL. The case of equivalent inner- and outer-disk sky distributions is considered in more detail in ABM.

By also marginalizing over the inclination, we can place similar limits on $f$ for cold disks within $1^\circ$ of the invariable plane. Assuming that the model disk pole locations are uniformly distributed in polar area, then

$$P(O|f, i \leq 1^\circ, \sigma) = \frac{\int_0^1 P(O|f, \sigma, i) i di}{\int_0^1 i di}.$$ \hfill (3)

We can then find $f$ at which $P(O|f, i \leq 1, \sigma) = 0.05$, plotted in Figure 3 as the solid line. We can place tighter limits on a disk in the invariable plane, as above, than on any disk in any inclination up to $1^\circ$ because more of our fields were located in the invariable plane. However, we find for $\sigma < 1.75^\circ$ we can exclude at 95% CL or better the existence of a distant disk at any inclination $i \leq 1^\circ$ to the invariable plane that contains at least 1.2 times as many $D > 185$ km KBOs as the Classical Kuiper belt.
4. Conclusions

We have provided strong limits on the existence of a distant cold disk. The simple expectation of a dense thin disk in the invariable plane appears to be ruled out. However, it is possible that a thin disk composed of objects smaller than $D = 185$ km, undetectable in much of our survey, is present. This would require an extreme change in the size distribution of KBOs just beyond ~50 AU, as objects larger than $D \approx 1000$ km have been found at distances near 50 AU. It is not clear what would cause such a large and sudden change in the size distribution.

Other explanations for the observed lack of distant KBOs involve dropping the density of objects beyond 50 AU. One possibility is that the outer Kuiper belt was dynamically excited by a stellar encounter early in the history of the solar system (Ida et al. 2000). An increase in the mean eccentricity and inclination of distant KBOs, thus lowering their apparent sky density and possibly halting accretion of large KBOs, would make a distant disk much harder to detect. Dynamical excitation by a stellar encounter results in a distinctive orbital distribution of KBOs, and could yield limits on the birth cluster environment of the solar system (Adams & Laughlin 2001).

It is also possible to explain the lack of KBOs beyond 50 AU if the primordial planetesimal disk ended at this distance. If Neptune and Uranus have migrated significantly over the age of the solar system (Malhotra 1993, 1995; Thommes, Duncan, & Levison 1999), the primordial solar nebula surface density beyond ~30 AU could have been very small initially. This could 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. Circumstellar disks around other stars have been observed to have diameters ranging between 50–1000 AU (McCaughrean & O’Dell 1996; Brown et al. 2000). A truncation of the solar nebula near 50 AU would fit easily within this range, with important implications for planetary formation models of our Solar System.

In order to distinguish between these theories and further constrain the distant KB population, deeper and wider survey observations of the Kuiper belt (to limiting magnitudes of $R > 25$) will be necessary. Based on the limits we have found here, a survey covering approximately 20 square degrees near the invariable plane should be able to detect a distant disk dynamically excited to a thickness of $10^\circ$ with even half the number of objects as the CKB. This would constrain the density and distribution of the Kuiper belt at distances beyond 50 AU, including the Scattered Disk Objects, enabling a better comparison between our solar system and extrasolar systems.

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Fig. 1.— Fields from this survey, and others deep enough to provide limits on the location of distant thin disk at $R = 24.8$, are shown here in invariable plane coordinates. The heavy line shows the location of the ecliptic plane. The lighter curves show the locations where a distant disk, inclined to the invariable plane by $1^\circ$, might escape detection in surveys to date. The distant disk is assumed to have a Gaussian thickness of $0.5^\circ$, contain as many $D > 185$ km objects as the “classical” Kuiper belt, and be excluded if there is $< 5\%$ chance of being consistent with our observations.
Fig. 2.— The probability of detecting a distant disk with varying thickness and inclination (averaged over ascending nodes) to the invariable plane. This assumes that the number of objects larger than $D = 185$ km is similar to the number of $D > 185$ km KBOs in the classical Kuiper belt.
Fig. 3.— Assuming the distant cold disk is in the invariable plane \( (i = 0^\circ) \), we calculate the upper limit to the ratio \( f \) of \( D > 185 \) km objects relative to the classical Kuiper Belt, shown by the dashed line. By marginalizing over the inclination (averaged over inclination pole angular area) we can also calculate the upper limit to the ratio \( f \) for all cold disks with \( i \leq 1^\circ \) to the invariable plane, shown by the solid line. Disk populations above each line are inconsistent at \( \geq 95\% \) CL with our non-detection.
Table 1. Field Information

| Field | Dates of Observation<sup>a</sup> | RA (J2000) | Dec | Ecliptic Coords. | Invariable Exp Time Filter | Filter | $E_o^b$ | $m_{50}^b$ | w |
|-------|---------------------------------|------------|-----|-----------------|----------------------------|--------|---------|----------|----|
| A     | 5/19/98 | $11^h 37^m 34^s$ | $+2 13 20$ | 174.0 | -0.19 | -1.63 | 12×480 | $R$ | … | … | … |
|       | 5/28/98 - 5/29/98 * | $11^h 37^m 22^s$ | $+2 14 34$ | 173.9 | -0.18 | -1.63 | 19×480 | $R$ | 73 | 24.9 | 0.19 |
| B     | 5/19/98 | $13^h 02^m 36^s$ | $-6 46 00$ | 197.0 | -0.03 | -1.61 | 18×480 | $R$ | … | … | … |
|       | 5/28/98 - 5/29/98 * | $13^h 02^m 00^s$ | $-6 42 26$ | 196.9 | -0.09 | -1.67 | 24×480 | $R$ | 75 | 25.2 | 0.15 |
| D     | 5/19/98 | $20^h 27^m 52^s$ | $-19 20 00$ | 304.6 | -0.22 | 0.24 | 18×480 | $R$ | … | … | … |
|       | 5/28/98 - 5/29/98 * | $20^h 27^m 35^s$ | $-19 19 47$ | 309.1 | -1.40 | 0.81 | 26×480 | $R$ | 65 | 25.4 | 0.22 |
| E<sup>c</sup> | 5/10/99 - 5/11/99 * | $12^h 05^m 00^s$ | $-0 30 00$ | 181.4 | 0.04 | -1.48 | 33×480 | $VR$ | 78 | 25.4 | 0.37 |
| F     | 5/10/99 - 5/11/99 * | $12^h 04^m 34^s$ | $-0 32 28$ | 181.3 | -0.01 | -1.53 | 33×480 | $VR$ | 78 | 25.4 | 0.37 |
| G     | 5/10/99 - 5/11/99 * | $14^h 00^m 00^s$ | $-12 12 00$ | 212.2 | 0.03 | -1.50 | 30×480 | $VR$ | 88 | 25.9 | 0.23 |
|       | 5/18/99 - 5/19/99 * | $13^h 59^m 21^s$ | $-12 15 15$ | 212.1 | -0.08 | -1.61 | 33×480 | $VR$ | 88 | 25.9 | 0.23 |
| H     | 3/27/01 - 3/28/01 * | $10^h 24^m 35^s$ | $12 01 15$ | 153.5 | 1.93 | 0.80 | 14×480 | $VR$ | 95 | 24.7 | 0.33 |
| J     | 3/27/01 - 3/28/01 * | $10^h 24^m 02^s$ | $11 27 37$ | 153.6 | 1.36 | 0.23 | 17×480 | $VR$ | 93 | 24.8 | 0.34 |
| K     | 3/27/01 - 3/28/01 * | $12^h 15^m 23^s$ | $-00 09 53$ | 183.6 | 1.38 | -0.15 | 15×480 | $VR$ | 95 | 24.9 | 0.27 |
| L     | 3/27/01 - 3/28/01 * | $12^h 14^m 10^s$ | $-00 44 11$ | 183.5 | 0.73 | -0.80 | 18×480 | $VR$ | 85 | 24.9 | 0.24 |

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

<sup>b</sup>$m_R$ and $E_o$ are fit to the detection efficiency $E$ for detection of implanted KBOs using $E = \frac{E_o}{\sqrt{2}} \text{erfc}\left(\frac{m - m_{50}}{\sqrt{2}w}\right)$. $E_o$ is the peak detection efficiency for each field, $m_{50}$ is the point where the efficiency is 50% of $E_o$, and $w$ is a width parameter.

<sup>c</sup>Detection efficiencies for fields E and F are based on averages from nights 1 & 2 and nights 3 & 4, as these fields search the same section of sky.
Table 2. Objects Discovered

| MPC Designation | Field | Arc Length | $m_R^a$ (AU) | $a^b$ | $e^b$ | $i$ (°) | Heliocentric Dist. (AU) | Diameter $^c$ (km) | $^d$ |
|-----------------|-------|------------|-------------|-------|-------|--------|------------------------|-------------------|-----|
| 1998 KD66       | B     | 10 d       | 24.7        | ⋯     | ⋯     | 6.4 ± 2.9 | 42.9 ± 3.7               | 117               | 8.4 |
| 1998 KE66       | B     | 10 d       | 25.0        | ⋯     | ⋯     | 2.5 ± 0.9 | 41.0 ± 3.4               | 94                | 8.9 |
| 1998KF66        | B     | 10 d       | 24.5        | ⋯     | ⋯     | 6.7 ± 1.5 | 31.8 ± 2.0               | 70                | 9.5 |
| 1998 KG66       | B     | 10 d       | 25.1        | ⋯     | ⋯     | 3.5 ± 1.5 | 45.2 ± 4.1               | 109               | 8.5 |
| 1998 KY61       | D     | 42 d       | 23.7        | 44.1 ± 0.1 | 0.05 ± 0.10 | 2.1 ± 0.0 | 46.5 ± 0.0              | 220               | 7.0 |
| 1998 KG62       | D     | 2 opp      | 22.9        | 43.4 ± 0.0 | 0.05 ± 0.01 | 0.8 ± 0.0 | 45.3 ± 0.0               | 301               | 6.3 |
| 1998 KR65       | D     | 2 opp      | 22.9        | 43.5 ± 0.0 | 0.02 ± 0.00 | 1.2 ± 0.0 | 44.4 ± 0.0               | 289               | 6.4 |
| 1998 KS65       | D     | 2 opp      | 23.7        | 43.7 ± 0.0 | 0.03 ± 0.00 | 1.2 ± 0.0 | 42.3 ± 0.0               | 181               | 7.4 |
| 1999 JV127      | E     | 8 d        | 23.7        | 18.2 ± 0.2 | 0.15 ± 0.08 | 19.2 ± 0.7 | 20.9 ± 0.3              | 43                | 10.5 |
| 1999 JA132      | E     | 9 d        | 23.9        | 42.0 ± 3.8 | 0.07 ± 0.13 | 7.3 ± 0.7 | 45.2 ± 1.1              | 189               | 7.3 |
| E2-01$^e$       | E     | 1 d        | 24.9        | ⋯     | ⋯     | 7.1 ± 3.5 | 31.7 ± 4.2             | 58                | 9.9 |
| 1999 JB132      | F     | 8 d        | 23.5        | ⋯     | ⋯     | 17.1 ± 11. | 39.1 ± 3.7             | 170               | 7.6 |
| 1999 JC132      | F     | 1 d        | 24.3        | ⋯     | ⋯     | 5.4 ± 2.1 | 39.0 ± 2.6             | 117               | 8.4 |
| 1999 JD132      | F     | 2 opp      | 23.6        | 45.4 ± 3.3 | 0.22 ± 0.16 | 10.5 ± 0.0 | 42.8 ± 0.2             | 198               | 7.3 |
| 1999 JE132      | F     | 9 d        | 24.1        | 32.4 ± 5.0 | 0.20 ± 0.22 | 29.8 ± 6.4 | 39.1 ± 1.4             | 129               | 8.2 |
| 1999 JF132      | F     | 9 d        | 24.0        | ⋯     | ⋯     | 1.6 ± 0.4 | 43.1 ± 2.1             | 164               | 7.7 |
| 1999 JH132      | F     | 9 d        | 25.5        | ⋯     | ⋯     | 0.6 ± 0.2 | 41.1 ± 2.4             | 75                | 9.4 |
| 1999 JJ132      | F     | 9 d        | 25.5        | ⋯     | ⋯     | 3.2 ± 1.2 | 50.1 ± 2.8             | 111               | 8.5 |
| 1999 JK132      | F     | 9 d        | 24.8        | ⋯     | ⋯     | 16.0 ± 5.9 | 39.0 ± 2.5             | 93                | 8.9 |
| 1999 KT16       | F     | 1 d        | 25.1        | ⋯     | ⋯     | 8.5 ± 3.7 | 46.3 ± 3.1             | 114               | 8.4 |
| 1999 KK17       | F     | 9 d        | 25.0        | ⋯     | ⋯     | 8.7 ± 16. | 49.8 ± 7.5             | 139               | 8.0 |
| 1999 KL17       | G     | 90 d       | 25.2        | 46.2 ± 0.2 | 0.03 ± 0.17 | 2.8 ± 0.0 | 47.6 ± 0.0             | 115               | 8.4 |
| 1999 KR18       | G     | 89 d       | 24.9        | 43.3 ± 0.3 | 0.21 ± 0.03 | 0.6 ± 0.0 | 52.6 ± 0.1             | 162               | 7.7 |
| G3-01$^e$       | G     | 9 d        | 25.6        | 39.9 ± 2.7 | 0.16 ± 0.05 | 1.6 ± 0.1 | 33.4 ± 1.4             | 47                | 10.4 |
Table 2—Continued

| MPC Designation | Field | Arc Length | $m_R^a$ (AU) | $a^b$ | $e^b$ (°) | $i$ | Heliocentric Dist. (AU) | Diameter (km) | $H^d$ |
|-----------------|-------|------------|--------------|-------|-----------|----|------------------------|----------------|-------|
| 2001 FB185 H    | 1 d   | 24.6       | ...          | ...   | 4.5 ± 1.5 | 39.8 ± 3.1 | 106                      | 8.7            |
| 2001 FC185 J    | 1 d   | 23.8       | ...          | ...   | 21.2 ± 8.9 | 39.0 ± 3.4 | 147                      | 7.9            |
| 2001 FE193 K    | 1 d   | 23.2       | ...          | ...   | 3.1 ± 1.1  | 42.8 ± 2.5 | 234                      | 6.9            |
| 2001 FG193 K    | 1 d   | 24.2       | ...          | ...   | 3.4 ± 1.6  | 41.8 ± 2.5 | 141                      | 8.0            |
| 2001 FD193 K    | 1 d   | 24.2       | ...          | ...   | 12.3 ± 4.6 | 44.7 ± 2.7 | 161                      | 7.7            |
| 2001 FC193 K    | 1 d   | 24.8       | ...          | ...   | 2.8 ± 1.5  | 46.4 ± 2.6 | 132                      | 8.2            |
| 2001 FJ193 L    | 1 d   | 24.5       | ...          | ...   | 1.1 ± 0.6  | 36.4 ± 2.4 | 93                       | 8.9            |
| 2001 FF193 L    | 1 d   | 23.8       | ...          | ...   | 2.0 ± 1.6  | 44.7 ± 2.6 | 194                      | 7.3            |
| 2001 FH193 L    | 1 d   | 24.8       | ...          | ...   | 8.9 ± 3.5  | 40.9 ± 2.6 | 102                      | 8.7            |
| 2001 FL193 L    | 1 d   | 24.9       | ...          | ...   | 1.0 ± 0.6  | 40.9 ± 2.5 | 97                       | 8.8            |

$^a$All 1999 and 2001 objects were detected in the $VR$ filter. The listed magnitude may be transformed to standard $R$ via $R = VR - 0.46(V - R - 0.5)$. As $0.3 \lesssim V - R \lesssim 0.7$ for KBOS (Tegler & Romanishin 2000), the $R$ mag varies by 0.2 mag or less with color.

$^b$No data are given when the arc is too short to provide meaningful constraint.

$^c$Diameters assume albedo of 0.04.

$^d$Absolute magnitude in $R$

$^e$Objects E2-01 and G3-01 were not reported to the MPC due to insufficient S/N on the recovery observations.