DEEP IMAGING OF THE KUIPER BELT WITH THE KECK 10-METER TELESCOPE

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ABSTRACT

We present a new, pencil-beam survey of the Kuiper Belt taken with the Keck 10-meter telescope. The cumulative surface density of Kuiper Belt Objects measured to apparent red magnitude $m_R = 26.1$ is $31(+12, -14)$ deg^{-2}, while to $m_R = 26.6$ it is 40 ± 33 deg^{-2}. These numbers are compatible with an extrapolation of the luminosity function deduced earlier from measurements in the $20 \leq m_R \leq 25$ range (Jewitt, Luu and Trujillo 1998), and confirm a Kuiper Belt differential size distribution index $q \sim 4$.

Subject headings: comets – solar system: formation

1. Introduction

The solar system beyond Neptune contains a rich assortment of planetary bodies collectively known as Kuiper Belt Objects (KBOs). Recent ground-based measurements have revealed more than 60 KBOs (as of April 1998), with diameters ranging from the limits of detection near 100 km up to 800 km (Jewitt and Luu 1993, 1995 (hereafter JL95); Irwin, Tremaine, and Zytkow 1995; Williams *et al.* 1995; Jewitt, Luu and Chen 1996 (hereafter JLC96); Gladman and Kavelaars 1997; Luu *et al.* 1997; Jewitt, Luu and Trujillo 1998 (hereafter JLT98)). The cumulative luminosity function (CLF) of the Kuiper Belt is one of the most important measurable quantities because, in magnitude limited surveys, it reflects both the size distribution and the radial distance distribution of the KBOs. Through models, the CLF may be used to constrain the size and distance distributions. The size distribution is important because it may tell us about the conditions in which the KBOs grew (Stern and Colwell 1997, Kenyon and Luu 1998) as well as about subsequent collisional modification (Farinella and Davis 1996). The distance distribution carries additional information about accretion, and about the dynamical evolution of the Kuiper Belt in the 4.6 Gyr since formation (e.g., Holman and Wisdom 1993; Duncan, Levison and Budd 1995; Malhotra 1996). The CLF is well determined in the magnitude range $20 \leq m_R \leq 25$ (JLT98), and is described by

$$\log[\Sigma(m_R)] = \alpha(m_R - m_0) \quad (1)$$

where $\alpha = 0.58 \pm 0.05$ and $m_0 = 23.27 \pm 0.11$ (JLT98). KBOs brighter than $m_R = 20$ are relatively rare, and await detection by wide-field surveys that are currently underway. Objects fainter than $m_R = 25$ are potentially very numerous, but have not yet been the subject of a concerted ground-based observational effort (a reported measurement of these objects with the Hubble Space Telescope is discussed later). In this Letter, we present new measurements of the surface density of KBOs fainter than $m_R = 25$.

2. Observations

Observations were taken at the Keck 10-meter telescope on a range of dates from 1994 to 1996 (see Table 1) using the LRIS charge-coupled device (CCD) camera (Oke *et al.* 1995). We used LRIS in imaging mode with an R filter and a standard integration time per image of 900 seconds. In 900 seconds, an object moving at 3 arcsec hr^{-1} will trail by 0.75 arcsec, producing a trailing loss of ~ 0.2 magnitude in seeing of 0.75 arcsec Full Width at Half Max (FWHM) (e.g., Tancredi and Lindgren 1994). The LRIS image scale is 0.215 arcsec per pixel. We used the central 1600×2040 pixels (41.9 arcmin^2) of the field of view to avoid partially vignetted regions near the edge. The seeing was carefully monitored during the integrations, and the alignment of the primary mirror segments was periodically adjusted using the IMALIGN algorithm. Photometric calibration of the data was obtained through observations of faint standards (Landolt 1992).

Two separate strategies were used to secure the data. For the "medium-deep" survey, we used the usual technique of imaging each field three times in order to detect KBOs by virtue of their motion relative to the fixed stars. In total, we observed 24 medium-deep fields (1007.0 arcmin^2) in seeing that varied from 0.75 arcsec to 0.93 arcsec FWHM.

For the "ultra-deep" survey, we recorded a continuous series of images of a single field throughout each night. The images were dithered so as to eliminate possible problems caused by defective pixels (thus reducing the effective area further). Images from the series were then combined to make three ultra-deep images per field, each having effective integration time $\sim$ 4500 seconds, which were then searched for KBOs. The image combinations were made assuming a grid of KBO rates in the range 1.5 - 3.3 arcsec hr^{-1} West, 0.7 - 1.3 arcsec hr^{-1} North, with grid spacings of 0.3 arcsec hr^{-1}. The rates were chosen to encompass the 37 - 80 AU distance range where we expect to find objects. The 0.3 arcsec hr^{-1} grid spacing was selected empirically so that we would not miss any KBO in the 37 - 80 AU heliocentric range. From experiments with both real and artificial KBOs, we found that we could tolerate a rate error of 0.3 arcsec hr^{-1} without loss of sensitivity. In total, we observed 3 ultra-deep fields (combined area 101.2 $arcmin^2$), with average seeing each night near 0.75 arcsec FWHM.

Photometry was performed using a circular aperture 10 pixels (2.1 arcsec) in diameter, with sky subtraction from a contiguous annulus of 30 pixels (6.5 arcsec) outer diameter. Experiments with other aperture sizes showed photometric stability at the 0.1 - 0.3 mag level.

The limiting magnitudes of the survey observations were measured by searching for synthetic images of KBOs added randomly to the data. The synthetic KBOs all had Moffat profiles with $\beta = 2.5$ (Moffat 1969), and were artificially trailed to simulate movement of the real KBOs during the 900-sec integrations. We checked that the synthetic KBOs had shapes like those of real KBOs and that they were correctly photometrically scaled to the data. We generated KBOs of apparent magnitudes 25.3 - 27, with ~ 5 KBOs per 0.1 magnitude bin. The synthetic KBOs were "discovered" and measured using exactly the same procedures employed on real KBOs. From simulations with different values of the seeing, θ [arcsec], we found that a probability of detection equal to 50% of the maximum was reached at red magnitude $m_R(50) = (25.9 \pm 0.1) - 2.5\log(\theta)$. Thus, our best and worst medium-deep images have $m_R(50) = 26.2 \pm 0.1$ (for $\theta = 0.75$ arcsec) and 26.0 ± 0.1 ($\theta = 0.93$ arcsec), respectively. These are compatible with independent determinations of $m_R(50)$ using LRIS data by Smail *et al.* (1995), when correctly scaled for the difference in seeing, integration time, and trailing loss. Simulations of the medium-deep data gave $m_R(50) = 26.1 \pm 0.1$, and for the ultra-deep data $m_R(50) = 26.6 \pm 0.1$ (Table 1).

3. Discussion

We found six new KBOs in the combined Keck data; examples are shown in Fig. 1. The properties of the new KBOs are listed in Table 2 (c.f. Fig. 1). Except for 1995 WY2, each KBO was observed only on the night of discovery. For this reason, in principle, there is a small chance that the newly detected KBOs might be near-Earth asteroids, whose intrinsic motions coincidentally mimic the slow, retrograde movement expected of a KBO. With observations from only a short time-base on a single night, we are unable to eliminate this possibility from the absence of diurnal parallax in the normal way (JL95). However, in our other surveys we have not found such accidental slow movers, and it is highly unlikely that such objects might be found in the Keck data. We proceed on the assumption that the slow apparent motions are indicative of large geocentric distance.

Single-night observations of the newly detected KBOs provide only minimal constraints on their orbits. Experience with other single-night KBOs suggests that we can trust the distances to the KBOs more than we can trust the other orbital parameters. The distances (Table 2) fall within the distance range defined by previously known KBOs. We compute diameters of KBOs under the assumption of uniform red geometric albedo, $p_R = 0.04$ (see JLT98 for a discussion of this assumption). Limiting magnitude $m_R = 26.1$ corresponds to an object diameter $D_{0.04} \sim 80$ km at $R = 50$ AU. Therefore, all KBOs in the line of sight with $D_{0.04} \geq 80$ km and $R \leq 50$ AU fall within the sensitivity limits of the Keck data. From $\Sigma(m_R = 26.1) = 31$ deg^{-2} (Fig. 2) and a nominal ecliptic projected area $A \sim 10^4$ deg^{-2} we find $N = \Sigma A \sim 3.1 \times 10^5$ KBOs with $D_{0.04} \geq 80$ km and $R \leq 50$ AU. Scaled to $D_{0.04} = 100$ km using a $q = 4$ differential size distribution, we find $N \sim 1.6 \times 10^5$. This compares favorably with $N \sim 7 \times 10^4$ based on earlier data (JLC98), which is good to a factor of ~ 2 due to, e.g., the poorly constrained inclination distribution. The consistent population estimates suggest that the large end of the KBO size distribution is well established. The mass of a $q = 4$ distribution in which there are N objects larger than D_{min} is

$$M = \frac{\pi \rho N D_{min}^3}{2} \left(\frac{0.04}{p_R}\right)^{3/2} \ln\left(\frac{D_{max}}{D_{min}}\right) \qquad (2)$$

where ρ is the bulk density and the size distribution extends to D_{max}. We take $p_R = 0.04$, $D_{min} = 100$ km, $N = 1.6 \times 10^5$, $\rho = 2000$ kg m^{-3} and maximum object size equal to Pluto ($D_{max} = 2300$ km) to find $M = 1.6 \times 10^{24}$ kg ($\sim 0.3 M_\oplus$, where $1 M_\oplus = 6 \times 10^{24}$ kg is one Earth mass). Systematic uncertainties in the mass estimate arise from the density (factor of 2), and are dominated by the albedo term (factor of 10?). A safe conclusion would be that the mass of the observable objects in the Kuiper Belt is of order a few tenths of $M_\oplus$. The mass in smaller objects is observationally unconstrained. If the $q = 4$ size distribution extends to 1 km, the total mass may be higher by a factor ~ 2, but still would be consistent with dynamical constraints which limit the mass to be $< 1 M_\oplus$ (Hamid *et al.* 1968).

The new cumulative surface densities are plotted in Fig. 2. Also shown in Fig. 2 is the fit to the CLF determined from observations in the range $20 \le m_R \le 26.6$, including the new Keck measurements (Eq. 1). Refitting the CLF yields the new parameters $\alpha = 0.54 \pm 0.04$ and $m_0 = 23.20 \pm 0.10$. Observers using the Hubble Space Telescope (Cochran *et al.* 1995) reported a high density of KBOs near the noise limit of the data at $m_V \sim 28.6$ (corresponding to $m_R \sim 28.1$ with $V - R \approx 0.5$). This measurement has been criticized by Brown *et al.* (1997) on statistical grounds but was recently further defended by Cochran *et al.* (1998). The Cochran *et al.* (1995) datum lies above the extrapolated CLF by a factor of ~ 30 (Fig. 2). There are at least three possible explanations for this discrepancy:

1) The fitted CLF may be in error. This seems unlikely, because the CLF has been determined from ground-based observations taken with different detectors, telescopes and limiting magnitudes, with no evidence for significant discrepancies between independent measurements. In particular, a smooth fit from $m_R = 24$ to $m_R = 28.1$ would only

be possible if the Keck data under-estimated the number of KBOs by factors of ~ 11 ($m_R = 26.1$) and ~ 23 ($m_R = 26.6$), which seems unlikely.

2) The CLF may steepen between the Keck ($m_R = 26.1, 26.6$) and HST ($m_R = 28.1$) limiting magnitudes. An increase in surface density by a factor of ~ 30 relative to the fitted CLF (in the magnitude range 26.6 to 28.1) would be required to fit the HST determination.

3) The Cochran *et al.* datum may be in error, as suggested by Brown *et al.* (1997).

4. Summary

1. The cumulative surface densities of Kuiper Belt objects brighter than apparent red magnitude $m_R = 26.1$ are $31(+12, -14)$ deg^{-2} and 40 ± 33 deg^{-2} at $m_R = 26.6$.

2. The cumulative luminosity function in the magnitude range $20 \leq m_R \leq 26.6$ is well-fitted by Eq. (1) with $\alpha = 0.54 \pm 0.04$ and $m_0 = 23.20 \pm 0.10$. The mass of KBOs with diameters $D_{0.04} \geq 100$ km and heliocentric distances $R \leq 50$ AU is of order $0.3 M_\oplus$.

3. The surface density of Kuiper Belt objects at $m_R = 28.1$ (Cochran *et al.* 1995) is a factor of ~ 30 higher than the extrapolated cumulative luminosity function from ground-based data. Either the luminosity function is very much steeper in the $26.6 \leq m_R \leq 28.1$ magnitude interval or the HST datum is in error.

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FIGURE CAPTIONS

Figure 1. Images of two KBOs detected in this survey. The 3 left panels show the KBO K-UD ($m_R \sim 25.0$) detected in the ultra-deep survey, while the 3 right panels show the KBO K15 ($m_R \sim 25.7$) detected in the medium-deep survey. The panels are 86 arcsec × 43 arcsec, with N to the top and E to the left. The white circle has projected diameter 3.9 arcsec.

Figure 2. The plotted line is the fitted CLF, which includes the present Keck data. JLT98 = Jewitt, Luu, and Trujillo (1998); JLC96 = Jewitt, Luu, and Chen (1996).