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THE FREQUENCY OF BINARY KUIPER BELT OBJECTS

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ABSTRACT

We estimate the frequency of widely spaced (separations greater than 0″.5) Kuiper Belt binaries (KBBs) from surveys for new Kuiper Belt objects (KBOs) with the Deep Ecliptic Survey and through recovery observations for newly discovered KBOs at the Magellan telescopes. We find the frequency of KBBs versus discovery separation to be related by an inverse power law when combining our results with those for the fraction of close binaries (separations less than 0″.5) found in the literature. For wide separations, our data and the resulting model agree with the model proposed by Goldreich et al. in 2002. However, including the frequency at the smallest separation rules out the semimajor-axis dependence of the Goldreich et al. model at the 99% confidence level, indicating that there is likely a turnover in the distribution at very close separations, or that the number of close binaries has been underestimated. In either case, the binary-frequency distribution favors binary formation models invoking gravitational rather than physical interactions—such as those proposed by Goldreich et al. and Astakhov et al. (2005).

Subject headings: Kuiper Belt — planets and satellites: formation

1. INTRODUCTION

Kuiper Belt objects (KBOs) are small (comet- to lunar-sized), icy bodies that orbit the Sun beyond Neptune (≥30 AU). Collectively these $\sim 10^5$ bodies (>100 km in diameter, with uncounted smaller ones; Luu & Jewitt 1996) make up a disk of material ~10%–20% the mass of Earth (Schulz 2002). Binaries within the belt offer a natural laboratory in which to study the outcome of collisions and gravitational exchanges that occurred during the early stages of the solar system.

The discovery of Kuiper Belt binaries (KBBs) is an ongoing observational challenge. Currently, 23 KBOs (including Pluto) are known to be in binary systems; two of these are in systems with more than two bodies, a primary and multiple moons (Brown et al. 2005; Weaver et al. 2006). Three effective methods exist for binary detection: (1) direct imaging (by which the overwhelming majority have been discovered), (2) measurement of a high-amplitude light curve with the signature of eclipsing bodies (Sheppard & Jewitt 2004), and (potentially) (3) discovery by stellar occultation. In this Letter, we present the results of two direct-imaging surveys that resulted in the discovery of binaries with wide separations (>0″.5). We establish a binary-frequency distribution with respect to discovery separation distance and compare our results with the predictions of current formation models.

2. OBSERVATIONS

A number of formal KBO surveys have resulted in direct imaging of KBBs. These include ground-based programs by the Deep Ecliptic Survey (DES; Millis et al. 2002; Elliot et al. 2005) and the Magellan telescopes, and space-based programs with the *Hubble Space Telescope* (*HST*). The DES was a 5 year National Optical Astronomy Observatory survey program, which had the primary goal of discovering and determining reliable orbits for hundreds of KBOs for the purposes of understanding the dynamics of this region of our solar system. A recovery program for these newly discovered KBOs was established a few years into the project at Las Campanas Observatory, Chile, utilizing the 6.5 m Magellan telescopes and high-resolution Raymond and Beverly Sackler Magellan Instant Camera (MagIC; Osip et al. 2004). Discoveries of binaries in the DES and Magellan data sets were the by-products (Kern 2006) of investigating the sample of new KBOs that required recovery to firmly establish their orbits. This sample was unbiased with respect to an object's being a binary. The *HST* surveys (STIS and Deep, Noll 2003; NIC2, Stephens & Noll 2005) include objects chosen because their positional uncertainties were less than 5″, guaranteeing that the objects would be found within the camera's field of view. The object list is also unbiased with respect to an object's being a binary.

The Magellan survey was based on a subset of objects discovered by the DES, so these samples overlap almost entirely. The samples of objects for the DES and *HST* overlap by ~27%. Space-based observations are best for discovering closely spaced binaries (separations of ≥0″.013), while ground-based observations are sensitive only to more widely spaced binaries (separations of a fraction of the seeing disk on a given night, depending on the instrumental pixel scale and atmospheric effects; listed as "Resolution" in Table 1). Since these surveys are sensitive to binary discovery for different regions of binary component separations, we can establish the frequency of binary systems versus the semimajor axis of the binary orbit and then compare our results with predictions of KBB formation models. We approximate the discovery separations to be representative of the semimajor axes of the systems; binaries with eccentric orbits spend most of their time at wider separations and are most likely to be measured near aphelion. Table 1 lists the surveys, telescopes, site and instrument characteristics, and number of resultant KBB discoveries. The surveys are sensitive to discovery of secondary components within ~1 mag of their primaries, with the exception of the *HST* STIS survey, which was specifically designed to look for binaries with components having greater differential magnitudes. The binary-frequency analysis that follows is not bias-corrected for magnitude differentials between components; it simply counts the number of binaries found versus the number of objects observed for each survey.

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TABLE 1
FRACTION OF KUIPER BELT BINARIES DETECTED IN DIRECT-IMAGING SURVEYS

Survey	Telescope Diameter (m)	Resolution (arcsec)	Plate Scale (arcsec pixel^{-1})	No. Objects Observed	No. Binaries Discovered	Binary Fraction[a] (%)	Reference
HST NIC2	2.4	0.013	0.075	81[b]	9	11^{+5}_{-2}	Stephens & Noll 2005
HST STIS	2.4	0.1	0.050	29[c]	2	$7^{+7.8}_{-2.3}$	Noll 2003
HST Deep (WFPC2, NIC2)	2.4	0.15	0.1, 0.075	122	6	$5^{+2.7}_{-1.3}$	Noll 2003
Magellan	6.5	≥0.3 (0.9[d])	0.069	212	3	$1.4^{+1.3}_{-0.4}$	Kern 2006
DES	4.0	≥1.2 (1.65[d])	0.52	634	1	$0.16^{+0.35}_{-0.05}$	Kern 2006

[a] Plotted with different symbols in Fig. 2, where the gray crosses for the Magellan and DES points denote the seeing on the individual frames where binary objects were discovered. The error bars are asymmetric as a result of non-Gaussian statistics (see Appendix of Burgasser et al. 2003).
[b] Refined analysis with point-spread function image fitting analysis.
[c] Sensitive to magnitude differences as large as 2.5 mag.
[d] Median seeing for all images.

Figure 1 shows the currently known binaries and their discovery characteristics, plotted as secondary magnitude versus discovery separation in arcseconds. Noted in Figure 1 are the seeing and magnitude limits for our DES (*dot-dashed lines*, *dark gray area*) and Magellan (*solid lines*, *light gray area*) surveys. The *HST* observations are resolution-limited but sensitive to the span of plotted magnitudes, that is, objects with separations greater than the vertical line for each survey (*dotted line*, *HST* Deep; *short-dashed line*, *HST* STIS; *long-dashed line*, *HST* NIC2) could be detected at any magnitude shown. Ground-based direct-imaging observations are sensitive to detection of only about half of the currently known KBB population. If there were many widely spaced secondary components of similar brightness or size, our surveys should have detected them. That this is not the case argues that if they exist, secondary components in widely spaced systems are physically different from their primaries, either significantly smaller, darker, or both.

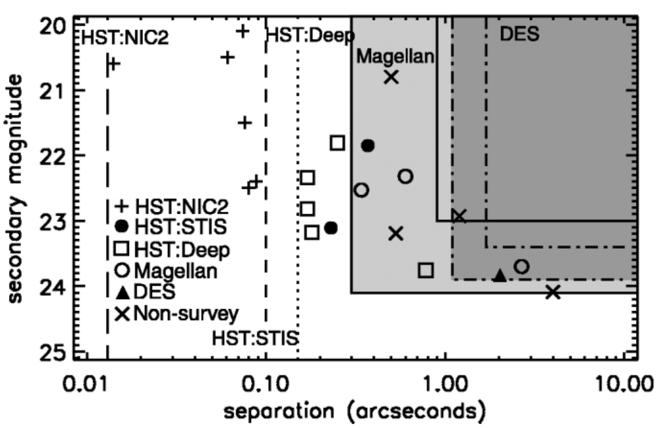

FIG. 1.—KBB discovery characteristics: secondary magnitude vs. discovery separation. Each symbol represents discovery by a different survey. Crosses denote binaries not discovered by published surveys. The dark gray area outlined by the dot-dashed lines represents the lower limit sensitivity for the DES observations with the Mosaic camera and the 4 m (Kitt Peak Mayall and Cerro Tololo Blanco) telescopes at 1″.1 (*outer line*) and 1″.7 (*inner line*) seeing with 240 s integrations at 1.2 air masses with S/N of 10. Likewise, the light gray area outlined by the solid lines represents the same sensitivity with MagIC on Magellan for 180 s integrations at 0″.3 (*outer line*) and 0″.9 (*inner line*) seeing, respectively. The sensitivity limits for the *HST* Deep, STIS, and NIC2 surveys are plotted as dotted, short-dashed, and long-dashed lines, respectively. The Pluto-Charon system lies off the graph at the top (separation ~0″.9, secondary magnitude ~16.4). Nearly half of the known binaries are not observable with ground-based techniques at this time.

3. DISCUSSION

Four KBB formation models have been proposed since discovery of the first KBB (other than Pluto-Charon) in 2001 (Veillet 2001). Weidenschilling (2002) forms a binary through physical collisions between two objects within the Hill radius of a third, larger body; the collision fragments combine to form a single object that remains bound around the large body. The observational prediction of this model is for many widely spaced binaries and few closely spaced binaries. Goldreich et al. (2002) assume the existence of a transitory binary inside the Sun-binary Hill sphere and stabilize it, removing energy from the system so that the two bodies can become more tightly bound, through interactions with either (1) another single large body or (2) a "sea" of small bodies. Further investigation of the two scenarios (Astakhov et al. 2005) finds that the second mechanism for energy dispersion is in contradiction to the gravitational instability theory for the formation of planetesimals (Goldreich & Ward 1973). However, the first mechanism is legitimate, and the model predicts that observationally there should be many closely spaced binaries and few widely spaced binaries. Funato et al. (2004) propose an "asteroid-like" (large- and small-component) binary formation through physical collisions, followed by an exchange of the small, secondary component with subsequently larger bodies during additional gravitational interactions to form approximately equal-sized binaries—similar to some of the observed KBBs. The observational prediction for this model is one of binaries with high eccentricities. Astakhov et al. (2005) provide a physical basis for transitory binary formation inside the Sun-binary Hill sphere by means of a chaos-assisted capture model (Astakhov et al. 2003) and then numerically investigate stabilization of the transitory system through multiple gravitational scattering with small intruders (1%–2% of the total binary mass). The observational prediction for this model is for binaries to span the range of possible eccentricities (0–0.99) and for them to have small ratios (<0.1) of semimajor axis to Hill radius.

Figure 2 shows the frequency of binaries for a particular survey versus discovery separation sensitivity. The dashed line shows the model of Goldreich et al. (2002) for the fraction of KBBs over a distribution of semimajor axes. They define three regions (labeled r1, r2, and r3 in Fig. 2) in which differing forces are at work. The model parameters are the typical radius of a primary KBO, which Goldreich et al. take to be $R \sim 100$ km; the Hill radius of the binary system, $R_{\rm H} \sim 10^4 R$; the radius beyond which small bodies are not significantly affected by large bodies, $r_u \sim 10^3 R$; and the binary orbit semimajor axis,

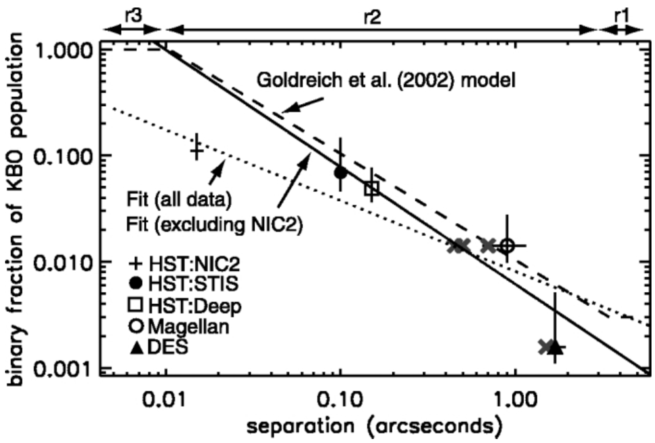

Fig. 2.—Binary frequency vs. discovery separation. Each symbol represents discovery by a different survey, as in Fig. 1. For the DES and Magellan observations, at fractions of 0.16% and 1.4%, respectively, a point with the appropriate symbol is plotted at the median sensitivity of the survey with a horizontal line extending to mark the 1 σ sensitivity level around this point. For a small fraction of time the seeing was as good as 1".2 in the DES data set, and 0".3 at Magellan. The gray crosses on these lines denote the seeing on the frames where binary objects were discovered. In all cases, binaries were discovered in better than the median seeing. *HST* is primarily limited by telescope and instrument resolution in how close a companion it can observe, while ground-based facilities have additional atmospheric limitations. Note that the error bars are asymmetric because of non-Gaussian statistics (see Burgasser et al. 2003, Appendix). The model projected by Goldreich et al. (2002) in the corresponding regions (r1, r2, and r3, discussed in the text) is plotted as a dashed line. Two maximum likelihood fits have been modeled to the data, one including the *HST* NIC2 point (*dotted line*) and one excluding this point (*solid line*). The equations for these lines are given in the text. Without the *HST* NIC2 point, the Goldreich et al. model is in agreement with the data; however, it overestimates the close binary fraction when compared with the *HST* NIC2 observations. If we fit all the data, including the *HST* NIC2 point, then the Goldreich et al. (2002) model is ruled out at the 99% confidence level.

a, of the potential binary pair. The binary fraction, $ap(a)$, in region 1 (r1), where $r_u < a < R_H$ (Goldreich et al. assume ~3″, or 87,000 km at the distance of Pluto), is constant at 0.003. One KBB has been discovered (not by a survey) at a distance greater than 3″. In region 2 (r2), where $R < a < r_u$, the binary fraction given by equation (11) of Goldreich et al. (2002) can be expressed as an integral distribution, $p(>a)$ for objects with semimajor axis greater than a:

$$p(>a) \sim 3(R/a). \qquad (1)$$

This is the precise region where the surveys are sensitive. For comparison of the binary fractions from the surveys with the Goldreich et al. model, we express the integral probability distribution, $p(>s)$, of the discovery binary separations, s, as a power law, with an exponent α and normalizing constant s_0:

$$p(>s) = 3(s/s_0)^{\alpha}. \qquad (2)$$

This equation holds for $s > s_0$ and $\alpha < 0$, the case we are considering (region r2 of the Goldreich et al. model). A maximum likelihood fit (Fig. 2, *dotted line*) of equation (2) to the binary frequency data (only the survey points, not the crosses) yields $\alpha = -0.67 \pm 0.11$ and $s_0 = 0.00072^{+0.00072}_{-0.00046}$, corresponding to $R \sim 40$ km in the Goldreich et al. (2002) model. The fit falls within the uncertainties of the *HST* NIC2 and the DES data and slightly below the 1 σ uncertainties for the *HST* STIS, *HST* Deep, and Magellan data. The maximum likelihood model represents the data well, since 23% of random data samples would have greater deviations from the fit. One object, 2005 EO_{304}, was identified as binary in the Magellan data set but "missed" in the original DES images, primarily as a result of the difference in the component brightnesses. Retrospective examination confirmed the duplicity of this object in the primary's discovery images. For larger seeing disks, the light from an unequal secondary (due to either albedo or size) is easily lost in the light of a brighter primary. With respect to the *HST* NIC2 observations, none of their detected binaries come from the fainter half of their data, which, as the authors point out, may imply that the fraction of close binaries is being underestimated (Stephens & Noll 2005).

If we apply the maximum likelihood fit to the binary frequency data without the *HST* NIC2 point (*solid line*), we find $\alpha = -1.10^{+0.26}_{-0.28}$ and $s_0 = 0.0099^{+0.0094}_{-0.0050}$, corresponding to $R \sim 75$ km in the Goldreich et al. (2002) model. For this case 66% of random data samples show a greater deviation from the maximum likelihood model, indicating a slightly better fit than that with all the data. However, the fit with all the data is certainly acceptable. With a smaller range of binary separations, the error bar on the power index α for this fit is significantly larger than for the fit with all the data. Compared with the solutions from our maximum likelihood fitting, if all the points and uncertainties are accepted at face value, we rule out Goldreich et al. model at the 99% confidence level. However, if the *HST* NIC2 point is a lower limit, the data agree well with the Goldreich et al. model. Alternatively, perhaps the binary frequency distribution turns over at close separations and is not well described by a single power law as applied to the full range of the observations.

Finally, region 3 (r3) represents the situation in which objects spiral in to become contact binaries, $a < 3R$ and $ap(a) > 1$. Direct-imaging surveys today are not sensitive enough to evaluate the validity of the model in this region. Over time, lightcurve observations of large numbers of KBOs may be able to provide additional constraints on the frequency of very close binaries. Goldreich et al. (2002) find that for $r < 300$ km, accretion by an object spiraling in could result in a contact binary or make a substantial contribution to the growth of a large body. They also state that their model allows for multiple-component systems to exist, a hypothesis that is now observationally supported (Brown et al. 2005; Weaver et al. 2006). Fundamentally, this model suggests that there should be fewer KBBs with increased separation distance and that the probability of finding a body in a binary system with separation greater than r_u is independent of a.

4. CONCLUSIONS

The main conclusion from the data is that there are many more close binaries than wide binaries, even if the distribution levels off at a binary separation distance less than ~0".1. Astakhov et al. (2005) provide a physical basis for the transitory binary assumed as the starting point of Goldreich et al.'s (2002) model, which fits the data well without the *HST* NIC2 point but does not agree at close separations with the data if the *HST* NIC2 point is more than a lower limit. Astakhov et al.'s (2005) extension of the proposed model by numerical investigation of the interaction of various-sized bodies within the Hill sphere of the primary KBO show promising correlations in both frequency and orbital eccentricity space with the observations. These two models appear to be a better description for the binary population as a whole, as they are observed, than either the Weidenschilling (2002) or Funato et al. (2004) models. The latter models effectively explain the formation of single binary systems in the Kuiper Belt—objects with wide separations or high eccentricities, respectively, but not the broader observed sample. The models are consistent with a cold primordial disk (Morbidelli et al. 2003).

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