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2007 TY430: A COLD CLASSICAL KUIPER BELT TYPE BINARY IN THE PLUTINO POPULATION

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ABSTRACT

Kuiper Belt object 2007 TY430 is the first wide, equal-sized, binary known in the 3:2 mean motion resonance with Neptune. The two components have a maximum separation of about 1 arcsec and are on average less than 0.1 mag different in apparent magnitude with identical ultra-red colors ($g - i = 1.49 \pm 0.01$ mag). Using nearly monthly observations of 2007 TY430 from 2007 to 2011, the orbit of the mutual components was found to have a period of 961.2 ± 4.6 days with a semi-major axis of 21000 ± 160 km and eccentricity of 0.1529 ± 0.0028. The inclination with respect to the ecliptic is 15.68 ± 0.22 deg and extensive observations have allowed the mirror orbit to be eliminated as a possibility. The total mass for the binary system was found to be $7.90 \pm 0.21 \times 10^{17}$ kg. Equal-sized, wide binaries and ultra-red colors are common in the low-inclination "cold" classical part of the Kuiper Belt and likely formed through some sort of three-body interactions within a much denser Kuiper Belt. To date 2007 TY430 is the only ultra-red, equal-sized binary known outside of the classical Kuiper Belt population. Numerical simulations suggest 2007 TY430 is moderately unstable in the outer part of the 3:2 resonance and thus 2007 TY430 is likely an escaped "cold" classical object that later got trapped in the 3:2 resonance. Similar to the known equal-sized, wide binaries in the cold classical population, the binary 2007 TY430 requires a high albedo and very low density structure to obtain the total mass found for the pair. For a realistic minimum density of 0.5 g cm^{-3} the albedo of 2007 TY430 would be greater than 0.17. For reasonable densities, the radii of either component should be less than 60 km, and thus the relatively low eccentricity of the binary is interesting since no tides should be operating on the bodies at their large distances from each other. The low prograde inclination of the binary also makes it unlikely that the Kozai mechanism could have altered the orbit, making the 2007 TY430 binary orbit likely one of the few relatively unaltered primordial binary orbits known. Under some binary formation models, the low-inclination prograde orbit of the 2007 TY430 binary indicates formation within a relatively high velocity regime in the Kuiper Belt.

Key words: comets: general – Kuiper Belt: general – minor planets, asteroids: general – Oort Cloud – planets and satellites: formation

Online-only material: color figures

1. INTRODUCTION

Small solar system bodies, such as asteroids and Kuiper Belt objects (KBOs), may be leftover remnants of the planetesimals that went into the formation of the terrestrial and giant planets. These small bodies' orbital and physical properties give insight into the solar system's origins and evolution. KBO binaries are particularly informative about the conditions at the time when they formed, which must have been at an earlier epoch of solar system history.

The Kuiper Belt is dynamically structured with three main dynamical classes (Figures 1–4). (1) Classical KBOs have semi-major axes between about 40 and 50 AU with moderate eccentricities and inclinations. These objects may be regarded as the population originally predicted for the Kuiper Belt (Fernandez & Ip 1981), but they have higher eccentricities and inclinations than expected (Jewitt et al. 1998). The dynamics of the classical KBOs have shown that the outer solar system has been highly modified through the evolution of the planets (Hahn & Malhotra 2005). There appears to be two subsets of classical KBOs. The low-inclination "cold" classical population has generally smaller and redder objects compared to the high-inclination "hot" classical population (Tegler & Romanishin 2000; Brown 2001; Levison & Stern 2001; Trujillo & Brown 2002; Peixinho et al. 2008). These two classical populations likely represent different formation regions from the outer solar system. Through migration and scattering of the planets very early in the solar system, the two classical populations came to reside where we see them now (Gomes 2003; Levison & Morbidelli 2003; Batygin et al. 2011). (2) Scattered disk objects have large eccentricities with perihelia near the orbit of Neptune ($q \sim 30$–45 AU). The scattered disk objects are likely to have been moved to their current orbits through interactions with Neptune (Gomes et al. 2008).

(3) Resonant KBOs are in mean motion resonances with Neptune and generally have higher eccentricities and inclinations than classical KBOs. Most of the resonance objects were likely captured into their resonances from the outward migration and circularization of Neptune's orbit (Malhotra 1995; Levison et al. 2008). Where the resonance objects came from and how and when this capture occurred are still highly debated. The 3:2 resonance, called Plutinos since Pluto is in this resonance, appears to be the most populated resonance (Jewitt et al. 1998; Chiang & Jordan 2002; Sheppard et al. 2011). The other resonances with a significant number of known objects are the outer mean motion resonances 5:3, 7:4, 2:1, and 5:2 (Elliot et al. 2005; Hahn & Malhotra 2005; Gladman et al. 2008).

Binary small bodies are a particularly good way to obtain clues about the solar system's past. Remarkably, the small bodies in the various solar system reservoirs appear to have significantly

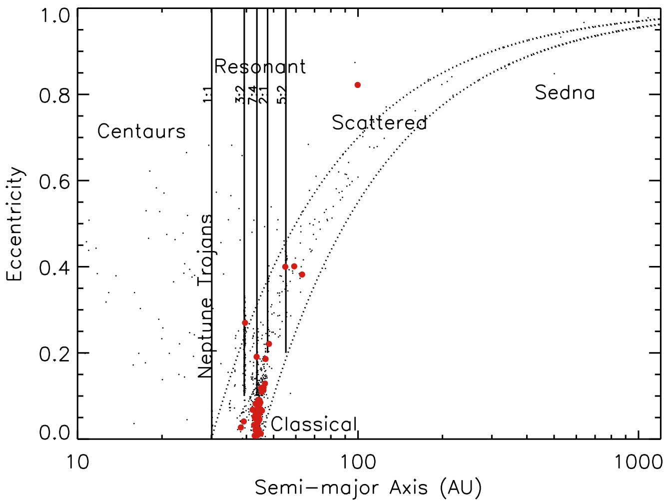

Figure 1. Semi-major axis vs. eccentricity for all multi-opposition observed TNOs. Objects considered equal-sized binaries (Δmag < 1 mag) are shown with big red filled circles. This figure shows several distinct dynamical KBO populations. Vertical dashed lines show the main resonances with Neptune as well as the Neptune Trojans in the 1 : 1 resonance. Scattered disk objects have perihelia 30 AU $\lesssim q \lesssim$ 45 AU as shown between the dashed lines. Classical objects are in the lower center portion of the figure and include the main Kuiper Belt with its high- and low-inclination populations. An edge near 50 AU can clearly be seen for low-eccentricity objects. Centaurs are on unstable orbits between the giant planets.

(A color version of this figure is available in the online journal.)

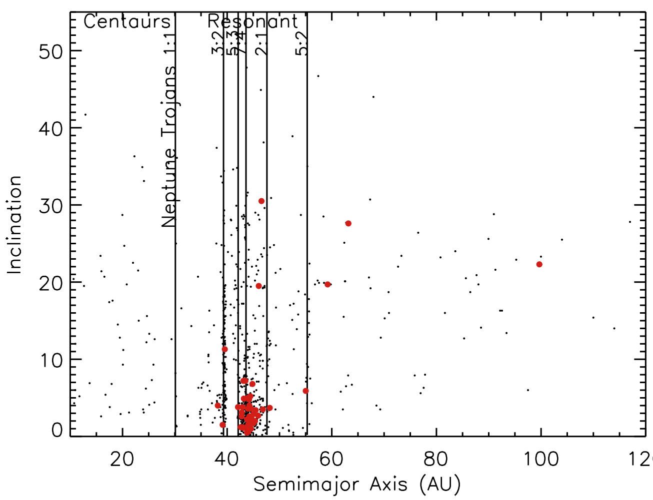

Figure 2. Semi-major axis vs. inclination for all multi-opposition observed TNOs. Objects considered equal-sized binaries (Δmag < 1 mag) are shown with big red filled circles.

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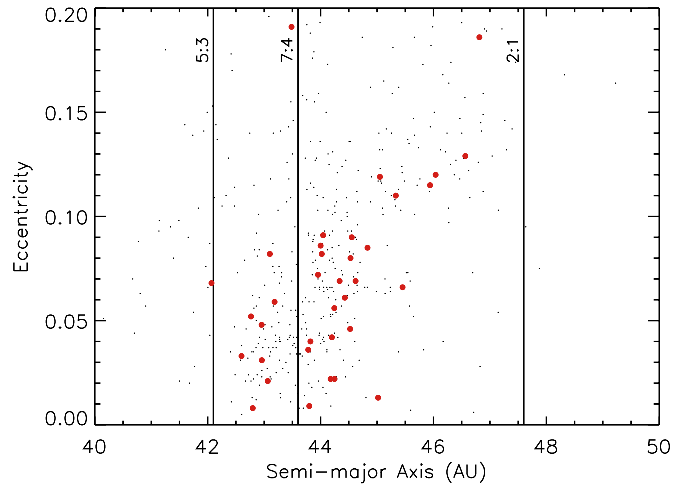

Figure 3. Expanded version of Figure 1 to better see the distribution of equal-sized binaries in the main classical Kuiper Belt. No enhancement of binaries is seen near 44 AU, which has been called the kernel area by Petit et al. (2011). There is an apparent lack of binaries near 43.5 AU, which is near the 7:4 resonance as well as above an eccentricity of 0.1.

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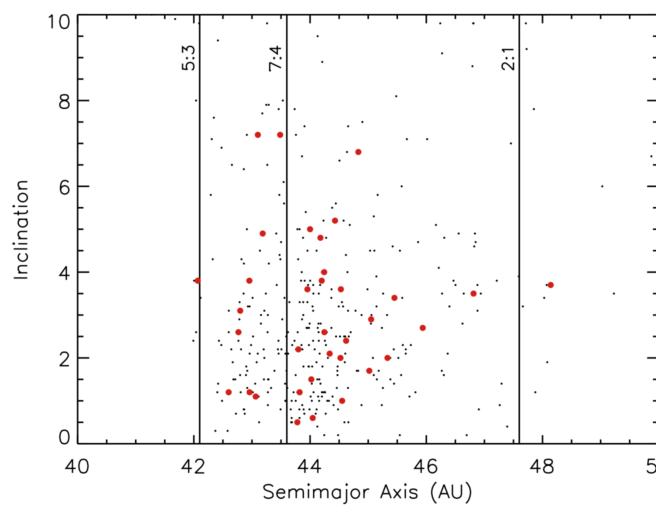

Figure 4. Blown-up version of Figure 2 to better see the distribution of equal-sized binaries in the main classical Kuiper Belt. Most binaries have inclinations less than about 5 deg.

(A color version of this figure is available in the online journal.)

different binary characteristics (Richardson & Walsh 2006; Noll et al. 2008a). In the main asteroid belt, most secondaries are close to and significantly smaller than the primaries (Merline et al. 2002; Margot et al. 2002; Marchis et al. 2006b). This is indicative of formation through direct collisions. The few binaries known in the Jupiter Trojan population hint at these objects being of very low density, implying they may be similar to comets and Trans-Neptunian Objects (TNOs; Marchis et al. 2006a). Starting with the discovery of the first KBO binary other than Pluto, it has become apparent that most of the low-inclination classical Kuiper Belt binaries have large separations and similar-sized components (Veillet et al. 2002; Noll et al. 2008a). Because of the large angular momentum in these equal-sized, wide binary systems, they cannot be formed by direct collisions. Direct formation by gravitational collapse, the dynamical friction of a sea of KBOs, three-body interactions, some other collisionless interactions, or a combination of these are the best viable scenarios for binary formation in the classical Kuiper Belt (Nesvorný et al. 2010; Goldreich et al. 2002; Weidenschilling 2002; Funato et al. 2004; Astakhov et al. 2005; Lee et al. 2007; Schlichting & Sari 2008a; Gamboa Suarez et al. 2010). The cold classical disk also has a high fraction of binaries, irrespective of separation and difference in magnitude of the individual components, compared to the hot classical, resonant, and scattered populations, about 30% versus 5% binary fraction, respectively (Stephens & Noll 2006; Noll et al. 2008b).

Unlike the low-inclination classical KBOs, many of the other known KBO binaries do not have such equal-sized and wide components. The different types of binary formation mechanisms proposed will each tend to create a particular subset of satellite semi-major axes, eccentricities, inclinations, and secondary diameters (Kern & Elliot 2006a; Noll et al.

Table 1
2007 TY430 Heliocentric Orbital Elements

a (AU)	*e*	*i* (deg)	MA (deg)	*ω* (deg)	Ω (deg)	Epoch
39.548	0.270	11.3	352.6	205.2	196.7	2012 Mar 14

Notes. The orbital elements are from the minor planet center and are the semi-major axis (*a*), inclination (*i*), eccentricity (*e*), mean anomaly (MA), argument of perihelion (*ω*), longitude of the ascending node (Ω), and epoch.

2008a). Thus, understanding the orbital elements and physical characteristics of the components of a binary is essential to constraining how the binary may have formed. Understanding the formation mechanism of binaries gives insight into the original solar nebula and the collisional environment in the distant past. The two distinct binary populations seen in the cold and hot dynamical classes are strong evidence of a different history. For example, Parker & Kavelaars (2010) use the fragile nature of the wide binaries in the cold classical region as evidence to show that cold classical KBOs were not likely to have been implanted dynamically, as suggested by Levison et al. (2008). Binaries also likely played an important role in planet formation by acting as a heat source in the planetesimal disk, transforming gravitational potential energy into kinetic energy of planetesimals in the disk (Perets 2011).

2007 TY430 is a unique binary KBO because it is the first known equal-sized, wide binary in the 3:2 mean motion resonance with Neptune, which is the innermost well-populated Neptune resonance. The other known 3:2 resonance binary objects (including Pluto, Orcus, (47171) 1999 TC36, and (208996) 2003 AZ84) have significantly smaller and relatively closer secondaries (magnitude differences greater than 2 mag) that are more indicative of formation through direct collisions (Stern 2002; Brown et al. 2006; Canup 2011). Because 2007 TY430 indicates a different binary formation mechanism operating within the 3:2 resonance population, 2007 TY430 was extensively observed over the past several years in order to determine the orbital and physical properties of its two components.

2. OBSERVATIONS

KBO 2007 TY430 was discovered with the 8.2 m Subaru telescope (Sheppard et al. 2008) during a survey for faint Neptune Trojans (Sheppard & Trujillo 2010a). The Suprime-Cam wide-field imager was used, which has ten 2048 × 4096 pixel CCDs with a pixel scale of 0.20 arcsec per pixel (Miyazaki et al. 2002). At discovery it was apparent that 2007 TY430 was elongated compared to the background stars. Upon closer examination it was found that 2007 TY430 was a binary with the two components having a separation of about 0.67 arcsec and within about 0.1 mag of each other (Sheppard & Trujillo 2008). 2007 TY430 was at a heliocentric distance of about 29.3 AU when discovered. Table 1 shows the heliocentric orbit determined for 2007 TY430.

Director's Discretionary Time (DDT) was immediately requested with the 8.1 m Gemini telescope in order to monitor the binary to obtain the orbit of the mutual components (Figure 5). GMOS on Gemini South was used for the 2007 to early 2008 DDT observations. GMOS queue time on Gemini North was used for the later 2008 through 2011 observations. Each GMOS has three 2048 × 4608 pixel CCDs with 0.0730 arcsec per pixel for GMOS South and 0.0728 arcsec per pixel for GMOS North (Hook et al. 2004). The observations were only executed in excellent seeing (<0.6 arcsec FWHM). Mainly Sloan *i*-band images were obtained because of the superior seeing at longer wavelengths from the ground, but some Sloan *g*- and *r*-band images were obtained when the two components of the binary were well separated to measure their individual colors.

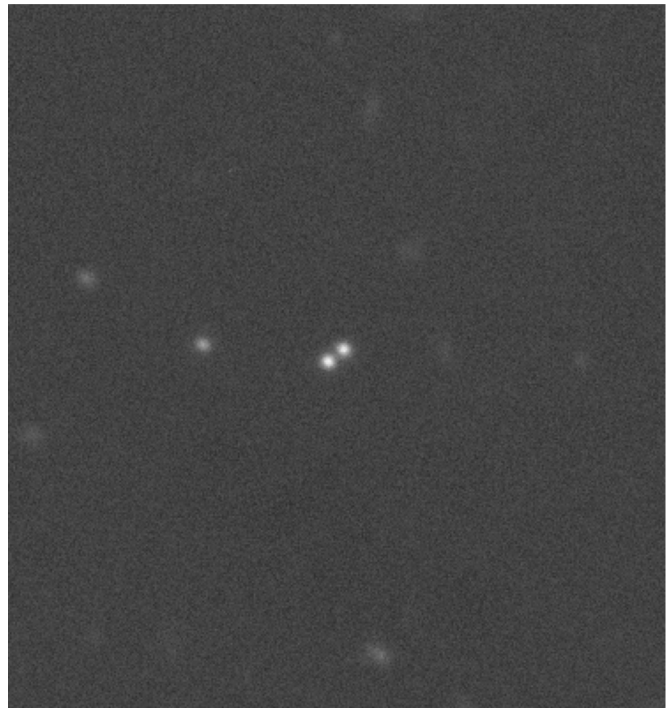

Figure 5. Equal-sized Plutino binary 2007 TY430 is easily seen near the center of this image from the GMOS detector on the Gemini telescope in 2007 December. The separation between the components was about 0.7 arcsec.

Table 2 shows the astrometry and photometry between the two components of the binary for all observations obtained for 2007 TY430. In addition to the Subaru and Gemini data, 2007 TY430 was observed with the Wide Field Planetary Camera 2 on the *Hubble Space Telescope* (*HST*) in 2008 September and is included in Table 2 (Noll et al. 2009). The maximum observed separation of the two components was about 1 arcsec. The maximum difference in magnitude between the components was about 0.3 mag. Many times the two components had nearly equal magnitudes with an average difference of about 0.1 mag. A few times, the two components switched as to which one was brighter (Table 2). The relatively fast change in brightness differences between the two components compared to the long orbital period of the binary, and the differences in brightness when observed near the same spot in the orbit for two different epochs, show that the individual components are not in synchronous rotation.

3. ANALYSIS

3.1. Heliocentric Orbit of 2007 TY430 and the 3:2 Resonance

Table 1 shows the heliocentric orbital elements for 2007 TY430 from the minor planet center. The semi-major axis and eccentricity are easily recognized as a 3:2 resonance object or Plutino. Figure 1 shows that 2007 TY430 is near the outer edge of the 3:2 resonance. In order to determine the stability of 2007 TY430's orbit, 10 clones were made using the orbital elements and full covariance matrix of the orbital elements from the AstDys Web site (http://hamilton.dm.unipi.it/astdys/) including observations spanning a more than 3 year arc. Using the Swift

Table 2
Observations of 2007 TY430 Binary Components

UT Date	ΔR.A. ($''$)	ΔDecl. ($''$)	ΔMag (mag)
2011 Jan 06.201	−0.488 ± 0.021	−0.066 ± 0.020	+0.16 ± 0.03
2010 Sep 18.533	−0.737 ± 0.019	−0.419 ± 0.019	+0.22 ± 0.01
2010 Feb 09.222	0.0 ± 0.120	0.0 ± 0.120	...
2009 Dec 24.277	0.379 ± 0.019	0.000 ± 0.016	+0.08 ± 0.03
2009 Dec 07.273	0.436 ± 0.025	0.045 ± 0.015	+0.20 ± 0.02
2009 Nov 05.353	0.638 ± 0.020	0.191 ± 0.019	+0.11 ± 0.02
2009 Oct 16.451	0.719 ± 0.019	0.255 ± 0.016	+0.07 ± 0.02
2009 Sep 27.400	0.801 ± 0.017	0.300 ± 0.015	+0.07 ± 0.02
2009 Aug 31.583	0.892 ± 0.015	0.382 ± 0.015	+0.05 ± 0.02
2009 Aug 24.622	0.928 ± 0.020	0.410 ± 0.024	+0.21 ± 0.02
2009 Aug 08.625	0.946 ± 0.027	0.428 ± 0.027	+0.18 ± 0.03
2009 Feb 01.250	0.792 ± 0.022	0.619 ± 0.022	+0.25 ± 0.02
2009 Jan 07.208	0.737 ± 0.026	0.637 ± 0.026	+0.27 ± 0.02
2008 Nov 29.191	0.601 ± 0.036	0.564 ± 0.036	+0.18 ± 0.03
2008 Oct 31.401	0.482 ± 0.015	0.510 ± 0.015	+0.14 ± 0.03
2008 Sep 20.525	0.248 ± 0.001	0.399 ± 0.001	+0.22 ± 0.10
2008 Jan 08.054	−0.712 ± 0.031	−0.456 ± 0.031	+0.05 ± 0.02
2007 Dec 22.031	−0.694 ± 0.030	−0.475 ± 0.030	+0.10 ± 0.03
2007 Dec 12.058	−0.639 ± 0.037	−0.431 ± 0.037	+0.08 ± 0.03
2007 Nov 30.023	−0.621 ± 0.030	−0.475 ± 0.030	−0.06 ± 0.02
2007 Nov 27.061	−0.584 ± 0.035	−0.456 ± 0.035	+0.09 ± 0.02
2007 Nov 19.181	−0.621 ± 0.025	−0.502 ± 0.025	−0.04 ± 0.02
2007 Nov 14.187	−0.648 ± 0.018	−0.493 ± 0.018	−0.02 ± 0.02
2007 Oct 14.367	−0.460 ± 0.066	−0.500 ± 0.066	...

Notes. This table shows the offsets of the two components for each observation. UT date shows the year, month, and day. All data are from Gemini except the 2007 October 14 discovery data from Subaru and the 2008 September 20 observations from *HST* by Noll et al. (2009). The ΔMag is the difference in magnitude between the two components. On 2010 February 9, the individual binary components were not resolved and thus zero was chosen for the offset.

integrator program (Levison & Duncan 2000) with the four giant planets and relatively short time steps of about 40 days, the clones were numerically integrated backward in time for the age of the solar system. All ten clones are stable in the 3:2 resonance for the first 1 Myr. Eight of the ten clones remained in the 3:2 resonance for at least 10 Myr, which based on the classification method of Gladman et al. (2008) suggests that it is acceptable to call 2007 TY430 a Plutino, but likely an unstable one. Four of the ten remain in the 3:2 resonance for the age of the solar system with some interactions with the Kozai resonance.

The loss of some of the 2007 TY430 clones is not surprising since objects in the 3:2 resonance can be unstable over the age of the solar system (de Elia et al. 2008; Almeida et al. 2009; di Sisto et al. 2010). 2007 TY430 has a large libration amplitude of ∼120 deg (see also orbit calculations from Marc Buie's Web site at www.boulder.swri.edu/buie/kbo/astrom that has up to date information first published in Elliot et al. 2005). For the eccentricity and inclination of 2007 TY430, this libration amplitude puts it in the unstable part of the Plutino resonance (Tiscareno & Malhotra 2009), so it is not surprising that the orbital integrations showed a lack of long-term stability.

Since the backward numerical integrations did not show 2007 TY430 to be a strongly stable object, its past history cannot be reliably constructed. There are two major possibilities for the origin of 2007 TY430. The first is that 2007 TY430 was swept up into the 3:2 resonance, which is the likely case for most of the Plutinos (Hahn & Malhotra 2005). These Plutinos likely formed closer to the Sun than their current locations. Based on the Brouwer's constant as described in Murray-Clay & Schlichting (2011), the current relatively large heliocentric orbital eccentricity of 2007 TY430 (Table 1) suggests that if it was captured into the 3:2 resonance by an outward, smooth, slowly migrating Neptune, 2007 TY430 would originally have had a semi-major axis of about 31 AU if initially in a circular orbit. Over time, chaotic diffusion could have caused 2007 TY430 to move to higher and higher libration amplitudes until reaching its current situation of being near the outer "edge" of the 3:2 resonance. The second possibility is that 2007 TY430 used to be in a different region of the Kuiper Belt (e.g., the low-inclination "cold" classical region) and escaped into the scattered disk. While in the scattered disk, 2007 TY430 could have entered into the outskirts of the 3:2 resonance in the common phenomenon of resonance sticking (Lykawka & Mukai 2007), as the 3:2 resonance is known to catch scattered-disk objects (Lykawka & Mukai 2006). Resonance sticking naturally explains the large libration amplitude at the present epoch and thus, dynamically, the second scenario above seems the most likely. If scenario two is correct, it is unknown if 2007 TY430 came from an inner extension of what is now the cold classical belt or from what we see as the classical belt today before being pushed into the resonance. How long 2007 TY430 has been in the Plutino resonance and how long ago it left the cold classical region also cannot be determined.

Table 3
Binary Orbital Elements of 2007 TY430

Parameter	Value
$a_{\rm bin}$	21000 ± 160 km
$e_{\rm bin}$	0.1529 ± 0.0028
$i_{\rm bin}$	15.68 ± 0.22 deg
$\omega_{\rm bin}$	321.9 ± 4.0 deg
$\Omega_{\rm bin}$	332.7 ± 1.4 deg
$\mathrm{MA}_{\rm bin}$	290.4 ± 4.4 deg
$P_{\rm bin}$	961.2 ± 4.6 days
$M_{\rm sys}$	$7.90 \pm 0.21 \times 10^{17}$ kg
Mean longitude	224.9 ± 1.1 deg

Notes. Binary orbital elements are the semi-major axis ($a_{\rm bin}$), inclination with respect to the J2000 ecliptic ($i_{\rm bin}$), eccentricity ($e_{\rm bin}$), argument of periapse ($\omega_{\rm bin}$), longitude of the ascending node ($\Omega_{\rm bin}$), mean anomaly ($\mathrm{MA}_{\rm bin}$), period ($P_{\rm bin}$), total system mass ($M_{\rm sys}$), and mean longitude ($\lambda_{\rm bin} \equiv \Omega_{\rm bin} + \omega_{\rm bin} + \mathrm{MA}_{\rm bin}$). All orientation angles are given with respect to J2000 ecliptic. Mean anomaly is at epoch JD 2454300.0 (geocentric).

3.2. Orbit of Mutual Components of 2007 TY430

Using a two-body version of the code developed in Ragozzine & Brown (2009), the best-fit orbital properties of 2007 TY430 were found using thousands of individual Powell and Levenberg–Marquardt minimizations (Table 3). The combination of these minimizations provides a strong quadratic locus of points in chi-squared (χ^2) versus parameter space, as expected, with clear evidence that the global minimum was found. A single Keplerian orbit provides an excellent fit (reduced chi-squared ($\chi^2_{\rm red}$) = 0.74 with 46 degrees of freedom) and thus no non-Keplerian parameters were included (Figure 6). The residuals to the fit follow a Gaussian distribution. The data span a large enough range in time and viewing angle that the mirror degeneracy (which has $\chi^2_{\rm red} \simeq 2$) is strongly broken and the mirror orbital solution is clearly rejected. The season of potential mutual events ended several years ago.

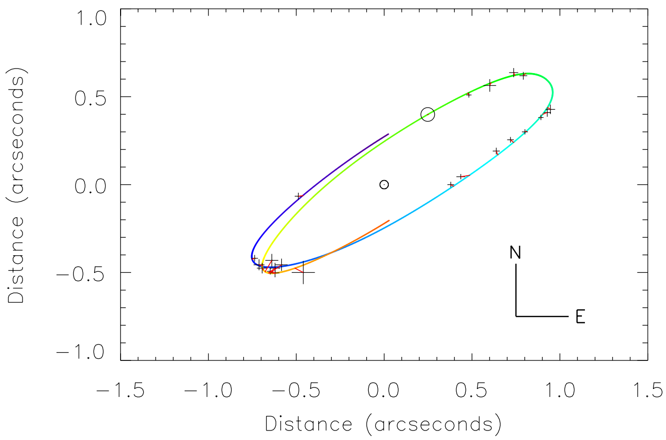

Figure 6. Orbital fit using the observations of 2007 TY430 from the Gemini telescope and *HST* between 2007 November and 2011 January. This plot shows the relative motion of one component around the other (which is held fixed at the center). Small crosses show the detected resolved component astrometric observations from Table 2 and are connected by red lines to the predicted position of these observations from the best-fit orbital parameters (Table 3) which are strongly constrained by the high precision astrometry and the excellent phase coverage. A line traces out the relative orbit over the time span of observations with color representing time (red starting 100 days before the first observation and purple ending 100 days after the last observation). Parallax and proper motion cause the apparent orbit to deviate from a closed Keplerian ellipse. Because of the very small error bars on the *HST* observation, it is highlighted with a circle. The dot at the center is a scale component of 2007 TY430 (50 km radius or 2.4 mas) with a circle ten times the normal size to show its location.

Following the method of Brown et al. (2005) from Press et al. (1992), a Monte Carlo suite of 29 random realizations of the data was created and the global minimum for each was determined for each data set. The best fit for each fit parameter and ancillary value are computed and then the standard deviation of the results is reported as the error in Table 3. Investigation of the distributions of the parameters showed that all the errors were nearly Gaussian. The mean and median of the parameters retrieved from the Monte Carlo simulation were not significantly different from the best-fit value, therefore the best fit on the nominal data set is listed as the central estimate of each parameter as shown in Table 3.

From the parameters in Table 3, the current obliquity is 25 ± 0.5 deg. With the range of heliocentric inclinations observed from the stable clones (7–18 deg), the mutual inclination never reaches above about 30 deg, suggesting that the 2007 TY430 binary in its current heliocentric orbit would not be subject to Kozai oscillations (Perets & Naoz 2009; Ragozzine 2009).

3.3. *Physical Parameters of 2007 TY430*

The colors of 2007 TY430 are shown in Table 4. 2007 TY430 is one of the reddest known objects ever observed ($g - i = 1.49 \pm 0.01$ mag) and is well above the ultra-red color cutoff ($g - i > 1.2$ mag) defined in Sheppard (2010). The term ultra-red objects was coined by Jewitt (2002) and has become associated with the low-inclination classical Kuiper Belt (Tegler & Romanishin 2000; Trujillo & Brown 2002; Peixinho et al. 2008) or Oort Cloud objects (Sheppard 2010) because most objects in these regions appear to have ultra-red surface colors. The composition of the ultra-red material is unknown, but spectral synthesis analysis suggests that the ultra-red color may be associated with organic material (Doressoundiram et al. 2008; Barucci et al. 2008; Fulchignoni et al. 2008).

Table 4
Physical Properties of 2007 TY430

Quantity	Measurement
H	6.94 ± 0.02 mag combined
r	21.23 ± 0.01 mag combined
$g - r$	1.07 ± 0.01 mag combined
$r - i$	0.42 ± 0.01 mag combined
$g - i$	1.49 ± 0.01 mag combined
R	20.94 ± 0.01 mag combined
$B - R$	2.03 ± 0.01 mag combined
$V - R$	0.74 ± 0.01 mag combined
$R - I$	0.63 ± 0.01 mag combined
$B - I$	2.66 ± 0.01 mag combined
$g - i$	1.49 ± 0.02 mag component 1
$g - i$	1.50 ± 0.02 mag component 2
S	36 ± 2 combined
J	19.91 ± 0.09 mag combined
J-H_2O	-0.16 ± 0.13 mag combined
J-CH_4	0.07 ± 0.15 mag combined
p_v	≈ 0.23 assuming $\rho \sim 0.75$
r	≈ 50 km assuming $\rho \sim 0.75$

Notes. H is the combined absolute magnitude of the two components in the V band. The colors are from the Sloan g, r, and i bands and have also been converted to the Johnson–Kron–Cousins system B, V, R, and I bands using Smith et al. (2002). S is the spectral gradient of the object as described in Sheppard (2010). J is the J-band infrared color of 2007 TY430, and J-H_2O and J-CH_4 are the colors using the water and methane narrowband filters in the infrared K band as described in Trujillo et al. (2011). The last two rows show what the albedo (p_v) and individual radii (r) of the two components of 2007 TY430 would be if the objects had a reasonable density of $\rho = 0.75$ g cm^{-3}.

Because of the near linearity in the optical colors of most KBOs (Doressoundiram et al. 2008), the spectral gradient, S, of an object can be found using two unique optical broadband filters. The spectral gradient is basically a very low resolution spectrum of an object and is usually expressed in percent of reddening per 100 nm in wavelength. Following Sheppard (2010), the spectral gradient for 2007 TY430 was found to be $S = 36 \pm 2$, putting 2007 TY430 within the low-inclination "cold" classical Kuiper Belt color population shown in Table 5 of Sheppard (2010).

Both components of the 2007 TY430 binary have indistinguishable ultra-red colors (Table 4). Like 2007 TY430, the colors of each component of other TNO binary pairs are similar to each other, though the colors of each binary system as a whole span a wide range of colors from near neutral to ultra-red. This suggests the formation of each TNO binary in a specific location within a homogeneous disk during the formation of the solar system (Benecchi et al. 2009). Infrared observations of 2007 TY430 using the Gemini NIRI instrument with the narrowband water and methane filters (Trujillo et al. 2011) show that 2007 TY430 does not have any significant amounts of water or methane ice on its surface (Table 4).

Similar to the moderate to high albedos found for low-inclination cold classical objects (Brucker et al. 2009), the equal-sized, wide, ultra-red binary 2007 TY430 requires a moderate to high albedo and very low density structure to obtain the total mass found for the pair (Figure 7). For a likely absolute minimum density of 0.5 g cm^{-3}, the albedo of 2007 TY430 would be greater than 0.17. For reasonable densities, the radii

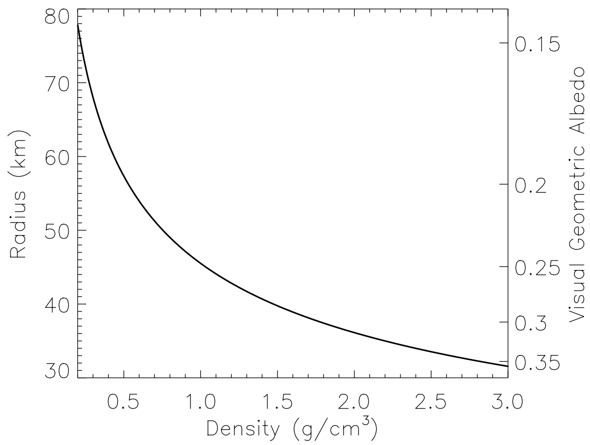

Figure 7. Density vs. radius (left y-axis) and visual geometric albedo (right y-axis) for each of the (assumed identical) components of 2007 TY430. In order to have a reasonable density ($\rho > 0.5$ g cm^{-3}), the albedo is required to be at least moderate ($p_v > 0.17$). This minimum density also requires the two components to have radii less than 60 km.

of either component should be less than 60 km, and thus the relatively low eccentricity of the binary is interesting since no tides should be operating on the bodies at their large distances from each other. For instance, assuming a realistic density of 0.75 g cm^{-3}, results in an albedo of about 0.23, and radii of the individual components of about 50 km.

3.4. Percentage of Wide Binaries in Kuiper Belt

Through an ultra-deep survey for Neptune Trojans using the Subaru and Magellan telescopes (Sheppard & Trujillo 2010a, 2010b), only one object, 2007 TY430, was found to be a binary. The Neptune Trojan ultra-deep survey detected about 900 faint KBOs. Interestingly, the brightest and likely one of the largest objects detected in the ultra-deep survey was 2007 TY430 ($m_R = 20.94 \pm 0.01$). The vast majority of the objects found in the Neptune Trojan survey were very faint ($m_R \sim$ 24–25 mag) KBOs with expected radii of only a few tens of kilometers. These discoveries were all checked by eye for binarity at discovery, like 2007 TY430. Most were not followed up to obtain orbits, but the survey was conducted within a few degrees of the ecliptic with most KBOs found to be between 40 and 50 AU, in the heart of the cold classical belt. Adding in the hundred or so KBOs detected in a similar ultra-deep survey for satellites of Saturn, Uranus, and Neptune (Sheppard et al. 2005, 2006) puts the number of KBOs detected in excellent seeing conditions at about one thousand with only one binary detection ($0.1^{+0.1}_{-0.07}$%). The vast majority of the KBOs discovered in the Neptune Trojan survey were in excellent seeing ranging between 0.45 and 0.8 arcsec, allowing easy detection of any found widely separated binaries. Only the brightest KBO found showed a binary nature. Nesvorný et al. (2011) demonstrated that binaries that may have formed through gravitational collapse with radii of less than or equal to 2007 TY430's are less likely to survive because collisions should be able to disrupt the pair over time. This is consistent with the non-detection of any binaries for the thousand smaller KBOs imaged in very good seeing conditions, though observational biases must be taken into account (Naoz et al. 2010).

Previous ground-based surveys have estimated about 1% of TNOs to be widely separated equal-sized binaries. These surveys detected significantly brighter and thus likely larger objects. The Deep Ecliptic Survey (DES), with an average photometric depth of only 22.5 mag in the R band (Elliot et al. 2005), found 4 out of 634 objects to be binaries from the ground, of which only about 212 were found in good seeing with a fine pixel scale using the Magellan telescope (Osip et al. 2003; Kern & Elliot 2006a). An unpublished Keck survey targeted 150 known KBOs and found no obvious binaries from the ground, but it is unknown the brightness distribution of the objects observed (Schaller & Brown 2003). Lin et al. (2010) found two nearly equal mass binaries in the Canada–France ecliptic plane survey and from this suggest that over 1.5% of low-inclination classical KBOs likely have large separation equal-sized binaries (>0.4 arcsec separation). Thus surveys of brighter KBOs show that about 1%–2% are binaries with separations detectable from the ground, while this work shows that there is likely significantly less than this for fainter and smaller objects.

There are observational biases against detecting binaries at smaller sizes. For instance, the Hill spheres (see Section 4.1) of the fainter and thus smaller objects are smaller, making any stable binaries closer to each other. This work went over 2 mag fainter than the DES, thus it was sensitive to objects that were a factor of 2.5 smaller, with a factor of 2.5 smaller Hill radius. This smaller Hill radius would have made the 2007 TY430 binary undetectable from the ground at discovery, but it would still have been an obvious binary if imaged when the components were their furthest distance from each other, which is the configuration in which eccentric binaries spend most of their time. From Table 5, four wide binaries would still have been detected from the ground even if their separations were halved, as their separations at discovery would have been about 0.6 arcsec or greater, similar to the separation of 2007 TY430 at discovery. Observing many very faint KBOs with *HST*, in a serendipitous (such as Fuentes et al. 2010) as well as a direct targeted search, would help eliminate this selection effect and help determine if smaller objects really do have fewer satellites than larger objects.

4. DISCUSSION

The ultra-red color and wide equal-sized binary nature of 2007 TY430 makes it very similar to the unique characteristics of the low-inclination classical Kuiper Belt. This strongly favors the argument that 2007 TY430 originated as a typical low-inclination "cold" classical KBO (assuming that the cold classical population forms in situ). Weak chaos over long timescales (or stronger chaos on faster timescales) slowly removed 2007 TY430 from the cold classical region into a dynamically excited orbit in the scattered disk (see Volk & Malhotra 2011). Eventually 2007 TY430 became trapped in the unstable outskirts of the 3:2 resonance where it is seen today. During this process, the binary remained stable. This would suggest that 2007 TY430's formation environment is likely the cause of its ultra-red color and wide binary nature and not its current orbital characteristics. This bolsters the argument of Benecchi et al. (2009) who suggest that similar colors for binary components indicate common formation conditions, regardless of present location.

4.1. Stability of 2007 TY430

The Hill sphere of an object orbiting the Sun is the region where satellites are generally stable around the object, given by

$$r_H = a_p \left[\frac{(m_{p1} + m_{p2})}{3\, M_\odot} \right]^{1/3}, \quad (1)$$

Table 5
Equal-sized TNO Binaries

Name	H (mag)	i (deg)	e	a (AU)	ΔMag (mag)	Sep (arcsec)	S	Class
2003 WU188	5.7	3.8	0.04	44.20	0.7	0.042	...	cl
(60621) 2000 FE8	6.9	5.9	0.40	55.02	0.6	0.044	10.2	r 5:2
2001 RZ143	6.4	2.1	0.07	44.34	0.1	0.046	...	cl
1998 WV24	7.5	1.5	0.04	39.14	0.3	0.051	9.4	inner cl
2003 QA91	5.5	2.4	0.07	44.62	0.1	0.056	...	cl
(80806) 2000 CM105	6.7	3.8	0.07	42.07	0.6	0.059	32.2	cl
2003 QR91	6.5	3.5	0.19	46.81	0.2	0.062	...	cl
2001 FL185	7.1	3.6	0.07	43.95	0.8	0.065	22.1	cl
2000 WT169	6.1	1.7	0.01	45.02	0.43	0.07	...	cl
(79360) 1997 CS29	5.3	2.2	0.01	43.80	0.09	0.07	28.5	cl
(60458) 2000 CM114	6.6	19.7	0.40	59.20	0.57	0.074	5.4	sc
2002 VT130	5.8	1.2	0.03	42.60	0.44	0.08	...	cl
(134860) 2000 OJ67	6.1	1.1	0.02	43.06	0.8	0.08	25.9	cl
(123509) 2000 WK183	6.6	2.0	0.05	44.52	0.4	0.080	31.9	cl
(65489) Ceto 2003 FX128	6.3	22.3	0.82	99.68	0.6	0.085	15.4	sc/cent
1999 XY143	6.0	7.2	0.08	43.10	0.38	0.09	...	cl
(275809) 2001 QY297	5.6	1.5	0.08	44.02	0.42	0.091	27.2	cl
1999 OJ4	7.1	4.0	0.03	38.21	0.16	0.097	28.2	inner cl
1999 RT214	7.8	2.6	0.05	42.77	0.81	0.107	29.5	cl
2001 XR254	5.7	1.2	0.03	42.96	0.09	0.107	15.1	cl
2006 SF369	6.7	27.6	0.38	63.18	0.1	0.11	...	r 3:1
2003 TJ58	8.0	1.0	0.09	44.55	0.50	0.119	20.5	cl
2001 QQ322	6.4	4.0	0.06	44.24	0.2	0.13	...	cl
2001 QC298	6.1	30.5	0.13	46.56	0.58	0.130	7.1	sc
(148780) Altjira 2001 UQ18	5.7	5.2	0.06	44.43	0.7	0.177	...	cl
2000 CQ114	7.0	2.7	0.12	45.94	0.4	0.178	30.9	cl
(58534) Logos 1997 CQ29	6.6	2.9	0.12	45.05	0.4	0.20	...	cl
(66652) Borasisi 1999 RZ253	5.9	0.6	0.09	44.05	0.33	0.21	...	cl
2000 QL251	6.6	3.7	0.22	48.14	0.05	0.25	6.6	2:1
(160091) 2000 OL67	6.8	2.0	0.11	45.33	0.6	0.26	...	cl
(119067) 2001 KP76	6.6	7.2	0.19	43.49	0.1	0.29	...	cl
2003 QY90	6.4	3.8	0.05	42.96	0.1	0.34	28.2	cl
2004 KH19	...	35.3	0.12	40.77	0.71	0.4	...	cl
2006 BR284	7.3	1.2	0.04	43.82	0.50	>0.5	...	cl
2006 JZ81	6.9	3.6	0.08	44.53	0.98	>0.5	...	cl
2002 XH91	5.5	5.0	0.09	44.00	1.04*	0.58	...	cl
(88611) 2001 QT297	5.8	2.6	0.02	44.25	0.7	0.61	...	cl
2006 CH69	...	1.8	0.04	45.74	0.28	0.61	...	cl
2007 TY430	**6.9**	**11.3**	**0.27**	**39.55**	**0.1**	**0.67**	**36.0**	**r 3:2**
2002 VF130	7.2	19.5	0.12	46.04	0.31	0.733	...	sc
(160256) 2002 PD149	6.3	4.9	0.06	43.19	0.4	0.74	...	cl
2000 CF105	6.9	0.5	0.04	43.78	0.7	0.78	22.4	cl
1998 WW31	6.1	6.8	0.09	44.83	0.4	1.2	6.8	cl
2003 UN284	7.4	3.1	0.01	42.80	0.6	2.0	...	cl
2005 EO304	6.3	3.4	0.07	45.45	1.2*	2.67	30.9	cl
2001 QW322	7.8	4.8	0.02	44.18	0.0	4	8.6	cl

Notes. Equal-sized binaries have ΔMag less than 1 mag. The heliocentric orbital elements are from the minor planet center and are the semi-major axis (a), inclination (i), and eccentricity (e). H is the absolute magnitude of the object in the V band, ΔMag is the difference in magnitude of the two components, Sep is the discovery separation of the two components, S is the spectral gradient for the object, and Class is the dynamical class of the object, where cl = classical, sc = scattered, cent = centaur, and r = resonance. Both 2002 XH91 and 2005 EO304 have ΔMag of greater than 1 mag, but have been included because of their large separations and thus are denoted by an asterisk. Color information references: Tegler & Romanishin 2000; Hainaut & Delsanti 2002; Doressoundiram et al. 2002; Tegler et al. 2003; Petit et al. 2008; Benecchi et al. 2009. Binary information references: Veillet et al. 2002; Noll et al. 2002, 2004a, 2004b, 2008a; Osip et al. 2003; Stephens & Noll 2006; Kern & Elliot 2006b; Grundy et al. 2007; Petit et al. 2008; Grundy et al. 2009; Lin et al. 2010; Grundy et al. 2011; Parker et al. 2011.

where a_p is the heliocentric distance of the object in AU, $M_\odot$ is the mass of the Sun, and m_{p1} and m_{p2} are the mass of the first and second components of the binary, respectively. The Hill radius for 2007 TY430 is about 3.015×10^5 km.

Using the heliocentric semi-major axis of 2007 TY430 from Table 1 and a total mass of $7.90 \pm 0.21 \times 10^{17}$ kg for the binary gives $a_{\rm bin}/r_H$ of about 0.07 for 2007 TY430. While this is still well within the stable region of orbital phase space, it is among the widest known binaries (Nesvorný et al. 2003; Nicholson et al. 2008; Noll et al. 2008a).

Widely separated binaries were probably much more common in the past as they are unstable over the age of the solar system

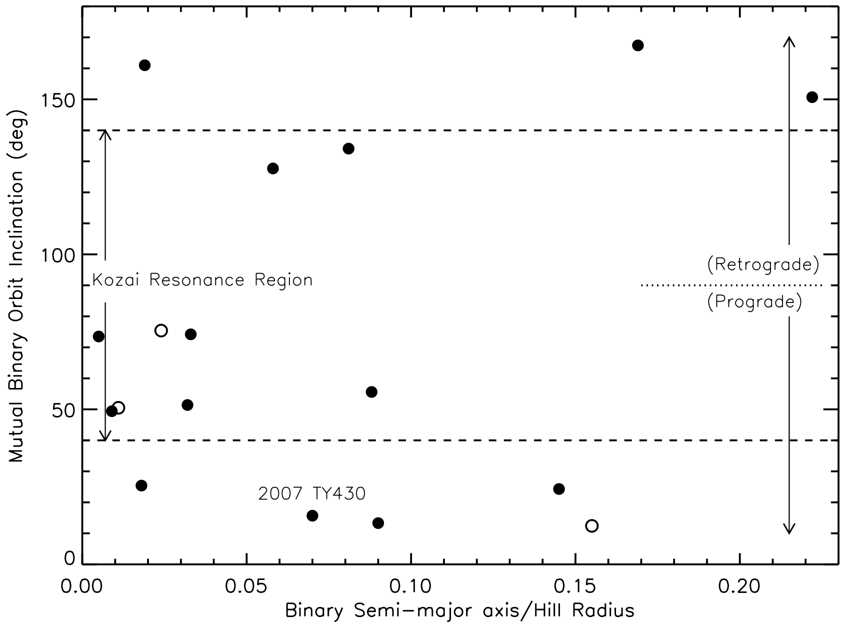

Figure 8. Semi-major axis/Hill radius (a_{bin}/r_H) vs. the mutual orbit inclination with respect to the J2000 ecliptic for the known KBO equal-sized binaries with known mutual inclinations. KBOs (26308) 1998 SM165, (42355) Typhon, and 2005 EO304 are shown with open symbols because they are not technically equal-sized binaries as their ΔMag are greater than 1 mag, but they all have large semi-major axes and so are included here. Many of the KBO binaries have likely been influenced by the Kozai mechanism. 2007 TY430 is in the lower center of this figure. The Kozai resonance likely affects distant circular orbits between about 40 and 140 deg (dashed lines) based on irregular satellites and numerical simulations (Kozai 1962; Carruba et al. 2002; Nesvorný et al. 2003; Sheppard et al. 2006). Interestingly, most of the very large semi-major axis, equal-sized binaries appear to have moderate to low eccentricities and low inclinations, making them unsusceptible to the Kozai resonance and tides.

from dynamical perturbations (Petit & Mousis 2004; Noll et al. 2006, 2008a; Petit et al. 2008; Parker & Kavelaars 2010). It is possible that the cold classical KBOs have had lower numbers of collisions or fewer planet interactions allowing the largest population of surviving wide, equal-sized binaries in the Kuiper Belt. 2007 TY430 has similar separation and component sizes as the cold classical KBOs 1998 WW31 and 2000 CF105 (Table 5). Petit & Mousis (2004) determined that these two binary KBOs were only stable for about 1–2 Gyr. The Petit & Mousis (2004) result is likely a lower limit on the binary lifetimes since they used a steeper size frequency distribution for the smaller KBOs than currently believed to exist, allowing for more small impactors to disrupt the binaries than is currently likely (Fraser et al. 2008; Fuentes & Holman 2008; Fuentes et al. 2009; Fraser 2009). The 2007 TY430 binary probably has a similar timescale of stability, though 2007 TY430 is in the Plutino population and not the low-inclination classical belt. The timescales of destruction for wide binary TNOs by Parker & Kavelaars (2010) also suggest 2007 TY430 would not have a high probability for surviving for the age of the solar system, and thus 2007 TY430 could just be one of a few binaries left of a once much larger population of binaries.

4.1.1. 2007 TY430: The Case for a Primordial Binary Orbit

The inclinations of many TNO binary components are generally high (Naoz et al. 2010). The Kuiper Belt binary 2001 QW322 was found to have a fairly low eccentricity ($e < 0.4$) yet a very large inclination ($i \sim 125$ deg) and semi-major axis (∼120,000 km; Petit et al. 2008). Because of 2001 QW322's large inclination, its relatively low eccentricity and large semi-major axis can be explained by the Kozai mechanism (Perets & Naoz 2009). Most binary minor planets do not appear to have primordial orbits as they could have been affected by either tidal forces or have high eccentricities or high inclinations at which the Kozai mechanism may operate (Ragozzine 2009; Naoz et al. 2010).

The binary orbit of 2007 TY430 is compared to other known equal-sized binary orbits in Figures 8 and 9. 2007 TY430 does not have orbital elements similar to other TNO binaries shown in a similar Figure 3 of Naoz et al. (2010), which compares the normalized separations of the binary components to their eccentricities. The $\log(a_{\mathrm{bin}}/r)$ for 2007 TY430 is slightly greater than 2.5, but still in a stable region of Naoz et al.'s Figure 3. Interestingly, when including recent results from Parker et al. (2011), it appears most of the equal-sized binaries with very large semi-major axes appear to have moderate to low eccentricities and low inclinations, making them unsusceptible to the Kozai resonance and tides. This is in contrast to many of the lower semi-major axis, equal-sized binaries that appear susceptible to the Kozai mechanism because of their large mutual inclinations and higher eccentricities. This result is likely because the large semi-major axis objects would become unstable to perturbations if their eccentricities or inclinations were too large.

2007 TY430 is the lowest eccentricity, wide-component, equal-sized binary known. Because the mutual orbital elements of the 2007 TY430 binary have low inclination, low eccentricity, and large semi-major axis (Figures 8 and 9), the Kozai mechanism and tidal interactions have not likely modified the primordial orbit of 2007 TY430 (Chyba et al. 1989; Murray & Dermott 1999; Perets & Naoz 2009). Modification of the 2007 TY430 binary could have occurred over the age of the solar system from direct collisions on either of the two components, from relatively massive bodies passing within the Hill sphere of the two components or interactions with the giant planets (Petit & Mousis 2004; Nesvorný et al. 2011).

The high eccentricities and inclinations of other TNO binary components suggest formation in a dense collisional environment. In this environment, gravitational encounters can create

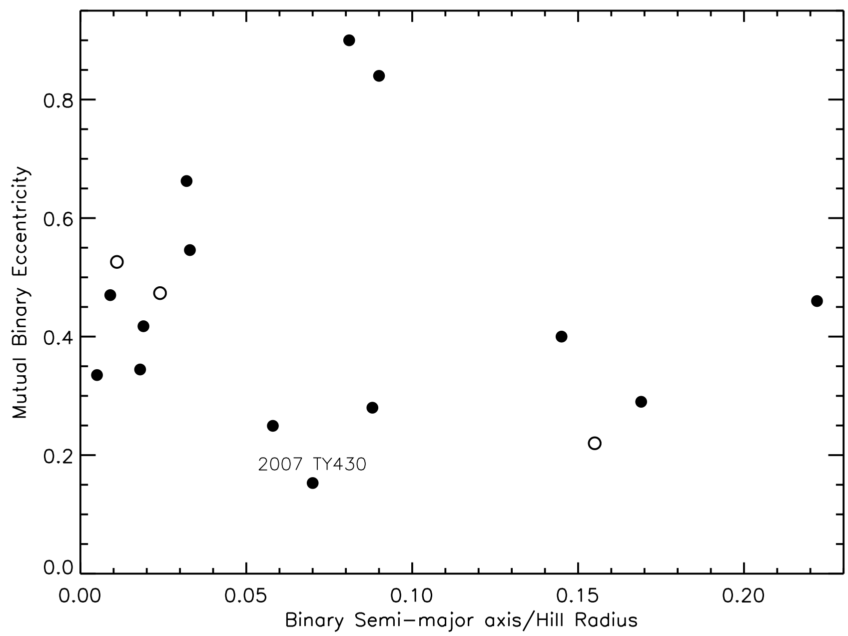

Figure 9. Semi-major axis/Hill radius ($a_{\rm bin}/r_H$) vs. the mutual orbit eccentricity for the known KBO equal-sized binaries with known mutual inclinations. 2007 TY430 is in the lower middle portion and has the lowest eccentricity of any known equal-sized binary; this along with 2007 TY430's low prograde inclination make it unlikely that tides or the Kozai resonance have significantly altered its binary orbit over the age of the solar system. Again, KBOs (26308) 1998 SM165, (42355) Typhon, and 2005 EO304 are shown with open symbols because they are not technically equal-sized binaries as their ΔMag is greater than 1 mag, but they all have large semi-major axes and so are included here.

these high eccentricities and inclinations along with secular Kozai effects and tidal evolution (Naoz et al. 2010). Other binaries observed to date could have formed in a similar manner as 2007 TY430, but later three-body encounters or direct collisions after binary formation changed the binary components' orbits to be highly inclined and eccentric. It is thus possible that 2007 TY430 simply has escaped any significant collisions or gravitational encounters while other known binaries have not or formed in a different collisional environment. This could be because 2007 TY430 diffused out of the low-inclination classical belt early on and the Plutino orbit made it less susceptible to collisions. Thus, 2007 TY430's binary orbit could be more primordial than many of the other known equal-sized wide binary objects observed to date.

4.2. Formation of the 2007 TY430 Binary System

The proposed binary formation by Funato et al. (2004) from exchanged binaries is unlikely since TNOs appear to lack the many high-eccentricity binaries suggested by this mechanism (Naoz et al. 2010), of which 2007 TY430 is another example of a low-eccentricity binary. Weidenschilling (2002) proposed a hybrid mechanism of a direct collision between two bodies while in the Hill sphere of a third body, which can directly form large separation binaries. This mechanism would only be likely to occur during the formation of the Kuiper Belt, as many more large bodies than currently observed are required as well as low velocities are needed. A similar mechanism, the L^3 mechanism proposed by Goldreich et al. (2002), has a third body strongly interacting with two other bodies while they each are within the other body's Hill sphere. The L^3 mechanism should dominate over the Weidenschilling (2002) mechanism because strong gravitational interactions should occur much more frequently than the actual collisions of objects. Chaos-assisted capture (Astakhov et al. 2005; Lee et al. 2007) is effectively the same as the L^3 mechanism; in chaos-assisted capture, two bodies are temporarily trapped in their mutual Hill spheres and can become permanently trapped when a third "intruder" body is scattered by the pair. This mechanism would create wide separation binaries with equal size and moderate eccentricity.

A second binary formation mechanism proposed by Goldreich et al. (2002), the L^2s mechanism, involves two objects forming an unbound transient binary that becomes bound with the aid of the dynamical friction from a sea of small objects. Any binary formation that involves dissipation of energy in a smooth and gradual manner, like the L^2s mechanism, will likely form retrograde binaries (Schlichting & Sari 2008b).

Because of 2007 TY430's prograde orbit, it is unlikely to have formed by the L^2s mechanism. Unlike the L^2s mechanism, the L^3 mechanism of Goldreich et al. (2002) should form equal populations of prograde and retrograde binaries (Schlichting & Sari 2008b). So 2007 TY430 could have formed through the L^3 mechanism which would only be likely if the KBOs had relatively large velocities, called super-Hill velocities (Schlichting & Sari 2008a, 2008b).

The Hill velocity (Rafikov 2003; Goldreich et al. 2004; Murray-Clay & Chiang 2006; Lee et al. 2007) is defined as

$$v_H = \left[\frac{G(m_{p1}+m_{p2})}{r_H}\right]^{1/2}, \qquad (2)$$

where G is the gravitational constant. For 2007 TY430, the Hill velocity is about 0.4 m s^{-1}, which is much less than the Keplerian velocity of its Plutino-type orbit that is about 4 km s^{-1}.

Formation through the L^3 mechanism would require large velocities between KBOs that several authors do not think were prevalent in the early Kuiper Belt (Goldreich et al. 2002; Schlichting & Sari 2008b; Murray-Clay & Schlichting 2011). Goldreich et al. (2002) suggest that the velocities of KBOs were about one-third of the Hill velocity, which would make retrograde orbits through the L^2s mechanism the dominant binary formation mechanism. This is because binary formation efficiency from gravitational encounters decreases significantly with higher relative velocities since the sphere of influence or time an object affects another is decreased (Noll et al. 2008a; Schlichting & Sari 2008b). Murray-Clay & Schlichting (2011) argue that sub-Hill velocities and the binary formation from dynamical friction (L^2s mechanism) is the best mechanism for the equal-sized binary formations. 2007 TY430 does not fall in along these formation lines because it is not retrograde, meaning large velocities during formation were likely and thus dynamical friction unlikely to be the capture mechanism. A weakness to the high-velocity scenario is that Schlichting & Sari (2008b) suggest that the velocity would need to be finely tuned and stay in such a state for a considerable amount of time in order for a high velocity regime to form these prograde, equal-sized binaries.

To date, not enough equal-sized binary orbital inclinations are known to draw a strong conclusion. Only 17 equal-sized KBO binaries have known inclinations (Figure 8). Of these, 5 are retrograde and 12 are prograde, but 3 of the prograde objects have ΔMag > 1 mag and thus are not quite equal-sized binaries. Several authors have suggested that the observed inclinations of TNO binaries are consistent with them being randomly distributed (Noll 2003; Chiang et al. 2007; Grundy et al. 2011). This suggests that the Kuiper Belt disk was in the dispersion-dominated (dynamically hot) regime during binary formation (see Stewart & Ida 2000; Collins & Sari 2006; Schlichting & Sari 2008b). Lee et al. (2007) point out that there are more prograde than retrograde binaries and determine this as a sign of how the binaries formed. Schlichting & Sari (2008b) suggest that this sign is showing the velocity regime in which the binaries formed. Schlichting & Sari (2008b) predicted that over 97% of the binaries with comparable masses will have retrograde orbits if the relative velocities of the KBOs were low. Since it appears to be well below 50%, the relative velocities must have been significantly higher, as discussed above for the formation of 2007 TY430.

Binary formation from direct gravitational collapse of an overdensity of concentrated cm- to meter-sized solids was suggested by Nesvorný et al. (2010). This mechanism appears to be able to produce a wide range of distant equal-sized binaries with a large range of eccentricities with most having prograde inclinations. This mechanism could explain 2007 TY430, but may have trouble producing the retrograde binaries found to date.

4.3. Plutino Resonance and the Cold Classical Belt

The Neptune mean motion resonance populations could have been emplaced by one of the two favored mechanisms. (1) The slow migration outward of Neptune by over 10 AU from its formation location from planetesimal scattering would have allowed Neptune to sweep many objects into the resonances we see today (Malhotra 1995; Hahn & Malhotra 2005). This scenario would likely mean that the inner 3:2 resonance would have a significantly different population of objects than the more outer resonances that would have swept through the classical Kuiper Belt population. This scenario would also suggest the resonance populations should have a cold component representative of the cold classicals along with a hot component representing the objects from closer in. (2) The chaotic population of the resonances could have occurred if Neptune was scattered with a relatively large eccentricity out from near the current Saturn region to near its present semi-major axis (Levison & Morbidelli 2003; Tsiganis et al. 2005; Levison et al. 2008). As Neptune circularized its orbit through interactions with planetesimals, objects in the resonance areas would become trapped. In this scenario, the resonance populations would be more uniform and not have a cold component, unlike the slow migration scenario.

The resonance populations should have a cold component if Neptune experienced extensive slow, smooth migration. This cold component should be similar in characteristics to the low-inclination classical Kuiper Belt, that is, equal-sized binaries should be common as well as ultra-red material (Murray-Clay & Schlichting 2011). This cold component should also have lower eccentricities compared to other objects, meaning there could be a correlation between binaries, color, and eccentricity as well as with inclination in the resonance populations. In the Levison et al. (2008) scenario, chaotic scattering of Neptune and then circularization, the resonance populations should match the scattered disk in characteristics.

No obvious cold component is observed in the 3:2 resonance population and the statistics are too low for the other resonance populations to determine if there is a cold component (Murray-Clay & Schlichting 2011). The 3:2 having no cold component is still consistent with slow, smooth migration since the 3:2 does not sweep through the cold classicals (Murray-Clay & Schlichting 2011). Thus the 3:2 resonance is not as strong as a marker as the other resonances, which should have cold components as they swept through the classical region of the Kuiper Belt. It is possible that sweeping of the ν_8 resonance through the 3:2 resonance and inner classical Kuiper Belt cleared out much of these regions (Petit et al. 2011). If this is true, the ν_8 resonance likely did not sweep through until after the formation of any equal-sized binaries since the binaries are unlikely to have formed as the density of such objects would have been too low.

2007 TY430 has a moderately inclined and eccentric heliocentric orbit, and thus would be considered part of the hot component of the 3:2 resonance on dynamical grounds. Although 2007 TY430 could easily have been emplaced recently by dynamical scattering and resonance sticking, it is interesting to speculate on the meaning of this cold-classical-like binary if it was placed in the resonance primordially. As discussed above, if 2007 TY430 was captured from an originally low-eccentricity, low-inclination orbit by slow, smooth migration, it would have originated around 31 AU by conservation of Brouwer's integral. This would suggest that the primordial cold classical region extended much further inward than is seen today, but the observational evidence for a cold region of the 3:2 resonance is insufficient (Murray-Clay & Schlichting 2011). If its dynamical history was well known, the relatively high eccentricity and inclination of 2007 TY430 could have been seen as an indication that the slow, smooth migration model is insufficient. More binary objects need to be discovered in the 3:2, but the existence of 2007 TY430 in the hot region of the 3:2 and no other known equal-sized 3:2 resonance objects would favor chaotic scattering by Neptune over slow smooth migration.

4.4. Other Known Equal-sized Wide Binaries

Table 5 shows the other known equal-sized TNO binaries. Here, equal sized is defined as the components having less than 1 mag difference between components. This magnitude difference corresponds to mass ratios less than 4, assuming similar albedos and densities for the two components and the lack of significant rotational brightness variations. As shown in Table 5 and Figures 1–4, the equal-sized binary population is mostly in the low-inclination classical belt. Interestingly,

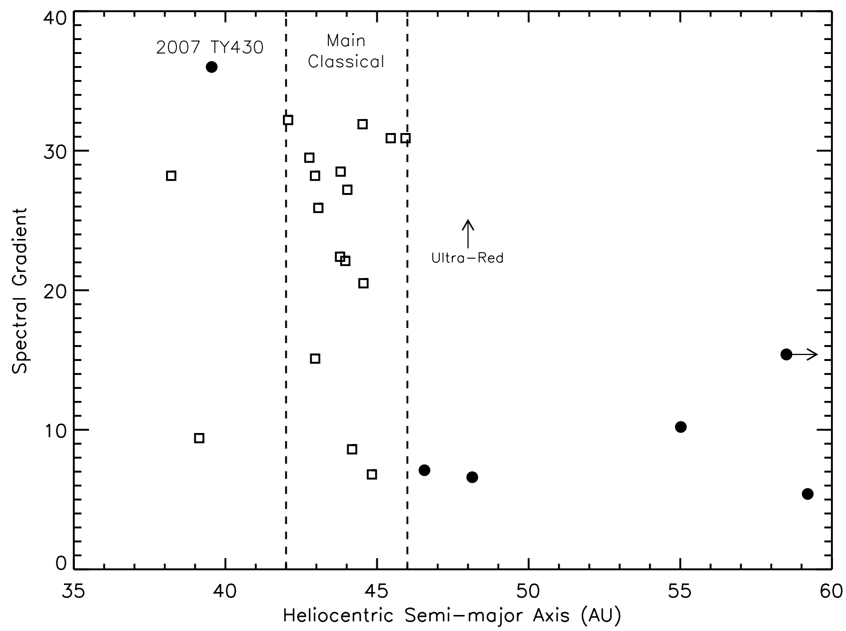

Figure 10. Color spectra gradients of the equal-sized binaries with known colors are shown vs. the heliocentric semi-major axis. The classical KBOs are shown with squares, while the resonant and scattered disk objects are shown with filled circles. Most of the main classical KBOs between about 42 and 46 AU have very red or ultra-red ($S > 20$ as defined in Sheppard 2010) colors, while only 2007 TY430 shows an ultra-red color outside of the classical belt. Both 1998 WV24 and 1999 OJ4 are a little closer in AU than the main classical belt, but since both have relatively low eccentricities they are considered part of the inner classical belt. Thus, the inner classical Kuiper Belt is likely an extension of the main classical Kuiper Belt as both show ultra-red, equal-sized binaries. Since all of the equal-sized binaries outside the classical belt, except for 2007 TY430, do not have ultra-red colors, it likely means that equal-sized binaries formed in multiple locations and not just in the cold classical belt.

most of the equal-sized binary TNOs not in the low-inclination classical belt appear to be in mean motion resonances. We see no obvious increase in the binary population between the semi-major axes of 43.5 and 44.5 AU, which has been called the "Kernel" area by Petit et al. (2011) as this region appears to be somewhat more dense than the rest of the classical Kuiper Belt (Figures 3 and 4). It does appear that there is an absence of equal-sized binaries around 43.5 AU, which is near the 7:4 resonance, as well as very few with eccentricities greater than 0.10.

The colors of the equal-sized binaries are not all ultra-red, as many are near neutral in color (Tegler & Romanishin 2000; Trujillo & Brown 2002; Gulbis et al. 2006; Peixinho et al. 2008; Petit et al. 2008; Benecchi et al. 2009; Sheppard 2010). As Figure 10 shows, the only equal-sized binary that is ultra-red in color ($S \gtrsim 25$ as defined in Sheppard 2010) and not in the classical population is 2007 TY430 (colors are from the database described in Hainaut & Delsanti 2002). In all, only one of six equal-sized binaries with known colors outside of the classical population has an ultra-red color, which is 2007 TY430 (Table 5). In contrast, 13 of 17 equal-sized binaries in the classical population have spectral gradients near or within the ultra-red color region ($S > 20$).

Numerically integrating the non-classical equal-sized binaries from Table 5 (2000 QL251, 2000 FE8, 2006 SF369, 1998 WV24, 2000 CM114, and 2001 QC298) with ten clones each for 500 Myr found all but 2000 CM114 were fairly stable. Some of the clones of 2000 QL151 (6/10, 1 a little chaotic) and 2006 SF369 (10/10, 3 a little chaotic) were experiencing Kozai oscillations (not unusual for resonant objects). Thus only 2000 CM114 is likely to have come from the classical region, but its inclination is currently very large and is not ultra-red in color. Since all of the equal-sized binaries outside the classical belt, except for 2007 TY430, do not have ultra-red colors, it suggests that equal-sized binaries are formed in multiple locations and not just in the cold classical belt. As shown in Figure 10, the inner classical Kuiper Belt is likely an extension of the main classical Kuiper Belt as both have low-inclination, ultra-red, equal-sized binaries. If the ultra-red, equal-sized binary of 1999 OJ4 were formed in the inner classical belt, where we see it today, it must have formed before any clearing through the ν_8 resonance sweeping mechanism since the density of KBOs would have been too low for likely equal-sized binary formation after any significant clearing of the region.

5. SUMMARY

2007 TY430 is the first known wide, equal-sized binary with an ultra-red color outside of the classical Kuiper Belt. The binary is near the outer edge of the 3:2 mean motion resonance with Neptune and could have become "stuck" at its current location after escaping from the main classical Kuiper Belt.

1. The binary components of 2007 TY430 were observed on approximately a monthly basis between 2007 and 2011 with the Gemini telescope in excellent seeing conditions. The components had a maximum separation of about 1 arcsec with an average of about 0.1 mag difference between them.
2. Through the extensive observations, the mutual orbit of 2007 TY430's components were found to have a large semi-major axis (21000 ± 160 km), moderate to low eccentricity (0.1529 ± 0.0028), and low prograde inclination (15.68 ± 0.11 deg) with the mirror orbit rejected with high confidence. The low inclination, large semi-major axis, and relatively low eccentricity of the mutual binary components mean neither tides nor the Kozai mechanism should have significantly altered the binary orbit of 2007 TY430. The possible primordial orbit for the components of 2007 TY430 is unique compared to many other

known binary KBOs. It appears that the KBO binaries with the largest mutual component semi-major axes have on average lower eccentricities and inclinations compared to the smaller semi-major axis binaries. This is likely because the largest semi-major axis objects would become unstable to perturbations if their eccentricities or inclinations were too large.

3. The favored formation mechanism for the low-inclination prograde orbit of 2007 TY430 is the L^3 mechanism proposed by Goldreich et al. (2002). Under the model of Schlichting & Sari (2008a), this would suggest the KBOs had relatively large velocities relative to each other during binary formation. The gravitational collapse mechanism of binary formation proposed by Nesvorný et al. (2010) is also a good fit for the prograde binary 2007 TY430, but this mechanism has not yet been shown to work similarly on the known retrograde equal-sized binaries.
4. The wide binary nature of 2007 TY430, when compared to previous simulations of similarly separated objects, suggests 2007 TY430 is likely not a stable binary for the age of the solar system. Thus, 2007 TY430 could just be one of the few remaining binaries from a once much larger population. Since all of the equal-sized binaries outside the classical belt, except for 2007 TY430, do not have ultra-red colors, it likely means that equal-sized binaries formed in multiple locations and not just in the cold classical belt. The inner classical Kuiper Belt is likely an extension of the main classical Kuiper Belt as both have low-inclination, ultra-red, equal-sized binaries. If the ultra-red, equal-sized binary of 1999 OJ4 formed in the inner classical belt, where we see it today, it must have formed before any clearing from any possible ν_8 resonance sweeping.
5. The total system mass of $7.90 \pm 0.21 \times 10^{17}$ kg means 2007 TY430 has a moderate to high albedo and low density. Assuming a reasonable density of 0.75 g cm^{-3} results in an albedo of about 0.23 with radii of the individual components at about 50 km. The individual components of 2007 TY430 were measured to have identical ultra-red colors. No obvious water or methane ice signatures were detected on the surface of 2007 TY430 from infrared observations using special water and methane ice near-infrared filters.
6. Out of about 1000 faint KBOs detected in ultra-deep surveys with the Subaru and Magellan telescopes, only 2007 TY430 was found to be an obvious wide binary. 2007 TY430 was the brightest object detected of the 1000 objects. Combining this result with previous works suggests that the larger KBOs are more likely to have wide binaries, but further observations of the faintest objects with *HST* are required to confirm this.

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REFERENCES

Almeida, A., Peixinho, N., & Correia, A. 2009, A&A, 508, 1021
Astakhov, S., Lee, E., & Farrelly, D. 2005, MNRAS, 360, 401
Barucci, M., Brown, M., Emery, J., & Merlin, F. 2008, in The Solar System Beyond Neptune, ed. M. Barucci, H. Boehnhardt, D. Cruikshank, & A. Morbidelli (Tucson, AZ: Univ. Arizona Press), 143
Batygin, K., Brown, M. E., & Fraser, W. C. 2011, ApJ, 738, 13
Benecchi, S., Noll, K. S., Grundy, W., et al. 2009, Icarus, 200, 292
Brown, M. 2001, AJ, 121, 2804
Brown, M., Bouchez, A., Rabinowitz, D., et al. 2005, ApJ, 632, L45
Brown, M., van Dam, M., Bouchez, A., et al. 2006, ApJ, 639, L43
Brucker, M., Grundy, W., Stansberry, J., et al. 2009, Icarus, 201, 284
Canup, R. 2011, AJ, 141, 35
Carruba, V., Burns, J. A., Nicholson, P. D., & Gladman, B. J. 2002, Icarus, 158, 434
Chiang, E., Lithwick, Y., Murray-Clay, R., et al. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson, AZ: Univ. Arizona Press), 895
Chiang, E. I., & Jordan, A. B. 2002, AJ, 124, 3430
Chyba, C., Jankowski, D., & Nicholson, P. 1989, A&A, 219, L23
Collins, B., & Sari, R. 2006, AJ, 132, 1316
de Elia, G., Brunini, A., & di Sisto, R. 2008, A&A, 490, 835
di Sisto, R., Brunini, A., & de Elia, G. 2010, A&A, 519, 112
Doressoundiram, A., Boehnhardt, H., Tegler, S., & Trujillo, C. 2008, in The Solar System Beyond Neptune, ed. M. Barucci, H. Boehnhardt, D. Cruikshank, & A. Morbidelli (Tucson, AZ: Univ. Arizona Press), 91
Doressoundiram, A., Peixinho, N., de Bergh, C., et al. 2002, AJ, 124, 2279
Elliot, J. L., Kern, S. D., Clancy, K. B., et al. 2005, AJ, 129, 1117
Fernandez, J., & Ip, W. 1981, Icarus, 47, 470
Fraser, W. C. 2009, ApJ, 706, 119
Fraser, W. C., Kavelaars, J. J., Holman, M. J., et al. 2008, Icarus, 195, 827
Fuentes, C., George, M., & Holman, M. 2009, ApJ, 696, 91
Fuentes, C., & Holman, M. 2008, AJ, 136, 83
Fuentes, C., Holman, M., Trilling, D., & Protopapas, P. 2010, ApJ, 722, 1290
Fulchignoni, M., Belskaya, I., Barucci, M. A., de Sanctis, M. C., & Doressoundiram, A. 2008, in The Solar System Beyond Neptune, ed. M. Barucci, H. Boehnhardt, D. Cruikshank, & A. Morbidelli (Tucson, AZ: Univ. Arizona Press), 181
Funato, Y., Makino, J., Hut, P., Kokubo, E., & Kinoshita, D. 2004, Nature, 427, 518
Gamboa Suarez, A., Hestroffer, D., & Farrelly, D. 2010, Celest. Mech. Dyn. Astron., 106, 245
Gladman, B., Marsden, B. G., & Vanlaerhoven, C. 2008, in The Solar System Beyond Neptune, ed. M. Barucci, H. Boehnhardt, D. Cruikshank, & A. Morbidelli (Tucson, AZ: Univ. Arizona Press), 43
Goldreich, P., Lithwick, Y., & Sari, R. 2002, Nature, 420, 643
Goldreich, P., Lithwick, Y., & Sari, R. 2004, ARA&A, 42, 549
Gomes, R. 2003, Icarus, 161, 404
Gomes, R., Fernandez, J., Gallardo, T., & Brunini, A. 2008, in The Solar System Beyond Neptune, ed. M. Barucci, H. Boehnhardt, D. Cruikshank, & A. Morbidelli (Tucson, AZ: Univ. Arizona Press), 259
Grundy, W., Noll, K. S., Buie, M., et al. 2009, Icarus, 200, 627
Grundy, W., Noll, K. S., Nimmo, F., et al. 2011, Icarus, 213, 678
Grundy, W., Stansberry, J., Noll, K. S., et al. 2007, Icarus, 191, 286
Gulbis, A., Elliot, J. L., & Kane, J. 2006, Icarus, 183, 168
Hahn, J., & Malhotra, R. 2005, AJ, 130, 2392
Hainaut, O., & Delsanti, A. 2002, A&A, 389, 641
Hook, I., Jorgensen, I., Allington-Smith, J., et al. 2004, PASP, 116, 425
Jewitt, D. 2002, AJ, 123, 1039
Jewitt, D., Luu, J., & Trujillo, C. 1998, AJ, 123, 2110
Kern, S. D., & Elliot, J. L. 2006a, ApJ, 643, L57
Kern, S. D., & Elliot, J. L. 2006b, Icarus, 183, 179
Kozai, Y. 1962, AJ, 67, 591
Lee, E., Sergey, A., & Farrelly, D. 2007, MNRAS, 379, 229
Levison, H., & Duncan, M. 2000, AJ, 120, 2117
Levison, H., & Morbidelli, A. 2003, Nature, 426, 419
Levison, H., Morbidelli, A., Vanlaerhoven, C., Gomes, R., & Tsiganis, K. 2008, Icarus, 196, 258
Levison, H., & Stern, S. A. 2001, AJ, 121, 1730
Lin, H., Kavelaars, J., Ip, W., et al. 2010, PASP, 122, 1030

Lykawka, P. S., & Mukai, T. 2006, Planet. Space Sci., 54, 87
Lykawka, P. S., & Mukai, T. 2007, Icarus, 192, 238
Malhotra, R. 1995, AJ, 110, 420
Marchis, F., Hestroffer, D., Descamps, P., et al. 2006a, Nature, 439, 565
Marchis, F., Kaasalainen, M., Hom, E., et al. 2006b, Icarus, 185, 39
Margot, J., Nolan, M., Benner, L., et al. 2002, Science, 296, 1445
Merline, W., Weidenschilling, S., Durda, D., et al. 2002, in Asteroids II, ed. W. Bottke Jr., A. Cellino, P. Paolicchi, & R. Binzel (Tucson, AZ: Univ. Arizona Press), 289
Miyazaki, S., Komiyama, Y., Sekiguchi, M., et al. 2002, PASJ, 54, 833
Murray, C. D., & Dermott, S. F. 1999, Solar System Dynamics (Cambridge: Cambridge Univ. Press)
Murray-Clay, R., & Chiang, E. 2006, AJ, 651, 1194
Murray-Clay, R., & Schlichting, H. 2011, ApJ, 730, 132
Naoz, S., Perets, H., & Ragozzine, D. 2010, ApJ, 719, 1775
Nesvorný, D., Alvarellos, J., Dones, L., & Levison, H. 2003, AJ, 126, 398
Nesvorný, D., Vokrouhlicky, D., Bottke, W., Noll, K. S., & Levison, H. 2011, AJ, 141, 159
Nesvorný, D., Youdin, A., & Richardson, D. 2010, AJ, 140, 785
Nicholson, P., Cuk, M., Sheppard, S., Nesvorný, D., & Johnson, T. 2008, in The Solar System Beyond Neptune, ed. M. Barucci, H. Boehnhardt, D. Cruikshank, & A. Morbidelli (Tucson, AZ: Univ. Arizona Press), 411
Noll, K. S. 2003, Earth Moon Planets, 91, 395
Noll, K. S., Grundy, W., Benecchi, S., & Levison, H. 2009, IAU Circ., 9074
Noll, K. S., Grundy, W., Chiang, E., Margot, J., & Kern, S. D. 2008a, in The Solar System Beyond Neptune, ed. M. Barucci, H. Boehnhardt, D. Cruikshank, & A. Morbidelli (Tucson, AZ: Univ. Arizona Press), 345
Noll, K. S., Grundy, W., Stephens, D., Levison, H., & Kern, S. D. 2008b, Icarus, 194, 758
Noll, K. S., Levison, H., Grundy, W., & Stephens, D. 2006, Icarus, 184, 611
Noll, K. S., Stephens, D., Grundy, W., & Griffin, I. 2004a, Icarus, 172, 402
Noll, K. S., Stephens, D., Grundy, W., Osip, D., & Griffin, I. 2004b, AJ, 128, 2547
Noll, K. S., Stephens, D., Grundy, W., et al. 2002, AJ, 124, 3424
Osip, D. J., Kern, S. D., & Elliot, J. L. 2003, Earth Moon Planets, 92, 409
Parker, A. H., & Kavelaars, J. J. 2010, ApJ, 722, L204
Parker, A. H., Kavelaars, J. J., Petit, J.-M., et al. 2011, ApJ, 743, 1
Peixinho, N., Lacerda, P., & Jewitt, D. 2008, AJ, 136, 1837
Perets, H. 2011, ApJ, 727, L3
Perets, H., & Naoz, S. 2009, ApJ, 699, L17
Petit, J.-M., Kavelaars, J. J., Gladman, B. J., et al. 2008, Science, 322, 432
Petit, J.-M., Kavelaars, J. J., Gladman, B. J., et al. 2011, AJ, 142, 131
Petit, J.-M., & Mousis, O. 2004, Icarus, 168, 409
Press, W., Teukolsky, S., Vetterling, W., & Flannery, B. 1992, Numerical Recipes in C: The Art of Scientific Computing (2nd ed.; New York: Cambridge Univ. Press)
Rafikov, R. 2003, AJ, 126, 2529
Ragozzine, D. 2009, PhD thesis, CalTech
Ragozzine, D., & Brown, M. 2009, AJ, 137, 4766
Richardson, D., & Walsh, K. 2006, Annu. Rev. Earth Planet. Sci., 34, 47
Schaller, E., & Brown, M. 2003, BAAS, 35, 993
Schlichting, H., & Sari, R. 2008a, ApJ, 673, 1218
Schlichting, H., & Sari, R. 2008b, ApJ, 686, 741
Sheppard, S. 2010, AJ, 139, 1394
Sheppard, S., Jewitt, D., & Kleyna, J. 2005, AJ, 129, 518
Sheppard, S., Jewitt, D., & Kleyna, J. 2006, AJ, 132, 171
Sheppard, S., & Trujillo, C. 2008, IAU Circ., 8962
Sheppard, S., & Trujillo, C. 2010a, ApJ, 723, 233
Sheppard, S., & Trujillo, C. 2010b, Science, 329, 1304
Sheppard, S., Trujillo, C., & Marsden, B. G. 2008, MPEC-2008-M38
Sheppard, S., Udalski, A., Trujillo, C., et al. 2011, AJ, 142, 98
Smith, J. A., Tucker, D. L., Kent, S., et al. 2002, AJ, 123, 2121
Stephens, D., & Noll, K. S. 2006, AJ, 131, 1142
Stern, A. 2002, AJ, 124, 2300
Stewart, G., & Ida, S. 2000, Icarus, 143, 28
Tegler, S., & Romanishin, W. 2000, Nature, 407, 979
Tegler, S., Romanishin, W., & Consolmagno, S. 2003, ApJ, 599, L49
Tiscareno, M., & Malhotra, R. 2009, AJ, 138, 827
Trujillo, C., & Brown, M. 2002, ApJ, 566, L125
Trujillo, C., Sheppard, S., & Schaller, E. 2011, ApJ, 730, 105
Tsiganis, K., Gomes, R., Morbidelli, A., & Levison, H. 2005, Nature, 435, 459
Veillet, C., Parker, J. W., Griffin, I., et al. 2002, Nature, 416, 711
Volk, K., & Malhotra, R. 2011, ApJ, 736, 11
Weidenschilling, S. 2002, Icarus, 160, 212