PHYSICAL CHARACTERIZATION OF THE BINARY EDGEWORTH–KUIPER BELT OBJECT 2001 QT$_{297}$

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Abstract. Following our discovery of 2001 QT$_{297}$ as the second known binary Edgeworth–Kuiper Belt Object (EKBO) in October of 2001 [IAUC 7733], we have carried out additional high spatial resolution ground based imaging in October and November of 2001 and July, August, and September of 2002. Using the Raymond and Beverly Sackler Magellan Instant Camera (MagIC) on the Baade and Clay 6.5 m telescopes at Las Campanas Observatory in Chile, we have obtained accurate astrometric and photometric measurements in the Sloan r', i', and g' filters. Superb seeing conditions and PSF fitting allow an accurate determination of the binary component separation and position angle over time as well as a detailed study of color and temporal variability of the individual components. Here we present a physical characterization of the individual components of 2001 QT$_{297}$ based on these astrometric, color and variability measurements. We find the primary to exhibit colors about 0.3 magnitudes redder than solar with no evidence for variability. The secondary component, however, exhibits strong variability (∼0.6 magnitudes) with a best fit period of 4.7526 ± 0.0007 h for a single peak lightcurve or 9.505 ± 0.001 h for a dual peaked lightcurve. The colors measured for the secondary also suggest variability. Based on a preliminary orbit fit for the pair using observations spanning a one year arc, we are able to estimate a system mass of $\sim 3.2 \times 10^{18}$ kg and provide constraints to the surface albedo of 9–14% for assumed densities between 1 and 2 g/cm^3.

1. Introduction

Pluto was discovered in 1930, and rotational variability was well observed for several decades (cf. Stern, 1992). However, it wasn't until 1978 that the ninth planet in the solar system was found to have a companion, Charon (Christy and Harrington, 1978). Subsequent study of this binary system, especially during a 5-year period of mutual eclipses and occultations, provided a detailed characterization of Pluto and Charon, including accurate estimates of their diameters, albedos, masses, and densities (Tholen and Buie, 1997; Young et al., 2000). For solar-system bodies without a binary companion or natural satellite, accurate estimates of most of these physical characteristics require a close spacecraft encounter.

Until recently Pluto–Charon remained the only known binary system in the trans-Neptunian region. Pluto and Charon are large and close (currently < 32 AU) objects in comparison to the bodies thus far detected in the Edgeworth–Kuiper

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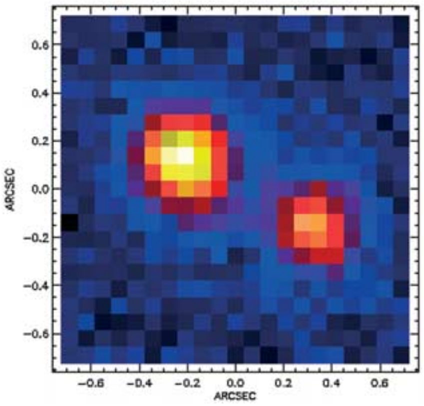


Figure 1. Discovery observation of the binarity of 2001 QT_{297}. This single 300 second exposure was obtained with MagIC at the Magellan Project Baade 6.5 m telescope on UT 11 October 2001 using a Sloan r' filter under exceptional seeing of 0.31 arc seconds.

Belt (EKB). The Pluto–Charon system is thought to have formed via a catastrophic collision, reaccretion of the debris cloud, and relatively rapid tidal evolution to the presently observed locked state (where the orbital period is identical to Pluto's rotation period such that Pluto always shows the same face to Charon). A similarly evolved binary EKBO with much smaller diameters ($\sim$100–300 km) would have tidally evolved in a short time period (Toth, 1999; Weidenschilling et al., 1989) to a separation of approximately 2000 km, which would subtend an angle of only 0.06 arcsec at a distance of 44 AU. Such a pair could not be resolved from any ground-based observatory (current adaptive optics systems are strictly only limited by the faint magnitude) and would provide a substantial challenge even utilizing the highest resolution available from the Hubble Space Telescope.

The previous argument would seem to limit our present study of the EKB to magnitudes, colors, and orbital elements. However, the first binary EKBO, 1998 WW_{31}, was serendipitously discovered as a widely separated pair (angular separation of 1.2 arcsec) in re-analysis of images by C. Veillet and collaborators taken in December 2000 at the Canada France Hawaii Telescope (Veillet, 2001). In an October 2001 observing run that included additional physical studies of 1998 WW_{31} and routine astrometry of EKBOs discovered by the Deep Ecliptic Survey (Millis et al., 2002), we made the unexpected discovery that 2001 QT_{297} is also a binary (Elliot, 2001a,b). Our discovery observations (Figure 1) indicate a separation of only 0.61 arc seconds and a magnitude difference between the components ranging from approximately 0.6 to 0.9 magnitudes, implying a small ratio ($\sim$1.3) for the radii of the two bodies and providing initial evidence of variability.

2. Observations and Analysis

The discovery and all subsequent follow-up observations for this program were carried out with the Raymond and Beverley Sackler Magellan Instant Camera (MagIC) at the Magellan Project Baade and Clay 6.5 m telescopes. MagIC is a highly efficient cryo-cooled CCD camera system utilizing a SITe 424a (2 k × 2 k) detector and equipped with a filter compliment including BVRI, and Sloan u', g', r', i', z'. Deployed at the f/11 focus of the Baade and Clay 6.5 m telescopes, MagIC's field of view is 140 arc seconds on a side with a pixel scale of 0.069 arc seconds/pixel.

Following the discovery and confirmation observations on UT 11–12 October 2001, we have carried out 5 additional successful observing runs to investigate color and variability of the binary components and to establish an initial orbit fit to the high accuracy astrometry that we have obtained. Initial follow-up was carried out at the Baade telescope on UT 1–4 November 2001 using fractional nights during a previously scheduled instrument engineering run. The next successful observations were not until UT 13 July 2002, when time series photometry and color measurements were obtained (using the Sloan g', r', i' filters). An additional 7 hours of temporal monitoring was obtained (using Sloan r' and i' filters) on UT 18 July 2002. Following the successful July runs, astrometric observations were added on UT 7 August 2002 and 8 September 2002. Binary component separations and position angles are calculated from all the Sloan r' measurements for each night. These values are provided in Table I along with the measured time series differential photometry for the two binary components.

All frames were processed with standard overscan subtraction and flat fielding (using a combination of twilight and dome flats). For each night, the binary pair and a group of stellar comparisons were identified in each frame and standard circular aperture photometry was carried out to determine object centers, peak signal levels, and background levels. These parameters were then used as input for point spread function (PSF) modeling (Elliot et al., 1989; Bosh et al., 1993; Elliot et al., 2003). A roughly 2 × 2 arc second sub-array was selected from the calibrated image for each object, and an analytic PSF (in our case, either a circular Lorentzian or a circular truncated Guassian model (Schechter et al., 1993) produced similar results) was fit to each object individually by least squares with the following free parameters: the object center (in row and column), the peak signal from the object, the background level, image diameter, and a parameter ("shape index") that describes the shape of the PSF. Those objects that were confirmed point sources (similar diameter and shape index) were selected to form a set of comparison stars, and the brightest of these stars was defined to be the reference star for the field. Next a common PSF was fit to all of these stars, determining a common background, diameter and shape index. For the reference star, the free parameters were the peak signal, and position (row and column center). For each additional star in the fit, the ratio of its peak signal to that of the reference star plus row and column offsets from the reference star were fit. The binary components were fit as separate sources in this common fit with the initial position and peak value for the primary taken from the previous circular aperture photometry and for the secondary estimated from inspection of the calibrated frame. After the fitting was complete, the instrumental magnitude of the reference star, determined from the circular aperture photometry, and the fitted ratios for the other objects were used to calculate differential magnitudes for the target(s) and comparison stars.

2.1. VARIABILITY

PSF profile fits to data on each of the nights are listed in Table I. Clearly demonstrated in these data is a change in relative magnitude of the two components over the first two nights and to a lesser degree over the subsequent early follow-up observations in November. Careful comparison with multiple field stars on all images for 11 and 12 October indicates the change in relative magnitude can be attributed entirely to variability of the secondary component. Such variability in solar system objects is generally regarded as evidence of rotation of either an elongated body or a surface with gross albedo differences (although interaction with a third body can not be ruled out). With evidence for variability of the secondary component, a concerted effort was made to carry out temporal monitoring of the pair during their next opposition in July 2002. The differential photometry results obtained on UT 18 July 2002 for the primary and secondary components of 2001 QT_{297} and a check star are plotted in Figure 2. The primary component demonstrates little variability suggesting no rotation or a more spherical shape with no large-scale albedo variation. The secondary, however, shows strong variability of more than half a magnitude over the 7 hour observing interval.

The variability data for the UT 18 July 2002 observations suggests a possible single peak lightcurve of about 0.6 magnitude (peak to peak) amplitude with a period between 4.5 and 5 hours or a dual peaked lightcurve with twice that period. Since all evidence for variability can be attributed directly to the secondary component, we are able to use our complete data set of differential magnitude observations between the primary and secondary to determine a precise rotational period for this body. The advantage here is that the long time interval from October 2001 to July 2002 gives excellent leverage to the lightcurve phasing (i.e., with over 1200 rotations over the interval, a 3 second change in period will result in a one hour shift in phase). By first exploring phase dispersion minimization analysis of the entire data set and subsets on UT 13 and 18 July 2002, we were able to reduce the number of possible periodicities to explore. Additional explicit phasing of the entire data set was used to explore consistency between nights with recognizable slopes and turn-around points and to discriminate periodicities with contradictory data.

Our best phasing of the existing variability data, including a light time correction, leads to two preferred interpretations that are consistent with the current

TABLE I

2001 QT$_{297}$ photometry and astrometry

Update	Julian date	Delta_mag	Sloan_filter	Separation ($''$)	Position_angle °
2001-Oct-11				0.606 ± 0.005	117.2 ± 0.5
	2452193.50875	0.88 ± 0.04	r'		
	2452193.54084	0.64 ± 0.03	r'		
	2452193.56951	0.58 ± 0.02	r'		
2001-Oct-12				0.608 ± 0.008	116.1 ± 0.8
	2452194.57804	0.90 ± 0.04	r'		
2001-Nov-01				0.66 ± 0.02	108.9 ± 2.1
	2452214.501725	0.71 ± 0.17	r'		
	2452214.510515	0.73 ± 0.23	r'		
	2452214.519235	0.53 ± 0.14	r'		
	2452214.529020	0.62 ± 0.17	i'		
	2452214.536645	0.73 ± 0.20	i'		
	22452214.54428	0.54 ± 0.12	i'		
	2452214.552600	0.72 ± 0.12	i'		
	2452214.562565	0.59 ± 0.18	i'		
2001-Nov-02				0.67 ± 0.02	105.9 ± 2.3
	2452215.497845	0.76 ± 0.19	r'		
	2452215.507160	0.36 ± 0.21	r'		
	2452215.515540	0.71 ± 0.12	r'		
	2452215.525000	0.72 ± 0.11	i'		
	2452215.544020	0.76 ± 0.10	r'		
2001-Nov-03				0.67 ± 0.04	106.7 ± 3.3
	2452216.506450	0.23 ± 0.14	r'		
	2452216.513250	0.64 ± 0.15	i'		
	2452216.520910	0.69 ± 0.08	i'		
2001-Nov-04				0.66 ± 0.02	102.1 ± 3.1
	2452217.495250	0.24 ± 0.24	r'		
	2452217.501065	0.45 ± 0.09	r'		
	2452217.572790	0.78 ± 0.26	r'		
	2452217.581665	0.81 ± 0.46	r'		
2002-Jul-13				0.76 ± 0.03	335.6 ± 1.6
	2452468.715270	1.00 ± 0.05	r'		
	2452468.762605	0.74 ± 0.08	r'		
	2452468.768470	0.80 ± 0.06	i'		
	2452468.774115	0.67 ± 0.05	i'		
	2452468.783717	0.62 ± 0.12	g'		
	2452468.793260	0.66 ± 0.05	r'		
	2452468.814015	0.54 ± 0.07	r'		
	2452468.834775	0.64 ± 0.04	r'		

TABLE I

Continued

Update	Julian date	Delta_mag	Sloan_filter	Separation ($''$)	Position_angle °
2002-Jul-18				0.78 ± 0.05	333.8 ± 5.3
	2452473.634430	0.99 ± 0.29	r'		
	2452473.668605	1.24 ± 0.15	r'		
	2452473.709265	0.84 ± 0.10	r'		
	2452473.736175	0.75 ± 0.11	r'		
	2452473.743860	0.77 ± 0.10	i'		
	2452473.771090	0.66 ± 0.15	r'		
	2452473.797980	0.73 ± 0.19	r'		
	2452473.805605	0.49 ± 0.09	i'		
	2452473.832620	1.00 ± 0.09	r'		
	2452473.864590	1.27 ± 0.19	r'		
	2452473.872205	1.14 ± 0.07	i'		
	2452473.897450	0.81 ± 0.10	r'		
	2452473.932750	0.70 ± 0.08	r'		
2002-Aug-07				0.92 ± 0.13	332.2 ± 8.4
	2452493.690120	0.87 ± 0.29	r'		
2002-Sep-08				0.93 ± 0.07	315.0 ± 6.6
	2452525.740135	0.94 ± 0.19	r'		

complete data set. Either the secondary has a rotation period of 4.7526 ± 0.0007 h with a single peaked lightcurve (Figure 3 upper) presumably due to surface albedo/compositional variation; or the rotation period is 9.5055 ± 0.0010 h for a dual peaked lightcurve (Figure 3 lower) indicating an elongated body with a semi-major to semi-minor axis ratio of approximately 1.8.

In either case, the implication remains that this was not a tidally evolved pair that underwent some gentle perturbation of the orbit to a more distant semi-major axis (i.e., via the effect of solar tides). Rather, the evidence for rapid variations is suggestive of the secondary component having undergone a subsequent impact that imparted both a change in orbital angular momentum to the system as well as rotational angular momentum to the body. Unfortunately the timescale for tidal evolution of the two components in their current orbit is longer than the age of the solar system and therefore not constraining on the time that such an impact occurred.

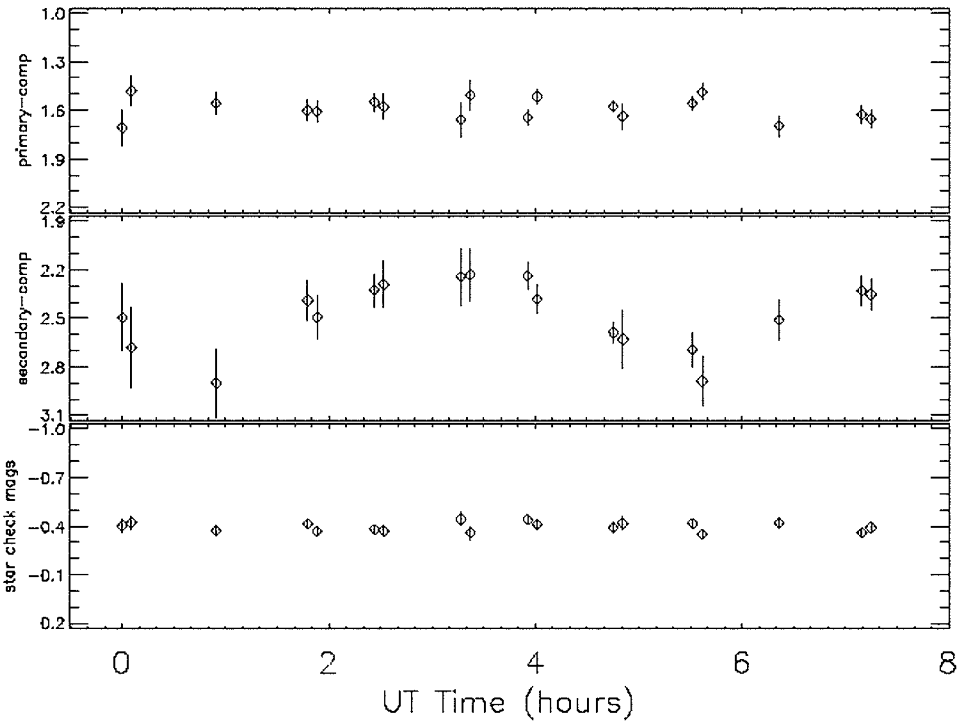
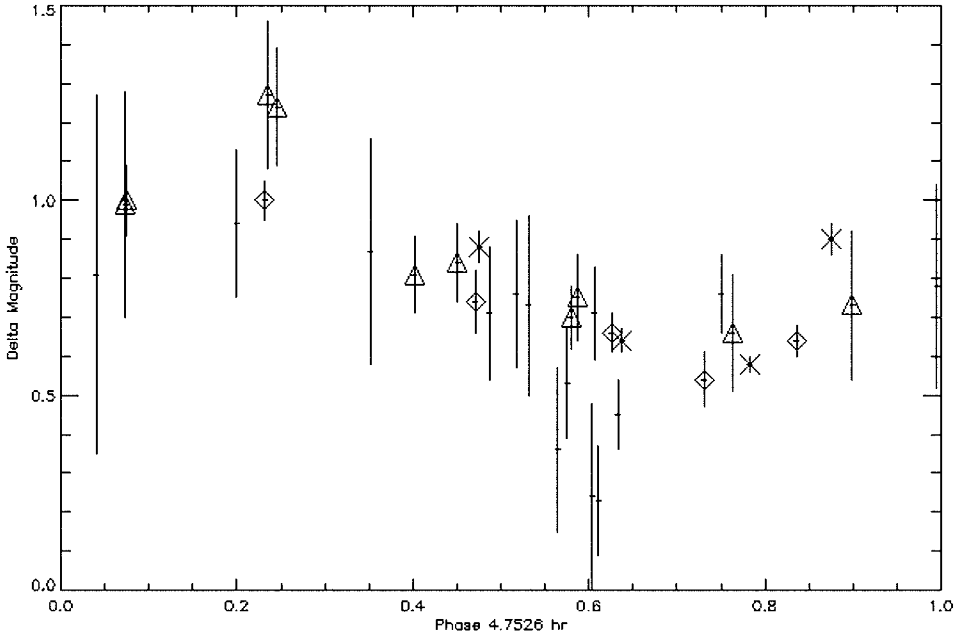


Figure 2. Differential photometry plot from the night of UT 2002 July 18. The upper panel shows the magnitude difference between a comparison star and the 2001 QT_{297} primary, the center panel plots the difference between the star and the secondary component, and the lower panel plots the difference between the comparison star and a check star.

2.2. COLORS

Two color observations (using Sloan g', r', i' filters) were obtained for both binary components at a single phase on UT 13 July 2002. Applying zero-point magnitude and extinction corrections, calculated from a set of Sloan standard star observations, to the PSF fits for this night yields primary and secondary magnitude estimates listed in Table II. While we make use of the Sloan filters for their well defined bands and high throughput, we have adopted the transformation equations of Fukugita et al. (1996) to estimate the more often used BVRI colors for each component of the binary system. The primary component is consistently about three tenths of a magnitude redder than solar colors and well within the ‘normal’ range of small outer solar system bodies. At this phase, the secondary component colors are identical to the primary within the uncertainties.

While accurate two color observations have only been obtained on one night thus far in our runs, we have obtained single color (Sloan r' and i') observations on five nights including very modest temporal coverage on UT 18 July 2002. Recognizing the variability of the secondary outlined in the preceding section



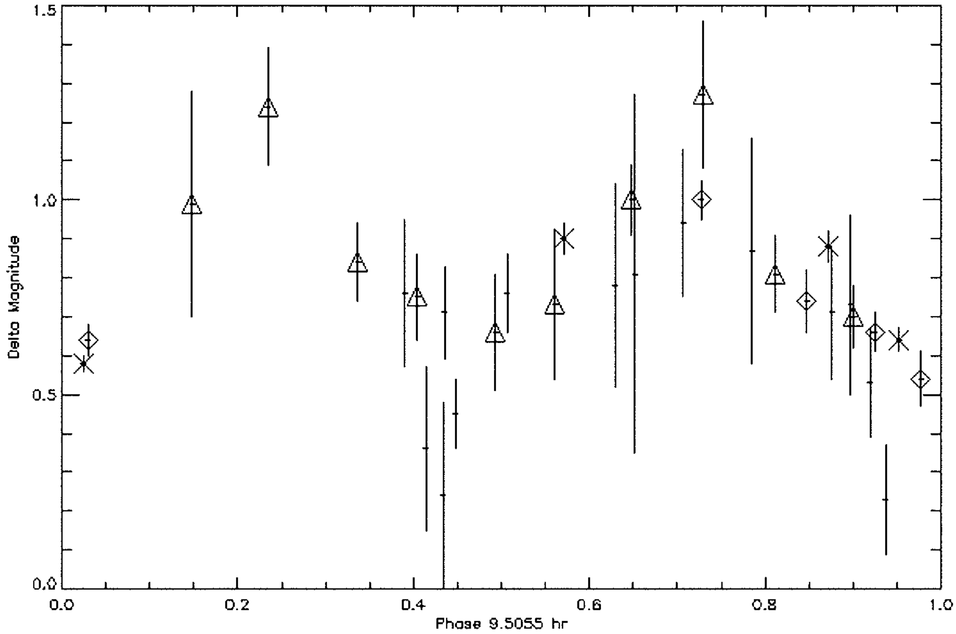


Figure 3. Upper: Lightcurve phased to 4.7526 h and lower: Lightcurve phased to 9.5055 h. The most complete temporal sampling was achieved on UT 2002 July 18 (triangles), UT 2002 July 13 (diamonds) and UT 2001 October 11 (Xs), with other nights plotted using the (–) symbol. Data points and their associated uncertainties are plotted for all measurements in the Sloan r' filter tabulated in Table I.

TABLE II

2001 QT_{297} colors

Object	Julian date	g'	r'	i'	B-V[a]	V-R[a]	R-I[a]
Primary	2452468.785	23.79 ± 0.03	22.94 ± 0.02	22.55 ± 0.01	1.01 ± 0.04	0.61 ± 0.04	0.64 ± 0.03
Secondary	2452468.785	24.41 ± 0.07	23.55 ± 0.05	23.26 ± 0.05	1.00 ± 0.08	0.61 ± 0.07	0.59 ± 0.06
Secondary		del_mag(r') − del_mag(i')[b]		I'-i'	R-I		
	2452468.785	−0.01 ± 0.05		0.29 ± 0.05	0.53 ± 0.06		
	2452473.740	−0.02 ± 0.13		0.28 ± 0.13	0.52 ± 0.13		
	2452473.800	0.24 ± 0.10		0.54 ± 0.10	0.79 ± 0.10		
	2452473.868	0.13 ± 0.19		0.43 ± 0.19	0.68 ± 0.19		
	2452214.525	−0.09 ± 0.18		0.21 ± 0.18	0.45 ± 0.18		
	2452215.520	−0.01 ± 0.12		0.29 ± 0.12	0.53 ± 0.12		
	2452216.510	−0.41 ± 0.16		−0.11 ± 0.16	0.12 ± 0.16		

[a] Using transformations of Fukugita et al. (1996).

[b] Differential magnitudes between primary and secondary.

and using the differential magnitudes for both the Sloan r' and i' filters tabulated in Table I, our admittedly sparse data set is suggestive of possible strong color variation across the surface of the secondary component. Moreover, R-I colors (derived from the r'-i' measurements) cover a magnitude range from 0.79 ± 0.10 to 0.12 ± 0.16 (Table II lower) indicating one of the reddest and the bluest EKBO surface measured in these passbands (cf. Jewitt and Luu, 2001). Interestingly, the bluest measurements (recorded on UT 03 November 2001) correspond to at or near the peak brightness of the 2001 QT$_{297}$ secondary while the reddest measurements (recorded UT 18 July 2002) correspond to at or just preceding the minimum brightness of the secondary. This again hints toward an impact origin for the present orbit of this binary where the blue/bright region can be interpreted as fresher excavated material, the reddest/faint region can be interpreted as a heavily irradiated unaltered surface with the remainder of the red surface being some combination of these two extremes.

3. Orbit

A preliminary orbit fit to the astrometric separations and position angles tabulated in Table I is shown in Figure 4. The orbital parameters and their associated uncertainties are as follows: period = 876 ± 227 days, semi-major axis = 31,409 ± 2500 km, eccentricity = 0.31 ± 0.08, inclination = 128.1 ± 6.5 degrees, node ascending longitude = 96.7 ± 13.4 degrees, argument of periapsis = 330.3 ± 22.4 degrees, and Epoch = 2001.787 ± 0.122. The orbit fits are dependent on the final weighting of the measured positions and still suffer from an overall uniqueness problem due to the fact that the data acquired to date still consists of only two primary epochs (October–November 2001) and (July–September 2002). Additional observations will be needed to more tightly constrain the orbital parameters for this binary.

3.1. Mass, size, albedo

Using the current best estimates of orbital period and semi-major axis, we derived a system mass of $\sim 3.2 \times 10^{18}$ kg (while the uncertainties for the period and semi-major axis estimates are still large, they are correlated such that each feasible fit provides a similar system mass with an uncertainty of about $+0.3 \times 10^{18}$ and -0.2×10^{18} kg). Further adopting a mean magnitude difference between the two binary components of ∼0.8 magnitudes and similar albedo and density values for the two bodies, we derived a mass ratio for the components of just over 3. Given the system mass and component mass ratio, we estimate size and albedo of the binary components under two plausible density conditions. First, assuming a density similar to that of Pluto (∼2.0 g/cm^3) we estimate the radius of the primary to be 78 km and that of the secondary to be 54 km with an albedo of 14%. At another

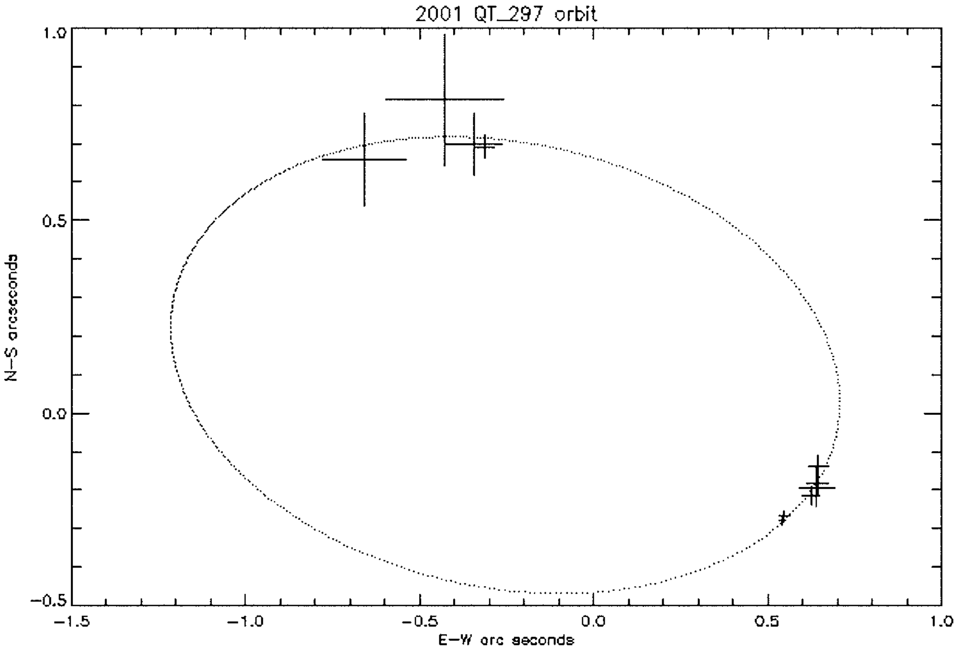


Figure 4. Orbit plot for the binary pair 2001 QT$_{297}$. The x-axis indicates the East-West positional offset in arc seconds of the secondary from the primary (at the origin). The y-axis indicates the North-South positional offset in arc seconds of the secondary from the primary. The points are a plot of the fit orbit and the crosses show the recorded positional offsets and their uncertainties.

extreme for a solid body, we assumed a density of 1.0 g/cm^3 (for a composition of primarily water ice and matching the density inferred for 20000 Varuna (Jewitt and Sheppard, 2002)) and estimate primary and secondary radii of 98 and 68 km respectively with an albedo of 9%. Table III provides a comparison of the physical properties of 2001 QT$_{297}$ with those of the other EKBO binary objects with known parameters, Pluto–Charon and 1998 WW$_{31}$. Of primary interest is the fact that the oft adopted EKBO albedo estimate of 4% (based on measurements for a handful of cometary nuclei) does not appear a representative value for objects in the EKB unless in the unlikely case that their bulk densities are far lower than that of pure water ice. Additional evidence for the general inapplicability of cometary nuclei albedo values to EKBOs is found in combined visible and sub-mm observations of a handful of the largest EKBOs (e.g., Jewitt et al., 2001).

Continued resolved astrometric observations of 2001 QT$_{297}$ will allow us to refine the orbit parameters leading to a more accurate and precise mass determination for the system. Combined with accurate size and albedo estimates derived from simultaneous (or appropriately phased) visible observations of the individual components with thermal observations of the system with SIRTF, we will be able to uniquely determine the bulk density of this binary pair. Similar combinations of simultaneous visible and thermal observations of EKBOs should soon lead to

TABLE III

EKBO binary characteristics

Binary	Period (days)	Semi-major axis (km)	Radius (km)	Albedo
Pluto–Charon[1]	6.38726 ± 0.00007	19,636 ± 8	1175 ± 25	0.44–0.61
			625 ± 25	0.38
1998 WW_{31}	574 ± 10	22,300 ± 800	118 & 98[a]	0.09
			148 & 123[b]	0.07
2001 QT_{297}	876 ± 227	31,409 ± 2500	78 & 54[a]	0.14
			98 & 68[b]	0.09

[1] Tholen and Buie (1997) and references therein.

[2] Veillet et al. (2002).

[a] Density = 2.0 g/cm^3.

[b] Density = 1.0 g/cm^3.

accurate estimates of size and albedo for a statistically significant sample of these bodies as well as additional density estimates for the growing number of discovered binary systems.

Acknowledgements

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