The Astronomical Journal, 124:3424–3429, 2002 December

DETECTION OF TWO BINARY TRANS-NEPTUNIAN OBJECTS, 1997 CQ_{29} AND 2000 CF_{105}, WITH THE *HUBBLE SPACE TELESCOPE*

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Received 2002 May 15; accepted 2002 September 17

ABSTRACT

Images of the trans-Neptunian objects 1997 CQ_{29} and 2000 CF_{105} obtained with the *Hubble Space Telescope* WFPC2 camera show them to be binary. The two components of 1997 CQ_{29} were separated in our images by $0''.20 \pm 0''.03$ in 2001 November and by $0''.33 \pm 0''.01$ in 2002 June/July. The corresponding minimum physical distances are 6100 and 10,200 km. The companion to 2000 CF_{105} was $0''.78 \pm 0''.03$ from the primary, at least 23,400 km. Six other objects in the trans-Neptunian region, including Pluto and its moon Charon, are known to be binaries; 1997 CQ_{29} and 2000 CF_{105} are the seventh and eighth known pair. Binarity appears to be a not uncommon characteristic in this region of the solar system, with detectable companions present in $4\% \pm 2\%$ of the objects we have examined.

Key words: Kuiper belt — Oort cloud

1. INTRODUCTION

The first trans-Neptunian binary (TNB) was identified in 1978 with the discovery of Charon, Pluto's moon (Christy & Harrington 1978). The first binary Kuiper belt object, 1998 WW_{31}, was announced in 2001 (Veillet 2001), though it has since been identified in images taken as early as November 1998 (Veillet et al. 2002). More discoveries have followed in rapid succession (Table 1) so that, as of 2002 February, a total of six trans-Neptunian binaries were known.

The discovery of TNBs opens up a significant new tool for physical study of trans-Neptunian objects (TNOs). Through analysis of the orbit, it offers the only direct means of determining the mass of these distant objects for the foreseeable future. When combined with optical and thermal wavelength photometry, density can also be determined. Both mass and density have a priori uncertainties of at least an order of magnitude for TNOs, so the value of direct observations cannot be underestimated.

Binaries offer further opportunities for physical study through mutual occultations. The series of Pluto-Charon mutual events that occurred soon after the discovery of Charon led to surface albedo maps and separate spectra, revealing the very distinct surface compositions of Pluto and its satellite (Buie et al. 1987; Fink & DiSanti 1988; Buie, Tholen, & Horne 1992; Young et al. 1999). Veillet et al. (2002) suggest that 1998 WW_{31} will begin a series of mutual events in approximately 50 yr. TNOs have periods of 250 yr or more so it will be necessary to discover and determine the orbits of approximately 10 TNBs before it will be likely to find one having mutual occultations within the next decade.

Two TNOs, 1997 CQ_{29} and 2000 CF_{105}, are the focus of this work. 1997 CQ_{29} was discovered at Mauna Kea Observatory by Chen et al. (1997), and 2000 CF_{105} was discovered at Kitt Peak National Observatory by the Deep Ecliptic Survey team (Millis et al. 2002). Both objects are classical TNOs in orbits of small eccentricity and low inclination. In this paper we describe the discovery of binary companions to 1997 CQ_{29} and 2000 CF_{105}, making them the seventh and eighth known TNBs (Noll & Stephens 2002; Noll et al. 2002).

2. OBSERVATIONS

The objects 1997 CQ_{29} and 2000 CF_{105} were observed as part of a large photometric survey of TNOs that we are carrying out using the *Hubble Space Telescope* (*HST*). The data were dark-subtracted, flat-fielded, and flux-calibrated using standard Space Telescope Science Institute on-the-fly pipeline calibration steps, including up-to-date dark files. Cosmic-ray hits were removed by combining pairs of filtered observations with the standard CRREJ routine found in the STSDAS IRAF software package (Baggett et al. 2002).

We used the WFALL aperture, centered at pixel (133, 149) on the WF3 chip (Biretta et al. 2001), for all observations in our photometric survey. This is the corner of the WF3 chip nearest the x and y readout registers, a position that reduces the magnitude of the charge transfer efficiency correction required (Whitmore, Heyer, & Casertano 1999; Dolphin 2000). The WFALL aperture was also chosen to increase the likelihood of finding objects with uncertain ephemeris positions. The telescope was tracked during all

TABLE 1
TRANS-NEPTUNIAN BINARIES

Object	Dynamical Class	Separation (km)[a]	Δ (m)	Reference
Pluto/Charon	Plutino	19,366	1.4	Christy & Harrington 1978
1998 WW_{31}	Classical	22,300	0.4	Veillet 2001
2001 QT_{297}	Classical	19,000	0.55	Elliot 2001
2001 QW_{322}	Classical	126,000	0	Kavelaars et al. 2001
1999 TC_{36}	Plutino	8,300	1.9	Trujillo & Brown 2002
1998 SM_{165}	Scattered	5,600	1.9	Brown & Trujillo 2002
1997 CQ_{29}	Classical	8,100	0.24	Noll & Stephens 2002
2000 CF_{105}	Classical	23,360	0.87	Noll et al. 2002

[a] Semimajor axis listed for Pluto/Charon and 1998 WW_{31}. For other objects mean separation at time of observations is listed.

observations correcting both for the proper motion of the TNO and the parallax induced by *Hubble's* orbital motion.

In follow-up observations of 1997 CQ_{29} we placed the target on the PC chip to take advantage of the better sampling on that detector. As with the other observations, the telescope was tracked at the apparent rate of the TNO.

2.1. *1997 CQ_{29}*

1997 CQ_{29} was first imaged by us from 6:44 to 7:22 UT on 2001 November 17, when it was at a distance of 41.85 AU from Earth. We obtained images with the WFPC2 camera on *HST* in three broadband filters approximating the *V* (F555W), *R* (F675W), and *I* (F814W) bands. There were two 160 s exposures in each filter. The sequence started with a single F555W exposure, followed by two each in F675W and F814W, and ended with a second single F555W.

We identified 1997 CQ_{29} in our images both by its lack of motion relative to tracking and by its position at (66, 92) on the WF3 chip, 8″.76 from the predicted position. Stars and galaxies in the field moved by a total of 0″.46 between the first and last exposure.

As shown in Figure 1, the image of 1997 CQ_{29} is clearly elongated. The orientation of the spacecraft was such that north is approximately 30° from the vertical in our images, as indicated by the long arrow. The axis of the elongation is rotated by $16^\circ \pm 4^\circ$ east of north relative to the brighter of the two components, component A. The elongation appears in all six individual images at a similar angle and separation. We note that the direction of the elongation is almost perpendicular to the apparent motion of stars and galaxies, which moved diagonally from east to west in the images as shown. We also examined engineering data that tracks jitter during the observations. No unusual jitter was seen, ruling this out as a possible source of error. Based on this visual evidence, we concluded that 1997 CQ_{29} is a probable binary and proceeded to obtain confirming images.

Three additional sets of observations of 1997 CQ_{29} were made from 7:30 to 8:26 UT on 2002 June 18, 3:09 to 4:05 UT on 2002 June 30, and 3:39–4:35 UT on 2002 July 12. On

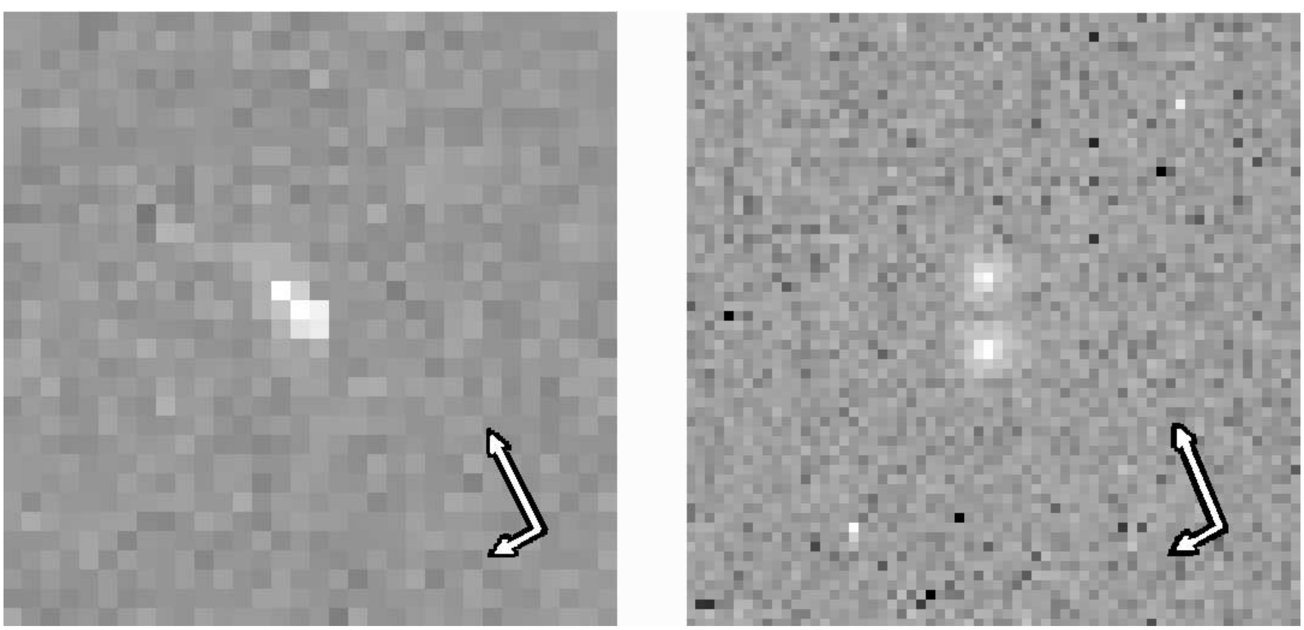

FIG. 1.—*Left*: Combination of two individual 160 s integrations in the F814W filter taken on 2001 November 17. We show a portion of the WF3 chip around the location of 1997 CQ_{29}. The elongation of 1997 CQ_{29} is apparent, though the individual components are not clearly resolved. *Right*: Combination of three 800 s images taken on 2002 June 30 through the F814W filter. The image shown is a 30″ portion of the PC chip centered on 1997 CQ_{29}. In this image the binary is clearly resolved. The long arrow indicates north on each panel, and the short arrow east.

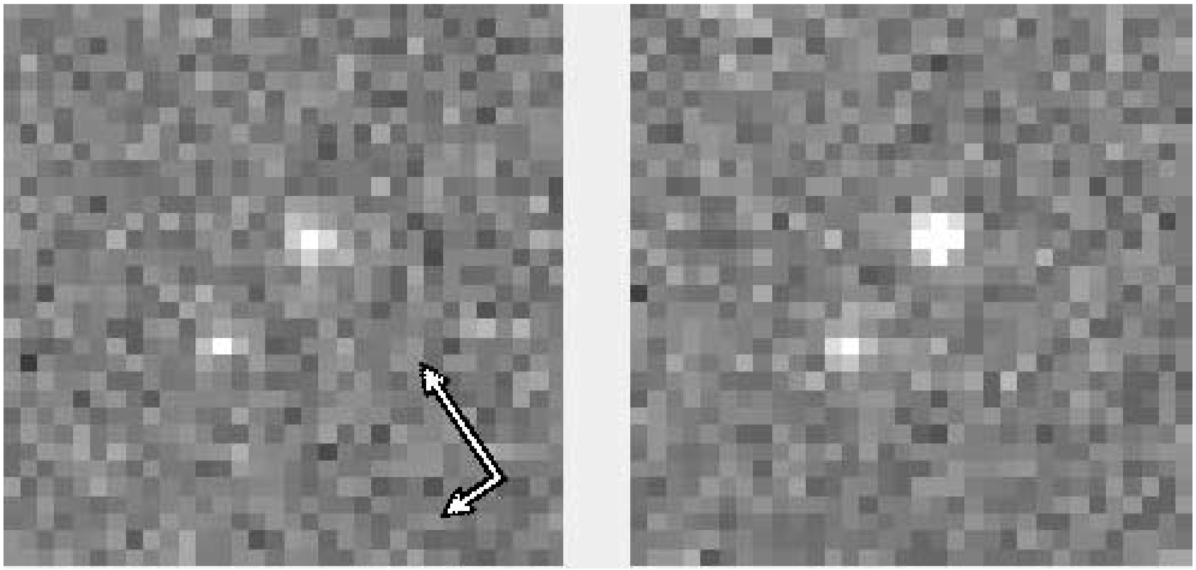

FIG. 2.—*Left to right*: F555W and F814W images of 2000 CF_{105} taken with WFPC2 on 2002 January 12. The images shown are combinations of two individual 260 s integrations in each filter as described in the text. We show a portion of the WF3 chip around the location of 2000 CF_{105}. The two components are cleanly separated and are visible in both filters. North and east are indicated by the long and short arrows, respectively.

each date we obtained three 800 s exposures in the F814W filter with the 1997 CQ_{29} on the PC chip. In all three cases the binary was easily detected and clearly resolved, as shown in Figure 1. The higher resolution of the PC, the better signal-to-noise ratio resulting from longer integrations, and obvious presence of the two components on four separate dates leaves no doubt about the binarity of 1997 CQ_{29}.

2.2. *2000 CF_{105}*

2000 CF_{105} was observed in two filters, F555W and F814W, on 2002 January 12 from 1:12 to 1:49 UT. As with 1997 CQ_{29}, the observing sequence began and ended with an F555W exposure. A pair of F814W exposures occurred between the F555Ws. Because 2000 CF_{105} is fainter, we exposed this object in only two filters with two 260 s exposures per filter.

The brighter component of 2000 CF_{105}, component A, was found $0\farcs58$ from the WFALL aperture at pixel (133, 155). A second, fainter object, component B, can be seen to the east in Figure 2 at pixel (138, 161). 2000 CF_{105} A and B were stationary during the observations. Stars and galaxies were trailed, moving a total of $1\farcs1$ from the first to last exposure. As shown in Figure 2, the two components of 2000 CF_{105} are cleanly separated by an angular distance of $0\farcs78 \pm 0\farcs03$ at a position angle of $106\fdg6 \pm 2\fdg5$ measured from A.

2000 CF_{105} was subsequently observed from the Keck I telescope (Fig. 3; see also Romanishin et al. 2002). On the night of 2002 April 11 (UT) 2000 CF_{105} was observed in four 10 minute integrations simultaneously in B and R bands, using the LRIS instrument in imaging mode. The images were individually bias-subtracted and flat-fielded and then combined into a single image. For the combined image shown in Figure 3 the individual exposures were shifted to align the images of 2000 CF_{105}, which was moving at $-0\farcs235$ hr^{-1} in right ascension and $0\farcs00$ hr^{-1} in declination. As can be seen in Figure 3, 2000 CF_{105} appears elongated in the east-west direction, with the fainter component to the east. Romanishin et al. report a separation of $0\farcs8 \pm 0\farcs2$ at a position angle of $103^\circ \pm 5^\circ$. This matches the orientation seen in the WFPC2 image and confirms the presence of the companion.

3. ANALYSIS

3.1. *1997 CQ_{29}*

In order to determine the separation and to obtain separate photometric magnitudes for the two components of 1997 CQ_{29} in the November data, we fitted the observed

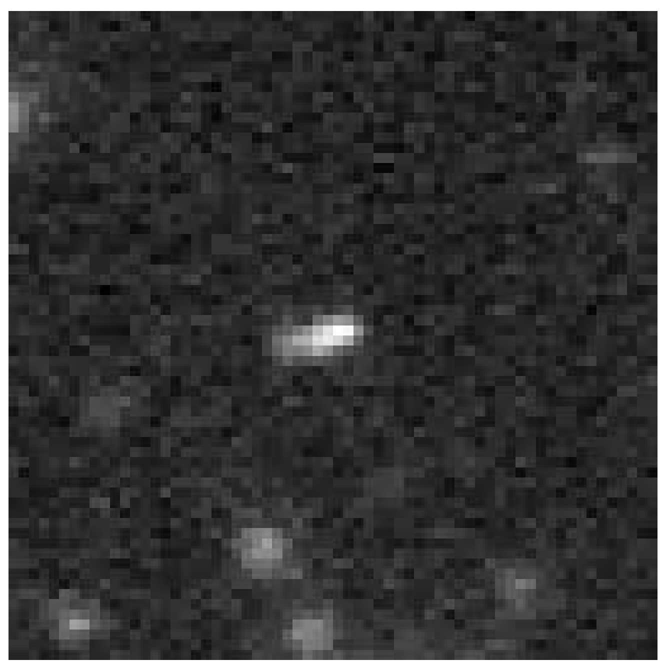

FIG. 3.—Image of 2000 CF_{105} obtained with LRIS at the Keck I telescope on 2002 April 11. The individual images have been shifted and registered with offsets computed to match the small motion of 2000 CF_{105}. North is up, and east to the left, in this image. Motion during the individual integrations was less than 0.2 pixels. Pixels are $0\farcs215$ on a side. The object is clearly elongated in a direction that matches the two resolved components in the *HST* image, confirming the existence of the binary companion.

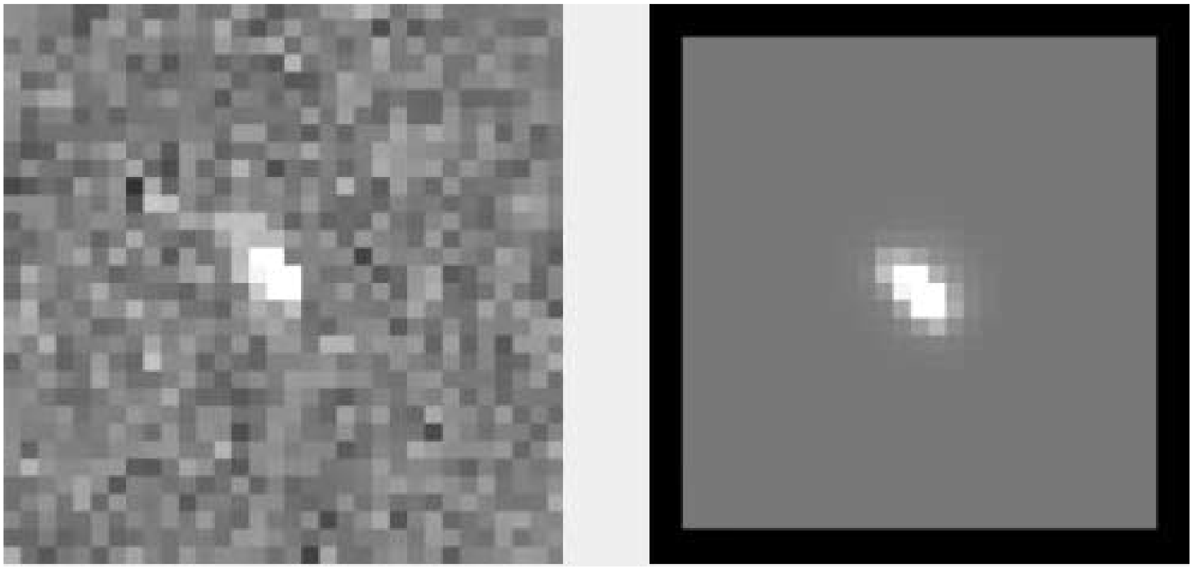

FIG. 4.—*Left*: F814W image of 1997 CQ_{29}. *Right*: Best-fit model created with synthetic PSFs combined as described in the text.

image by iteratively combining scaled synthetic point-spread functions (PSF) generated by the Tiny Tim software tool (Krist & Hook 1997). An example is shown in Figure 4. Both the separation and the relative magnitude of the components were allowed to vary. After finding a preliminary fit, we repeated the procedure over a finer grid. A best fit was determined by finding the parameters that yielded a minimum in the least-squares residuals between the model and observed data. Errors were estimated from the residuals.

From the iterative fit we determined a mean separation of $0''.20 \pm 0''.03$ on 2001 November 17. We note that this is $0''.04$ larger than reported by Noll & Stephens (2002) because the separation of the PSF centers is slightly larger than the separation of the peaks in the brightness distribution. This separation is near the resolution limit of the wide field portion of WFPC2, where the pixel scale is $0''.1$ pixel^{-1}, though it is sufficiently large that the two components can be reliably resolved. We applied the same technique to determine separations in the 2002 June/July data, even though the objects are clearly resolved and separate. Positional information is summarized in Table 2.

Magnitudes are converted to the standard Johnson-Cousins system, using the SYNPHOT software package. Details of our photometric pipeline are described in more detail in a forthcoming paper. We measure a Johnson V magnitude of $V = 23.78 \pm 0.13$ and Cousins R and I magnitudes of $R = 23.27 \pm 0.19$, $I = 22.54 \pm 0.09$ for the component A. Component B was found to have $V = 24.02 \pm 0.22$, $R = 23.54 \pm 0.23$, and $I = 23.06 \pm 0.18$ (Table 3). The photometry we obtained in 2002 June/July is generally consistent with the I-band magnitudes determined in 2001 November, as detailed in Table 3.

The one exception is the unusually faint magnitude recorded for the component A on 2002 June 18. The faintness initially caused us to misidentify the components in this image, but, when combined with the other images and possible mutual orbits, it is clear that on June 18 1997 CQ_{29}A is almost a full magnitude fainter than on the other three dates when we measured it. Note, in particular, that the observations in 2002 June and July were each separated by approximately 12 days. This is far shorter than any plausible period for the binary, as discussed below. And there is essentially no change between the 30 June and 12 July magnitudes for either component. Finally, the measured magnitude of component B is almost identical in all four observations. It is possible that the unusually low measured magnitude for component A is due to some unrecognized observational error. It is also possible that 1997 CQ_{29}A has an intrinsic light curve with a large amplitude. Further observations to set limits on light curves would be valuable.

The discovery of binaries is valuable because it offers the possibility of determining the mass and density of the objects, basic physical parameters that would otherwise require spacecraft to measure. We have not yet determined the orbits for either of the binaries that we have detected. It is possible, however, to make estimates of diameter and mass by making assumptions about the albedo and density of the objects and using measured magnitudes. If we assume an albedo of $q = 0.04$, as is customarily done for TNOs, we find that the two components of 1997 CQ_{29} have diameters of $d(\mathrm{A}) = 220$ km and $d(\mathrm{B}) = 200$ km, following the formalism of Romanishin & Tegler (1999). If we further assume a bulk density of 1 g cm^{-3}, we calculate a combined mass of 9.76×10^{21} g, or 1/1500th the mass of Pluto and Charon. It is also possible to make educated guesses about possible orbital periods, as we discuss separately below.

TABLE 2

POSITIONAL DATA

Date	Object	Separation	Position Angle
2001 Nov 17.29	1997 CQ_{29}	0.20 ± 0.03	16 ± 4
2002 Jun 18.33........		0.337 ± 0.010	334.0 ± 1.2
2002 Jun 30.15........		0.334 ± 0.004	337.9 ± 0.9
2002 Jul 12.17.........		0.331 ± 0.010	340.7 ± 0.8
2002 Jan 12.06........	2000 CF_{105}	0.78 ± 0.03	106.6 ± 2.5
2002 Apr 11.3.........		0.8 ± 0.2	103 ± 5

TABLE 3
Photometry

Date	Object	Component	V	R	I	$V-I$
2001 Nov 17	1997 CQ_{29}	A	23.78 ± 0.13	23.27 ± 0.19	22.54 ± 0.09	1.24 ± 0.16
		B	24.02 ± 0.22	23.54 ± 0.23	23.06 ± 0.18	0.9 ± 0.3
2002 Jun 18		A	...	...	23.42 ± 0.04	...
		B	...	...	23.03 ± 0.03	...
2002 Jun 30		A	...	...	22.63 ± 0.03	...
		B	...	...	22.96 ± 0.04	...
2002 Jul 12		A	...	...	22.69 ± 0.03	...
		B	...	...	23.06 ± 0.04	...
2002 Jan 12	2000 CF_{105}	A	24.25 ± 0.11	...	22.99 ± 0.08	1.26 ± 0.14
		B	25.12 ± 0.24	...	23.55 ± 0.13	1.6 ± 0.3

3.2. *2000 CF_{105}*

On 2002 January 12 2000 CF_{105} was 41.30 AU from the Earth. At this distance the angular separation we observed, 0″78, corresponds to a minimum separation of 23,360 km. Because of the wide separation, we were able to measure individual magnitudes for each component of the binary with standard aperture photometry, using the IRAF PHOT routine. We used an aperture radius of 3 pixels and a background annulus with inner diameter of 20 pixels and a thickness of 20 pixels. An aperture correction factor was calculated using synthetic PSFs. We determined $V = 24.25 \pm 0.11$ and $I = 22.99 \pm 0.08$ for the brighter component A and $V = 25.12 \pm 0.24$ and $I = 23.55 \pm 0.13$ for component B (Table 3). The uncertainties are relatively large, especially for the fainter component B, because of the faintness of these objects. 2000 CF_{105}A is one of the faintest TNOs we have observed, and 2000 CF_{105}B is more than a magnitude fainter than the nominal magnitude limit we used for target selection. Significantly fainter companions would not be detected by our relatively short integrations.

Romanishin et al. (2002) report that the two components of 2000 CF_{105} differ by 0.6 ± 0.2 mags in the R band, consistent with *HST* relative photometry. Absolute photometry with the Keck data has not been reported.

Using the same procedure as we did for 1997 CQ_{29}, we estimate diameters for the two components to be $d(A) = 170$ km and $d(B) = 120$ km for an albedo of 0.04. Assuming a density of $\rho = 1$ g cm^{-3}, we find a combined mass of 3.48×10^{21}g, 4200 times less than Pluto and Charon.

3.3. *Orbits*

It is possible to estimate the period of TNBs using Kepler's third law by making an assumption about the semimajor axis and eccentricity of the orbit. This exercise is necessary in order to plan follow-up observations and is also useful as a yardstick for comparison with the actual orbit once it is known. We note that, of the two TNBs with measured orbits, one, Pluto/Charon, is nearly circular, while the other, 1998 WW_{31}, has an eccentricity of $e = 0.8$ (Veillet et al. 2002).

For our initial guess for 1997 CQ_{29} we assumed that $e = 0$ and that the observed separation in 2001 November, $a = 6070$ km, is the semimajor axis. For this set of assumptions we derive an orbital period of 42.6 days. We used this value to plan our follow-up observations in 2002 June and July. The separation we observed in 2002 June/July was larger, an average of 10,200 km. Using the same assumptions, this would yield a period of 92 days.

The four epochs of observation allow us to determine some basic facts about the orbit of 1997 CQ_{29}. As can be seen in Table 2, on the dates in 2002 June and July, each separated by approximately 12 days, the position angle measured from component A to B increases steadily. The average rate over the nearly 24 days from 2002 June 18 to July 12 is 0°281 day^{-1}. However, the average rate from November 17 to June 18, a period of 212.85 days, must be significantly higher, averaging 1°494 day^{-1}. We have insufficient data to resolve these discrepant rates. It is apparent, however, that the orbital plane is inclined relative to our line of sight and/or the orbit is significantly eccentric. Additional observations will be required to determine the orbit of 1997 CQ_{29}.

If we perform the same exercise for 2000 CF_{105}, we find an orbital period for a circular orbit would be 539 days, comparable to the 547 day period of 1998 WW_{31} (Veillet et al. 2002) and significantly longer than the apparent period of 1997 CQ_{29}. The similarity of position angles observed in 2002 January and April is consistent with a long period, though the uncertainties are sufficiently large that nothing more quantitative can be said.

3.4. *Colors*

The $V-I$ color index can be computed for each binary component from the measured V and I photometry. Color can, in principle, be used to infer the surface composition and resurfacing history of TNOs (see Jewitt & Luu 2001). In the 75 objects surveyed by us, $V-I$ ranges from 0.8 to 1.6, which is to be compared with $V-I\,(\mathrm{Sun}) = 0.71$. That is, TNO colors range from neutral to extremely red, as has been noted before (Luu & Jewitt 1996).

The colors of 1997 CQ_{29} and 2000 CF_{105} are listed in Table 3. The brighter A components of both binaries have colors, $V-I \sim 1.25$, that are average for classical TNOs observed in our survey. Their companions differ by about 1 σ, more neutral in the case of 1997 CQ_{29}B and redder in the case of 2000 CF_{105}B. Unfortunately, the uncertainties in the colors are sufficiently large that we cannot reach conclusions beyond stating that 2000 CF_{105}B is unlikely to have neutral colors, while 1997 CQ_{29}B is not significantly more red than 1997 CQ_{29}A. Future observations that reduce the photometric uncertainties will be required to reach stronger conclusions.

3.5. *Frequency of Binaries*

We have observed 75 TNOs so far in our photometric survey using *HST* and have examined all of these for possible binary companions. Of those 75, we have detected companions to three, 1997 CQ_{29}, 2000 CF_{105}, and the previously known binary 1998 WW_{31}. This statistic applies to companions with separations greater than $\sim 0''.15$ and *V*-band differences of less than ~ 1 mag. Although 1998 WW_{31} was identified as a binary prior to its inclusion in our target list, the magnitude of 1998 WW_{31} and the precision of its orbit determination matched the criteria for inclusion, and it would have been added even if the binary were not known. Also, the order in which snapshot targets are scheduled is random and outside the control of the observers. The probability that 1998 WW_{31} would have been observed at this point in our observing program is approximately 50%. Given these considerations, we believe it is proper to consider 1998 WW_{31} as part of an unbiased sample. We then conclude that the frequency of binaries consistent with the limits above is simply 3/75 or $\approx 4\% \pm 2\%$. We note that, because of the large statistical uncertainty, the exclusion of 1998 WW_{31} from the sample would not alter this conclusion substantially.

A frequency of $\approx 4\% \pm 2\%$ is in marginal agreement with the detection of eight TNBs out of a total of more than 500 TNOs detected to date. However, the uneven sampling and data quality of this larger population complicates any statistical conclusions from this larger sample. Many of the objects have been observed only a few times and some are effectively lost. Many of the detected binaries, 1997 CQ_{29} for example, could not be detected by most ground-based systems, including those equipped with adaptive optics. 2000 CF_{105} is just detectable with ground-based systems, and indeed it has been verified as binary from the ground (Romanishin et al. 2002). Furthermore, the magnitude limit and angular resolution in individual observations of TNOs is a strong function of equipment and observing conditions. Nevertheless, the overall detection rate of $\approx 1.5\% \pm 0.5\%$ supports the rate inferred from our more uniform survey.

It is worth noting that half of known TNBs, four of eight, have been discovered with *HST* (Trujillo & Brown 2002; Brown & Trujillo 2002; Noll & Stephens 2002; Noll et al. 2002). Since far more observations of TNOs are made by ground-based telescopes than by *HST*, this fact would appear to imply that TNBs separated by more than an arcsecond are less frequent than more closely spaced companions, an assertion borne out by Table 1 when one considers that $1''$ at 40 AU is a physical distance of 29,000 km.

We also note that all three of the binaries detected by us and five of the eight objects in Table 1 are classical TNOs. Two are in the 3 : 2 resonance, and one is possibly a scattered object. Of the 75 objects observed in our program so far, 65% are classical TNOs with low eccentricity and inclination, 24% are Plutinos, and 11% are scattered disk objects. There does not seem to be sufficient evidence at present to make any conclusions about the relative frequency of binaries in the different dynamical populations, though eventually this information may be useful in determining the origin and history of TNBs and the dynamical classes in the Kuiper belt.

Finally, it is worthwhile to make a comparison between TNBs and binaries found in the main-belt and near-Earth populations. A total of six binaries have been identified out of a sample of 300 main-belt targets by Merline et al. (2001), a rate, at first glance, roughly similar to that being found in the Kuiper belt. However, it must be noted that the relative sizes and separations of main-belt and Kuiper belt binaries appear to be significantly different (Margot 2002). If a population of TNBs with faint and close-in companions, similar to the main-belt binaries, exists, the fraction of TNBs could be significantly higher than our current estimate. If collisions are the main source of binaries in both populations, the frequency of binaries and their orbital and size distribution can be used to probe the efficiency of binary formation from such events. The near-Earth asteroid (NEA) population has a higher frequency of binaries, as high as 16% for objects over 200 m in diameter (Margot et al. 2002). However, mechanisms other than collisions, e.g., tidal breakup, may be responsible for this larger number among the NEAs, and this population may be less relevant for comparison to TNBs.

Based on observations made with the NASA/ESA *Hubble Space Telescope*. These observations are associated with proposal 9060. Support for proposal 9060 was provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

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