DETECTION OF TWO BINARY TRANS-NEPTUNIAN OBJECTS, 1997 CQ 29 AND 2000 CF 105, WITH THE HUBBLE SPACE TELESCOPE

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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% ± 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
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 CQ29

1997 CQ29 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 CQ29 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 CQ29 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° ± 4° 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 CQ29 is a probable binary and proceeded to obtain confirming images.

Three additional sets of observations of 1997 CQ29 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

\begin{table}
\centering
\caption{Trans-Neptunian Binaries}
\begin{tabular}{lcccl}
\hline
Object & Dynamical Class & Separation (km) & $\Delta$ (m) & Reference \\
\hline
Pluto/Charon & Plutino & 19,366 & 1.4 & Christy & Harrington 1978 \\
1998 WW31 & Classical & 22,300 & 0.4 & Veillet 2001 \\
2001 QT297 & Classical & 19,000 & 0.55 & Elliot 2001 \\
2001 QW322 & Classical & 126,000 & 0 & Kavelaars et al. 2001 \\
1999 TC36 & Plutino & 8,300 & 1.9 & Trujillo & Brown 2002 \\
1998 SM165 & Scattered & 5,600 & 1.9 & Brown & Trujillo 2002 \\
1997 CQ29 & Classical & 8,100 & 0.24 & Noll & Stephens 2002 \\
2000 CF105 & Classical & 23,360 & 0.87 & Noll et al. 2002 \\
\hline
\end{tabular}
\end{table}

\footnotesize
\textsuperscript{a} Semimajor axis listed for Pluto/Charon and 1998 WW31. For other objects mean separation at time of observations is listed.

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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 CQ29. The elongation of 1997 CQ29 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 CQ29. In this image the binary is clearly resolved. The long arrow indicates north on each panel, and the short arrow east.
each date we obtained three 800 s exposures in the F814W filter with the 1997 CQ29 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 CQ29.

2.2. 2000 CF105

2000 CF105 was observed in two filters, F555W and F814W, on 2002 January 12 from 1:12 to 1:49 UT. As with 1997 CQ29, the observing sequence began and ended with an F555W exposure. A pair of F814W exposures occurred between the F555Ws. Because 2000 CF105 is fainter, we exposed this object in only two filters with two 260 s exposures per filter.

The brighter component of 2000 CF105, component A, was found 0\,\textquoteright\,58 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 CF105 A and B were stationary during the observations. Stars and galaxies were trailed, moving a total of 1\,\textquoteright\,1 from the first to last exposure. As shown in Figure 2, the two components of 2000 CF105 are cleanly separated by an angular distance of 0\,\textquoteright\,78 ± 0\,\textquoteright\,03 at a position angle of 106\,\textdegree\,6 ± 2\,\textdegree\,5 measured from A.

2000 CF105 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 CF105 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 CF105, which was moving at −0\,\textquoteright\,235 hr\,−1 in right ascension and 0\,\textquoteright\,00 hr\,−1 in declination. As can be seen in Figure 3, 2000 CF105 appears elongated in the east-west direction, with the fainter component to the east. Romanishin et al. report a separation of 0\,\textquoteright\,8 ± 0\,\textquoteright\,2 at a position angle of 103\,\textdegree\, ± 5\,\textdegree. This matches the orientation seen in the WFPC2 image and confirms the presence of the companion.

3. ANALYSIS

3.1. 1997 CQ29

In order to determine the separation and to obtain separate photometric magnitudes for the two components of 1997 CQ29 in the November data, we fitted the observed

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Fig. 2.—Left to right: F555W and F814W images of 2000 CF105 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 CF105. The two components are cleanly separated and are visible in both filters. North and east are indicated by the long and short arrows, respectively.

Fig. 3.—Image of 2000 CF105 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 CF105. 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\,\textquoteright\,215 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.
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 \(d(A) = 220\) km and \(d(B) = 200\) 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 \(9.76 \times 10^{21}\) g, or \(1/1500\)th the mass of Pluto and Charon. It is also possible to make educated guesses about possible orbital periods, as we discuss separately below.
July. The separation we observed in 2002 June/July was useful to plan our follow-up observations in 2002 June and July. We derived an orbital period of 42.6 days. We used this information to derive an orbital period of 42.6 days. We used this period to study the orbital motion of the binary. We observed that the observed separation in 2001 November, 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 CF105A is one of the faintest TNOs we have observed, and 2000 CF105B 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.

Romaniushin et al. (2002) report that the two components of 2000 CF105 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 CQ29, 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 $3.48 \times 10^{21}$g, 4200 times less than Pluto and Charon.

### 3.2. 2000 CF105

On 2002 January 12 2000 CF105 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 CF105A is one of the faintest TNOs we have observed, and 2000 CF105B 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.

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### 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 WW31, has an eccentricity of $e = 0.8$ (Veillet et al. 2002).

For our initial guess for 1997 CQ29 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 CQ29. 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 CQ29.

If we perform the same exercise for 2000 CF105, we find an orbital period for a circular orbit would be 539 days, comparable to the 547 day period of 1998 WW31 (Veillet et al. 2002) and significantly longer than the apparent period of 1997 CQ29. 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 $V$–$I$ (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 CQ29 and 2000 CF105 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 $\sigma$, more neutral in the case of 1997 CQ29B and redder in the case of 2000 CF105B. Unfortunately, the uncertainties in the colors are sufficiently large that we cannot reach conclusions beyond stating that 2000 CF105B is unlikely to have neutral colors, while 1997 CQ29B is not significantly more red than 1997 CQ29A. Future observations that reduce the photometric uncertainties will be required to reach stronger conclusions.

#### Table 3

| Date       | Object      | Component | $V$       | $R$       | $I$       | $V$–$I$ |
|------------|-------------|-----------|-----------|-----------|-----------|---------|
| 2001 Nov 17| 1997 CQ29   | 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 CF105  | 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  |
3.5. 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\textsubscript{29}, 2000 CF\textsubscript{105}, and the previously known binary 1998 WW\textsubscript{31}. This statistic applies to companions with separations greater than ~0.15" and V-band differences of less than ~1 mag. Although 1998 WW\textsubscript{31} was identified as a binary prior to its inclusion in our target list, the magnitude of 1998 WW\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{29} for example, could not be detected by most ground-based systems, including those equipped with adaptive optics. 2000 CF\textsubscript{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 most ground-based systems, including those equipped with adaptive optics. 2000 CF\textsubscript{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.

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