On the Detection of Two New Trans-Neptunian Binaries from the CFEPS Kuiper Belt Survey

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ABSTRACT. We report here the discovery of new near-equal-mass trans-Neptunian Binary (TNB) L5c02 and the putative detection of a second TNB (L4k12) among the detections in the second and third years of the Canada-France Ecliptic Plane Survey (CFEPS). These new binaries (internal designations L4k12 and L5c02) have moderate separations of 0.4″ and 0.6″, respectively. The follow-up observation confirmed the binarity of L5c02, but L4k12 still lacks follow-up observations. L4k12 has a heliocentric orbital inclination of ∼35°, marking this system as having the highest heliocentric orbital inclination among known near-equal-mass binaries. Both systems are members of the classical main Kuiper belt population. Based on the sample of objects searched, we determine that the fraction of near-equal-mass wide binaries with separations >0.4″ is 1.5% to 20% in the cold main classical Kuiper belt, and if our detection of the binarity L4k12 holds, 3% to 43% in the hot main classical objects are binary. In this article we describe our detection process, the sample of objects surveyed, and our confirmation observations.

Online material: color figure

1. INTRODUCTION

Just as the detection of the first trans-Neptunian object (TNO, neglecting Pluto), 1992 QB1, by Jewitt & Luu (1992) led to an avalanche of new TNO discoveries, the serendipitous discovery of the first trans-Neptunian binary (TNB, neglecting the Pluto-Charon system), 1998 WW31, by Veillet et al. (2002) spurred the discovery of dozens more such systems. There are currently more than 50 TNBs known (Noll et al. 2008a). The growing catalog of known TNOs and TNBs discovered in characterized surveys permits the use of these objects as probes of structure formation and evolution in the outer solar system.

The large sky separation (1.2″) and the similar brightness (Δmag ~ 0.4) of the two components of the 1998 WW31 provided the first clue to the enigmatic nature of TNBs. That this was the first kind of TNB discovered, however, is partially due to the observational requirement of being able to split the two sources in order to determine that one is observing a binary. Since the TNOs are rather faint, most observations are of rather low signal-to-noise ratio (S/N) (~10) and to detect a TNB in such observations generally requires that the two components have an angular separation of the order for the seeing of the observations. The next TNB discovered, 2001 QT297 (Osip et al. 2008), also had large separation that was at the limit of the resolution of the observations. The discovery separation of 2001 QW322 (∼4″, Petit et al. 2008) was much larger than the seeing of the observations, perhaps indicating that large separation binaries are more than just an artifact of the observing circumstances. At this time, about ~10% of the known TNBs have separation in excess of 1″. The pathway of wide separation TNBs are, as yet, not well understood. In general, the study of binary systems provides very direct information on the physical nature of the constituent members. Binary systems provide the only reliable means to derive the masses of TNOs. Furthermore, if their sizes can be computed by using albedos obtained from optical and infrared measurements, their average bulk densities can be estimated to roughly 10% accuracy. While these measurements provide data on the physical characteristics of the binary components, knowledge of the physical properties for the TNO population provides inputs for understanding the formations of the TNBs themselves.

In the cold classical disk of TNOs inclinations <5°, the occurrence rate of TNBs with separation larger than 0.1″ is about 17–32%, while only 3–10% for the other dynamical classes (Stephens et al. 2006; Noll et al. 2008a, 2008b). The differences in the proportion of TNBs could be the result of the dynamical histories of different TNO populations, indicative of different formation histories or survival rates for TNBs in the two...
populations. To help understand the difference in TNB properties and thus unravel the formation conditions of the outer solar system, more attention should must be given to the census of different types of TNBs (i.e., wide binaries vs. close binaries) in different regions of the trans-Neptunian belt.

Several large-scale ground-based surveys of TNOs have been performed or are in process. These include the Deep Ecliptic Survey at Cerro Tololo Inter-American Observatory and Magellan (Millis et al. 2002; Elliot et al. 2005), the Keck Telescope survey (Trujillo & Brown 2003), and the Canada-France Ecliptic Plane Survey (CFEPS) (Jones et al. 2006; Kavelaars et al. 2009; Petit et al. 2010). The first two surveys have yielded three TNBs out to a total of 362 TNOs based on the CFEPS observations. In our TNB search and our search technique are described in §§ 2.1 and 2.2. The results of our search and follow-up observations are given in §§ 2.3 and 2.4. Section 3 provides a discussion and summary.

2. OBSERVATION AND ANALYSIS

The CFEPS used the observations of the very wide subcomponent of the Canada-France-Hawaii Telescope Legacy Survey (CFHT-LS). The CFEPS Kuiper belt study is a primary scientific goal of the CFHLS-VW (Legacy Survey–Very Wide), which employs the MegaCam camera with a 1° × 1° field of view. The purpose is to provide a Kuiper Belt survey with quantitatively known detection biases and long-term tracking to achieve precise orbits of Kuiper belt objects (KBOs). CFEPS has surveyed fields whose ecliptic latitudes range between ±2° from the ecliptic plane. Approximately 500 deg² have been covered with a detection limit of about 24.3 mag in g′ and subsequently reimaged for tracking, in r′ and i′. At completion of the CFHT-LS component of the survey, approximately 200 TNOs had been discovered and tracked to three oppositions; here, we report on the search for TNBs among these TNOs (Petit et al. 2010).

The CFEPS images of newly discovered TNOs can be used to determine if any of the TNOs are in fact TNBs. The most direct method is to look for separate components of the binary systems, as has been done by previous authors. A visual search of the discovery images for TNBs is only sensitive to large (≥1") separation TNBs, because of the limitation in angular resolution of the detector (∼0.187" pixel⁻¹) and seeing condition (≥0.7"). No TNBs were found during the initial visual inspection of the CFEPS discovery images.

2.1. Point-Source Modeling

To improve our sensitivity to smaller separation TNBs (<1") we examine and compare the point-spread functions of individual KBO images to check if they are truly point sources or possible extended sources similar to that employed in previous TNB searches (Kern and Elliot 2006; Stephens et al. 2006). The IRAF® DAOPHOT package was used to build a point-source model (PSF) for each of the three CFHT/MegaCam images in which a CFEPS TNO was discovered. Several (10–15) isolated bright (S/N ≥50) point sources were hand-selected as the model inputs. The DAOPHOT package computes the average shape of the point sources to obtain the PSF model (Fig. 1). The model input stars were selected to be within ~1′ from the target TNO to avoid the distortion across the CFHT/MegaCam field.

The utility of the PSF modeling approach to binary detection can be determined via construction of artificial binaries. The IRAF/ADDSTAR task was used to create artificial near-equal-magnitude TNBs by adding a series of closely separated doublet sources whose total fluxes are similar to those of the TNOs being examined. These simulations reveal that TNBs with separations larger than about 80% of the FWHM of the image have goodness-of-fit χ² values more than 2-σ larger than the χ² for point sources in the same image. Artificial binaries with separations smaller than 80% of the FWHM of the image could not be distinguished from point sources using this method.

For each image of a given TNO, the χ² goodness-of-fit parameter was determined. Sources whose value of χ² differed significantly from that of similar brightness point sources in the image were flagged as possible TNBs. Visual examination of the flagged candidates revealed that in all but one case the observed large residuals were caused by proximity to background sources and not a close companion. In one case, L5c02, the deviant χ² value appeared to be associated with a close companion (see Fig. 2). The large number of false positives and the low rate of successful detection is likely due to the combination of low S/N of the CFEPS TNO detection images coupled with the low frequency of large (>0.7") separation TNBs.

2.2. Source Elongation

Examination of the image shape along a single spatial dimension using a simple functional form provides an improved approach for binary detection. This approach reduces the number of degrees of freedom (as compared to the PSF fitting approach) while increasing the available signal by collapsing the source profile along one spatial dimension. A one-dimensional Gaussian provides a reasonable match to astronomical images and has only three degrees of freedom: total flux, centroid, and width.

Using the ellipse fitting routine in IRAF/IMEXAM, the ellipticity and position angle of each TNO can be determined. The flux along the minor axis of the TNO image is then collapsed...
and the best-fit Gaussian shape parameters along the major axis are determined. The width of the Gaussian that best matches the collapsed TNO light profile is then compared to the distribution of widths for point sources in the image, also collapsed along the same direction as the TNO image. The deviation of the width computed for the TNO from the expected value based on the reference point sources is used to flag possible TNBs. Those sources with width more then 2-σ larger than the mean for point sources in the same frame were examined visually. Again, all TNOs flagged for visual inspection were found to have

![Image](image1.png)

**Fig. 1.**—Example of the PSF of single stars in a CFEPS field that is constructed by averaging the PSFs of several single stars around a TNO: (a) cross section of the PSF; (b) two-dimensional projection.

![Image](image2.png)

**Fig. 2.**—Comparison of (a-c) the original images of three TNOs (L4j05 [nondetection], L4k12, and L5c02) that are detected by CFEPS; (d-f) their images after subtraction from the reference PSF; (g-i) fitting of their PSF profiles (solid lines) along the elongated axis to the reference PSFs (dashed lines). The normalized pixel values of TNOs are shown in dots around the dashed lines. See the electronic edition of the *PASP* for a color version of this figure.
background contamination, except for two sources: L5c02 (previously detected as binary using PSF modeling) and perhaps L4k12. Tests with artificially created near-equal-magnitude TNBs revealed that this one-dimensional fitting approach is sensitive enough to detect binaries with separations larger than one-third of the FWHM.

2.3. Detected TNBs

Figure 2 presents a comparison of the image subtraction and elongation fitting of three CFEPS TNOs: L4j05, L4k12, and L5c02. Two of the sources in Figure 2 (L4j05, L4k12) have residuals that are normal for point sources in their images and values of $\chi^2$ consistent with a point source. The TNO L4j05 is found to have an elongation width consistent with point sources detected in the same frame and is presented as an example of a nondetection. L4k12, however, exhibits significant deviation from the corresponding one-dimensional Gaussian fitting of point sources in the image, revealing the extended nature of this source. The TNO L5c02 exhibits obvious residuals compared to the PSF model and also exhibits a one-dimensional Gaussian shape that is much broader than the point sources in the same frame.

Using these two procedures (PSF modeling fitting and profile elongation) we identified two binary candidates (L5c02 and L4k12) out of 63 TNOs examined. Those 63 TNOs are the brightest TNOs from CFEPS samples ($r \lessim 23.0$). Table 1 gives the orbital parameters and photometric data of these two objects.

| Object | $a$ (AU) | $e$ | $I$ (deg) | Dynamical class | Magnitude | Mutual period (day)$^*$ |
|--------|---------|----|--------|----------------|----------|------------------------|
| L4k12  | 40.77   | 0.117 | 35.23 | Classical | 23.0 ($r^*$) | 325 |
| L5c02  | 45.74   | 0.035 | 1.79  | Classical | 22.8 ($r^*$) | 280 |

$^*$ Assume that the semimajor axis is equal to separation of two components with $2g/cm^3$ bulk density.

2.4. Follow-up Observations

In order to confirm the binary nature of L4k12 and L5c02, we have obtained high-resolution follow-up images using the Subaru 8 m and WIYN 3.5 m observatories.

Observations of L5c02 obtained with the WIYN telescope on 2008 May 3 are presented in Figure 3. An elongated structure with a length of about 0.67″ (21,000 km at 44.2 AU) is clearly revealed in this image. The two components from this image are not fully resolved; however, simultaneous PSF modeling using two point sources reveals that this object is well represented by two sources of comparable magnitudes.

Observations of L4k12, obtained with Subaru on 2009 April 23, are shown in Figure 4. An elongated structure with a major axis of about 0.8″ (25,000 km at 43.6 AU) is quite prominent in the images. Although the 0.4″ to 0.8″ separation change is plausible, it is possible this single Subaru image is of a background star behind the TNO. If the elongated structure is not due to background star behind the TNO, this image is well modeled by the doublet source, with both sources having comparable magnitudes.

Table 2 provides a summary of the information on the CFEPS discovery, recovery, and follow-up observations.

3. DISCUSSION AND SUMMARY

The images of the new TNOs discovered by CFEPS have been examined with a view to detect the presence of binaries. Both the methods of PSF subtraction and a newly developed scheme of 2D Gaussian profile fitting have been used. We only examine the objects brighter than $g \sim 23$, because both methods are S/N-sensitive. Of the 63 new TNOs (31 of 63 are classical belt objects, 20 are the resonant objects) examined, two (L4k12 and L5c02)
and L5c02) have been identified to be wide binaries and L5c02 has been confirmed. Both of them are classical TNOs.

To estimate the binary fraction in different dynamical classes, especially in cold and hot components of the classical Kuiper belt, it is important to realize that an \( i < 5 \)° orbit could be drawn from either a low-inclination or higher-inclination component when both are modeled as Gaussians. We used the CFEPS survey simulator (Kavelaars et al. 2009) to determine that for \( g \lesssim 23 \), about 7% of the \( i < 5 \)° detections are actually from the hot component, and thus it is problematic to label a particular TNO as cold just because it has \( i < 5 \)°. Conversely, if L4k12 does turn out to be binary, with heliocentric \( i \sim 35 \)°, the probability that it is drawn from the narrow-inclination cold population is essentially negligible. In our 31 classical belt objects sample, 23 of 31 are \( i < 5 \)°. Therefore, we expect that \( \approx 21 \) are cold classical belt objects and 10 are hot components. For the 95% confidence interval, based on the Poisson uncertainty, we have constrained the binary rate to between 1.5% and 20% for the cold belt and between 3% and 43% for the hot belt. Also, the 95% confidence interval for zero detections is an upper limit of three sources, and so we know the binary fraction among the resonant sources is below 3/20, or 15%.

This fraction is substantially lower than that determined from high-resolution HST imaging (see Noll et al. 2008b) but is consistent with the fraction of wider separation systems reported in Kern and Elliot (2006). We note that L4k12 is has the highest heliocentric orbital inclination among all currently known binary sources.

The present numerical algorithm will be a promising approach in the search of TNBs in large surveys like Pan-STARRS, which is expected to multiply the number of detected TNOs many times. A systematic search as described in the present work will shed new light on the orbital distribution of TNBs and their origin.

Additional high-quality tracking observations of L4k12 from GEMINI (A. H. Parker 2009, private communication) have not resolved (seeing FWHM \( \sim 0.5 \)″) this source as binary. Given the lack of follow-up observations of our Subaru confirmation data, we caution that L4k12 may actually be a tight binary (separation \( < 0.5 \)″) discovered in the CFEPS images during its apocenter passage. We are continuing to monitor this source in an attempt to fully resolve the nature of this putative TNB.

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**TABLE 2**

| Telescope | UT date | \( \Delta \) mag | Separation (") | PA (deg) |
|-----------|---------|----------------|---------------|---------|
| L4k12     | ...     | ...            | 0.4           | 270     |
| CFHT      | 2005 May 14.4 | ... | 0.71          | 270     |
| Subaru    | 2009 Apr 23.6 | 0.71          | 0.61          | 28      |
| CFHT      | 2005 Apr 11.3 | 0.26          | 0.62          | 35      |
| CFHT      | 2006 Feb 06.3 | 0.13          | 0.75          | 95      |
| WIYN      | 2008 May 03.2 | 0.32          | 0.67          | 207     |

4 PA is the angle east of north.