Visible–IR Colors and Lightcurve Analysis of Two Bright TNOs: 1999 TC$_{36}$ and 1998 SN$_{165}$

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Abstract

We report on observations of two bright Trans-Neptunian Objects (TNOs) – 1999 TC$_{36}$ and 1998 SN$_{165}$ – during two observational campaigns, as part of the Meudon Multicolor Survey of Outer Solar System Objects. $V - J$ color was measured for 1999 TC$_{36}$ ($V - J = 2.34 \pm 0.18$), which combined with previous measured colors in the visible, indicate a red reflectivity spectrum at all wavelengths. Photometric V-band lightcurves were taken for both objects over a time span of around 8 hours. We have determined a possible rotational period of $P = 10.1 \pm 0.8$ h for 1998 SN$_{165}$, making it the seventh TNO with an estimated period. From its lightcurve variation of $\Delta m = 0.151^{+0.022}_{-0.030}$, we have inferred an asymmetry ratio of $a/b \geq 1.148^{+0.024}_{-0.031}$. For 1999 TC$_{36}$, we did not detect any rotational period or periodic signal variation within the uncertainties, but the analysis of its lightcurve hints to a slight systematic magnitude decrease.

Key words: Solar System, Kuiper Belt, Minor planets, asteroids, Techniques: photometric, Methods: data analysis, Methods: statistical

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1 Introduction

Beyond the orbit of Neptune there exists a population of bodies remnant from the formation of the solar system, planetesimals whose number density inhibited further accretion and whose orbits are, in general, stable on solar system time scales. These are the so-called Trans-Neptunian Objects (TNOs), also known as Edgeworth-Kuiper Objects (EKO}s or Kuiper-Belt Objects (KBOs). Postulated by Edgeworth (1943, 1949) and Kuiper (1951), their existence has only recently been confirmed observationally by Jewitt & Luu (1993).

The Edgeworth-Kuiper Belt (EKB) is also most probably the source of the short-period comets (Duncan et al. 1988) and a transient population of objects between the orbits of Jupiter and Neptune: the Centaurs.

Although there are no strict definitions, the TNOs are generally classified in three groups: resonant objects, classical objects and scattered objects. The resonant objects trapped in orbital resonances with Neptune, mainly in the 2:3 like Pluto, and are therefore also called Plutinos. The classical objects have semi-major axes mostly confined between 40 and 48 AU. Scattered objects have highly eccentric and inclined orbits. Presently, about 590 TNOs and 33 Centaurs are known.

The physical properties of the TNOs and Centaurs are still poorly understood. Spectroscopic studies of these objects are only possible with 8-10 meter class telescopes and limited to the brightest ones. Therefore, broadband photometry is still the most feasible method allowing a compositional survey relevant for statistical work. At present, several adequate samplings of the visible colors of these objects are published, allowing already some statistical analysis (e.g.: Tegler & Romanishin 2000, Doressoundiram et al. 2001, Hainaut & Delsanti 2002, and references therein). However, this data is not yet enough to support or refute some claimed relations between colors, sizes and orbital parameters. On the other hand, Barucci et al. (2001) showed the importance of the \( V - J \) color in any taxonomical work characterizing the TNOs, but with \(~20 \) objects measured so far (Boehnhardt et al. 2001, Davies et al. 2000, and references therein) IR data is still scarce.

Precise and unequivocal determination of TNOs’ rotational periods is difficult to accomplish. Romanishin & Tegler (1999) detected for the first time lightcurve variability among this class of objects, estimating rotational periods for 1995 QY\(_9\), 1994 VK\(_8\) and 1994 TB. Presently, three more TNOs have published periods with good accuracy: Varuna (Farnham 2001, Jewitt & Sheppard 2002), 1996 TO\(_{66}\) (Hainaut et al. 2000) and 1998 SM\(_{165}\) (Romanishin et al. 2001). This latter object has recently been found to be a binary (Brown & Trujillo 2002). Centaurs, which are brighter and easier to study, are better
sampled, with rotational periods published for Chiron (Bus et al. 1989), Asbolus (Brown & Luu 1997), Pholus (Buie & Bus 1992), 1999 UG5 (Gutiérrez et al. 2001), 2000 QC243 and 2001 PT13 (Ortiz et al. 2002).

Knowledge of rotation rates of TNOs and Centaurs may provide insight into their collisional evolution. Indeed, the present wide color diversity among TNOs may have originated from collisional resurfacing processes. Moreover, albedo measurements, spectroscopic studies, and accurate multicolor photometry on these objects depend critically on the knowledge of their rotational properties (or magnitude variations). This is necessary due to the non-simultaneity of the observations in the several bands and the long exposure time needed, particularly in the infrared. Large samples are usually necessary for precise determination of the rotational periods. Such samples are hard to obtain due to the faintness and small magnitude variations expected in the vast majority of the TNOs. The identification of short term magnitude variations is, consequently, of most importance, as it allows us to filter candidates for rotational period detections.

We here report on observations of two TNOs. Our results consist of a possible determination of a rotational period for 1998 SN165 and a measurement of the \( V - J \) color for 1999 TC36. Within our observational errors we can exclude a rotational period inferior to 8 hours for 1999 TC36. These two objects are of increasing interest, since 1999 TC36 has recently been reported to possess a companion object (Trujillo & Brown 2002) and it has been suggested that 1998 SN165 belongs to a new dynamical sub-class of TNOs (Doressoundiram et al. 2002).

2 Observations

This study is based on two observational campaigns: one dedicated to J-band photometry and the other to lightcurve analysis.

J-band photometric data was obtained on the 9th of August 2000, with the ARNICA near-infrared camera on the 3.58 m Italian National Telescope (TNG; La Palma, Spain) equipped with a HgTeCd array detector with \( 256 \times 256 \) pixels (pixel scale=1”, pixel size=40 \( \mu m \)).

V-band relative photometric data was obtained on the 30th of September 2000, at the 3.6 m New Technology Telescope (NTT; ESO, La Silla, Chile) with the SUSI2 CCD camera on the f/11 Nasmyth focus, equipped with a mosaic of two EEV CCDs with \( 2048 \times 4096 \) pixels each (pixel scale=0.16”, pixel size=15 \( \mu m \)). This night was non-photometric – seeing varied from 1.3” to 2.6”.

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The sufficiently small angular motion of the targets allowed for sidereal tracking rate in all runs (see table 1).

3 Data Reduction

V-band lightcurve data was reduced with IRAF’s CCDRED package. For 1999 TC36, we used an aperture radius of 4.5" centered around the object (and reference stars) with the sky level estimated by using the mode value within a concentric ring between 11.2" and 12.8" (farther than 4.3 times the worst seeing). Relative magnitude was computed relative to a “superstar” made with the 3 brightest field stars, whose stability was verified. To check for the significance of eventual magnitude variations on the target, two stars of about the same magnitude as the object were also measured. For 1998 SN_{165}, an aperture of 3.8" was used. This object was fainter than the previous and more sensitive to sky variations, therefore a smaller aperture was used in order to improve the S/N ratio. Sky was estimated on a ring between 8.0" and 9.6" in most of the images due to the presence of a close star in some of the frames. However, for images with seeings above 2.0", the sky ring was moved away to 11.2" to ensure that the sky was being estimated at distances were no (significant) signal from the object was expected. Magnitude was computed relative to a “superstar” made with the 2 brightest field stars that were also checked for stability. A star with magnitude close to the object’s was taken as a reference for fluctuations. Relative magnitudes obtained are presented in table 2.

Near-Infrared J-band data was reduced using both IRAF and MIDAS following the standard techniques of flatfielding, using twilight flats, estimation of a sky frame, subtraction of the sky from all frames, after proper scaling, determination of the offsets between frames based on the image headers and final image registration. Details on the reduction procedure can be found in Romon et al. (2001).
Table 2
Relative Magnitudes of 1999 TC\textsubscript{36} (on the left) and 1998 SN\textsubscript{165} (on the right) at UT date 2000-09-30.

| UT(h) | Exp(s) | Mag  | Error | UT(h) | Exp(s) | Mag  | Error |
|-------|--------|------|-------|-------|--------|------|-------|
| 0.1413| 120    | 2.296| 0.030 | 0.2233| 240    | 3.651| 0.043 |
| 0.3099| 120    | 2.288| 0.030 | 0.3794| 240    | 3.679| 0.044 |
| 0.4961| 120    | 2.294| 0.032 | 0.5486| 240    | 3.734| 0.040 |
| 0.6386| 180    | 2.319| 0.022 | 0.7299| 300    | 3.681| 0.033 |
| 0.9300| 134    | 2.305| 0.032 | 1.1677| 300    | 3.715| 0.032 |
| 1.3865| 180    | 2.312| 0.021 | 1.4627| 300    | 3.739| 0.037 |
| 1.5659| 180    | 2.312| 0.022 | 1.6422| 300    | 3.732| 0.034 |
| 1.7452| 180    | 2.300| 0.021 | 1.8236| 300    | 3.735| 0.034 |
| 2.0697| 180    | 2.286| 0.022 | 2.2150| 300    | 3.700| 0.032 |
| 2.3954| 180    | 2.268| 0.021 | 2.4990| 300    | 3.660| 0.031 |
| 2.6236| 180    | 2.282| 0.020 | 2.7492| 300    | 3.579| 0.029 |
| 2.8832| 180    | 2.297| 0.020 | 2.9792| 300    | 3.596| 0.031 |
| 3.1314| 180    | 2.295| 0.020 | 3.2747| 300    | 3.565| 0.032 |
| 3.6683| 180    | 2.300| 0.019 | 3.4986| 300    | 3.667| 0.031 |
| 3.9371| 180    | 2.286| 0.019 | 3.7495| 300    | 3.590| 0.028 |
| 4.4094| 180    | 2.318| 0.019 | 4.0168| 300    | 3.584| 0.030 |
| 4.6880| 180    | 2.283| 0.019 | 4.4973| 300    | 3.592| 0.029 |
| 4.9345| 180    | 2.288| 0.019 | 4.7706| 300    | 3.658| 0.031 |
| 5.1691| 180    | 2.269| 0.020 | 5.0189| 300    | 3.688| 0.033 |
| 6.0760| 180    | 2.256| 0.021 | 5.2530| 300    | 3.738| 0.035 |
| 6.3066| 180    | 2.265| 0.022 | 5.4889| 300    | 3.676| 0.034 |
| 6.5421| 180    | 2.274| 0.022 | 5.6821| 300    | 3.702| 0.035 |
| 6.7849| 180    | 2.256| 0.030 | 6.3979| 300    | 3.722| 0.038 |
| 6.9755| 180    | 2.196| 0.028 | 6.6228| 300    | 3.767| 0.044 |
| 7.1694| 180    | 2.269| 0.026 | 7.0591| 300    | 3.732| 0.054 |
| 7.4535| 180    | 2.165| 0.024 | 7.2462| 300    | 3.720| 0.048 |
| 7.6719| 180    | 2.203| 0.025 |       |        |      |       |
| 8.0148| 180    | 2.232| 0.027 |       |        |      |       |
| 8.2472| 180    | 2.219| 0.028 |       |        |      |       |
| 8.5034| 240    | 2.205| 0.024 |       |        |      |       |

4 Colors and Reflectivities

The $V−J$ color of 1999 TC\textsubscript{36} was calculated using the V magnitude reported by Doressoundiram et al. (2001), which was obtained with only 22 minutes of time difference with our J-band data (see table 3). To compare the spectral behaviors, we quote also the $BVRI$ colors for 1999 TC\textsubscript{36} and 1998 SN\textsubscript{165} (Doressoundiram et al. 2001), and $V−J$ color for 1998 SN\textsubscript{165} (McBride et al. 2002). Relative spectral reflectances at the central wavelengths of the broadband filters, normalized to the V filter, are plotted in figure 1.
Table 3
Colors for 1998 SN\textsubscript{165} and 1999 TC\textsubscript{36}

| Object  | \(V^*\)     | \(B - V^*\) | \(V - R^*\) | \(V - I^*\) | \(V - J\)  | \(H_V^*\) | Size(km)* |
|---------|-------------|-------------|-------------|-------------|-------------|------------|-----------|
| 1998 SN\textsubscript{165} | 21.55 ± 0.06 | 0.82 ± 0.08 | 0.33 ± 0.08 | 0.84 ± 0.08 | 1.27 ± 0.05\*\* | 5.67 ± 0.06 | 488       |
| 1999 TC\textsubscript{36}  | 20.49 ± 0.05 | 0.99 ± 0.09 | 0.65 ± 0.06 | 1.37 ± 0.07 | 2.34 ± 0.18 | 5.40 ± 0.05 | 552       |
| Sun     | –           | 0.67        | 0.36        | 0.69        | 1.08        | –          | –         |

* Values from Doressoundiram et al. (2001)
** Value from McBride et al. (2002)

Fig. 1. Relative spectral reflectances of 1998 SN\textsubscript{165} and 1999 TC\textsubscript{36} normalized to the V filter.

Analysis of figure 1 shows that 1999 TC\textsubscript{36} possess a red spectrum at all studied wavelengths, indicating that its surface may be covered by some organic material (Cruikshank 1989, Thompson 1987), while 1998 SN\textsubscript{165} presents an almost flat spectrum at all wavelengths. This illustrates the wide color diversity seen among the TNOs population, with colors varying from gray (1998 SN\textsubscript{165}) to red (1999 TC\textsubscript{36}).

5 Lightcurve Analysis
In figure 2 we plotted the lightcurve for 1998 SN\textsubscript{165} resulting from the data in table 2. We have also plotted the data for a reference star of about the same magnitude as the object, used to check for the significance of any eventual variability. It seems patent that the object has a periodic variation of magnitude.

A first test for non-random variation was performed with the Chi-Square Test, in which the null hypothesis is: there is no non-random variation (Collander-Brown et al. 1999). The weighted mean magnitude is calculated for the object
Fig. 3. Lomb-Scargle periodogram for 1998 SN$_{165}$. The frequency is in inverse hours and the power relates to the probability that the corresponding frequency is due to noise. The higher the power the lower the probability. The maximum power of 8.28 is at 0.199 $h^{-1}$.

$(\bar{x}_w)$ and then the Chi-Square:

$$\chi^2 = \sum_{i=1}^{n} \frac{(x_i - \bar{x}_w)^2}{\sigma_i^2}$$

were $x_i$ are the relative magnitude values, $\sigma_i$ the corresponding errors and $n$ the number of data-points. Assuming that the errors are gaussian, and that $n$ is a large number, the mean limiting distribution is $\langle \chi \rangle^2 = n - 1$ and the variance is $\sigma^2 = 2(n - 1)$. For 1998 SN$_{165}$ and using a 26 data-point sample, we obtained $\chi^2 = 79.96$, which is $7.8\sigma$ ($\sigma = 7.07$) above the mean $\langle \chi \rangle^2 = 25$. Since the result is larger than $3\sigma$, we have a significant rejection of the null hypothesis.

To search for any periodic signal concealed in the data, we applied the Lomb-Scargle periodogram (Lomb 1976; Scargle 1982; Horne & Baliunas 1986; Press et al. 1992). A high peak is detected at the frequency $f = 0.199 \, h^{-1}$ with a power of 8.28 (fig. 3).

To check for the level of significance in the estimated period, we carried out a Monte-Carlo simulation. Holding fixed the number of data-points, their time locations $t_i$ and the corresponding errors $\sigma_i$, 10 000 random data-sets were
constructed. Each random \( x_i \equiv x(t_i) \) was generated following a gaussian distribution of standard deviation \( \sigma_i \). Applying the Lomb-Scargle periodogram to each one of these random data-sets, we may estimate the probability of our detected frequency being due to noise — the false period probability \( (P_f) \). With only 4 events with higher powers than 8.28 we have a \( P_f = 0.04\% \), that is, a significance level of 99.96%.

By fitting a sine-wave of \( f = 0.199 \) \( h^{-1} \) to the data with the Levenberg-Marquardt algorithm, we determine the magnitude variation, i.e., peak to peak amplitude, of \( \Delta m = 0.151 \). After subtracting this signal sine-wave to the data, we obtained a noise sample with standard deviation \( \sigma_N = 0.031 \), which is of the order of our average error bars. This revealed a good signal subtraction.

To determine the error in the frequency, we also performed a Monte-Carlo simulation. Analogously to the previous simulation, we generated 1000 data-sets, now adding the gaussian noise to the signal obtained from the fitted sine wave and applying the Lomb-Periodogram to each set. The resulting distribution had a mean value of \( \langle f \rangle = 0.198 \) and a standard deviation of \( \sigma_f = 0.016 \). Therefore, our detected frequency is:

\[
f = 0.199 \pm 0.016 \ h^{-1}
\]

The error in the amplitude is estimated by taking the two extreme values (amplitude plus or minus its error from the fit), resulting from fitting the sine-wave with \( f = 0.199 + \sigma_f \) and \( f = 0.199 - \sigma_f \). We get a lightcurve amplitude of:

\[
\Delta m = 0.151^{+0.022}_{-0.030}
\]

However, we should be cautious in considering the significance of the detected frequency, since the lightcurve is not sufficiently sampled to allow detection of eventually more complex behaviors than a single sine-wave variation. Nevertheless, we may still make considerations on its rotational period and possible asymmetry. Assuming an uniform surface albedo for the object, the lightcurve is the result of the variation of the projected cross-section area of an elongated shape in rotation. Therefore, a full rotation produces a lightcurve with two minima and two maxima. With this assumption, the period found with our observations is only due to half rotation. Hence, the estimated rotation period is:

\[
P = 10.1 \pm 0.8 \ h
\]

Supposing a tri-axial ellipsoidal body (with \( a > b > c \)) rotating along the shortest axis \( (c) \) perpendicular to the line of sight, from the determined amplitude of the lightcurve \( \Delta m \) we estimate a minimum value for the ratio between
the semi-axis $a$ and $b$, from the equation $\Delta m \geq 2.5 \log a/b$:

$$\frac{a}{b} \geq 1.148^{+0.024}_{-0.031}$$

However, the hypothesis of a rotating non-uniform albedo object producing a mono-peak lightcurve cannot be ruled out, in which case the rotational period would be half of the computed value above.

In order to check for the real variability of the object’s magnitude, we performed also the Chi-Square test on a reference star. A $\chi^2 = 27.00$ was found, which is only $0.28\sigma$ above the $\langle \chi^2 \rangle$, well within the $3\sigma$ bounds of the null hypothesis. The results assure the stability of the relative photometry and thus confirm that the object’s variability is real. Also, the Lomb-Scargel periodogram applied to the reference star did not reveal any significant periodic signal.

5.2 1999 TC$_{36}$

We observed 1999 TC$_{36}$ over 8.362 hours and no apparent periodic variation seems present within this time span (see fig. 4).

With a sample of 30 data-points, we expect a $\langle \chi^2 \rangle = 29$ and $\sigma = 7.62$. The Chi-Square test on the object, resulted in a $\chi^2 = 77.274$, which is $6.34\sigma$ above the $\langle \chi^2 \rangle$. This would imply a rejection of the null hypothesis. However, if we reject the 2 lowest points that seem slightly wayward, we obtain a $\chi^2 = 46.78$, now only $2.69\sigma$ above $\langle \chi^2 \rangle$ and within the null hypothesis interval. Once more, we performed the same test on a close magnitude field star (see fig. 4), obtaining a $\chi^2 = 37.24$, only $1.08\sigma$ above $\langle \chi^2 \rangle$. This again assures the stability of the relative photometry. The Lomb-Scargle periodogram does not find any significant period in the data, neither in the object nor in the reference star. Comparing the data samples of the object and the reference star, we see a slight systematic magnitude decrease for the object ($\Delta m \approx 0.1$), that might indicate this object as a good candidate for a longer rotational period. However, this result should be taken with caution since the scatter of data at the end of the night increases due to the degradation of seeing conditions. Nonetheless, it is clear that the objects does not possess a detectable periodic variation below 8.4 h within the observed errors.
Fig. 4. Lightcurve for 1999 TC₃₆ and reference star obtained on the 2000-09-30. X-axis is in UT hours and Y-axis in relative magnitude to the chosen field stars. Magnitudes of the reference star were shifted for clarity ($\langle m_v \rangle = 2.32$).

6 Conclusions

A periodic signal of frequency $f = 0.199$ (periodicity $T = 5.03$ h) with a confidence level above 99.9\% is present on our V-band lightcurve of 1998 SN₁₆₅ with a peak-to-peak magnitude variation of $\Delta m = 0.15$. A possible rotational period of $P = 10.1 \pm 0.8$ h and asymmetry ratio of $a/b \geq 1.15$ are estimated. This rotational period is to be taken with caution and should be confirmed with better sampled observations. For 1999 TC₃₆, we do not detect any periodic variation over our 8.4 h time-span within the uncertainties. If 1999 TC₃₆ has a detectable rotational period it warrants longer observations. From the relative reflectance spectra obtained with the BVRIJ colors, of 1999 TC₃₆ we see that it possesses a red spectrum, probably resulting from a cover of organic material on its surface.
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