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Letter to the Editor

Short-term rotational variability in the large TNO 2005FY$_9$*

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ABSTRACT

Context. Despite the fact that 2005FY$_9$ is one of the largest trans-Neptunian objects (TNOs) and a dwarf planet candidate, little is known about this object apart from constraints on its surface composition.
Aims. The goal of this work is to study 2005FY$_9$'s short-term variability in order to determine the amplitude of the lightcurve, which can be linked to the degree of elongation of the body or to the degree of albedo heterogeneity on the surface. Besides, the rotation period can be determined.
Methods. CCD photometric observations of the trans-Neptunian object 2005FY$_9$ in R band on 21 nights spanning several months were carried out using the 1.5 m telescope at Sierra Nevada Observatory and the 2.2 m telescope at Calar Alto Observatory.
Results. The time-series analysis leads to confident detection of short-term variability. The most significant periodicities are 11.24 ± 0.01 h and its double, but other possibilities cannot be ruled out. The 22.48 h double-peaked rotational phase curve is slightly preferred by our analysis. As for the amplitude of the lightcurve, we get a peak-to-peak variability of 0.03 ± 0.01 mag. This result is compatible with a nearly spherical body that has a very homogeneous surface. There is also the possibility that the body is rotating nearly pole on, but we believe this is less likely. Very weak constraints are obtained for the density and internal strength based on the rotational properties derived from the photometry.

Key words. Kuiper Belt – minor planets, asteroids

1. Introduction

Trans-Neptunian objects (TNOs) are believed to be remnants of the solar system formation. They are cold minor bodies of the outer Solar System and therefore are thought to be composed of ices and rock, formed in the early ages of the Solar System. They are the most likely source for the Centaurs and the short-period comets. Although the possible existence of a trans-Neptunian belt as the source for short period comets was explicitly proposed more than 25 years ago (Fernández 1980), it was not until late 1992 that the first TNO was discovered (Jewitt & Luu 1992). Since that time, around a thousand such objects have been found. In spite of suffering some collisional evolution and space weathering, as well as some thermal processing, these objects are among the least evolved in the Solar System. Therefore, the study of these bodies is an important tool for understanding the formation and early evolution of the Solar System.

Their rotational properties are important because valuable information can be gathered from analyzing spin periods, lightcurve amplitudes, and even pole orientations (e.g. Lacerda et al. 2006; Ortiz et al. 2006; Sheppard & Jewitt 2003). While TNOs pole orientations cannot be determined until many years after their discovery, because of the very small arcs travelled by TNOs in short time spans, the other properties are more easily accessible by telescopic observations. Unfortunately, only the brightest and presumably largest objects can have their lightcurves measured using medium-sized telescopes. 2005FY$_9$ is one of the largest TNOs known and is a remarkable object from many points of view. One of its peculiarities is that it shares many spectral features with Pluto (e.g. Licandro et al. 2006), so the surface composition of these two bodies may be similar. We have studied its short-term variability with the main goal of deriving its lightcurve amplitude and spin period so that additional physical properties of this important object can be determined.

Table 1. Dates and geometric data (range) of the observations.

Teles.	$r_{\rm h}$(AU)	Δ (AU)	α(deg)	Observing dates
OSN	51.92	51.26–51.19	0.82	1, 2, 6, 8 Feb. 06
OSN	51.93	51.08–51.07	0.57	1, 2 Mar. 06
OSN	51.93	51.15–51.18	0.70	7, 8, 10, 12 Apr. 06
OSN	51.97	51.99–51.91	1.09	14–18 Dec. 06
CAHA	51.98	51.58–51.52	0.98	11–16 Jan. 07

2. Observations and data reduction

The observations were carried out by means of the Instituto de Astrofísica de Andalucía 1.5 m telescope at Sierra Nevada Observatory (Granada, Spain) and the Calar Alto observatory 2.2 m telescope (Almería, Spain). We used data from 21 nights separated in 5 different observing runs. The first observing run was carried out in February 2006 and the last one in January 2007. The observing logs are shown in Table 1. The typical seeing during the observations ranged from 1.0 to 2.5 arcsec, with a median around 1.4 arcsec. The 1.5 m telescope observations were carried out by means of a 2k × 2k CCD with a total field of view of 7.8 arcmin × 7.8 arcmin. However, binning 2 × 2 was always used, giving a 0.46 arcsec/pixel scale. This scale was enough to have good point-spread-function sampling even for

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* Table 2 is only available in electronic form at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr (130.79.128.5)` or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/468/L13`

the best seeing cases. The 2.2 m telescope observations were obtained with the CAFOS instrument, a focal reducer imager and spectrograph with a plate scale of 0.51 arcsec/pixel.

Taking the object's slow drift rate (roughly 1 arcsec/h) into consideration, we used exposure times that were short enough to avoid getting elongated images of either the object or the field stars (depending on whether the telescope is tracked at sidereal or nonsidereal rate), but long enough to get a high signal-to-noise ratio for the object. An exposure time of 400 s was short enough to avoid noticeable trailing under the best foreseeable seeing conditions, but long enough so that the sky background was the dominating noise source. The observations were made through the Johnson Cousins *R* filter.

The images were bias-subtracted in the standard way and flat-fielded using a daily master flatfield frame, obtained as the median of a large set of dithered twilight images of the sky at blank fields. No cosmic ray removal algorithms were used, and we rejected the images in which a cosmic ray hit was close to the object. Relative photometry using seven field stars was carried out by means of Daophot routines. The synthetic aperture used was typically 3 to 5 arcsec in diameter (the smallest possible in order to get the highest signal to noise). Care was taken not to introduce spurious signals of faint background stars or galaxies in the aperture. Because of the small angular motion of the TNO, we were able to use the same field stars within each observing run. The typical error bars of the individual 400 s integrations were ~0.01 mag. This uncertainty was obtained by computing the standard deviation of the measurements.

The time-resolved observations were inspected for periodicities by means of the Lomb technique (Lomb 1976) as implemented in Press et al. (1992), but we also verified the results by using several other time-series analysis techniques, such as phase dispersion minimization (PDM), and the Harris et al. (1989) method. The reference stars were also inspected for short-term variability. We can thus be confident that no error has been introduced by the choice of reference stars.

The object was observed in more than one campaign, so the reference stars were not the same ones in the different runs. To apply time-series analysis to different data sets for the same object separated by several weeks or months, we scaled the data of the different runs so that they gave the same average value. Since an absolute calibration would not be accurate enough (and even if it were, the phase effect would introduce shifts to the data of each run), we preferred to normalize each run to a common value and apply the time-series analysis to the data combined this way. We are implicitly assuming that the rotation period is shorter than the typical 5-day observing runs. Nevertheless in our longest, the 6-night run, we checked that there was no continuous brightening or dimming trend in the dataset, which might be indicative of a long rotation period. The absolute brightness of 2005FY$_9$ is not relevant to the goals of this study, but we carried out an absolute calibration by observations of Landolt stars 95 301, 95 302, and GD71, on December 15, 2006. The magnitude of 2005FY$_9$ in *R* band was 16.8 ± 0.1.

3. Results

More than 600 images were analyzed. The photometry results from those images cannot be shown on a printed table because of its huge length. The data are shown in Table 2, which will be available as supplementary online material.

The Lomb periodogram for the relative photometry (Fig. 1) shows several peaks. The peak with the highest spectral power (with a confidence level well above the 99.99%) corresponds to a periodicity of 11.24 h (2.134 cycles/day). The periodogram shows other peaks of much weaker spectral power around the 11-h range, and there is also a very high peak at 20.57 h (1.167 cycles/day) that appears to be an alias of the main peak. By studying the data with different time-series analysis techniques such as PDM, one gets the second preferred period at 11.24 h, whereas the preferred period is at 20.57 h (1.167 cycles/day). Using the Harris method with 1-harmonic, one gets the preferred period at 20.57 h as well, but a significantly better solution is obtained at 22.48 h with 2-harmonics, which is twice the 11.24 h period obtained with the Lomb periodogram and therefore implies a double-peaked lightcurve. The confidence of this periodicity is also higher than 99.99%.

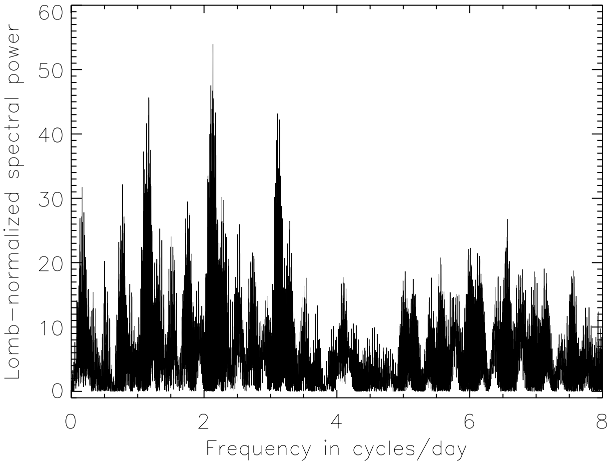

Fig. 1. Lomb periodogram for the 2005FY$_9$'s relative photometry showing several peaks (in cycles per day). The highest peaks are at 2.134 cycles/day (P = 11.24 h), 2.103 cycles/day (P = 11.41 h), and 1.167 cycles/day (P = 20.57 h), which appears to be an alias.

Visual inspection of the rotational phase curves for the three above–mentioned periodicities seems to favor 22.48 h, because of the two clearly marked brightness minima; but the rotational phase is not completely filled in this case, as can be seen in Fig. 2. According to the rotational phase curves, the spin period of this TNO could be 22.48 h, 11.24 h or 20.57 h. For all these periodicities, the peak-to-peak amplitude of the lightcurve is 0.03 ± 0.01 mag. This value is derived from the difference of the maximum to the minimum in the median rotational phase curves in Fig. 2. These results on amplitude and rotation period are compatible with Rabinowitz et al. (2007), who carried out absolute photometry to determine the slope of the phase curve of 2005FY$_9$ but could not determine a rotation period because of larger scatter and fewer data points.

4. Discussion

There are essentially two plausible causes for the periodic rotational variation that is observed in 2005FY$_9$. One of the possibilities is that the variations are induced by a nonspherical shape, and the other possibility is variations in the hemispherically averaged surface reflectivity of the object. It is impossible to distinguish one case from the other without additional data. A lightcurve from thermal emission observations could distinguish between both possibilities, but currently there is no instrument in the astronomical community that can address this (even for the largest TNOs). In the future, the ESA Herschel space mission should be able to achieve such a goal, but so far we can only take advantage of color-variation data that could possibly be linked

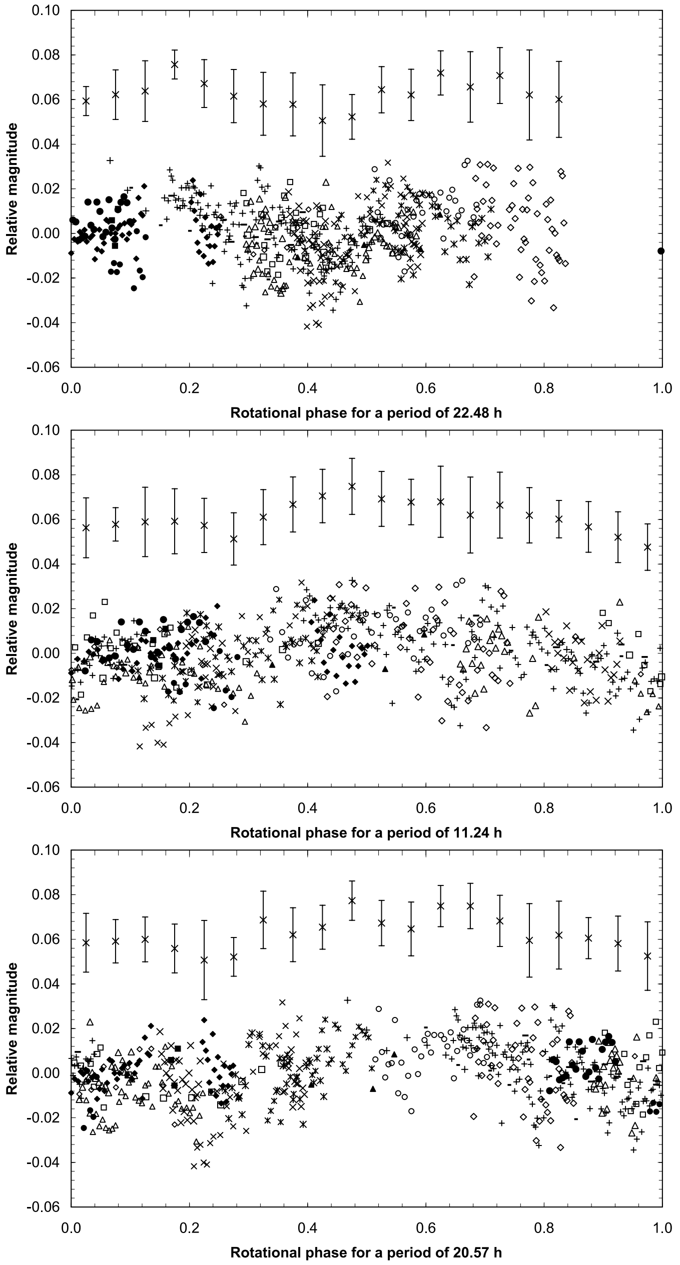

Fig. 2. Lightcurves (relative magnitudes vs. rotational phase) for the three possible periods. *Top*: for a 22.48 h period. *Middle*: for a 11.24 h period. *Bottom*: for a 20.57 h period. The plots also show the phase curves obtained by median-averaging the actual photometric data in rotational phase bins of 0.05 and displaced +0.06 mags in the y-axis. Error bars (standard deviation of the data in the phase bins) are shown in the median plots. The different symbols in the plots correspond to different observing dates.

to albedo variations. No important color variations have been reported for 2005FY$_9$, and also the spectra of the object do not show changes that could be related to surface features (Licandro, private communication). Therefore, this would slightly favor the possibility that the rotational variation is induced by shape rather than reflectivity variations. In that case the lightcurve would be double-peaked. We can derive an axial ratio for this object if we assume that the variations are entirely due to elongation and also if we assume that the aspect angle is near 90°. The resulting axial ratio would be 1.03.

But because the variability is so small, color variations associated to surface features would likely be too small to be detectable. Hence, there is no definite evidence for one possibility or the other. Nevertheless, a combination of slight surface-reflectivity variations and slight aspherical shape is also very likely.

A small-amplitude lightcurve from a highly nonspherical and heterogeneous object would also be possible provided that the object is rotating nearly pole on (rotation axis pointing to the Earth). Although this cannot be rejected at a 100% confidence level for the case of 2005FY$_9$, this is an unlikely possibility. Just to give an indication of how unlikely this possibility is, one can make some simple computations: Assuming an object with a similar axial ratio as Varuna or 2003EL$_{61}$, the aspect angle of the object would have to be smaller than 20 degrees to show a 0.03 mag variability. Assuming random pole orientations for the TNOs, the probability of observing an orientation smaller than 20 degrees would be around 6%. Besides, Eris, which is also a similar body in terms of size, etc., also shows a small–amplitude lightcurve (Duffard et al. 2007, in preparation), and it would be a remarkable coincidence that both objects were rotating nearly pole on. It appears more plausible that there is a common physical reason for this.

A possible common mechanism acting on both objects could be periodic ice resurfacing. This could also explain why the ice features are still clearly marked in the spectrum (Licandro et al. 2006), because space weathering would soon tend to hide the spectral signatures of the ices of very volatile species such as methane. Several ice resurfacing scenarios are possible. One possibility is the surface sublimation near perihelion and subsequent recondensation as the temperature drops away from perihelion. This would only work if the objects have high enough mass to retain the volatiles (e.g. Delsanti et al. 2004), but then one might perhaps expect an anticorrelation of albedo or maybe lightcurve amplitude with perihelion distance. We are currently investigating these possibilities (Santos Sanz et al. 2006). Ice resurfacing could also be produced by cryovolcanism (which is more likely present in large bodies) or even by collisions, provided that the average collision speed is low enough so that a large fraction of the ejecta can fall back to the object due to its own gravity. A typical collision speed within the Kuiper Belt is supposed to be 1.5 to 2 km s^{-1} (e.g. Stern 2002), which is slightly higher than the escape velocity of Pluto, but a large fraction of the ejecta will have slower speeds and can fall back. This will not be the case for smaller TNOs. Even micrometeoroid bombardment has the potential to rejuvenate the surface. All these possibilities must be studied quantitatively in the future.

Spectroscopic observations of 2005FY$_9$ have pointed out that this object appears to be similar to Pluto in composition (Licandro et al. 2006). Also, its magnitude is comparable to the magnitude that Pluto would show at that distance (in other words, their absolute magnitudes (H_v) are similar), so both objects presumably have a similar size. However, we have shown that 2005FY$_9$ exhibits a very small-amplitude lightcurve and a short rotation period compared to Pluto (but a slow rotation in comparison to most TNOs). In the case of Pluto, the presence of a large tidally-locked satellite like Charon is responsible for the long 6.4-day rotation period. In the case of 2005FY$_9$, no satellite has been detected so far, whereas a large body nearby would be detectable. The reason Pluto's lightcurve amplitude is larger than that of 2005FY$_9$ is not clear to us, but in principle the differences might be due to different orientations of the rotation axes. The large TNOs whose rotation rate has been determined appear to show a wide spread in rotation periods. The slow rotation of 2005FY$_9$ stands in clear contrast with fast rotators like 2003EL$_{61}$. This is probably an indication of the very different evolution paths of these bodies and most likely the result of very different collisional histories.

As in Ortiz et al. (2006), we have also calculated the density of the object using the tables provided by Chandrasekhar (1987) and assuming it is a strengthless body that adopts the shape of a Jacobi ellipsoid due to rotation. Under these assumptions, the lower limit to the density would be 76 kg/m^3, which is a very weak constraint. We also studied the rotational stability by using equations in Davidsson (2001). For a diameter of 1700 km (which is equivalent to assuming a Pluto-like geometric albedo) and for a rotation period of 11.24 h, the minimum density to avoid breakup would be 86 kg/m^3 and 88 kg/m^3 for a spherical and prolate body, respectively. For the 22.48h period, the lower limit to the density is 22 kg/m^3. Indeed, these values for the densities are very weak constraints, because much higher densities are expected from the large size of the body.

Conversely, one can assume that the object is solid and compute the internal strength needed to stay intact for two different densities like 1000 kg/m^3 and 500 kg/m^3 for the two extreme trial periods. In the shorter-period case, the internal strengths must be 2700 Kpa and 1350 Kpa. For the 22.48 h period the internal strengths must be 680 Kpa and 340 Kpa. All these values are much higher than what has been derived for comets and other icy bodies that may have a similar composition to the surface of 2005FY$_9$ and other dwarf planets candidates. Therefore, if TNOs and comets have similar surface properties, and hence share low strengths, one might expect that TNOs do not remain intact. With such low internal strengths, even gentle collisions might have the potential to chip material off from their surfaces.

5. Summary and conclusions

In this paper we report confident short-term rotational variability of one of the largest TNOs known, which appears to share a similar composition with Pluto and most likely qualifies as a future dwarf planet. But contrary to Pluto, 2005FY$_9$ exhibits small-amplitude lightcurve variations and a much shorter rotation, most likely 22.48 h or 11.24 h. We were not able to determine if the variability is produced by albedo variegations or by an elongated shape. The small amplitude is likely an indication that the object has a very homogeneous surface, with virtually no albedo contrast (or very small scale albedo variations) and an indication that the object is very close to spherical. A plausible physical process for the low contrast is the periodic ice resurfacing either by sublimation near perihelion and recondensation of volatiles farther from the sun or by some other process like perhaps cryovolcanism or even collisions with smaller bodies. There is also the possibility that the object could be far more distorted and have a strong albedo contrast provided that the object is rotating nearly pole on. We believe this possibility is unlikely.

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