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Light curves of the trans-Neptunian objects 1996 TP66 and 1994 VK8

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ABSTRACT

We have obtained a number of CCD images of two trans-Neptunian objects, 1994 VK8 and 1996 TP66, over two nights. The changes in magnitude of these objects have been examined, in a search for periodic variation. In the case of 1996 TP66, nothing other than random noise can be found to within the errors of ~0.04 mag. Although a periodic signal is found for 1994 VK8, it appears to be an artefact, as the same frequency appears in the variation of sky brightness and is probably due to the sampling of the data. However, 1994 VK8 does exhibit a variation of ~0.5 mag. This would suggest either significant non-sphericity or a change in surface composition over a large area. In either case 1994 VK8 warrants further investigation.

Key words: techniques: photometric – comets: general.

1 INTRODUCTION

One of the most exciting recent discoveries in Solar system science has been that of a belt of objects beyond the orbit of Neptune. These objects are interesting for two reasons. First, they are thought to be the remnants of the accretion disc that formed the Solar system, as predicted by Edgeworth (1943) and Kuiper (1951). Secondly, they could be a reservoir for short-period comets (Duncan, Quinn & Tremaine 1988).

The brightest trans-Neptunian object found so far (1996 TL66) has a magnitude of 20.6 (Jewitt, Luu & Trujillo 1998). The extreme faintness of this new class of object means that spectroscopy can be very difficult. In fact, to date, spectra have been obtained for only two trans-Neptunian objects, 1996 TL66 and 1993 SC (Brown et al. 1997; Luu & Jewitt 1998). Both of these are amongst the brightest of the known objects, with red magnitudes of ~21 and ~22 respectively. Hence at present, to obtain any physical information about trans-Neptunian objects, we have to rely on photometry. Photometry also has the advantage that it can be carried out simultaneously with the astrometry essential for orbit determination.

There are two methods of obtaining physical information from photometry. The first involves observing an object a number of times with the same filter to obtain a rotation light curve, which in turn allows some estimate of shape or global albedo distribution. The second involves using more than one filter which will give an estimate of colour. The colour of an object will give information about its surface composition. As there will be a time lapse between observations using different filters, large-scale time variability must be ruled out before any serious examination of colour can be performed.

In a related programme (Fitzsimmons et al., in preparation), we have carried out a number of deep-field searches looking for new trans-Neptunian objects. In these searches we observed fields for approximately 4 h on two separate nights. Two of the fields observed were centred on the known trans-Neptunian objects 1994 VK8 and 1996 TP66. This paper describes our analysis of these data to search for photometric variability in these objects.

2 OBSERVATIONS

The observations were carried out on the nights of 1997 October 25 and 26, using the prime-focus wide-field camera on the 2.5-m Isaac Newton Telescope on La Palma. The detector consisted of a mosaic of four Loral 2048×2048 CCDs, each of which has a pixel size of 0.15 μm. At the prime focus this gives a pixel scale of 0.37 arcsec and a field size of $12.6 \times 12.6\,\mathrm{arcmin}^2$ for each CCD, with the object in question being centred on the CCD with the highest sensitivity. The observations were taken through a Harris *R* filter and calibrated using standard stars from Landolt (1992). A total of 33 10-min exposures of 1996 TP66 were taken over two nights. In the case of 1994 VK8 a total of 36 10-min exposures were taken, again over the two nights. All of the images were bias-subtracted and then flat-fielded using a median sum of a series of offset images of the twilight sky.

In order to search for magnitude variation in the trans-Neptunian objects, the instrumental magnitude was measured for a number of field stars. These were then used to calculate the change in magnitude of the trans-Neptunian object. The stars were chosen to be as close as possible on the image to the object in question in order to limit the effect of any flux calibration or flat-field errors. Also, all the stars chosen had to appear in all of the images. This is important, as the images of each object taken on the two nights were centred on different coordinates.

The method used to calculate the instrumental magnitudes for the trans-Neptunian objects and the field stars was profile fitting. This method was chosen because in many of the frames the object was close to either a star or a charge leak spike. The point spread function was calculated for each image, using the software routines found in DAOPHOT and ALLSTAR (Stetson 1992). In each case this was based on at least nine non-saturated stars. It is important to note that these were not the field stars mentioned above, as in order to create a good point spread function the stars have to be considerably brighter than the trans-Neptunian objects. This point spread function was used to calculate the instrumental magnitudes. The errors were calculated for the object and the field stars using the readout noise, the Poisson noise, the flat-fielding error and the interpolation error. The average error for all of the guide stars was taken and this was added to the error for the object itself.

Care has to be taken using the profile fitting method, as the trans-Neptunian objects are moving and are thus not strictly point sources. At the time of observation the faster of the two objects, 1996 TP66, moved only 0.75 arcsec in a 10-min observation. This is well within the seeing disc, which was unfortunately never less than 1.4 arcsec FWHM for any of the observations discussed here. When the point spread function was subtracted from the image no residuals were found, confirming the viability of this technique.

Table 1. The instrumental magnitude of 1996 TP66 relative to nine field stars. The time is UT date in 1997 October.

Date (UT)	Rel. mag.	Error
25.8747	−0.010	0.035
25.8840	−0.099	0.034
25.8934	−0.086	0.034
25.9043	−0.114	0.034
25.9161	−0.196	0.029
25.9255	−0.147	0.027
25.9348	−0.133	0.028
25.9441	−0.142	0.026
25.9534	−0.115	0.030
25.9627	−0.090	0.028
25.9720	−0.156	0.028
26.0093	−0.154	0.026
26.0186	−0.122	0.031
26.8934	−0.200	0.027
26.9027	−0.108	0.024
26.9118	−0.132	0.027
26.9214	−0.163	0.027
26.9306	−0.134	0.025
26.9398	−0.111	0.027
26.9491	−0.085	0.027
26.9585	−0.128	0.024
26.9678	−0.167	0.023
26.9770	−0.143	0.024
26.9862	−0.133	0.026
26.9954	−0.138	0.027
27.0047	−0.139	0.025
27.0138	−0.112	0.024
27.0231	−0.104	0.021
27.0331	−0.120	0.023

3 RESULTS AND ANALYSIS

On examining the images for 1996 TP66, three exposures had to be discarded because of mergers with a charge leak spike from a bright star on the first night, and another exposure was rejected as 1996 TP66 had merged with a star. In addition, two fields had satellite tracks which crossed some of the field stars. To work around this problem the results were analysed twice, once with all of the offending stars removed from the calculation for all the fields, and then by removing the offending frames. There was no significant variation in the results.

Table 1 gives the instrumental magnitude of 1996 TP66 relative to the mean of nine field stars. The time shown is the UT date in 1997 October at the start of the exposure. Table 2 shows the instrumental magnitude of 1994 VK8 relative to the mean of 19 field stars.

Absolute calibration of the fields was done using exposures of the standard fields SA 113 and 92 (Landolt 1992) obtained throughout both nights. This gave mean R-band magnitudes of 20.95 ± 0.05 and 23.42 ± 0.14 for 1996 TP66 and 1994 VK8 respectively. Not surprisingly, the errors in 1994 VK8 are much larger than those for 1996 TP66 as it is much fainter. The data are shown graphically in Figs 1 and 2.

For both of these objects we see that for the most part the variation in the relative magnitude is within the errors. However,

Table 2. The instrumental magnitude of 1994 VK8 relative to 19 field stars. The time is UT date in 1997 October.

Date (UT)	Rel. mag.	Error
26.0431	0.085	0.121
26.0524	0.295	0.145
26.0615	0.124	0.111
26.0708	0.450	0.160
26.0800	0.267	0.130
26.0891	0.817	0.231
26.0985	0.616	0.162
26.1078	0.574	0.132
26.1179	0.641	0.148
26.1272	0.328	0.135
26.1363	0.567	0.170
26.1455	0.410	0.122
26.1548	0.542	0.196
26.1641	0.466	0.187
26.1734	0.572	0.186
26.1826	0.684	0.253
26.1920	0.289	0.140
26.2012	0.452	0.166
27.0615	0.184	0.139
27.0735	0.194	0.141
27.0827	0.045	0.123
27.0920	0.255	0.128
27.1014	0.218	0.155
27.1107	0.311	0.177
27.1199	0.236	0.142
27.1293	0.272	0.150
27.1384	0.295	0.155
27.1477	0.163	0.132
27.1567	0.347	0.194
27.1660	0.797	0.217
27.1753	0.532	0.191
27.1845	0.980	0.283
27.1936	0.586	0.219
27.2029	1.039	0.293
27.2131	0.623	0.212
27.2224	0.936	0.282

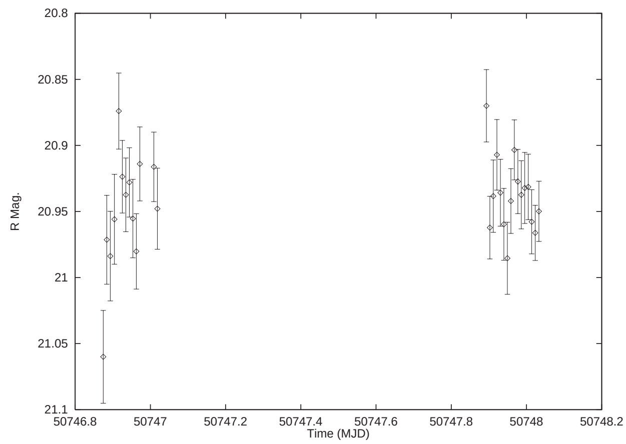

Figure 1. The variation of magnitude with time for 1996 TP66. The magnitude is scaled to the measured apparent magnitude of 1996 TP66 in the first field. For each exposure the magnitude is calculated relative to nine field stars. The *x*-axis gives the time in modified Julian date format.

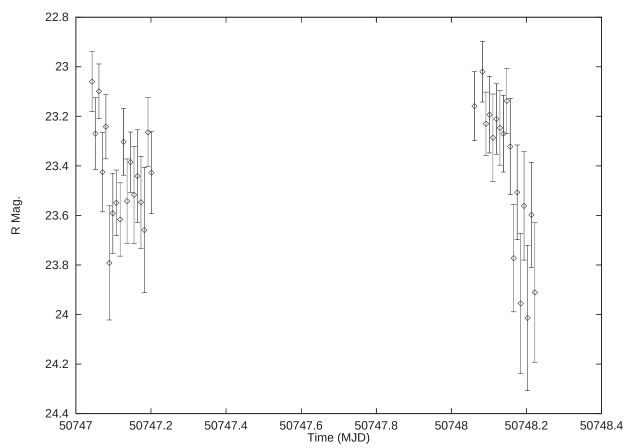

Figure 2. The variation of magnitude with time for 1994 VK8. The magnitude is scaled to the measured apparent magnitude of 1994 VK8 in the first field. For each exposure the magnitude is calculated relative to 19 field stars. The *x*-axis gives the time in modified Julian date format.

the last seven observations of 1994 VK8 stand out clearly. Although the change is not large compared with the errors, the fact that seven consecutive images show the same effect suggests that this is not simple random error. We do note that on the night in question the Moon rose at October 27.16 UT; however, we can find no reason why this should affect the relative magnitude. In order to test that any change in the magnitude of 1994 VK8 was not due to viewing conditions, we examined the instrumental magnitudes of the bright (~18 mag) stars used to calculate the point spread function. For every other observation of 1994 VK8 taken on the second night, the magnitude was calculated using aperture photometry and then corrected using the airmass and the mean extinction coefficient for La Palma (King 1985). With the exception of one observation, all were within 0.01 mag of the mean value. The one exception was 0.05 mag from the mean of the other observations and clearly this observation had undergone a large change in seeing. It is worth noting that this was not one of the observations that showed a significant change in the magnitude of 1994 VK8. We therefore conclude that the the changes in the magnitude of 1994 VK8 are not due to viewing conditions.

A better test for non-random variation than simple examination by eye is to test the null hypothesis using a chi-squared test. The null hypothesis is that there is no non-random variation. This was done for both of the objects using the following method. First the weighted mean magnitude was estimated using inverse variance weights for each of the observations. Then chi-squared was calculated:

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

where m is the number of observations, giving $m - 1$ degrees of freedom. Assuming that m is large enough and that the errors are Gaussian, the mean of the limiting distribution is $\langle \chi^2 \rangle = m - 1$ and the variance is $\sigma^2 = 2(m - 1)$. The initial results for the 29 observations of 1996 TP66 give a value for χ^2 of 41.8778 or 2σ above the mean. However, a closer examination shows that this is due to the influence of one wayward point; when this is removed the χ^2 value drops to 30.13 or 0.4σ above the mean. This strongly suggests that this point is a statistical aberration and the hypothesis that the variation is simply random can be accepted. The same method applied to the 36 observations of 1994 VK8 gives a value of χ^2 of 66.4 which is 3.8σ above the mean of the distribution. In this case, however, this cannot be reduced by removing a small number of wayward points. The largest value of χ^2 for a single magnitude measurement of 1994 VK8 was 2.22, whereas for 1996 TP66 it was 11.51. So there is therefore a strong case for rejecting the hypothesis that there is no non-random variation.

An examination by eye of Figs 1 and 2 shows no obvious periodicities. A more objective way of finding periodicities is the Lomb–Scargle method (Lomb 1976). This method produces a periodogram showing the relative strengths of the frequencies that are within the data. Scargle (1982) showed that this was exactly equivalent to least-squares fitting of sine waves to the data. Using the routine from Press et al. (1992), the light curves of both objects were examined for periodicities.

The Lomb–Scargle method applied to the data for 1996 TP66 produced the periodogram shown in Fig. 3(a). The frequency is in inverse days and the power relates to the probability that the corresponding frequency is simply random noise. The higher the power the lower the probability that the frequency is simply due to noise. It is important to note that this is the probability that the specific frequency is due to random noise, and does not mean that the probability that the data set contains a real signal is one minus this probability. The exact relationship between the power and probability depends on both the number and spacing of the data (see Press et al. 1992 for details).

1996 TP66 does not show any strong periodicity. The highest peak corresponds to a 1.96-h period which has a 54 per cent probability of being due to random variation. To test the significance of this periodicity a Fisher randomization test was carried out. This involved assigning the measured magnitudes to one of the times of observation chosen at random and then applying the Lomb–Scargle method to this data set. This was done 99 times and the results of these tests and the true results for 1996 TP66 are shown in Fig. 4(a). This figure clearly shows that the results for 1996 TP66 are well within the bounds of random variation.

The initial results for 1994 VK8 are very different. The periodogram shown in Fig. 3(b) gives the most probable period as 4.75 h with only a 3.4 per cent probability of it being due to

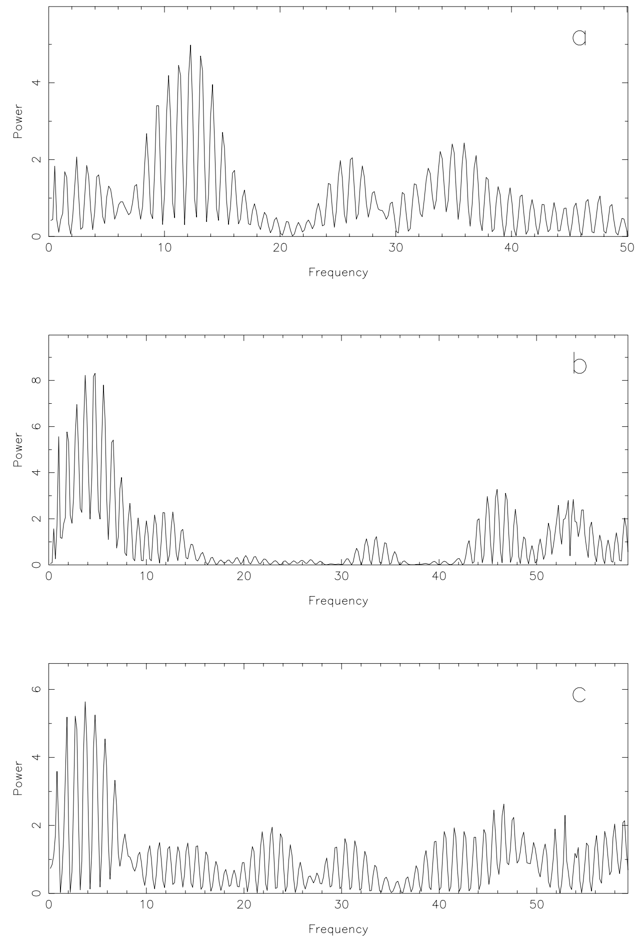

Figure 3. The periodograms for (a) 1996 TP66, (b) 1994 VK8 and (c) the mean of the field stars for 1994 VK8. The frequency is in d^{-1} and the power relates to the probability that the corresponding frequency is noise. The higher the power the lower the probability.

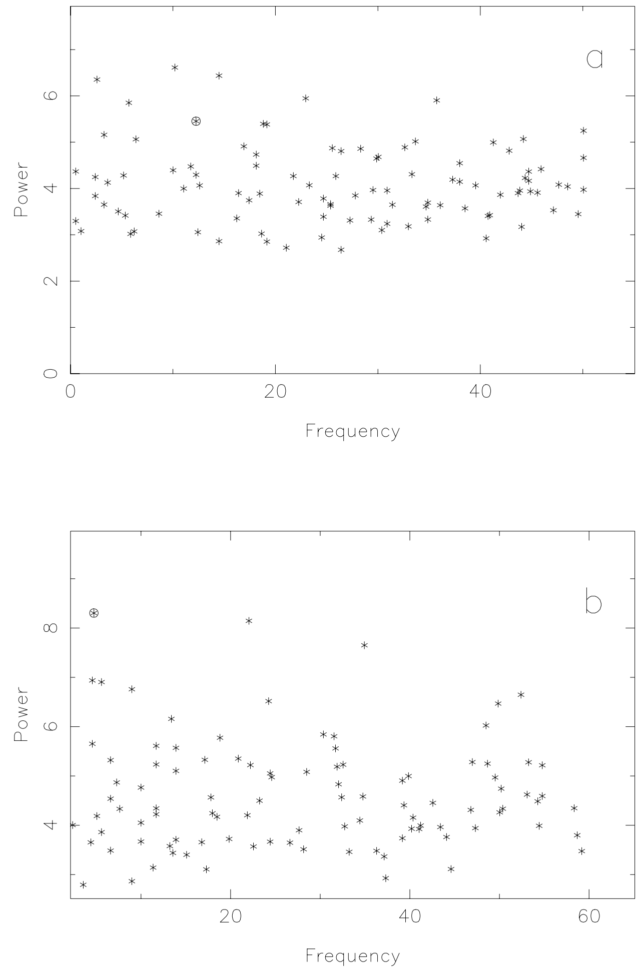

Figure 4. The results of Fisher randomizations for (a) 1996 TP66 and (b) 1994 VK8. For each of 99 random redistributions of the magnitude data, the most likely frequency and its corresponding power are marked by an asterisk. The true value for each object is marked by a circled asterisk.

random noise. However, the same period can be found in the variation of the reference stars and even in the sky counts, albeit with a higher probability that it is due to random noise. This can be seen in Fig. 3(c) which shows the periodogram for the mean of the field stars. This suggests strongly that the period found is not produced by a rotation of 1994 VK8 but is rather due to data sampling. The results of a Fisher randomization for 1994 VK8 are shown in Fig. 4(b). This figure clearly shows that similar powers to that found for 1994 VK8 can be produced by random variation.

4 CONCLUSIONS

We have examined the light curves of two trans-Neptunian objects. In the cases of 1996 TP66 and 1994 VK8 we find no frequency that has a higher probability than those of frequencies found in random noise. This of course in no way implies that these objects are not rotating; it simply means that any effect of rotation cannot be seen. Unfortunately, it is impossible to produce any limits on shape or albedo, as it is entirely possible that the line of sight was along the axis of rotation. There remains a significant change in the apparent brightness of 1994 VK8 of the order of 0.5 mag. This would imply either that 1994 VK8 has a significant non-sphericity, which would be unusual in an object with a diameter of hundreds of kilometres, or that there is significant variation in its surface composition. Both of these could indicate a collisional history. The variability means that this object would be a good candidate for further study with 4- and 8-m-class telescopes.

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