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Research Note

A historical light curve of 3C 345 and its periodic analysis

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Abstract. All data in the B band for quasar 3C 345 have been compiled into a light curve from twenty one publications, dating back to 1896; 1642 values are available. The light curve shows that 3C 345 is very active and exhibits very complicated non-sinusoidal variations. Using this data we have found a period of 10.1±0.8 years (or 21.8±1.5 years) for the outbursts in 3C 345. This value is in good agreement with the period of 11.4 year between outbursts found previously by Webb et al. (1988). Based on this period we can predict that the next outburst should be at its maximum around January 2002.

Key words: quasar: 3C 345

1. Introduction

More than 100 year of optical data exist for two extragalactic objects: 3C 273 and OJ 287 (Kidger et al. 1992). These objects are suitable for looking for periodic variations as several working groups have already done. Studies of these objects show that a wide range of periods exist but no enduring periods in the range from a few days to five years can be seen in the light curve of any analysed object (see Kidger et al. 1992). However, longer periodic variations remain an open question. To establish the reality of such long periods two prerequisites must be satisfied. First, the data sample must be of very long duration: at least six times the length of the periodicity being claimed would seem to be a valid criterion for demonstrating that any possible period is not simply a random event and probably has some physical significance. Second, the possible period should be of large amplitude and thus directly visible in the light curve; when the amplitude is low, much more than six cycles of the period will be necessary to demonstrate its reality.

3C 345 is a very active OVV quasar. In 1993, Schramm et al. (1993) constructed its historical optical light curve from sixteen publications and searched for periodicity using the Deeming (1975) Fourier analysis. They did not find any clear periodicity and interpreted the light curve as a slow secular decrease of the intensity with rapid, sporadic outbursts on top of it. However, their Fig. 3 shows that the variation is not sinusoidal, so the Deeming analysis is not the best method. In addition, they did not collect all published observations.

In this paper, we collect much more available observations and analyse it using the powerful Jurkevich V_m^2 test (Jurkevich 1971). First we list all references and give a general discussion on the light curve in Sect. 2. A detailed analysis using Jurkevich V_m^2 test is presented in Sect. 3. Our conclusions are given in Sect. 4.

2. Variability analysis of long-term light curves

We compile all available B-band optical data on 3C 345 from Sandage (1965), Kinman et al. (1968), Smyth & Wolstencroft (1970), Tritton & Selmes (1971), Lü (1972), Angione (1973), McGimsey et al. (1975), Barbieri et al. (1977), Pollock et al. (1979), Angione et al. (1981), Babadzhanyants et al. (1985), Smith et al. (1986), Webb et al. (1988), Kidger (1988), Xie et al. (1988), Kidger (1989), Kidger & Diego (1990), Sillanpää (1991). Vio et al. (1991), Webb et al. (1992), Dolan et al. (1994). The B-band data for 3C 345 consist of 1642 observations, dating from 1896. Because our purpose is to study the large-amplitude variations, we show no errors for the individual observations. The effect of errors on the periodicity analysis will be discussed in Sect 3. The B-band observations are used in this paper because there are more data available in the B-band than in other bands. We transform the photographic magnitude M_{pg} by the approximate relation M_B=M_{pg} $\pm$ 0.11 and the flux density, F, by M_B=[log4.49 x 10^6 -logF(mJy)]/0.4 (Sitko et al. 1985). The long-term light curve is shown in Fig. 1.

From Fig. 1 3C 345 is a very active object, with a range of variation of $\triangle B \geq 3.0$ mag. The source reached a maximum brightness of 15.15 mag in October 1982 and was brighter than 15.7, 15.4, and 15.22 mag on three occasions in 1937, 1948 (Ronald 1973) and 1971 (Webb 1988). Another possibly similar active period may exist in 1926 and 1959 but was not completely

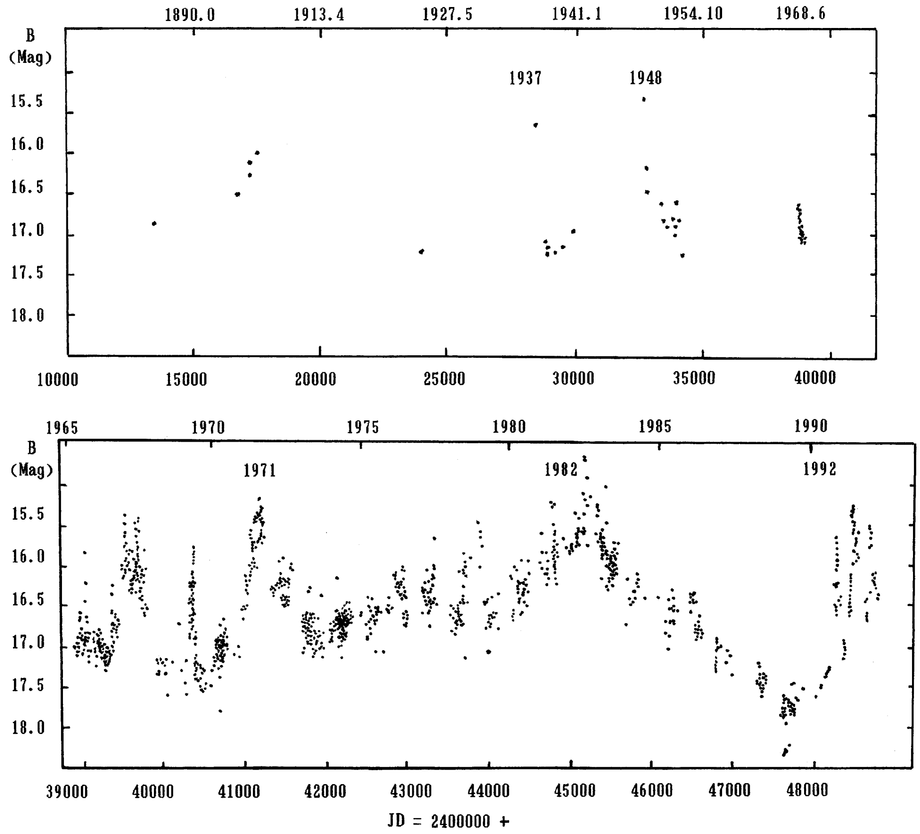

Fig. 1. The historical B-band light curve for3C 345, collected from the references listed in the text.

covered by observations. There are very few observations before 1954, but the light curve still shows violent activity even excluding the variation given by Ronald (1973). Regular optical photometric monitoring of 3C 345 has been carried out since 1965, showing four long-term phases of activity (time scale: one to a few year) until 1986 with short-term flares (time scale: several days to a few weeks) superimposed (Schramm et al. 1993). Since 1986, the optical flux had decreased almost monotonically (no flares were detected) and reached the faintest magnitude ever recorded ($B \geq 18.66$ in May 1990). A list of references concerning the optical variability of 3C 345 until 1988 can be found in Hewitt & Burbidge (1987, 1989). Some more recent references are given in this article.

In the following section, we use another powerful method, the Jurkevich V_m^2 method, to analyse the data of 3C 345, because this method is insensitive to the shape of the periodicity and long-term tendency of intensity,and is capable of finding multiple periods.

3. Periodic analysis and results

The two outbursts in 1971 and 1991, which are completely observed, have a very similar structure in their pulse amplitude, with a rapid decline from maximum. The outburst shape is very complex and not sinusoidal. In this case Fourier analysis (e.g. Deeming analysis) is not the best method for a period search. An alternative and powerful method is the Jurkevich V_m^2 test (Jurkevich 1971) which is insensitive to the mean shape of the light curve, less sensitive than Fourier analysis to uneven sampling and less inclined to generate spurious periodicities than Fourier analysis. We see this method as a complement to the better known Deeming analysis. The Jurkevich method has already been used in the context of BL Lac object in the case of ON 231 (Liu et al. 1996) and OJ 287 (Kidger et al. 1992).

The Jurkevich method is based on the expected mean square deviation. It tests a run of trial periods around which the data are folded. All data are assigned to m groups according to their phases around each trial period and the variance V_i for each group (bin), and the sums V_m^2 of all groups are computed. For a trial period equal to true one, if any, V_m^2 reaches its minimum. A "good" period will give a much reduced variance relative to those given by other "false" trial periods with almost constant values. No firm rule exists for assessing the significance of a minimum in the V_m^2 plot.

After analysing the results of the statistical F-test, we have a good guide in the fractional reduction of the variance, as in Kidger et al. (1992) and Liu et al. (1996),

$$f = (1 - V_m^2)/V_m^2$$

where V_m^2 is the normalized value. In the normalized plot, a value of V_m^2=1.0 implies that f=0 and hence there is no periodicity. The best period can be identified from the plot. In general, a value $f \geq 0.5$ generally implies that there is a very strong periodicity in the data, whilst $f \leq 0.25$ usually implies that the periodicity, if genuine, is a weak one. A further test is the relationship between the depth of the minimum and the noise in the

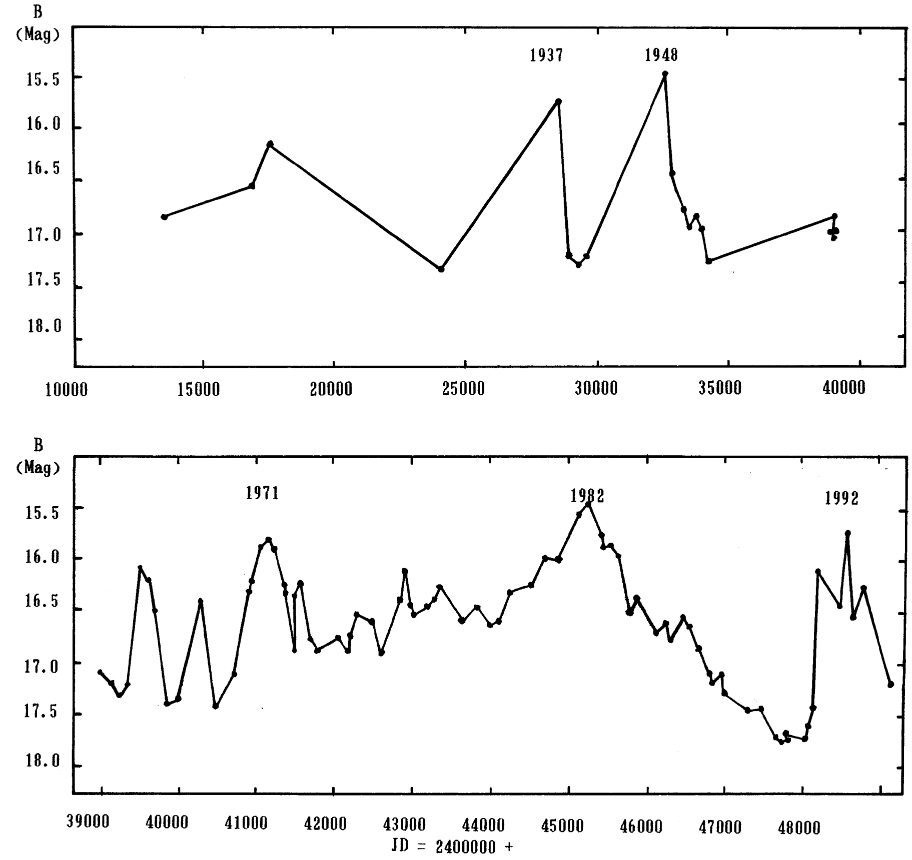

Fig. 2. One hundred day means of the historical B-band light curve of 3C 345.

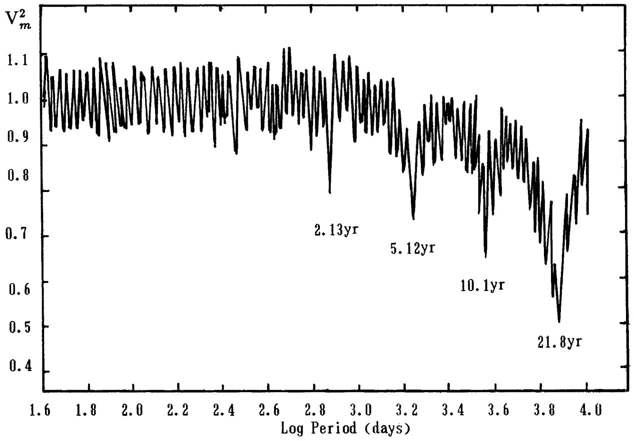

Fig. 3. The normalized Jurkevich test results for the period search for 3C 345, using the data shown in Fig. 1. The deep minimumm corresponds to a period of 21.8 yr

"flat" section of the V_m^2 curve close to the adopted period. If the absolute value of the relative change of the minimum to the "flat" section is larger than ten times the standard error of this "flat" section, the periodicity in the data can also be considered as significant, and the minimum as highly reliable. In the Jurkevich test, the parameter m can be modified: more groups give higher sensitivity, but fewer data points per group introduce a larger noise in the plot. So we analyse the data sample mainly using m=10, which gives us over 50 points per group. For comparing the results, we also use m=20 in some cases. During our analysing, we choose a very small interval between two successive trial periods, to search for short periods. The results of the run of values of V_m^2 is plotted against period in the same way that a Fourier analysis plots power against frequency.

The result of the analysis search with m=10 is shown in Fig. 3. A relatively broad minimum of V_m^2=0.500 in the V_m^2 plot clearly occurs at a trial period of 21.8 years, corresponding to a value of f=1.000. This period is consistent with the separation between the two well-observed outbursts during the interval from 1965 to 1993. A similar analysis with m=20 shows, that the V_m^2 plot with relatively larger noise, has also a minimum of V_m^2 =0.561 at about 20 years. Within the feature, we clearly see the fluctuations around the minimum which may be caused by large amplitude variability with a time scale as short as several weeks, which is definitely non-periodic. Its broad width may result from the period of 2.13 years discussed below and other adjacent periods, if present. To reduce the noise in the V_m^2 plot and to search for medially long periods, e.g. 2.13 years, we make an analysis for the data sample averaged over one day. The result shows noise is indeed less than in Fig. 3. The width of the minimum is also broad, but is much less than that in Fig. 3. and its depth is larger. The analysis with m=20 and m=5 shows the same effects.

In Fig. 3, there is also another minimum at a period of P=10.1±0.8 years. It is not the deepest one, but it is so sig-

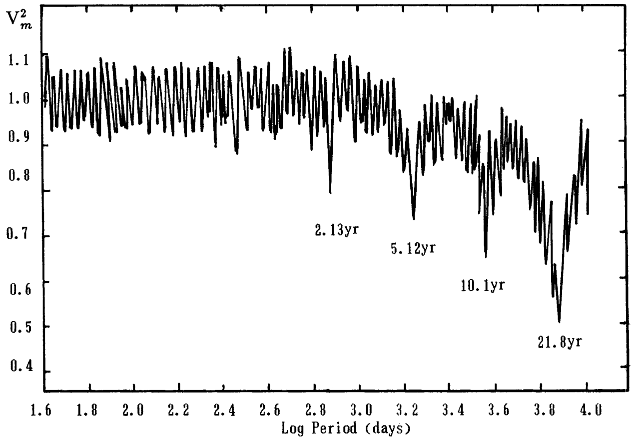

Fig. 4. As Fig. 2 for the 100-day means. The deepest minimum corresponds to a period of 20.8 yr

nificant with V_m^2=0.650 (in Fig. 3) that we cannot doubt its reality at all. We have considered the half width at half minimum as the "formal" error (cf. Jurkevich 1971) to derive all effects on the precision, including random variations in the exact interval between outbursts, poor coverage of some of the early outbursts and the larger error in some of the early photographic photometry, the uncertainty of observed data estimated from the figures in the literatures, random variations in intensity, and the changing width of the outburst structure. The error caused by the conversion from photographic to photoelectric values and by the measurement with different diaphragms are considered in this analysis as random variations in the intensity. They would reduce the depth of minima and therefore the significance of the periodicity found. These error also increase the "formal" error, and this effect has been taken into account. The broad width of the minima may also result from the broad structures of the bursts, the drift of the real period and the effect of adjacent periods, if present.

Apart from the periods mentioned above, in our detailed V_m^2 plot (Fig. 3) two very interesting and significant minima indicate the existence of other periods of P1=2.13 years, P2=5.12 year (∼2P1). Of all the periods, the one of P1=2.13 year is the shortest and most significant and is the fundamental one. It has a very deep structure of V_m^2=0.78 in Fig. 3 (f=0.282, larger than 0.25 and less than 0.5). In fact, the relations among these period imply that the period is indeed existent and the outbursts repeat themselves with almost the same behaviour from 1896 to 1993. This can also clearly be seen in Fig. 2. Such short periods far broaden the structures of the minima in the V_m^2 plot at periods of 10.1 and 20.8 years (see Fig. 4. V_m^2=0.76; f=0.32).

To compensate for the heavy weighting of recent data, we use the 100-day averaged light curve. This interval is long enough compared to the possible periods of 10.1 years and 20.8 years (∼2P; P=10.1 year) and unlikely to prevent a distribution of the long term variation findings. The result of the Jurkevich test shows a larger noise due to fewer points in every group and flickering effects in the early epochs. The minima at periods of 5.12 years and 10.1 years are also clear (Fig. 4).

4. Conclusion

We have assembled the historical light curve of the OVV quasar 3C 345 and searched for its possible periodicity using the Jurkevich method. Our results indicate that this object is very active and probable has two basic steady behaviours in the intensity variations. The first is periodic with the periods of 10.1 ± 0.8 years and 21.8 ± 1.5 years. The former is half the latter, and they are in fact the same. So, we only discuss the period of 10.1 years, though it is not the one corresponding to the deepest minimum. This is due to the following reasons: (1) the period of 21.8 years is just two times as long, and (2) for the period of 10,1 years all outbursts predicted to occur in 1949, 1971, 1982, 1991.11, are clearly seen at Fig. 1 and Fig. 2, although the outburst in 1949 is not observed completely.

The second is the 11.4 year period which Webb et al. (1988) found in the light curve of 3C 345 successfully predicted the 1991 outburst of this object (Kidger & Takalo 1990) and thus remains a possible genuine periodicity. We have found a period of 10.1 ± 0.8 years for the outbursts in 3C 345. This value is in good agreement with the period of 11.4 years.

Regarding the 10.1 years period, we tentatively provide below a theoretical explanation in the framework of the thin accretion disk theory. Several processes can cause limit cycles: (1) binary black hole, which is used by Sillanpää et al. (1988) to explain the periodic variations in BL Lac object OJ 287, (2) (global) radial oscillations (acoustic waves), with which Honma et al. (1992) explain the short-term periodic variability in NGC 6814, (3) thermal and viscous instability that gives rise to thermal limit cycles (S-shape), which was discussed by many authors (e.g. Meyer and Meyer-Hofmeister 1981, 1984, Horiuchi & Kato 1990), and (4) irradiation self-excited oscillations (e.g. Meyer and Meyer-Hofmeister 1990). The basic characteristics of the thermal limit cycles depend strongly on the viscosity parameter α, central black hole mass $M_6 = M/10^6 M_\odot$, accretion rate $\dot{M}$ and generalized stress tensor parameter μ (cf. Wallinder et al. 1992). However, the time duration of the bursts is almost independent of both μ and $\dot{M}$, and may be written empirically as

$$t_{burst} \doteq 4.52\alpha_{0.1}^{-0.62}M_6^{1.37}yrs,$$

when μ=0.5 and $\dot{M} \doteq 0.2\dot{M}_c$, where $\dot{M}_c = M_E/\epsilon$, M_E being the Eddington accretion rate and ϵ the accretion efficiency (Honma et al. 1991). The time interval between subsequent bursts depends strongly on μ, but weakly on $\dot{M}$. As both the origin and the properties of the presumed viscosity in accretion disks are unknown at present, its hydro-magnetic origin is one of the options. Horiuchi & Kato (1990) suggest that $\mu \doteq 0.5$ may hold if the escape rate of the magnetic field is low. With these values of the parameters, the thermal limit cycle time t_{cyc} (period) should be of the order of $2t_{burst}$, i.e.

$$t_{cyc} \doteq 9.0\alpha_{0.1}^{-0.62}M_6^{1.37}yrs.$$

If we adopt, for 3C 345, the typical values of α=0.1, μ=0.5 and $\dot{M} \doteq 0.2\dot{M}_c$ and search the central black hole mass M using a period of 10.1 years, we find an estimated mass of $M \doteq 1.09 \times 10^6 M_\odot$.

We have constructed the historical light curve of 3C 345 and found that it is very complicated and consists of a set of outbursts. The light curve consists of three different basic variations; the first one is secular, the second is periodic with a period of 10.1 ± 0.8 years,and the last one is sporadic and superposes on the other two variations. Based on this result, we can predict that the next outburst should reach its peak brightness during January 2002.

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