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A Periodicity Analysis of the Optical Variations of 3C 273 †⋆

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Abstract The authors have compiled measurements of ∼ 110 years in the B-band of the quasar 3C 273 and used this database to search for periodicity signals in the optical light curve. Two different methods were applied: the Jurkevich method and the discrete correlation function (DCF) method. They revealed the existence of periods of 2.0, (13.65 ± 0.20) and (22.50 ± 0.20) yr in the source variability. Possible origin of such a variability is discussed.

Key words: active galactic nucleus (AGN)— quasar 3C 273—variability—periodicity

1. INTRODUCTION

The nature of the central regions of quasars and other Active Galactic Nuclei (AGNs) is still an open problem. The study of AGN optical variability can yield valuable information on the mechanisms operating in these sources, with important implications for quasar modeling

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(see, for instance, Fan et al. 1998a). Some particular objects have been claimed to display periodicity in their light curves over a variety of time scales (e.g. Jurkevich 1971; Sillanpaa et al. 1988; Kidger et al. 1992; Babadzhanyants & Belokon 1991; Fan et al. 1998a, 1999a,b, and references therein), but, in general, clear identification of periodic behaviour has been very elusive due to complexity of the optical light curve and the lack of database large enough for an adequate sampling over a large time span.

The quasar 3C 273, the first to be identified as an extragalactic source, has been extensively studied for more than 35 yr. It is variable at all wavelengths (Curvoisier et al., 1988, 1990; Curvoisier, 1991; von Montigny et al., 1997; and references therein). Recently, Curvoisier (1998) reviewed the properties of the object. In the optical bands, this source has been monitored since 1887, thus amounts to one of the most complete historical records for an extragalactic source available today.

There has been intense interest in searching for possible periodicity in the historical light curve of 3C 273. Different authors have claimed the identification of different recurrent patterns in different subsamples of the variability data. Among others, there have been reports of a (9±1.2) yr period (Ozernoi & Chertoprud, 1966, Ozernoi, Gudzenko and Chertoprud, 1977), both a 13.4 yr and an 18.3 yr period (Babadzhanyants & Belokon, 1991), and some weak evidence for a period of 16 yr (Kunkel, 1967), which is also found in the radio band using VLBI data (Abraham & Romero, 1999).

In this paper, we shall investigate possible presence of periodicity in the entire historical (1887-1996) light curve using two different, well-proven methods. The paper has been arranged as follows: in Section 2 we present the methods used to search for the periodicities, along with the results obtained from their applications; in Section 3 we discuss the possible origin of the periodic variability in this quasar. In Section 4 we draw our conclusions.

2. PERIODICITY ANALYSIS, METHODS, AND RESULTS

2.1 Light Curves

As we mentioned in the Introduction, there exist optical B measurements of about 110 years available for 3C 273. They can be compiled from the following sources in the literature: Angione et al. (1981), Angione & Smith (1985), Barbieri & Erculiani (1968), Burkhead (1968, 1969, 1980), Burkhead & Lee (1970), Burkhead & Stein (1971), Burkhead & Rettic (1972), Burkhead & Hill (1975), Corso et al. (1986, 1988), Cutri et al. (1985), Hamuy et al. (1987), O'Dell et al. (1978a,b), Okyudo (1993), Sandage (1966), Schaefer (1980), Sillanpaa et al. (1988, 1991), Smith et al. (1987), Sitko et al. (1982), Takalo (1982), Takalo et al. (1992), and Tritton Selmes (1971). The resulting light curve is shown in Fig. 1.

2.2 Periodicity

The photometric observations of 3C 273 clearly indicate that the source is extremely variable. Whether this variability presents one or more periodic contributions has remained controversial: different periodicities have been claimed in the light curve even when the same data set is used (see Angione & Smith, 1985 for a discussion). New measurements have become recently available, allowing a better analysis of the full data set, and encouraging further studies with appropriate tests. We shall use two methods for the periodicity analyses below, namely, the Jurkevich method and the DCF method.

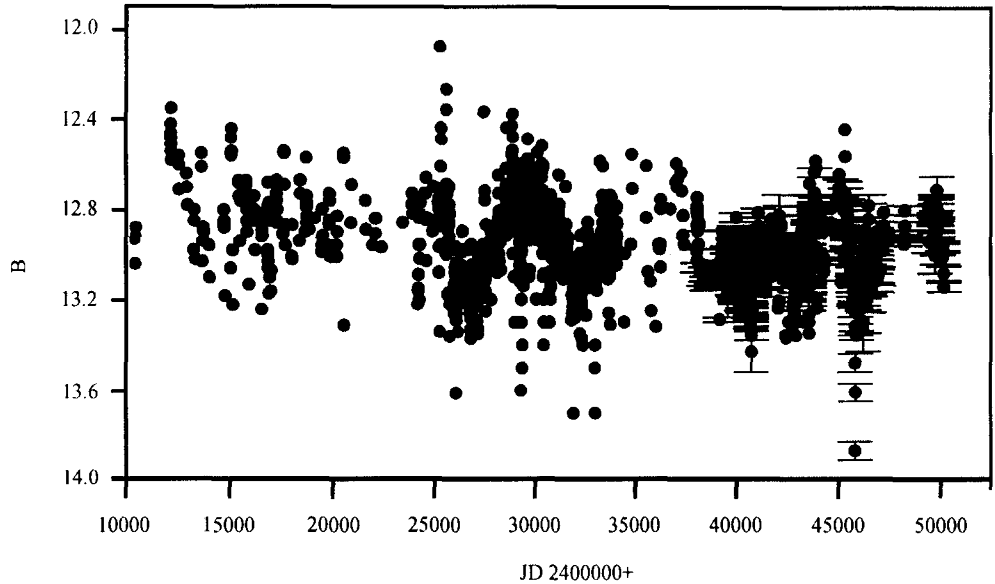

Fig. 1 Optical B light curve of 3C 273

2.2.1 Jurkevich Method

The Jurkevich method (Jurkevich, 1971, also see Fan et al., 1998a; Fan, 1999) is based on the expected mean square deviation and it is less liable to generate spurious periodicity than the Fourier analysis used by other authors (e.g. Babadzhanyants & Belokon, 1991). It tests a run of trial periods around which the data are folded. All data are assigned to m groups according to their phases in each trial period. The variance V_i^2 for each group and the sum V_m^2 of all groups are then computed. If a trial period equals the true one, then V_m^2 reaches its minimum. So, a "good" period will give a much smaller variance than the almost constant value given by the "false" trial periods. A further test is the relationship between the depth of the minimum and the noise in the "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 large enough as compared with the standard error of this "flat" section (say, five times), the periodicity in the data can be considered as significant and the minimum as highly reliable (see Kidger et al., 1992; Fan et al., 1998a; Fan, 1999). This can be adapted to discuss spike-like minima.

We have applied Jurkevich's method to the B-measurements of 3C 273, with the results shown in Fig. 2 ($m = 10$). This figure shows several minima corresponding to trial periods of 2, (13.65±0.2), (22.5 ± 0.2), (26.65 ± 0.15), and (43 ± 2.0) yr. The 2.0 yr spike-like minimum is eight times deeper than the noise level. There are also minima corresponding to 4.5, 7.5, and 9.0 yr. A possible period of 18.22 yr, which is consistent with the period of 18.3 yr found by Babadzhanyants & Belokon (1991), also shows up with a feature, but it is much narrower and weaker than the ~ 13 yr and the ~ 22 yr peaks. There is no sign of the 16 yr period observed in the VLBI radio data.

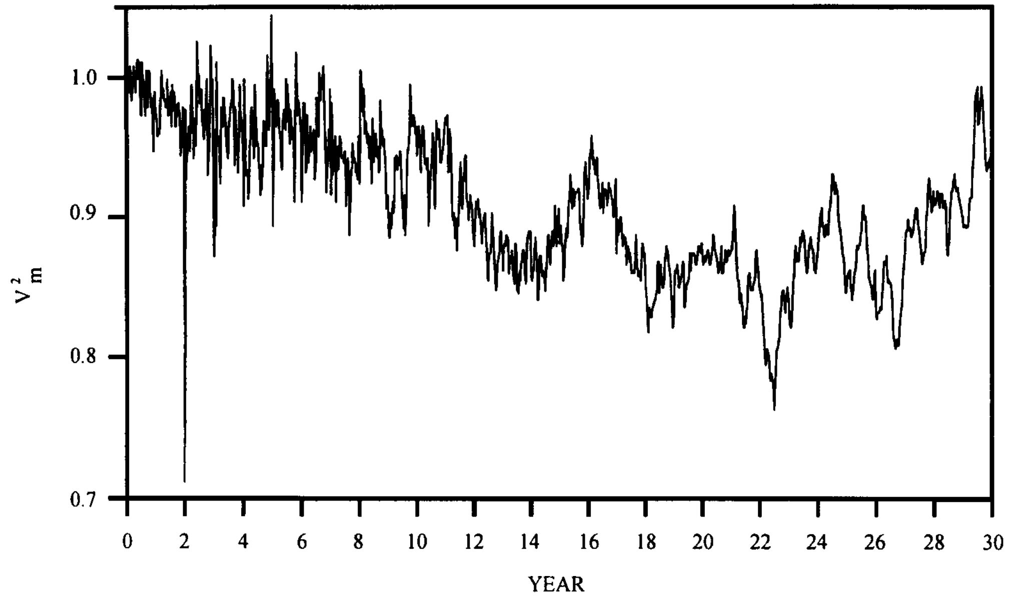

Fig. 2 Plot of V_m^2 vs trial period, P

It is interesting to note that the period 26.65 yr is twice as long as the period of 13.65 yr. We think they both have the same origin, one being a harmonic of the former. The same thing happens to the peaks at 43 ± 2.0 yr and 22.5 ± 0.2 yr, which are surely the same period.

2.2.2 The DCF Method

The DCF (Discrete Correlation Function) method is intended for correlation analysis between two data sets. It is described in detail by Edelson & Krolik (1988) (also see Fan et al., 1998b). This method indicates and evaluates the correlation between two variable temporal series with a time lag, and can be applied to the periodicity analysis of one temporal data set. If there is a period, P, in the light curve, then the DCF should show clearly whether the data set is correlated with itself with time lags of $\tau = 0$ and $\tau = P$. We have implemented the method as follows.

First, we calculated the set of unbinned correlation (UDCF) between data points in the two data streams a and b, i.e.

$$UDCF_{ij} = \frac{(a_i - \bar{a}) \times (b_j - \bar{b})}{\sqrt{\sigma_a^2 \times \sigma_b^2}}, \tag{1}$$

where a_i and b_j are points in the data sets, $\bar{a}$ and $\bar{b}$ are the average values of the data sets, and σ_a and σ_b are the corresponding standard deviations. Next, we averaged the points sharing the same time lag by binning the $UDCF_{ij}$ in suitably sized time-bins in order to get the DCF for each time lag τ:

$$DCF(\tau) = \frac{1}{M} \sum UDCF_{ij}(\tau), \tag{2}$$

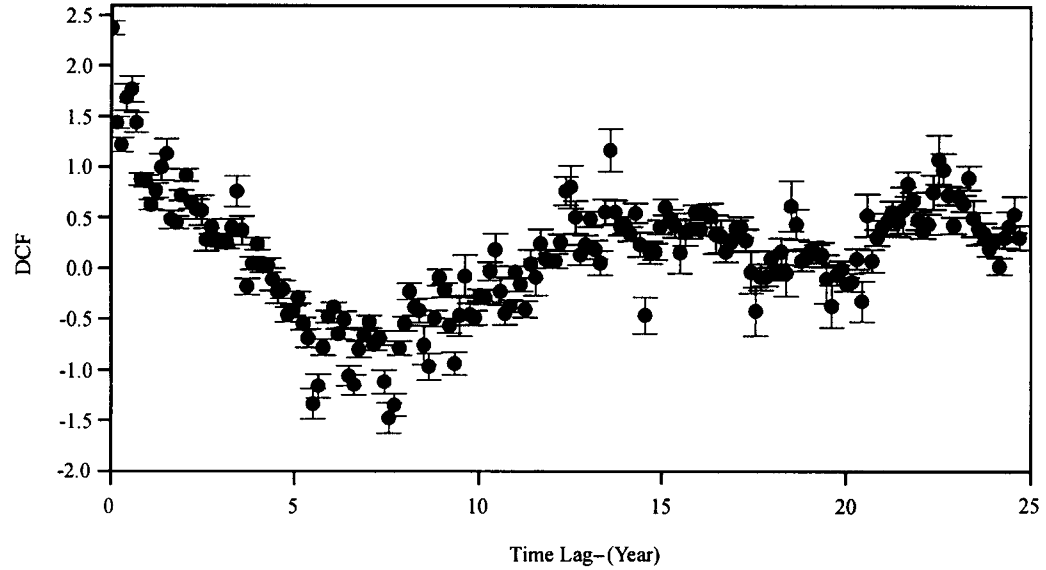

Fig. 3 DCF diagram for the B data

where M is the total number of pairs. The standard error for each bin is

$$\sigma(\tau) = \frac{1}{M-1}\left\{\sum [UDCF_{ij} - DCF(\tau)]^2\right\}^{0.5} . \tag{3}$$

The resulting DCF is shown in Fig. 3. Correlations are found at time lags of (1.0±0.5), (2.0±0.2), (13.49 ± 0.07) and (22.25 ± 1.02) yr, which are quite consistent with the periods, 2.0, 13.65±0.2, 22.5±0.20 yr, found with the Jurkevich method (Fig. 2). There should be periods of 2.0, ~13.5, and ~22.5 yr in the light curve in this sense.

3. DISCUSSION

The period searching in the B band light curve using two different methods gives almost the same results for the periods of 2.0 yr, ~13.5 yr, and 22.5 yr. The 13.5 yr period is also found by by Babadzhanyants & Belokon (1991) using Fourier analysis and is certainly real and not an artifact of the analysis technique. The above periods have been proved to be significant from an error analysis using the Monte Carlo method (see Lin, 1999).

Some models have been proposed to explain long-term periodic variations in AGNs (e.g. Sillanpaa et al., 1988; Meyer & Meyer-Hofmeister, 1984; Horiuchi & Kato, 1990; Abraham & Romero, 1999). Recurrent optical variations over time scales of years could be the effect of instabilities in the accretion disk usually thought to surround the central supermassive black hole in an AGN. In particular, thermal instabilities of slim disks could lead to burst-like oscillations. Homma et al. (1991) have performed numerical simulations to probe the stability of optically thick, slim transonic accretion disk models with radial-azimuthal component of the viscous stress tensor of the form $\alpha\beta^q P$, where α and q are constants, P is the pressure, and β the ratio of the gas to the total pressure. They have found that for $q = 0$ and reasonable values of the accretion rate in the cold (outer) and hot (inner) disk regions (0.1 and 2.0 times the critical rate, respectively), the disk exhibits burst-like oscillations with a recurrence time of

$$t_{\rm recur} \sim 172 \left(\frac{\alpha}{0.1}\right)^{-0.64} M_6^{1.36} \ \ {\rm yr}, \tag{4}$$

where $M_6 = M/10^6 M_\odot$ is the mass of the central black hole. If we identify this recurrence time with the variability period in the source frame $P^{\rm obs}/(1+z)$, we will get a mass for the hole of

$$M_6^{1.36} \sim 5.8 \times 10^{-3} \frac{P^{\rm obs}}{1+z} \left(\frac{\alpha}{0.1}\right)^{0.64} . \tag{5}$$

Since $\alpha \leq 1$, this implies an upper limit for the black hole mass of

$$M_6^{1.36} \leq 2.5 \times 10^{-2} \frac{P^{\rm obs}}{1+z}, \tag{6}$$

which yields for the period of 13.5 yr a mass of $\sim 0.4 M_6$. Such a mass is too small for 3C 273. The minimum black hole mass implied by the Eddington-limited accretion estimated from gamma-ray observations in the Klein-Nishima regime is about $10^8\ M_\odot$ (Dermer & Gehrels, 1995), and the ultraviolet excess in the spectrum can be fitted just by optically thick disk models which require at least masses of $5 \times 10^8\ M_\odot$ (Malkan, 1983). The actual mass is estimated, by different methods, to be of the order of $10^{10}\ M_\odot$ (Kafatos, 1980, Romero et al., 2000). We conclude, therefore, that the origin of the observed periodic behaviour of 3C 273 in optical wavelengths with time scales of a few years is not produced by thermal instabilities.

A perhaps more promising approach to account for the observed optical periodicity is to consider the effect of external perturbations to the accretion disk. Recently, Abraham & Romero (1999) have shown that the position angles, velocities, and formation epochs of different superluminal components in 3C 273 are consistent with a precessing inner jet. The jet seems to precess with a constant angular velocity, defining a cone with an opening angle of $\sim 3.9°$. It takes 16 years to complete a cycle in the observer's frame. The precession produces a modulation in the Doppler factor of the relativistic flow, but this does not necessarily imply a strong 16 yr variability period at optical frequencies because this emission is dominated by the disk-originated big blue bump (except when strong shocks are formed in the jet producing peaks at all optically thin frequencies). Romero et al. (2000) propose that the precession is driven by Newtonian torque of a companion black hole. In such a scenario, several possibilities can explain the presence of the optical periodicity (Valtaoja, 1997). Now, we mention only three of them.

Tidal disk perturbations. The secondary does not cross the accretion disk of the main black hole, but the perihelion passage produces tidal perturbations that lead to an enhanced accretion rate. The 13.5 yr period would correspond to the increase of the jet flow and its luminosity at each passage. A few years later a strong shock is formed farther in the jet and follows a helical pattern produced by the jet precession, yielding periodic flux variability with a 22.5 yr period (see Roland et al., 1994). The perturbation in the disk propagates as a spiral shock that breaks up and reforms the yielded short-lived "hot spots" on the disk surface (Chakrabarti & Wiita, 1993). Typical timescale over which these spots form and decay would correspond within this scenario to the 2 yr period.

Single penetration of the accretion disk. The secondary crosses the disk of the primary once per orbit. This produces a periodic excess of thermal emission at the same orbital period (say, 13.5 yr). The interaction gives rise to a strong perturbation that propagates inwards in the disk leading to enhanced jet emission and shock formation at later times. Once again, the spiral shock fragments lead to periodic flickering (the 2-yr period).

Double disk penetration. In this scenario the secondary black hole crosses twice the disk. We can attribute the shorter period to these events on the hypothesis that the secondary has a nearly circular orbit of about 4 years in the observer's frame. The longer (and stronger) periods then could correspond to enhanced jet activity where the emission is strongly beamed. The exact physical processes involved in the transformation of the accreting flow into the relativistic jet, as well as the corresponding time lags, are far from clear. Fragmentation of the spiral perturbation shock would lead to even faster flickering, which has been reported by several authors for 3C 273.

The optical information alone cannot be used to choose among the above mentioned scenarios. Models involving more than two black holes are of course also possible and cannot be ruled out on *a priori* grounds. A more detailed analysis, using gamma and radio data, will be presented elsewhere (Romero et al., 2000). However, we think that an external periodic perturbation seems to be the more plausible source of the periodicities present in the optical light curve. Additional support could be provided by the evidence of a recent galaxy merger in the host galaxy.

4. CONCLUSIONS

We have compiled all optical B-measurements available for 3C 273 and used them to search for periodicity by two different methods. Clear periods of 2, ∼ 13.5, and ∼22.5 yr have been found. In addition, there are signatures of possible periods of 4.5, 7.5, and 9 yr. The time scales of the periodic variations do not seem to agree with typical oscillations produced by slim disk instabilities. Instead, the observed behaviour can be expected if a central massive black hole is tidally perturbed by an orbiting companion with a smaller mass.

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