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# Periodic Variations of the Jet Flow Lorentz Factor in 3C 273

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**Abstract** 3C 273 has been observed with VLBI for more than 30 years. The entire data have shown that the position angle of the superluminal knots ejected from the core varies periodically with a period of ∼15 years. Moreover, their apparent velocity observed during the period 1963 – 1997 has systematically decreased by a factor of $\gtrsim 2$. These remarkable properties are explained in terms of a precessing jet model, in which the ejection Lorentz factor of the superluminal knots has been decreasing during the last thirty years and has superposed on it a short-term (∼5 year) oscillation. The periodic variations derived by the model-fitting are compared with the variations in the optical flux density. Binary black hole models are briefly discussed to show possible relations of the observed periods to the periods involved in a binary system (orbital motion, spin of black hole, accretion-disk rotation and Newtonian-driven precession etc.).

**Key words:** Galaxies: jets – quasars: individual: 3C 273 – Galaxies: nuclei – Radio continuum: galaxies – Radiation mechanisms: nonthermal

## 1 INTRODUCTION

The quasar 3C 273 ($z = 0.158$) is one of the classical radio sources showing apparent superluminal motion (Zensus et al. 1990, 1997). It has a large-scale jet ($\sim 20''$ of length, 3C 273A) emitting at radio, optical and X-ray bands. It has been suggested that its compact source (3C 273B) is a mini-blazar, undergoing strong and rapid variations in radio, optical-UV, X-ray and $\gamma$-ray bands at various time scales (from hours to years, Courvoisier et al. 1998, Türler

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et al. 1999, Stevens et al. 1998, Von Montigny et al. 1997). The most extensive data sets of 3C 273 are in the optical bands, which began in 1887 (Badbadzhanyants & Belokon 1992). The object has been observed with VLBI for more than thirty years. Thanks to these, the investigation of the variations in its VLBI properties and of their relation to the nature of the central engine is now possible (Krichbaum et al. 2000).

Babadzhanyants & Belokon (1992) used the optical (*B*-band) data sets to search for possible periodic variations. They found two main periods: 307 days and 13.4 years[1] . They suggested that both of these periods are connected to VLBI activities: the 307 day period to the ejection rate of superluminal knots ($\sim 1$ yr$^{-1}$.), while the apparent velocity of the VLBI components $C_2$–$C_9$[2] during the period 1963–1990 to the phase of the optical activity.

Abraham & Romero (1999) analysed the VLBI data over the period 1963–1988 and found that the position angle of the superluminal knots $C_2$–$C_9$ and their apparent velocity varied periodically with a period of $\sim$ 16 years. They suggested that the periodic variations are due to precession of the jet. In their precessing model, the ejection Lorentz factor is assumed to be constant for all the superluminal knots, implying that the variation of the apparent velocity observed in different knots is only due to different viewing angles.

Periodicities found in optical and radio variations are important for understanding the physics of active galactic nuclei. For example, Babadzhanyants et al. (1992) suggested that the 13.4 year period of the optical variations might be related to the orbital period of the supermassive binary system in the core of 3C 273. Similarly, in the optical light curve of the BL Lac object OJ 287 ($\sim$ 100 year time coverage), Sillanpää et al. (1988, 1996) found a 11.65 year period and suggested that this period is caused by the orbital motion of the binary black hole system. The binary black hole model, proposed by Sundelius et al. (1997), also see Lehto et al. (1996), Valtonen et al. (1999), can accurately determine the parameters of the binary system and has successfully predicted four optical events in OJ 287. Britzen et al. (2001) presented a binary black hole model and used it to explain the observed optical variations and the kinematics of jet components in QSO 0420–014.

In this paper we discuss the periodicities which have been found, and then investigate their relations to the binary black hole system in the core of 3C 273. Throughout the paper we assume $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$ for the Hubble constant and $q_0 = 0.5$ for the deceleration parameter.

## 2 OBSERVATIONAL RESULTS

Recently, Krichbaum et al. (2000) published the results obtained from an analysis of VLBI observations at 43 and 86 GHz for the period 1992–1997. Combining with earlier observational data, a much more detailed picture of the jet kinematics during the period 1963–1997 can be obtained. In Table 1 we list the ejection epoch, position angle and apparent velocity for all the superluminal components $C_2$–$C_{17}$. The data for components $C_2$–$C_5$ are taken from Abraham & Romero (1999) and for components $C_6$–$C_{17}$, from Krichbaum et al. (2000), except the value for the apparent velocity of component $C_9$, which is adopted from Bååth et al. (1991) and Krichbaum et al. (1990).

From a comparison of the ejection times of the superluminal components with the flux density variations at cm and mm wavelengths, the relation between the ejection of the compo-

[1] Here we use the time scales in the observer's frame, which can be transformed to the time scales in the source frame by dividing by a factor of (1+z).

[2] The designation of the VLBI components follows Krichbaum et al. (1990)

nents and the mm-cm outbursts is further established. The position angles of the components are shown in Fig. 1 as filled circles. It can be seen that since 1963 the position angle of the components have undergone a periodic variation between $\sim 225°$ and $\sim 265°$. This confirms the finding of Abraham & Romero (1999).

**Table 1** The Ejection Epoch, Position Angle and Apparent Velocity of the Superluminal Knots Observed During 1963–1997

| VLBI knots | Ejection epoch | Position angle (°) | $V_{\rm app}/c$ |
|---|---|---|---|
| $C_2$ | $1963.0 \pm 1.0$ | $230 \pm 5$ | $7.7 \pm 1.0$ |
| $C_3$ | $1970.2 \pm 1.0$ | $242 \pm 3$ | $5.2 \pm 0.3$ |
| $C_4$ | $1976.4 \pm 1.0$ | $262 \pm 4$ | $6.6 \pm 1.0$ |
| $C_5$ | $1978.6 \pm 1.0$ | $245 \pm 4$ | $7.7 \pm 0.5$ |
| $C_6$ | $1980.0 \pm 0.3$ | $226 \pm 10$ | $7.1 \pm 0.3$ |
| $C_7$ | $1982.4 \pm 0.4$ | $225 \pm 10$ | $4.8 \pm 0.1$ |
| $C_8$ | $1984.6 \pm 0.2$ | $236 \pm 10$ | $5.1 \pm 0.1$ |
| $C_9$ | $1988.0 \pm 0.2$ | $253 \pm 10$ | $5.4 \pm 0.2$ |
| $C_{10}$ | $1988.3 \pm 0.5$ | $257 \pm 15$ | $5.1 \pm 0.1$ |
| $C_{11}$ | $1989.8 \pm 0.3$ | $261 \pm 37$ | $4.0 \pm 0.3$ |
| $C_{12}$ | $1991.0 \pm 0.2$ | $241 \pm 15$ | $3.9 \pm 0.2$ |
| $C_{13}$ | $1993.0 \pm 0.2$ | $232 \pm 10$ | $5.2 \pm 0.3$ |
| $C_{14}$ | $1994.8 \pm 0.2$ | $232 \pm 10$ | $5.0 \pm 0.2$ |
| $C_{15}$ | $1995.4 \pm 0.4$ | $238 \pm 10$ | $3.1 \pm 0.7$ |
| $C_{16}$ | $1995.8 \pm 0.2$ | $238 \pm 15$ | $2.6 \pm 0.4$ |
| $C_{17}$ | $1996.0 \pm 0.3$ | $238 \pm 27$ | $>1.3 \pm 0.3$ |

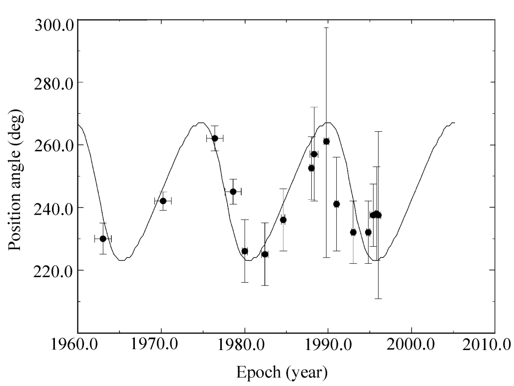


Fig. 1 The observed periodic variation of the position angle of the superluminal knots (filled circles) during the period 1963–1997. The solid curve represents the model-fitting by the proposed precessing jet model. See text.

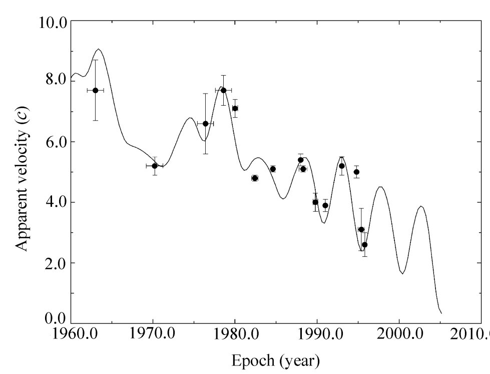


Fig. 2 The observed variation of the apparent velocity of the superluminal knots (filled circles). The solid curve represents the model-fitting by the proposed precessing jet model. See text.

However, contrary to their prediction, the apparent velocity does not vary periodically. This can be seen from Fig. 2, where the observed apparent velocity of the components is shown (filled circles). Fig. 2 clearly shows that the apparent velocity has decreased from $\sim 7.5\,c$

to $\sim 2.5\,c$ during the thirty year span. This result is remarkable and also contradicts the suggestion of Babadzhanyants & Belokon (1992) that the apparent velocity follows the periodic behaviour in the optical flux variations. Therefore, the results of Krichbaum et al. (2000) clearly indicate that in addition to the precession of the jet, there must be some other mechanism to cause the decrease of the apparent velocity. In the following sections we will propose a precessing jet model, in which the ejection Lorentz factor varies with time, to explain the observed phenomenon.

## 3 PRECESSING JET MODEL

The geometry of the precessing jet model is shown in Fig. 3 (Gower et al. 1982), Carrara et al. (1993). $Z$-axis is directed towards the observer and $X$-$Y$ plane is the plane of the sky. It is assumed that the jet is precessing around $Z'$-axis with angular velocity $\omega$. The precession cone has a half opening angle $\Omega$. The precession axis is specified by the angles $\eta_0$ and $\phi_0$, while the direction of the jet and the ejected components are defined by the angles $\eta(t)$ (position angle) and $\theta(t)$ (viewing angle). $\eta(t)$ and $\theta(t)$ can be calculated by the following formulae:

$$X(t) = \sin\Omega\cos\eta_0\sin\omega t + \sin\eta_0(\cos\Omega\sin\phi_0 + \sin\Omega\cos\phi_0\cos\omega t)\,, \quad (1)$$

$$Y(t) = -\sin\eta_0\sin\Omega\sin\omega t + \cos\eta_0(\cos\Omega\sin\phi_0 + \sin\Omega\cos\phi_0\cos\omega t)\,, \quad (2)$$

$$Z(t) = -\sin\Omega\sin\phi_0\cos\omega t + \cos\Omega\cos\phi_0\,, \quad (3)$$

$$\tan\eta(t) = \frac{X(t)}{Y(t)}\,, \quad (4)$$

$$\sin\theta(t) = \left(\frac{X(t)^2 + Y(t)^2}{X(t)^2 + Y(t)^2 + Z(t)^2}\right)^{\frac{1}{2}}\,, \quad (5)$$

$$\beta_{\rm app}(t) = \frac{\beta(t)\sin\theta(t)}{1-\beta(t)\cos\theta(t)}\,, \quad (6)$$

$$\delta(t) = \frac{1}{\Gamma(t)(1-\beta(t)\cos\theta(t))}\,, \quad (7)$$

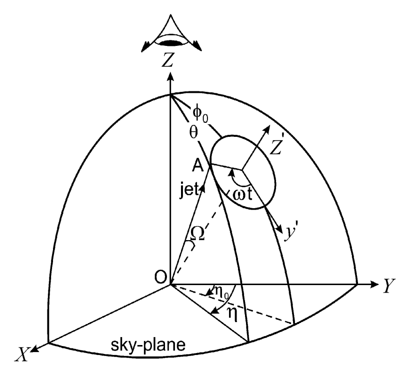


Fig. 3 The geometry of the precessing jet model

where $\beta(t) = (1-\frac{1}{\Gamma(t)^2})^{\frac{1}{2}}$, $\Gamma(t)$ is the Lorentz factor of the ejected components. $\beta_{\rm app}(t) = V_{\rm app}(t)/c$, $V_{\rm app}(t)$ apparent velocity, $\delta(t)$ Doppler factor, the precession period is $T = \frac{2\pi}{\omega}$.

## 4 MODEL-FITTING

In order to explain the observed variations of the position angle and the apparent velocity for the ejected components, the following values are adopted

$$\eta_0 = 245^\circ, \qquad \phi_0 = 13.5^\circ, \qquad \Omega = 5^\circ, \qquad \omega = 23.68^\circ{\rm yr}^{-1} \quad ({\rm or}\, T = 15.20\,{\rm years})\,.$$

These values are slightly different from those adopted in Krichbaum et al. (2000), which included some discussion on the model-fitting. In addition, here, the ejection Lorentz factor is fitted by the following function of time, which contains two variable terms, one monotonically decreasing, and one sinusoidal

$$\Gamma(t) = 8.33 - 0.167\,t + 1.2\sin[1.3\,(t + 2.32)]\,. \quad (8)$$

For the model-fitting, the observing epoch $t_{\rm obs}$ is given by $t_{\rm obs} = t + 1970.0$.

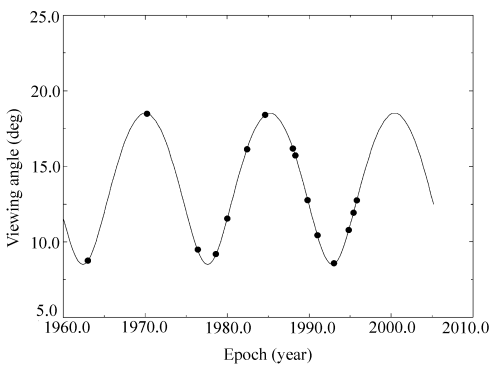


Fig. 4 The variation of the viewing angle predicted by the precessing jet model. Filled circles are for the superluminal knots $C_2$ to $C_{16}$ in order of epoch.

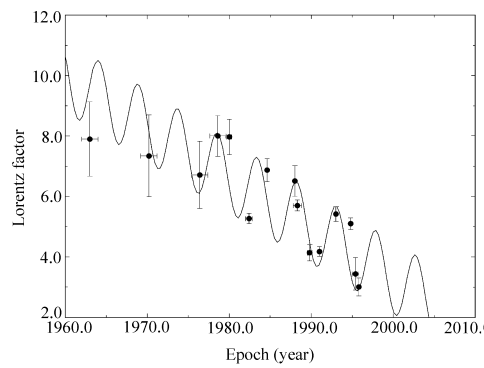


Fig. 5 The ejection Lorentz factor derived from the precessing jet model. Filled circles – observation, solid curve – model.

### 4.1 Model-fitting of the Position Angle Variations

From the formulae given above, the model-fit to the variation of the position angle of the ejected components is shown by the solid line in Fig. 1. It can be seen that the fit is very good and the periodic variation of the position angle has occurred for two periods.

### 4.2 Model-fitting of the Apparent Velocity Variations

Using the viewing angle $\theta(t)$ predicted by the jet precession model (shown in Fig. 4) and the ejection Lorentz factor given by Equation (8), the model curve for the apparent velocity can be calculated. The model-fit to the variation in the apparent velocity of the ejected components is shown by the solid line in Fig. 2. It can be seen that the proposed model fits the observed apparent velocity very well.

### 4.3 Model-fitting of the Ejection Lorentz Factor

Using the viewing angle obtained from the precession jet model for the observing epochs (Fig. 4, filled circles) and the observed apparent velocity, the ejection Lorentz factor can be calculated for each of the superluminal components ($C_2$–$C_{16}$). These values are shown in Fig. 5 as the filled circles. It can be seen that they are fitted very well by the proposed model[3] given by Equation (8). The results given above clearly show that, in addition to the precession of the jet, the Lorentz factor of the ejected components was changing during the period 1963–1997.

[3] Here we point out, if the apparent velocity for $C_9$ is adopted to be 6.2 given by Krichbaum et al. (2000) instead of 5.4 given in Table 1, the derived Lorentz factor would be 9.7, which seems too high to be fitted.

The decrease of the ejection Lorentz factor contains two parts: a monotonic decrease at a rate of –0.167 yr$^{-1}$ and a sinusoidal oscillation with an amplitude of $\sim$ 1.2 and a period of $\sim$ 4.8 years.

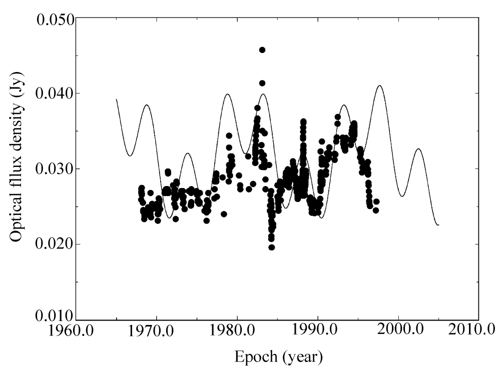


Fig. 6 A comparison between the observed optical flux density (filled circles) and the variability pattern (solid-line) predicted by a model, which consists of two sinusoids with periods of 15.2 and 4.8 year. See text.

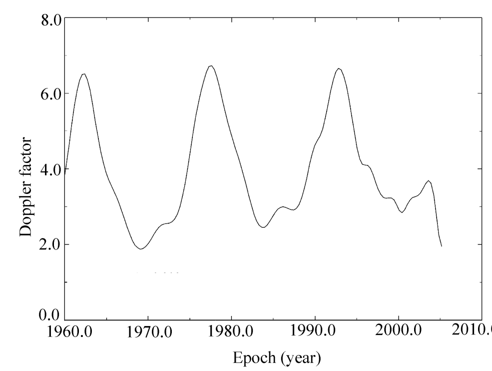


Fig. 7 Variations of the Doppler beaming factor in the proposed precessing jet model.

## 5 CORRELATION WITH OPTICAL VARIATIONS

As mentioned above, Babadzhanyants & Belokon (1992) found a 13.4-year period in the optical variations of 3C 273. This is close to the precession period of the jet ($\sim$ 15 years) we derived above. However, we find that the variations in the apparent velocity and ejection Lorentz factor (or ejection velocity) do not correlate with the phase of the optical activity.

In Fig. 6 the optical ($V$-band, filled circles) variations during the period 1968–1997 (Türler et al. 1999) are shown. The solid-line represents the pattern of variability predicted by a model consisting of two sinusoids with periods of 4.8 and 15.2 years

$$S(\mathrm{Jy}) = 0.005(2 + \cos A_1 + \cos A_2) + 0.022\,, \tag{9}$$

$$A_1 \equiv A_1(t_{\rm obs}) = \frac{2\pi}{T_1}(t_{\rm obs} - 1988.2)\,, \tag{10}$$

$$A_2 \equiv A_2(t_{\rm obs}) = \frac{2\pi}{T_2}(t_{\rm obs} - 1981.0)\,. \tag{11}$$

Here $T_1 = 4.8$ yr and $T_2 = 15.2$ yr.

Interestingly, the four optical peaks at ~1978, 1982, 1988 and 1993 are all correlated with the peaks in the model curve. Especially, the double-peak structure found by Babadzhanyants & Belokon (1992) in the optical light curve can now be well understood. Britzen et al. (2001) also found that there is a similar double-peak structure in the optical flaring in QSO 0420–014.

In Fig. 7 we present the curve for the variation of the Doppler factor derived by the precession jet model, which also reveals a 15-year period. Comparing Fig. 6 with Fig. 7, we find that the relationship between the optical variations and the variation of Doppler factor to be complex. For example, the optical peak at epoch ∼1993 is correlated with a maximum of the Doppler factor while the two optical peaks at epochs ∼1983 and ∼1988 occurred during a minimum of the Doppler factor.

## 6 DISCUSSION

From the analysis of the VLBI observations for the period 1963–1997, it is found that there may be four periods (or quasi-periods) involved in the VLBI behaviour of 3C 273. (From here on we will use timescales in the source frame in order to investigate the origin of the periods). They are: (1) rotation of position angle (∼ 13.1 yr); (2) a long-term variation of the ejection Lorentz factor $\Gamma$ (∼50–70 yr); (3) a short-term oscillation of the ejection Lorentz factor (4.1 yr); (4) a quasi-period of ∼0.8–1.7 yr for the ejection of the superluminal components. These periods may be correlated with the periods found in the optical flux variations. Since the periodicity found in the optical variations of the BL Lac object OJ287 has been successfully interpreted to be related to a binary black hole system in its core (Sillanpää et al. 1988; Lehto et al. 1996; Valtonen et al. 1999), it would be interesting to investigate the origin of the periods found in 3C 273 in the framework of binary black hole system. For supermassive binary black holes in galaxies and quasars, we refer to a recent review by Artymowicz (1998).

### 6.1 The 13-yr Precession Period

As we have shown in Section 4, the rotation in the position angle can be explained by the jet precession model. Jet precession can be produced by several effects. Begelman et al. (1980) suggested that the jets emanating from the black holes in binary systems can undergo geodetic precession around the orbital angular momentum. However, typical estimates of the geodetic period are hundreds of years, much longer than is observed in 3C 273. Babadzhanyants & Belokon (1992) suggested that gravitational deflection can cause the precession of a jet ejected by the black hole, orbiting around its massive companion. For the present case with an orbital period of 13.1 years and a precessing cone of 5°, the required mass of the companion is $\sim 2\times10^{11}\,M_\odot$, which seems too large. Here we apply the kinetic model proposed by Roos et al. (1993), also see Kaastra & Roos (1992), in which jet precession can be caused by a modulation of the jet velocity due to orbital motion in a binary black hole. The kinematic effect causes the jet axis to sweep out a cone with an opening angle proportional to the orbital/jet velocity ratio. Thus, in this case we can estimate the parameters of the binary black hole system from the observed precession period and the opening angle of the precession cone. It is assumed that the orbit is circular of radius $r$, and the masses of the black hole and its companion are $m$ and $M$. Then we have two equations

$$T_{\rm orb} = 1.7 r_{16}^{\frac{3}{2}}(M_8+m_8)^{-\frac{1}{2}}\,, \tag{12}$$

$$\tan\Omega = 0.038 r_{16}^{-\frac{1}{2}}(M_8+m_8)^{\frac{1}{2}}\beta_j^{-1}\,. \tag{13}$$

Here $r_{16}=r/10^{16}$ cm, $M_8$ and $m_8$ are the mass of the companion and the black hole in units of $10^8\,M_\odot$, and $\beta_j=\frac{V_j}{c}$, the jet velocity in units of the speed of light. Taking $T_{\rm orb}$=13.1 yr, $\Omega$= 5° and $\beta_j\sim1$, we can solve the above equations to obtain $r_{16}$≈17.7 (0.0574 pc) and $M_8$+$m_8$≈93.8. In order to estimate the masses we apply the results of black hole accretion disk model-fitting for the UV-optical-infrared radiation of 3C 273 by Sun & Malkan (1989). They found that the mass of the black hole that produces the UV-bump to be about $8.8\times10^8\,M_\odot$ (for a viewing angle

$\sim 0°$). Thus we estimate the mass of the companion is about $8.5\times10^9\,M_\odot$. These estimates seem reasonable. The time scale for gravitational radiation is about $5\times10^5$ yr.

### 6.2 50–70 yr Long Period

In Section 4, we introduced this period to describe the possibly periodic variations in the ejection Lorentz factor. Although this is an estimated period, it appears to be important for understanding the physical processes in the core of 3C 273. As shown in Fig. 5, during the period from 1963 to 1997, the ejection Lorentz factor of superluminal components in 3C 273 has decreased by a factor of $\gtrsim$2. But the time coverage of the VLBI observations is still not long enough to determine whether or not this variation is periodic. If we assume that the decreasing trend of the ejection Lorentz factor is going to come to its end soon and to be replaced by a rising trend in the near future, then we may have a period in the range of 50–70 years. It is not clear how this period is formed. Since the variation of the ejection Lorentz factor is presumably related to the processes in the accretion disk and the formation of the jet, we assume that it could be due to a long-term precession of the disk. As shown by Katz (1997) and Britzen et al. (2001), due to the gravitational torque of a companion, an accretion disk inclined to the orbital plane of a binary system will precess with a period of

$$T_{\rm prec}\approx\frac{4}{3}\frac{M+m}{M}\frac{{T_{\rm orb}}^2}{T_{\rm d}}\sec\chi\,, \tag{14}$$

where

$$T_{\rm d}=1.7\Big(\frac{r_d}{10^{16}{\rm cm}}\Big)^{\frac{3}{2}}{m_8}^{-\frac{1}{2}} \tag{15}$$

is the rotation period of the disk around the black hole ($r_{\rm d}$, the radius of the disk and $\chi$, the inclination of the disk to the orbital plane ($\sec\chi\sim1$)). Assuming $T_{\rm prec}=60\,$yr, from the above equations we obtain $T_{\rm d}\approx4.2\,$yr and $r_d\approx3.8\times10^{16}\,$cm.

### 6.3 Short Periods: 4 yr and 0.9–1.7 yr

As shown in Section 4, in addition to a long-term decreasing trend, the ejection Lorentz factor has a short-term oscillation with a timescale of $\sim$ 4.1 yr and an amplitude of $\sim$ 1.2 (Fig. 5). Since the oscillation of the Lorentz factor seems to be correlated with the short-term variations in optical flux density, it could be related to processes in the accretion disk of the black hole. Interestingly, as shown in the last subsection, when we explain the long-term variation of the ejection Lorentz factor to be due to precession of the disk, the required period of the disk rotation is just $\sim$ 4 years. The oscillation of the ejection Lorentz factor might be related to the transfer of mass and magnetic field from the disk to the jet. The ejection rate of $\sim$1-knot yr$^{-1}$ seems also related to the magnetohydrodynamic processes in the disk. For example, pulsations produced by different MHD instabilities (Mangalam & Wiita 1993) could modulate the transfer process of mass and magnetic field from the accretion disk to the jet, leading to the formation of superluminal knots and the change of ejection velocity.

## 7 CONCLUSION

We have suggested that the periods observed in 3C 273 with VLBI may be explained in the framework of a binary black hole system. These periods may be related to the binary orbital motion, the rotation and precession of the accretion disk around the black hole that ejects the jet.

However, investigations of the relationship between the physical processes occurring in binary black hole systems and VLBI behaviour in active galactic nuclei are rather difficult. The parameters estimated for the binary black hole model proposed in this paper represent a possible explanation of the observed periods, rather than a best fit. Future VLBI observations would show whether the position angle rotation will continue and whether the ejection Lorentz factor of the superluminal knots will change to one increasing with time. The confirmation of these two phenomena will be important. Like OJ287, 3C 273 might be another extragalactic source, in which the periodic variations are associated with a binary black hole system.

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