Chin. J. Astron. Astrophys. Vol. 7 (2007), No. 3, 364–374
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

A Possible Periodicity in the Radio Light Curves of 3C 454.3

Shan-Jie Qian[1,2], N. A. Kudryavtseva[2,4,5], S. Britzen[2], T. P. Krichbaum[2], Long Gao[1], A. Witzel[2], J. A. Zensus[2], M. F. Aller[3], H. D. Aller[3] and Xi-Zhen Zhang[1]

[1] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012; *rqsj@bao.ac.cn*
[2] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[3] Astronomy Department, University of Michigan, Ann Arbor, MI 48109, USA
[4] Astronomical Institute of St.-Petersberg State University, Petrodvoretz, St.-Petersburg, Russia
[5] International Max-Planck Research School for Radio and Infrared Astronomy at the Universities of Bonn and Cologne

Received 2006 September 22; accepted 2006 December 25

Abstract During the period 1966.5–2006.2 the 15 GHz and 8 GHz light curves of 3C 454.3 ($z = 0.859$) show a quasi-periodicity of ∼12.8 yr (∼6.9 yr in the rest frame of the source) with a double-bump structure. This periodic behaviour is interpreted in terms of a rotating double-jet model in which the two jets are created from the black holes of a binary system and rotating with the period of the orbital motion. The periodic variations in the radio fluxes of 3C 454.3 are suggested to be mainly due to the lighthouse effects (or the variation in Doppler boosting) of the precessing jets caused by the orbital motion. In addition, variations in the rate of mass accreting onto the black holes may be also involved.

Key words: radio continuum: galaxies — Quasars: individual: 3C 454.3

1 INTRODUCTION

In recent years many works have been devoted to the study of periodic properties discovered in extragalactic sources, especially in Blazars. These include periodic (or quasi-periodic) variations of flux density (or luminosity) in optical bands (e.g., for OJ287: Sillanpää et al. 1988; Lehto & Valtonen 1996; Valtonen et al. 1999; Villata et al. 1998; Valtaoja et al. 2000; Valtonen et al. 2006a, b, for AO 0235+16: Raiteri et al. 2001); periodic variations of flux density in radio bands (e.g., for AO0235+16: Raiteri et al. 2001, for 3C 454.3: Ciaramella et al. 2004; Kudryavtseva & Pyatunina 2006); periodic changes of the position angle of ejection of superluminal knots (e.g., Qian et al. 2001; Britzen et al. 2001; Abraham & Carrara 2000; Lobanov & Roland 2005); periodic changes of the trajectory of superluminal knots (e.g., for 3C 345: Qian et al. 1991; Lobanov & Roland 2005; Klare et al. 2005), etc. Up to now, the most reliable periodic phenomenon observed in blazars seems to be the 12 year quasi-periodic optical variations of the BL Lac object OJ287 which has been convincingly determined in the more than 100 year long records of optical observations since 1890s.

In the interpretations of these periodic phenomena various binary black hole models have been invoked. For the periodic optical variations in OJ287 all the proposed models invoke a binary system with two supermassive black holes. However, the mechanisms for the production of the optical outbursts can be divided into two classes: accretion models and lighthouse models.

– Accretion models
  These models (Lehto & Valtonen 1996; Valtonen et al. 2006a, b) propose that the optical periodicity is caused by a precessing binary black hole system of two supermassive black holes with a large eccentric

orbit. The observed periodic 'superflares' with double peaks are suggested to be due to the crossings of the secondary black hole into the accretion disk of the primary black hole during the pericenter passage. Thus in this class of models the optical emission is thermal (bremsstrahlung) and the observed flux increase reflects the enhanced accretion related to the disk crossings and the general enhancement of the accretion rate during the pericenter passage. Doppler boosting is not taken into account. Detailed models for a binary black hole system have been proposed to fit the past optical records of OJ287 and predict future optical events. If the timing of the optical activity (superflares) in OJ287 can be accurately predicted, then it is possible to calculate or determine the parameters of the binary black hole system (such as the masses of the black holes, the orbital parameters, etc.).

– Lighthouse models
  The periodic optical flares observed in OJ 287 are suggested to be caused by change of the orientation of the relativistically moving emission regions with respect to the line of sight, resulting in an increase of the Doppler boosting factor (Camenzind & Krockenberg 1992; Katz 1997; Villata et al. 1998; Qian et al. 2001) and the apparent optical flux density ($\propto\delta^3$). Katz (1997) proposed that in a binary black hole system the companion exerts a torque on the accretion disk of the primary black hole and results in the precessing of the relativistic jet from the primary sweeping across the line of sight and the periodic variation of the Doppler factor and thus the apparent flux density. Villata et al. (1998) suggested that the two black holes of the binary system both create relativistic jets which are bent significantly in different directions. In the course of the binary's orbit motion, the directions of the bent parts of the jets from the two black holes rotate with the orbital period, resulting in periodic double-peak flares. In this class of models only the variation of the Doppler boosting factor plays a role, and does not consider any change in the accretion in the central disk-hole systems.
– Alternative models
  Valtaoja et al. (2000) have argued against both the accretion models and lighthouse models for OJ287. They found that in OJ287 the first optical flare of the double-structure is thermal (non-polarized) and lacks a radio counterpart, but the second one is (polarized) synchrotron emission, and has a radio counterpart. They proposed an alternative model in which the first optical flare is caused by disk-crossing during the pericenter passage that occurs regularly, and the second one occurs about one year later in the relativistic jet in association with a radio outburst. For checking this model optical polarization measurements and VLBI studies of the optical-radio association are significant.

In this paper we will discuss the possible existence of a $\sim$13 year periodicity in the radio light curves of the optically violently variable (OVV) quasar 3C 454.3 at 8 GHz and 14.5 GHz in which two broad peaks (or bumps) are observed in one period. We propose that the periodicity can be interpreted in the frame of a binary black hole model in which two jets from the two black holes rotate with the period ($\sim$13 year) of the orbital motion. Model-fits to the light curves are given. It is shown that both the periodic Doppler boosting effect (lighthouse effect) and the variability of the accretion activity (i.e. the mass-energy inflow into the jets) should be taken into account in order to fully explain the light curves. We also discuss some alternative models and future observations for further studying the periodic phenomenon in 3C 454.3.

2 OPTICAL AND RADIO PROPERTIES OF 3C 454.3

3C 454.3 was early defined as a typical OVV quasar which at times shows flare-ups of 2–3 magnitudes. Its historical optical data go back to 1900 (Angione 1968). It has a flat spectrum in the cm-mm bands and belongs to the category of blazars, showing strong flux variability over the whole electromagnetic spectrum from radio to γ-ray (Villata et al. 2006; Pian et al. 2006).

2.1 Optical Variability

As shown by Villata et al. (2006), the optical variability of 3C 454.3 (cf. their fig. 1 (upper panel)) shows two different phases of activity. From 1966 till 2001 (during a 35 year span) the observed optical variability is moderate with m_R in the range of $\sim$15–17 magnitude. Before 1966 few data are available. The historical data during the 60 year span (from 1900 to 1960) given by Angione (1968) show a peak magnitude of $m_B\sim$15 (equivalent to $m_R\sim$14) at 1953.6, the most rapid variability was about 0.4 mag day $^{-1}$ and the total variation $\sim$2 mag (17 to 15) in B-band. From 2001 the amplitude of the optical variations starts to increase and 3C 454.3 was observed at m_R~13.5 in August/September 2001 (Fuhrmann et al. 2006). Recently, It was observed at m_R~12 on 2005.35 (May 9.36), becoming the brightest quasar in the sky (Villata et al. 2006). Thanks to the WEBT group, a multi-frequency campaign of observations was conducted in radio and optical bands during this period of high activity (see Villata et al. 2006; Pian et al. 2006; Fuhrmann et al. 2006).

With regard to the study of the radio periodicity in 3C 454.3 in this paper (see below), the unprecedented optical outburst in 2005 and the associated huge millimeter outburst are very significant, because they show us that a quasi-periodicity of ~12–13 year really exists (Here we would mention: by visual inspection of the radio light curves at 8 GHz and 15 GHz during the period 1966–2004 [1] and without accessing to any other information, we predicted the next peak of its activity would be occurring in 2006–2007. The optical outburst at 2005.35 which we later learned from the literature has verified our prediction, considering that radio outbursts usually lag behind optical ones by about ~1 year).

Quasi-periodicities in optical variations of 3C 454.3 have been studied. Webb et al. (1988) analyzed the B-light curves during the period (1971–1985) and obtained three (weak) periods: 6.4, 3.0 and 0.8 years. Su (2001) used an optical dataset (B-magnitude) including the years from 1900 to 1996 and found a period of 12.4 yr. These previous results of optical variations (the two periods of 6.4 and 12.4 yr) are unexpectedly consistent with the periods obtained for the radio variations (see below).

The optical emission from 3C 454.3 is polarized during outburst and non-outburst periods, and also when it reaches minimum brightness. It is a high polarization quasar, which was observed to be in high optical polarization states with a maximum polarization degree of ~16%. Its high polarization states are associated with strong variability, but not with high brightness (Visvanathan et al. 1973; Angel & Stockman 1980). Sometimes it is in very low polarization states with p~0% (Moore & Stockman 1981; Pollock et al. 1979). These polarization observations seem to show that the optical variations in both high and low states originate from the synchrotron emission of the jets. This is different from OJ287 (Valtaoja et al. 2000) and we will propose a double jet model to fit the radio light curves.

2.2 Radio Variability and Quasi-Periodicity

3C 454.3 is a radio quasar with a flat spectrum. As shown in Figure 1, its radio light curves at 8 GHz and 14.5 GHz over nearly 40 years show several outbursts. As well known, the existence of periodicity in radio light curves is still a controversial issue, even in the case of OJ287 in which periodic optical variations have been discovered (Sillanpää et al. 1988; Valtonen 2006a, b). However, Ciaramella et al. (2004) have made detailed analysis of the radio data (1970–1999) of 3C 454.3 at five frequencies (4.8, 8.0, 14.5, 22 and 37 GHz) using the autocorrelation method and pointed out that a strong and consistent periodicity of about 6 years (~6.0–6.5 yr) was found in the overall flaring behaviour. 3C 454.3 was regarded as providing the best evidence for radio periodicity in a sample of 77 extragalactic sources selected from the sample of Teräsranta et al. (1998).

By visual inspection of the radio light curves given by Ciaramella et al. (2004), we find that, if we take into account the apparent difference between the amplitudes of the peaks, the quasi-periodicity may be ~12–13 years with a second peak always weaker than the main peak. The unprecedented optical (and millimeter) outburst observed in 2005.35 described above seems to verify this identification (the optical outburst signals the coming of a new main peaking period following the radio peaks at epochs 1967 (8.0 GHz), 1981 (8 and 14.5 GHz) and 1994 (at 8 and 14.5 GHz). See Figure 1.

We should point out that normally in radio bands few blazars have been found to be periodic in their radio light curves. For example, even in the BL Lac object OJ287, where the optical light curve has a 12 year periodic flaring with a double structure, there is no periodic radio behaviour corresponding to the optical cycles. Especially, there are no outstanding individual radio outbursts corresponding to the optical double 'superflares' (Valtaoja et al. 2000). The radio outbursts consist of many short timescale (1–2 year) peaks overlapping on a bump which has a ~22–25 year period (about twice of the optical period, see Ciaramella et al. 2004). In contrast, in 3C 454.3 the radio outbursts are outstanding, having simple profiles (especially for the main bumps), thus its quasi-periodicity can be easily recognized.

[1] This research has made use of data from the Radio Astronomy Observatory, University of Michigan, which has been supported by the University of Michigan and the National Science Foundation.

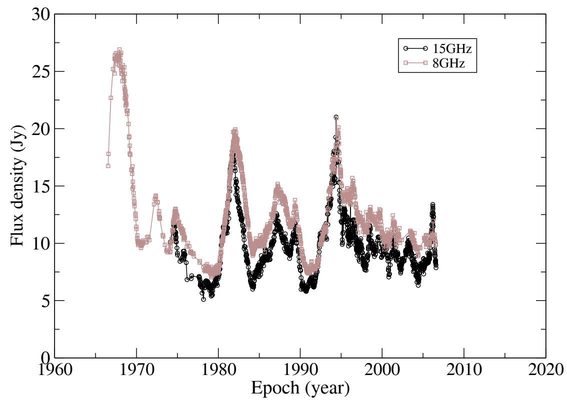

Fig. 1 3C 454.3: the 8 and 14.5 GHz light curves, showing a ∼12–13 year quasi-periodicity.

Most recently, Kudryavtseva & Pyatunina (2006) have studied the radio periodic behaviour in three sources (3C 454.3, CTA102 and 3C 446). They made a detailed analysis of the radio light curves at 37, 22, 15, 8 and 4.8 GHz for 3C 454.3 and found two periods of 6.2 and 12.4 yr. Also, Li et al. (2006) found a period of 6.2 yr, from a period analysis of the 37 and 22 GHz light curves. Thus, combining the results obtained by Webb et al. (1988), Su (2001), Ciaramella et al. (2004), Kudryavtseva & Pyatunina (2006) and Li et al. (2006), we would come to the conclusion that in both radio and optical regimes there seem to be present two quasi-periods (∼6.2 and ∼12.4 yr).

For the discussion below we summarize the radio behaviour of 3C 454.3 (shown in Fig. 1) as follows:

– (1) Since 1966, three major radio outbursts have been observed at 14.5 GHz, peaking at 1981.5, 1994.5 and 2006.2. Also second peaks (or bumps) were observed, occurring ∼7 years after the first bumps, the most noticeable one being at 1987.5, giving a double-bump structure during the period (1980–1991). Thus a 12–13-year periodicity could be identified. For the 8 GHz light curve there are also observed three outstanding cycles (1966.5, 1981.5, 1994), because the radio-mm outburst at 2005.6 is not noticeable at 8 GHz. In addition, for each cycle two broad peaks (bumps) are clearly seen and the second bumps are always less regular and with smaller amplitudes. This might imply that the two bumps could originate from different regions.
– (2) The relation between centimeter and millimeter outbursts in 3C 454.3 is observed to be different at different epochs. For example, during the period of the optical outstanding flare in 2005, the mm-flares at 1–3 mm are closely associated with the optical one and its amplitude is much larger than those at centimeter wavelengths (e.g., at 2.8 cm; see Villata et al. 2006; Krichbaum et al. in prep.). However, during the period 1990–2004, the mm-light curve is similar to the cm-light curve, showing a similar double-bump structure, but the amplitudes of the main mm-bumps are clearly smaller than those of the 14.5–8 GHz bumps. Generally, the outbursts at centimeter wavelengths lag behind the mm-outbursts, causing a difference between the periods determined in different frequencies. This complex relationship could be due to opacity and evolution effects of the shocked regions in the curved jet.

2.3 VLBI Structure

For proposing a model to interpret the periodic radio behaviour of 3C 454.3 the VLBI observations are important, that have been conducted since 1981.5 by Pauliny-Toth et al. (1987) and Pauliny-Toth (1998). The former paper gives the 2.8 cm VLBI results during the period 1981.4–1986.2 following the 1981.5 peak, and the latter gives 6 cm VLBI observational results over 1981.6–1991.9. These VLBI observations show that the source has a core-jet structure, ejecting superluminal knots following major radio outbursts. The complex core was once observed to show a 'superluminal' increase in its size. The VLBI jet is very curved and acceleration of the motion of its knots was observed (apparent speed from $\sim 5c$ to $\sim 20c$). However, in 3C 454.3 some features were observed to be remained stationary, showing their orientation could be directed to us (with viewing angle $\sim 0°$). The VLBI measurements suggest a small viewing angle (less than $\sim 2° - 5°$) and a large bulk Lorentz factor (larger than ∼20).

The results (structure and superluminal motion properties of 3C 454.3) obtained from mm-VLBI observations (e.g. Pagels 2004; Krichbaum et al. 1996) are consistent with those obtained from cm-VLBI observations. Most recently, during the strong optical-mm outburst in 2005, 43 GHz VLBI observations showed variations in structure and in its flux and polarization (Villata et al. 2006).

Basing on the epochs of the superluminal components ejected from the core of 3C 454.3, Kudryavtseva & Pyatunina (2006) found that the birth epochs of the VLBI components have similar periods to the above. The variation in the core structure after the 2005 optical flare (Villata et al. 2006) seems also to be consistent with their results.

2.4 Radio-Optical Correlation

The relation between the radio and optical variability is complex in 3C 454.3. In the early years, Pomphrey et al. (1976) already found a correlation between the optical and 2.8 cm radio events, revealing the optical leading the radio by ∼1.2 years. However, later observations did not confirm this simple relation, i.e., generally radio outbursts were not observed to be associated with optical outbursts (during the period 1966–2004), except one or two outstanding optical flares like those observed in 1979 and 2005). Observationally, the lack of the association is due to two reasons: (1) the range of the optical variability amplitude is usually small (less than ∼1 mag.); and (2) the radio outbursts are usually associated with small optical flares and *vice versa*.

The general lack of correlation between the optical and radio behaviours suggests that the optical and radio emissions originate in different regions and are possibly misaligned with respect to each other. Recently, Villata et al. (2006) suggested that before 2001 the radio region was more aligned with the line of sight and the radio variability was enhanced by Doppler boosting effects. On the contrary, since 2001 the optical activity increases and the 2005 optical flare reaches a peak of m_R∼12, an unprecedented high brightness. Thus in the last 5 years (2001–2005) the optical radiation region has a smaller viewing angle and is more enhanced by Doppler effects. However, during the period 2001–2004 the radio and mm activities were in their low states. The 2005 optical flare started a new activity in mm-cm bands with the unprecedented mm-flares (peaks of ∼45 Jy at 1 mm and ∼26 Jy at 3 mm), compared with the low activity during the 1985–2001 period (1–3 mm varied in the range between ∼2 Jy and ∼15 Jy, when the observed optical activity ranging between m_R∼15 and ∼16.5, was also at low activity). However, we should point out that in some cases even at low optical states, some close association between individual optical and radio flares can be recognized. For example, Tornikoski et al. (1994) found from their optical monitoring during 1980–1993 that the only prominent feature in the optical light curve was a strong flare peaked at ∼1988.7, which had its counterparts at 230, 90 and 37 GHz with possible delays and might be associated with the delayed 14.5 and 8 GHz outbursts (Fig.1). Another feature in the relation between the optical and radio flares is that the optical activity has considerably shorter timescales generally. This could be due to the accretion-energy supply processes (acceleration of electrons, radiative losses and injection rates, etc.), and not due to Doppler time dilution or narrower Doppler boosting profile for optical emission (see below).

3 MODEL-FITTING

We have three alternatives to make model -fitting.

(1) Binary black hole models as suggested by Lehto & Valtonen (1996) and Valtonen et al. (2006a) for OJ287. Periodicity is created by pericenter passage and disk passage of the secondary black hole during its orbital motion. This model mainly explains the double optical peaks in terms of the increase in the accretion onto the primary black hole and the secondary black hole crossing the disk of the primary. The optical flares are considered to be produced near the black hole-disk system. The radio outbursts do not show a similar periodicity and are regarded as a phenomenon associated with the optical flaring, but produced in the jet (only one jet from the primary is considered). This implies that the intermediate processes, which determine the transfer of the energy from accretion to the energy injected into the jet, would play a significant role, and these processes are not clarified in these models. Therefore, since the periodic behaviour in 3C 454.3 occurs in radio bands which probably is a phenomenon in the jet, the

binary black hole model proposed by Valtonen et al. (2006a) can not be directly applied to 3C 454.3. Moreover, since the optical flares in 3C 454.3 seem probably to be synchrotron in origin, the problem as to how to combine the disk-passage mechanism and Doppler boosting effect to explain the optical flares still remains.

(2) Binary black hole models with two jets rotating with the orbital motion, as suggested by Villata et al. (1998) for OJ287. Each jet produces one optical peak, thus forming a double optical flaring structure. The optical flares are caused purely by the Doppler boosting variation without considering the change in the accretion rate and the mass-energy transfer into the jet. The optical periodicity is due to the periodic variation in the Doppler factor. This model is proposed for explaining optical periodicity of optical flares with narrow profiles ($\sim$1 year). In its present form the model can not be applied to 3C 454.3, because in order to interpret the narrow width of the optical flaring profiles ($\sim$1 year) the bent parts of the two jets are required to vary over a large range of viewing angle between $\sim 6^\circ$ and $\sim 86^\circ$. This range of the viewing angle is too large to fit the profiles of the radio bumps observed in 3C 454.3. Moreover, the corresponding range for the Doppler beaming factor (δ^3) would be extremely large (bulk Lorentz factor is taken to be 10, see Villata et al. 1998), which seems to be inconsistent with the VLBI observations. Thus even for the optical flares in OJ287 alternative mechanisms for the narrow widths (or short timescales) of the optical flares (e.g. mechanism of acceleration of electrons emitting optical synchrotron) should be explored.

(3) Periodicity can be produced in a fully-collimated jet by helical motion of superluminal knots. This is like the 'lighthouse' model suggested by Schramm et al. (1993) for optical flaring in 3C 345. However, this mechanism is only used for short-term periodic behaviour (timescales of several months, or at most a few years) and for a single peak phenomenon, so does not seem to be applicable to 3C 454.3, where the periodicity lasts at least 40 years.

Taking into consideration that in the case of 3C 454.3, both optical and radio flares occur in the times of the main and secondary bumps, we think that a binary black hole model with two jets [2] could be the more plausible one. In this case, one jet produces the main bump and the other jet produces the secondary bump, and in each curved jet there could be two emitting regions, one of which emits at optical and mm wavelengths and the other emits at cm. The two regions could have different positions in the curved jets, with the optical regions situated closer to, and the radio regions, further from the binary system.

We further assume that both jets rotate together with a period (T year), which could be due to the orbital motion of the binary system as suggested by Villata et al. (1998), so that the different Doppler boosting profiles determine the relative timing of the optical flaring and radio flaring. The combination of the effects of accretion (mass-energy transfer into the jets) and Doppler boosting determine the strength of the optical and radio outbursts.

3.1 Formalism

Specifically, we assume two jets created from the two black holes of a binary system. The original jet axes are parallel to the normal of the orbital plane (i.e., the orbital angular momentum). We assume that the jets precess around the normal due to the orbital motion with the orbital period through the mechanism suggested by Roos et al. (1993), that is, the vector addition of the orbital velocity of the holes and the velocity of the jets produce the precession of the jets in the observer's frame (this assumption is different from that of Villata et al. (1998), in which the outer parts of the jet are bent backwards with respect to their orbital motion due to the magnetohydrodynamic interaction between the magnetized jet flows and the ambient medium). The bent parts which emit optical and radio emission make small angles with the normal of the orbital plane. The jet flows have a large Lorentz factor. We designate the bent parts of the two jets as component-1 (for the main radio bump) and comoponet-2 (for the secondary bump). We assume that at $t = 0$ the observer and component-1 are situated at the same azimuth angle (ϕ_1=0°) on the orbital plane and component-2 at ϕ_2=175°. The observer direction makes an angle i with the normal of the orbital plane and component-1 and component-2 make angle ψ_1 and ψ_2 with the orbital normal, respectively. As described above, the two jets rotate with an angular speed ω=2π/$T_{\rm obs}$ (in the observer's frame). We adopt a large Lorentz factor for the jets, as suggested by the VLBI observations (Pauliny-Toth et al. 1998). Then

[2] Two counter-jets are not involved here.

Table 1 Parameters for the Two Models

Parameter	Model-A	Model-B
Γ	20	20
$T_{\rm obs}$	12.8 yr	12.8 yr
ψ_1	3°	3°
ψ_2	10°	5°
ϕ_1	0°	0°
ϕ_2	175°	175°
i	2°	2°
ω	$2\pi/T_{\rm obs}$	$2\pi/T_{\rm obs}$
S_{b1}(15 GHz)	2.7×10^{-4}	2.7×10^{-4}
S_{b1}(8 GHz)	3.0×10^{-4}	3.0×10^{-4}
S_{b2}(15 GHz)	5×10^{-2}	8.3×10^{-4}
S_{b2} (8 GHz)	7.5×10^{-2}	1.24×10^{-3}
quiescent-level	5 Jy	5 Jy

Table 2 Epochs of the 15 GHz Peaks obtained by the Model-fittings

peak	epoch
secondary	1962.35
main	1968.95
secondary	1975.15
main	1981.75
secondary	1987.95
main	1994.55
secondary	2000.75
main	2007.35
secondary	2013.55
main	2020.15

the variation with time of the viewing angles (θ_1 and θ_2) of the two components can be written as:

$$\cos\theta_1(t) = \sin\psi_1\ \cos(\omega t + \phi_1)\ \sin i + \cos\psi_1\ \cos i, \tag{1}$$

$$\cos\theta_2(t) = \sin\psi_2\ \cos(\omega t + \phi_2)\ \sin i + \cos\psi_2\ \cos i. \tag{2}$$

Thus we have the Doppler factors (δ_1 and δ_2) and the flux densities (S_1 and S_2) of the components:

$$\delta_1(t) = [\Gamma_1(1-\beta_1\cos\theta_1)]^{-1}\,, \tag{3}$$

$$\delta_2(t) = [\Gamma_2(1-\beta_2\cos\theta_2]^{-1}\,, \tag{4}$$

$$S_1(t) = S_{b1}\,{\delta_1}^3\,, \tag{5}$$

$$S_2(t) = S_{b2}{\delta_2}^3\,, \tag{6}$$

where S_{b1} and S_{b2} are normalization constants for fitting the observed light curves. We also introduce a quiescent level to take account the flux density from the components which are not related to the beaming components.

Table 1 lists the parameters that we have chosen for two models (taking Γ_1=Γ_2): model-A and model-B. The only difference between model-A and model-B is the value of ψ_2: 10° for model-A and 5° for model-B, thus component-2 has a narrower Doppler profile width and a greater Doppler factor (see Figs. 2–11).

3.2 Results of Model-Fitting

Using model-A we obtain the fitting for the 8 GHz and 15 GHz light curves in Figures 2–6. Using model-B we obtain the fitting for the 15 GHz and 8 GHz light curves in Figures 7–11. The peaks fitted and predicted for 15 GHz light curve are shown in Table 2.

It can be seen that the model-fittings to the observed flux light curves are quite good. This implies that the periodic behaviour is dominated by the Doppler boosting effects (or the Doppler-boosting profiles) and that the accretion rates and the mass-energy inflow into both jets are inferred to be mostly stable during the period of $\sim$40 years. However, it can also be seen that deviations from the modelled light curves are apparent, e.g., the 8 GHz-peak in $\sim$1967.8 (Fig. 4) and the behaviour observed at 15 GHz in 2006 (Fig. 6). We would attribute these deviations to some wobble effects of the precessing jets or irregular variations in the black hole accretion rates (and the energy-inflow into the jets).

3.3 Estimates of the Masses of the Black Holes

In this paper we do not propose a specific binary black hole model to explain the dynamic properties of the jets, but we roughly estimate the masses of the supermassive black holes. We assume that the precession of the jet axes is due to the orbital motion through a mechanism suggested by Roos et al. (1993): when adding the orbital velocity of the hole to the jet velocity, the velocity vector of the jet precesses with the

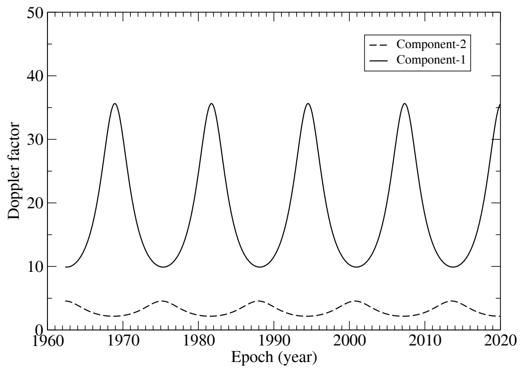

Fig. 2 Model-A: Doppler factors of component-1 and component-2.

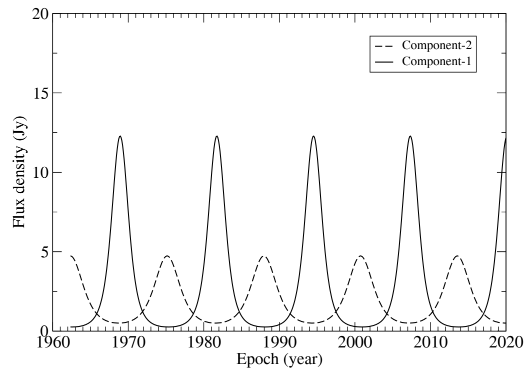

Fig. 3 Model-A: 15 GHz flux light curves (Doppler profiles) of component-1 and -2.

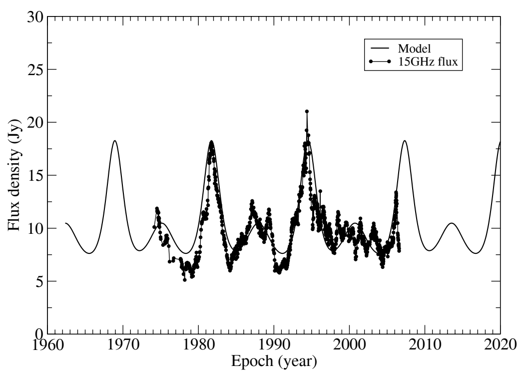

Fig. 4 Model-A: model-fitting of the 15 GHz light curve.

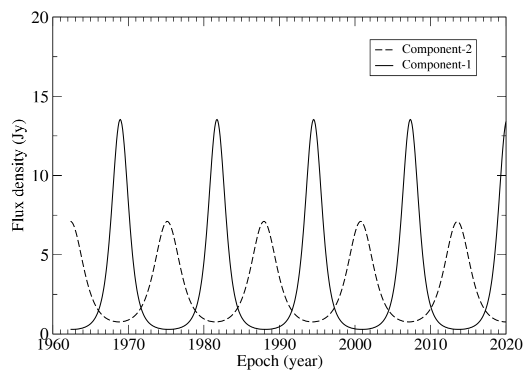

Fig. 5 Model-A: 8 GHz flux light curves (Doppler profiles) of component-1 and component-2.

binary period. Thus for a circular motion we have the formulae for the precessing angles of the primary and secondary black hole (cf. equations (3), (5) and (7) of Roos et al. 1993)

$$\psi_1 \approx 2.65^\circ \frac{m_8}{M_8}(M_8+m_8)^{\frac{1}{3}}\left(\frac{T_{\rm int}}{\rm yr}\right)^{-\frac{1}{3}}\cos\chi_1/\beta_{j1}, \tag{7}$$

$$\psi_2 \approx 2.65^\circ (M_8+m_8)^{\frac{1}{3}}\left(\frac{T_{\rm int}}{\rm yr}\right)^{-\frac{1}{3}}\cos\chi_2/\beta_{j2}, \tag{8}$$

where ψ_1 and ψ_2 are the angles of precession of the primary and secondary black hole (in degrees), m_8 and M_8 are the masses of the secondary and the primary black holes in units of $10^8 M_\odot$, $T_{\rm int}$, the intrinsic orbital period (= 6.9 yr), χ_1 and χ_2, the angles between the jet velocities and the orbital angular momentum (i.e. the normal of the orbital plane, in our case χ_1=χ_2=0), β_{j1} and β_{j2}, the velocities of the jets in units of c (the speed of the light). If we take ψ_1=5° and $m_8 \approx M_8$ ($\beta_j \sim 1$), then we obtain $M_8 \approx$ 22, i.e., $M_{\rm BH} \approx 2.2 \times 10^9 M_\odot$. This mass estimate is consistent with those obtained by other arguments (for example, the estimation of $1.5 \times 10^9 M_\odot$ from the bolometric luminosity of 3C 454.3 by Woo & Urry 2002).

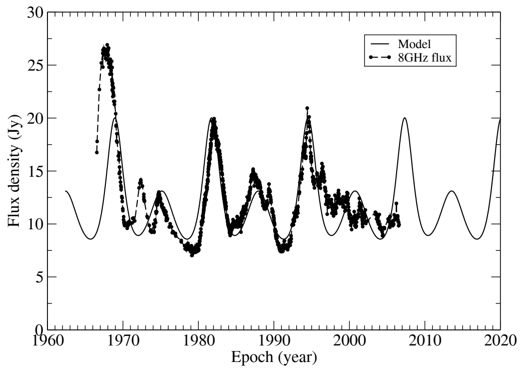

Fig. 6 Model-A: model-fitting of the 8 GHz light curve.

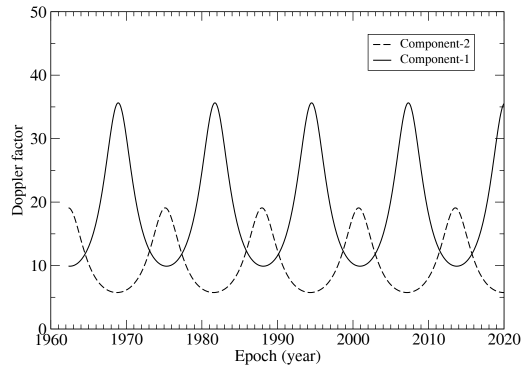

Fig. 7 Model-B: Doppler factors of component-1 and component-2.

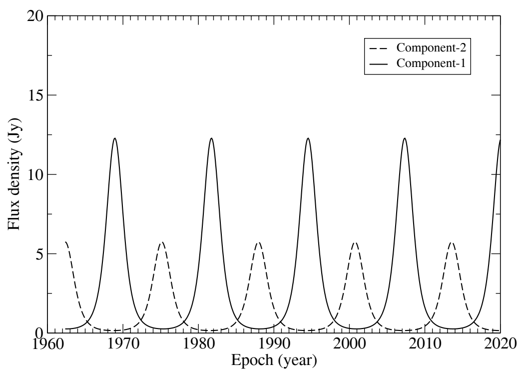

Fig. 8 Model-B: 15 GHz flux light curves (Doppler profiles) of component-1 and component-2.

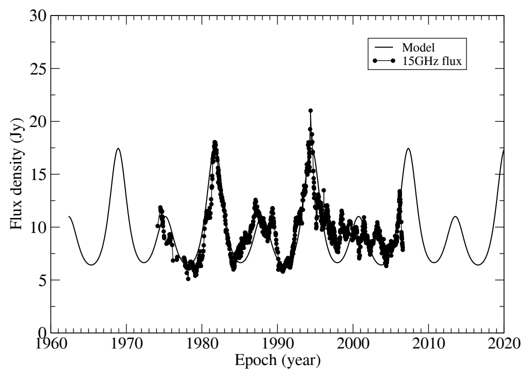

Fig. 9 Model-B: model-fitting for the 15 GHz light curve.

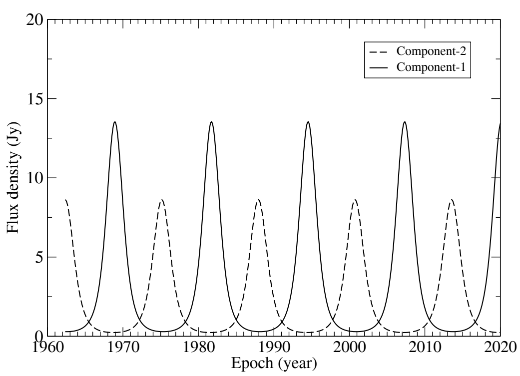

Fig. 10 Model-B: 8 GHz flux light curves (Doppler profiles) of component-1 and component-2.

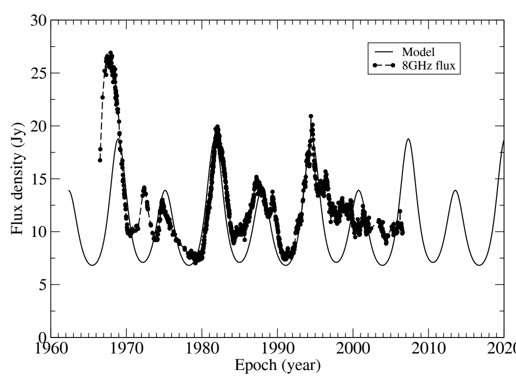

Fig. 11 Model-B: model-fitting for the 8 GHz light curve.

4 CONCLUSIONS

(1) The supposed model is not unique. In addition to the double-jet models proposed in this paper, models with a single jet are also plausible, but in this case the two emitting components would be assumed to be situated at different positions in the curved jet and their rotation would produce the Doppler boosting profiles. In this paper we do not invoke a specific model for a binary black hole system.
(2) In our model-fittings a number of parameters are adjustable. When choosing the parameters we consider mainly three items: (a) the width of the two radio bumps; (2) that the difference of Doppler factor at flaring and quiescent epochs should not be too large in order to avoid a huge difference in timescale of variability at different epochs (Valtaoja et al. 2000).
(3) We should consider both the effects of Doppler boosting and energy transfer into the jets (or accretion rates). In our models, the Doppler boosting determines the 'profiles' of the possible activity in the radio and optical bands. If the intrinsic (in the rest frame of the flows) strengths are stable, then the apparent activity follows the pattern of the Doppler boosting. This seems correct for the observed radio variations, for example during 1978–1995.
(4) As for the optical variations, they do not follow the Doppler boosting profiles derived from our models. This could imply we should adopt different parameters for the optical variations, i.e., the optically emitting regions could have orientations different from the radio regions. Moreover, optical flux variations could be largely determined by variations in the accretion rate and their much shorter timescales may be due to mechanisms for acceleration of electrons and radiative losses. The optical peak at 2005.4 and radio peak at 2006.2, both of which deviate from the predicted Doppler boosting maximum, further indicate the necessity of considering certain changes in the Doppler boosting pattern and in the accretion and transfer of energy into the jets.
(5) The radio periodic behaviour still needs to be tested, because the 2005 optical flare has a quite peculiar mm-radio outbursts, which had much narrower profiles than before, very different from those of the 1981 and 1994 radio flares. This may imply that the radio periodic behaviour could be a short-term phenomenon. It is still important to test the optical-radio relationship, to obtain more information on the combination of the black hole disk system and the Doppler boosting effect.
(6) The relationship between mm- and cm-outbursts needs to be further studied in order to study the evolution of the outbursts.
(7) At present, we cannot predict whether the periodic behaviour in 3C 454.3 in radio and optical bands will persist, and this should be observationally tested during the next period (2007–2020). Both optical and radio monitoring on intensity and polarization are required.

Acknowledgements S. J. Qian acknowledges the hospitality and financial support of the Max-Planck-Institut für Radioastronomie during his visit in 2006. N.A. Kudryavtseva was supported for this research through a stipend from the International Max-Planck Research School (IMPRS) for Radio and Infrared Astronomy at the Universities of Bonn and Cologne.

References

Abraham Z., 2000, A&A, 355, 915
Angel J. R. P., Stockman H. S., 1980, ARAA, 8, 321
Angione R. J., 1968, PASP, 80, 339
Britzen S., Roland J., Laskar J. et al., 2001, A&A, 374, 784
Camenzind M., Krockenberger M., 1992, A&A, 255, 59
Ciaramella A., Bongardo C., Aller H. D. et al., 2004, A&A, 295,330
Fuhrmann L., Cucchiara A., Marchili N. et al., 2006, A&A, 445, L1
Katz J. I., 1997, ApJ, 478, 527
Klare J., Zensus J. A., Lobanov A. P., Ros E., Krichbaum T. P., Witzel A., 2005, ASP, 340, 40
Krichbaum T. P., Alef W., Witzel A., 1996, IAUS, 175, 11
Kudryavtseva N.,A., Pyatunina T. B., 2006, Astronomy Reports, 50, 1
Lehto H. J., Valtonen M. J., 1996, ApJ, 460, 207
Li H. Z., Xie G. Z., Zhou S. B. et al., 2006, Chin. J. Astron. Astrophys. (ChJAA), 6, 421
Lobanov A. P., Roland J., 2005, A&A, 431, 831

Moore R. L., Stockman H. S., 1981, ApJ, 243,60
Pauliny-Toth I. I. K., Porcas R. W., Zensus J. A., Kellermann K. I., Wu S. Y., Nicolson G. D., Mantovani F., 1987, Nature, 328, 778
Pauliny-Toth I. I. K., 1998, In: Radio Emission from Galactic and Extragalactic Compact Sources (ASP Conference Series, vol.144), eds. J. A. Zensus, G. B. Taylor, J. M. Wrobel, p.75
Pagels A., Krichbaum T. P., Graham D. A. et al., 2004, In: Proccedings of the 7th Symposium of the European VLBI Network on New Developments in VLBI Science and Technology, eds., R. Bachiller, F. Colomer, J.-F. Desmurs, P. de Vicente, p.7 (astro-ph/0409328)
Pian E., Foschini L., Beckmann V. et al., 2006, A&A, 449, L21
Pollock J. T., Pica A. J., Smith A. G., Leacock R. J., Edwards P. L., Scott R. L., 1979, AJ, 84, 1658
Pomphrey R. B., Smith A. G., Leacock R. J. et al., 1976, AJ, 81, 489
Qian S. J., Witzel A., Krichbaum T. P. et al., 1991, AcASn, 32, 369
Qian S. J., Zhang X. Z., Krichbaum T. P. et al., 2001, Chin. J. Astron. Astrophys. (ChJAA), 1, 236
Raiteri C. M., Villata M., Aller H. D. et al., 2001, A&A, 377, 396
Roos N., Kaastra J. S., Hummel C. A., 1993, ApJ, 409, 130
Schramm K.-J., Borgeest U., Camenzind M., et al., 1993, A&A, 278, 391
Sillanpää A., Haarala S., Valtonen M. J., Sundelius B., Byrd G. G., 1988, ApJ, 325, 628
Su C. Y., 2001, Chin. A&A, 25, 153
Teräsranta H., Tornikoski M., Mujunen A. et al., 1998, A&AS, 132, 305
Tornikoski M., Valtaoja E., Terasranta H. et al., 1994, A&A, 289, 673
Valtaoja E., Teräsranta H., Tornokoski M. et al., 2000, ApJ, 531,744
Villata M., Raiteri C. M., Balonek T. J. et al., 2006, A&A, 453, 817
Villata M., Raiteri C., Sillanpää A., Takalo L. O., 1998, MNRAS, 293, L13
Valtonen M. J., Lehto H. J., Pietilä H., 1999, A&A, 342, L29
Valtonen M. J., Lehto H. J., Sillanpää A. et al., 2006a, ApJ, 646, 36
Valtonen M. J., Nilsson K., Sillanpää A. et al., 2006b, ApJ, 643, L9
Visvanathan N., 1973, ApJ, 179, 1
Webb J. R., Smith A. G., Leacock R. J. et al., 1988, AJ, 95, 374
Woo J. H., Urry C. M., 2002, ApJ, 579, 530