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A Periodicity Analysis of the Light Curve of 3C 454.3

Huai-Zhen Li[1,2], Guang-Zhong Xie[1,3], Shu-Bai Zhou[1,4], Hong-Tao Liu[1], Guang-Wei Cha[1],
Li Ma[5] and Li-Sheng Mao[5]

[1] National Astronomical Observatories / Yunnan Observatory, Chinese Academy of Sciences, Kunming 650011; *hzhli2003@163.com*
[2] Graduate School of Chinese Academy of Sciences, Beijing 100049
[3] Yunnan Astronomical Center, Yunnan University, Kunming 650091
[4] Physics Department, Yunnan University, Kunming 650091
[5] Physics Department, Yunnan Normal College, Kunming 650091

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Abstract We analyzed the radio light curves of 3C 454.3 at frequencies 22 and 37 GHz taken from the database of Metsähovi Radio Observatory, and found evidence of quasi-periodic activity. The light curves show great activity with very complicated non-sinusoidal variations. Two possible periods, a very weak one of 1.57 ± 0.12 yr and a very strong one of 6.15 ± 0.50 yr were consistently identified by two methods, the Jurkevich method and power spectrum estimation. The period of 6.15 ± 0.50 yr is consistent with results previously reported by Ciaramella et al. and Webb et al. Applying the binary black hole model to the central structure we found black hole masses of $1.53 \times 10^9 M_{\odot}$ and $1.86 \times 10^8 M_{\odot}$, and predicted that the next radio outburst is to take place in 2006 March and April.

Key words: galaxies: individual (3C 454.3)— galaxies: fundamental parameters — methods: data analysis

1 INTRODUCTION

The nature of active galactic nuclei (AGNs) is an important and open question in astrophysics. Variability is an important observed characteristic and a very powerful tool in understanding the central engine and energy production processes of AGNs. We can obtain much information on the physical mechanisms of AGNs by variability analysis: any confirmed periodicity would help us locate the relevant physical parameters and strongly limit the physical models (Lainela et al. 1999).

Some sources exhibit short-term variability on time scales of days, intraday, and even a fraction of an hour. It has been reported that 0219+418, 0317+185 and 1219+285 have short time scale variations (Xie et al. 1992, 1991a, 1988). Observations also show that some sources exhibit medium-time scale variability on time scales of weeks or months. Impey et al. (2000) claimed that PKS 0716+714 likely has a periodic variation on time scales of about 10 days and Ma et al. (2004) found that PKS 0716+714 has a variability period of 14 ± 0.1 days by using Jurkevich's method (1971a) and power spectrum analysis. Lainela et al. (1999) and Katajainen et al. (2000) have obtained a variability period about 65 days for 3C 66A and Xie et al. (2002a) also found that 3C 66A has a variability period of 63 ± 5 days. The long-term variation on timescale of yr in some AGNs has been claimed to be periodic from analyses of their historical light curves.

For example, 3C 345 has a variability period about 11.4 yr (Webb et al. 1988) and an outburst in 1991 was successful predicted (Kidger & Talalo 1990). Zhang et al. (1998) also found that 3C 345 has a period of 10 ± 0.8 yr by using the Jurkevich method (1971a). A 12-yr period was found in BL Lac object OJ287 (Sillanpää et al. 1988a; Kidger et al. 1992) and Sillanpää et al. (1988a, 1996) also successfully predicted the optical outburst in 1994. Fan et al. (2002) found that PKS 0735+178 exhibits a 14.2-yr period and Ding et al. (2004) found two periods of 5.26 ± 0.98 and 1.24 ± 0.05 yr from the light curves of PKS 0735+178 by using two different methods. Xie et al. reported the monitoring results of PKS 1510-089 and suggested a possible periodicity of about 672 ± 14 days (Xie et al. 2005a, 2002b, 2004a, 2006).

3C 454.3 (PKS 2251+158) is a strong radio source and an optically violent variable (OVV) quasars at redshift $z = 0.859$ (Penston et al. 1969). It shows large amplitude and rapid variations, a superluminal motion and a high polarization (Angione 1971; Barbieri et al. 1978; Angel et al. 1980; Fan et al. 1996). It has a "core-jet" structure (Pauliny-Toth et al. 1984) and varies strongly at centimeter (Kellermann & Pauliny-Toth 1967) and decimeter wavelengths (Fanti et al. 1979; Jones & Burbidge 1973). Its X-ray emission is weak and the Einstein Observatory in 1980 gave a flux density of only 0.5 μJy (Pauliny-Toth et al. 1987). 3C 454.3 also is a GeV γ-ray source which has been detected by COMPTEL (Blom et al. 1995). A light curve of 3C 454.3 in B-band from 1966 to 1979 has been given by Lloyd (1984). Lü & Hunter (1969) suggested there was a period of 340 days, but the predicted outburst of 1969 only showed about half of its expected amplitude (Lü 1972). The Florida light curve of 3C 454.3 did not show the extremely violent short-term activity (McGimsey et al. 1975), but some large intensity change has been observed: Xie et al. (2001a) reported a variation of 0.61 mag in 7 minutes, but the light curve was not perfect; Raiteri et al. (1998) detected a brightness decrease of 0.15 mag in the R-band and a brightness variation of 0.06 mag in the V-band in 1.7 hours; a time scale of 2.6 hours with 0.27 mag variation in R-band was observed by Villata et al. (1997). Tritton & Selmes (1971) reported variation of 1.5 mag over a period of 500 days. Its B-band brightness has often been between 16 and 17 mag (Webb et al. 1988; Sillanpää et al. 1988b), but recently, the WEBT news reported outburst $R = 12.0$ mag with a total variability range of 4 mag in the R-band. Webb et al. (1988) found there are three periods of 0.83, 2.97 and 6.39 yr in the B-band. Su (2001) found a period of 12.39 yr from the light curve of 3C 454.3 by using the Jurkevich method. In addition, the period of 6.07–6.55 yr for 3C 454.3 at 4.8, 8, 14.5, 22 and 37 GHz was obtained by Ciaramella et al. (2004). In this paper, we made great efforts to study the periodicity information in historical light curves of 3C 454.3, by using two different methods and radio data.

This paper has been arranged as follows, we first present the data and give a general discussion on the radio light curve in Section 2. A detailed analysis by two methods and the results are presented in Section 3. A theoretical analysis of the central structure is given in Section 4 and finally we present our conclusions in Section 5.

2 DATA AND VARIABILITY ANALYSIS OF THE LIGHT CURVES

We present the historical light curves of 3C 454.3 at 37 and 22 GHz from 1980 to 2004, taken from the database of the Metsähovi Radio Observatory (Teräsranta et al. 2005). The light curve of 3C 454.3 at the frequency 37 GHz consists of 631 points spanning about 24 yr, is shown in Figure 1. From Figure 1 one can find 3C 454.3 is a very active object with a range of variation $\Delta F_{37\ \mathrm{GHz}} = 12.49$ Jy. The source reached a maximum flux of $F = 16.82$ Jy in 1993 December at the frequency 37 GHz. One also can find there are two major and some minor outbursts. It is of interest to note that these variabilities indicate the possibility of periodicity. The light curve of 3C 454.3 at frequency 22 GHz is shown in Figure 2 and one can notice it is completely similar to the light curve at 37 GHz.

In the following section, we will analyze the periodicity in the light curve of 3C 454.3 by using the Jurkevich method and power spectrum density estimation.

3 PERIODICITY ANALYSIS

The Jurkevich method is based on the expected mean square deviation and was described in detail by Jurkevich (1971a). It is less liable to generate spurious periodicity. It involves testing a series of trial periods and the data under discussion are folded at the given trial period. Then, all data are divided into m

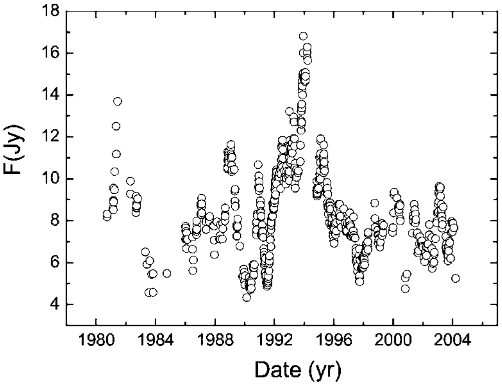

Fig. 1 Light curve of 3C 454.3 at 37 GHz over about 24 yr (631 data points).

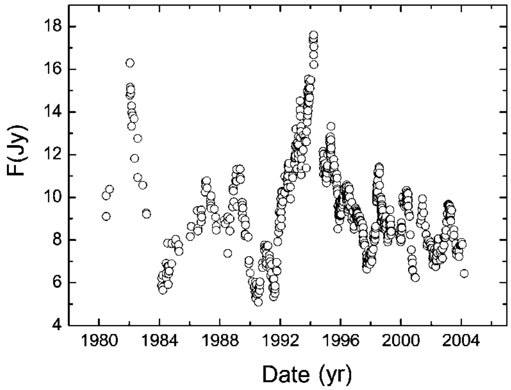

Fig. 2 Light curve of 3C 454.3 at 22 GHz over about 24 yr (755 data points).

groups according to their phases. The variance V_i for each group and the Sum V_m^2 of groups are computed. Jurkevich et al. (1971a, b) have described the computation of the variance in detail. The closer a trial period to a real period, the smaller the V_m^2 will be. If a trial period equals to a true one, then V_m^2 would reach a minimum. If V_m^2 shows several minimum values, then there are several possible periods. Following Jurkevich (1971a), we adopt the half width at half minimum (HWHM) as the error.

In order to estimate the reliability of the result, Kidger et al. (1992) and Liu et al. (1995, 1997) introduced a parameter f

$$f = \frac{1 - V_m^2}{V_m^2}, \tag{1}$$

where V_m^2 is the normalized value. If $f = 0$, it corresponds to $V_m^2 = 1.0$ and there is not periodicity at all. The best period can be found from the plot of the function f: In general, if $f \geq 0.5$, it suggests a very strong periodicity in the data sample; if $f \leq 0.25$, it indicates that the periodicity is only a weak one or even a spurious one. In the Jurkevich test, the parameter m is important and can be modified: more groups give higher sensitivity, but fewer data points per group introduce a large noise in the plot.

We analyze the data sample using $m = 10$, which gives over 60 points per group. The result from the Jurkevich method is shown in Figure 3. There are four obvious minimum values of V_m^2, indicating four possible periods from the trial. A minimum of $V_m^2 = 0.776$ at the period $P_1 = 1.57 \pm 0.12$ yr has $f = 0.29$ (larger than 0.25), indicating that the period possibly exists. In Figure 3, another minimum of $V_m^2 = 0.697$ at the period $P_2 = 3.11 \pm 0.17$ yr with $f = 0.44$ (larger than 0.25) is conspicuous and is consistent with the result of 2.97 yr found by Webb et al. (1988). One can note that the period P_2 is about twice the period P_1 ($P_2 \simeq 2P_1$).

In Figure 3, there is also another minimum value of $V_m^2 = 0.447$ at a period of $P_3 = 6.15 \pm 0.50$ yr with $f = 1.24$ (larger than 0.5), thus indicating a very strong periodicity. The period is consistent with the results of Ciaramella et al. (2004) and Webb et al. (1988). In addition, one can notice that the periodicity of P_3 is about four times the period P_1 ($P_3 \simeq 4P_1$). In Figure 3, there is a fourth minimum value of $V_m^2 = 0.322$ at a period of $P_4 = 12.37 \pm 0.43$ yr with $f = 2.1$. It is consistent with Su (2001) and equals the interval between the two maximum fluxes observed in 1981 and 1993 (see Fig. 1).

For comparing these results, we also analyze the data at 37 GHz using $m = 3$ and $m = 5$. The result of $m = 3$ shows three possible periods from among the trials: 1.56, 6.77 and 11.7 yr, and the result of $m = 5$ shows there are four possible periods, 1.55, 3.10, 6.21 and 11.7 yr. We note these results derived from two different values of m are entirely consistent.

In order to investigate the reliability of these results, we use the traditional power density approach to analyze the periodicity information of the 37 GHz data. The power density was estimated by an algorithm given by Lomb (1976) and the routine for the calculation was obtained from *Numeric Recipies* (1994).

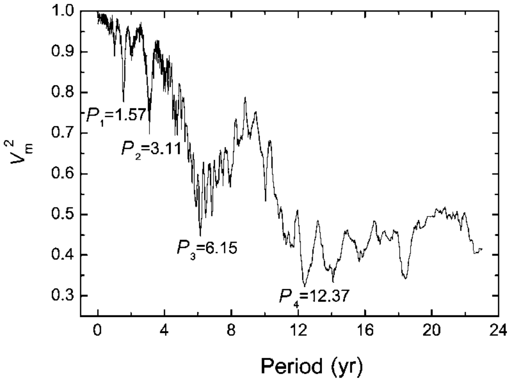

Fig. 3 Normalized Jurkevich test result for the period search in 3C 454.3 at 37 GHz using the data shown in Fig. 1.

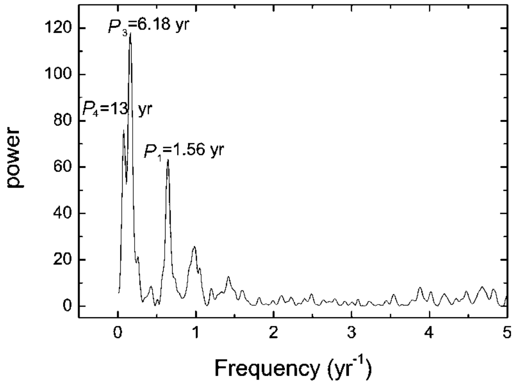

Fig. 4 Power spectrum test result for period search in 3C 454.3 at 37 GHz using the data shown in Fig. 1. Three peaks appear at periods 1.56, 6.18 and 13 yr.

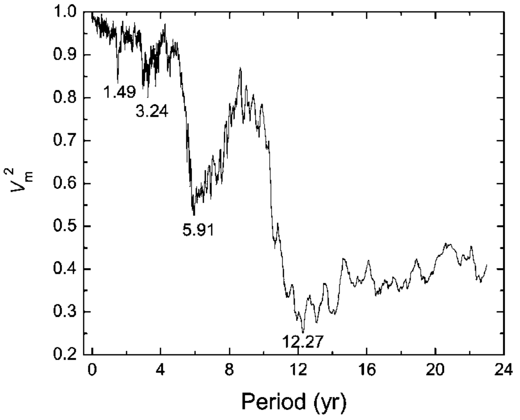

Fig. 5 Normalized Jurkevich test result for the period search in 3C 454.3 at 22 GHz using the data shown in Fig. 2.

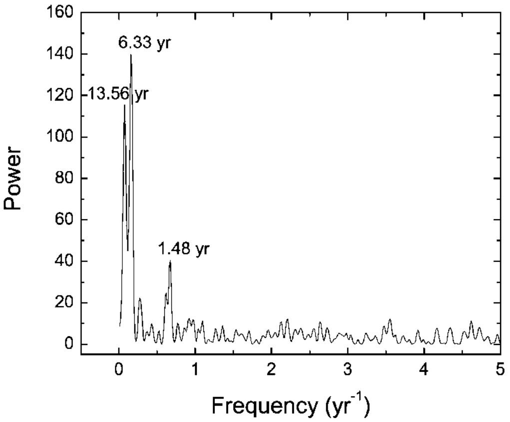

Fig. 6 Power spectrum test result for the period search in 3C 454.3 at 22 GHz using the data shown in Fig. 2. Three peak appear at periods 1.48, 6.33 and 13.56 yr.

Figure 4 gives the result, showing three significant peaks at $P_1 = 1.56 \pm 0.10$, $P_3 = 6.18 \pm 1.04$ and $P_4 = 13 \pm 2.6$ yr, and this means there are three possible periods and they are in good agreement with the results of $P_1 = 1.57 \pm 0.12$, $P_3 = 6.15 \pm 0.50$ and $P_4 = 12.37 \pm 0.43$ yr obtained by the Jurkevich method.

In order to further investigate the reliability of these results, we analyze the data at 22 GHz using the same foregoing methods. The results from the two different methods are shown in Figures 5 and 6, respectively. From the two figures, one can notice that there are three possible periods: 1.49, 5.91 and 12.27 yr. This is in good agreement with the previous results based on the 37 GHz data. The two periods of 5.91 and 12.27 yr are very strong with $f = 0.9$ and $f = 3$, respectively. The period of 1.49 yr is weak with $f = 0.2$. These are entirely similar to the results of the 37 GHz data: two very strong periods of 6.15 and 12.37 yr and one weak period of 1.57 yr.

We obtained nearly identified results from power spectrum density estimation and the Jurkevich method. Our analysis shows there are three possible periods of $P_1 = 1.57 \pm 0.12$, $P_3 = 6.15 \pm 0.50$

and $P_4 = 12.37 \pm 0.43$ yr present in the radio light curve of 3C 454.3. The period of 6.15 ± 0.50 yr is consistent with the previous work of Ciaramella et al. (2004) and Webb et al. (1988), who found that a period of about 6 yr exists in the light curves of 3C 454.3 at radio and B bands. The period of 12.37 ± 0.43 yr is consistent with the work of Su (2001). However, the total range of the observational data spans about 24 yr, which is merely twice the period of 12.37 ± 0.43 yr. Moreover, the period of $P_4 = 12.37 \pm 0.43$ yr is about two times the period $P_3 = 6.15 \pm 0.50$ yr ($P_4 \simeq 2P_3$), which is suggestive of a simple relation between P_4 P_3. Below we will further discuss the periods of $P_1 = 1.57 \pm 0.12$ and $P_3 = 6.15 \pm 0.50$ yr.

The present work differs from others in that we found there are two possible periods of 1.57 ± 0.12 yr and 6.15 ± 0.50 yr, and the longer period of $P_3 = 6.15 \pm 0.50$ yr is almost four times the period of the shorter $P_1 = 1.57 \pm 0.12$ yr ($P_3 \simeq 4P_1$). According to Liu et al. (1995), the duration of the data sample spans at least six times the length of the periodicity. However, the total observation range of the data sample we used spans about 24 yr, which is merely four times of the period of 6.15 ± 0.50 yr. Even so, we think the period of 6.15 ± 0.50 yr is indeed present, because the results from the power spectrum analysis and the Jurkevich method show strong periods at the two frequencies and are consistent with the results of other authors (Ciaramella et al. 2004; Webb et al. 1988). Regarding the period of 1.57 ± 0.12 yr, although it is not as strong as the period of 6.15 ± 0.50 yr, we also think it is real, because it has appeared in Figures 3–6. The reliability of the period of 1.57 ± 0.12 yr and the relation between the two periods of 6.15 ± 0.50 yr and 1.57 ± 0.12 yr need further investigation and more observations.

According to the foregoing results, the next radio outburst is predicted to take place in 2006 March and April. The blazar 3C 454.3 has gone through a dramatic, historical outburst at the beginning of May, 2005 (Fuhrmann et al. 2006). According to these results, the radio outburst lags by about one year behind the optical outburst and the lag is consistent with the results obtained by Pomphrey et al. (1976) and Hanski et al. (2002). Pomphrey et al. (1976) have reported a possible correlation between optical radio events 1.2 yr apart and Hanski et al. (2002) reported a possible correlation between optical and radio variations with time lags of 310 days.

4 THE CENTRAL STRUCTURE OF 3C 454.3

The foregoing results show that there are two long-term periods in the radio light curves of 3C 454.3 on timescales of 6.15 ± 0.50 and 1.57 ± 0.12 yr. First, we study the period of 6.15 ± 0.50 yr. We tentatively provide a theoretical explanation in the framework of the binary black hole model. Incidentally, Begelman et al. (1980) have pointed out that the binary black hole model for AGNs has orbital periods of the order of 10 yr and the precession period of exceeding 10^4 yr.

The binary black hole model provides an interpretation of emission variability from the central structure of the AGN. For 3C 454.3, we propose there is a binary black hole in its nucleus and the recurrent outbursts are the result of tidal interaction during each orbital period of 6.15 ± 0.50 yr. We assume an accretion disk similar to the one in a normal supermassive black hole in the center of AGNs and surrounding the primary black hole and possibly both black holes; the observed luminosity of the object is from the jet and any kind of turbulence in the disc surrounding the primary black hole and possibly both; the minimum period is caused by the eclipse of the binary pair system. So we can observe the outbursts that are similar to other object and the minima of light curves when the primary black hole is eclipsed by the secondary black hole.

4.1 The Masses of the Binary Black Hole System

The mass of a black hole, which cannot be less than $10^6 M_\odot$ (Magorrian & Tremaine 1999), is the important factor in its life. Based on our hypothesis, the black hole of the system is similar to a normal supermassive black hole in the center of AGNs. Then, we consider that the periodic light variations may occur in the accretion disks of the black hole systems and are contributed by the orbital motion of radiating regions around the black holes.

4.1.1 Mass of the Primary Black Hole

Mclure & Jarvis (2002) advanced a technique for estimating the black hole mass of high-redshift quasars from optical spectroscopy. The method is based on the following relationship given by Mclure & Jarvis

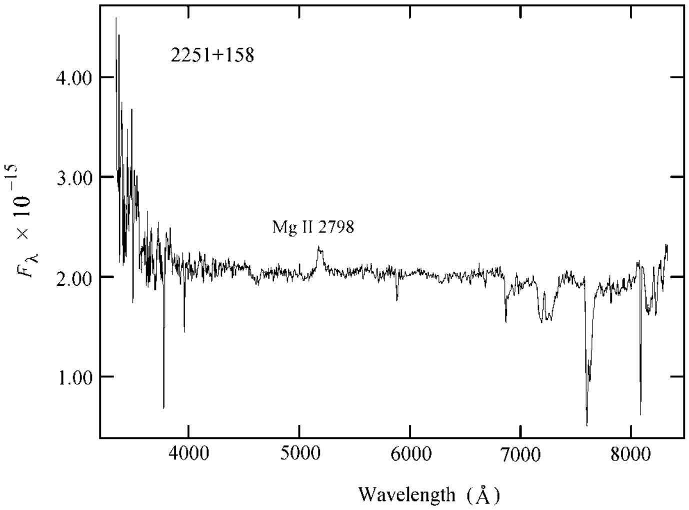

Fig. 7 Optical spectrum of 3C 454.3 obtained with the 2.16 m telescope of the Xinglong Station of National Astronomical Observatories, CAS.

(2002), relating the black hole mass to the full-width at half-maximum (FWHM) of the emission line MgII λ2798 Å and the UV luminosity at 3000 Å in the rest reference frame:

$$M_{\rm BH} = 3.37\Big(\frac{\lambda L_{3000}}{10^{37}W}\Big)^{0.47}\Big[\frac{\rm FWHM(MgII)}{\rm km\ s^{-1}}\Big]^2 M_\odot, \tag{2}$$

or,

$$M_{\rm BH} = 3.37 \times 10^6\Big(\frac{\lambda L_{3000}}{10^{44}\ {\rm erg\ s^{-1}}}\Big)^{0.47}\Big[\frac{\rm FWHM(MgII\lambda2798)}{\rm 1000\ km\ s^{-1}}\Big]^2 M_\odot. \tag{3}$$

We carried out optical spectrum observations of 3C 454.3 at the Xinglong Station of National Astronomical Observatories, CAS, using the 2.16 m telescope on 2003 July 28. The detector was an OMR spectrograph plus a TEK 1024 CCD camera with spectral resolution 4.86 Å pixel^{-1}. The effective spectral range is about 4900 Å and the calibration stars are HD2857 and Kopff27. We used the IRAF software package to process the primitive spectra. The result is shown in Figure 7. From the figure we obtain FWHM (MgIIλ2798)=67.11 Å, and $F_{3000\mathring{A}} = 2.065 \times 10^{-15}$ erg s^{-1}cm^{-2}Å^{-1}, in the rest reference frame. Then the luminosity at 3000 Å is $\lambda L_{3000\mathring{A}} = 1.3 \times 10^{46}$ erg s^{-1} on adopting the Hubble constant $H_0 = 70$ km s^{-1} Mpc^{-1} and deceleration parameter $q_0 = 0.5$. Based on Equation (3), the mass of the primary black hole is $M \sim 1.53 \times 10^9 M_\odot \approx 10^{9.18}\, M_\odot$, which is in good agreement with that of Woo & Urry (2002).

4.1.2 Mass of the Secondary Black Hole

According to Xie et al. (2005b), black holes in the centres of AGNs should be Kerr black holes. The mass of the Kerr black hole can be estimated by the formula

$$M_K = 1.62 \times 10^4 \frac{\delta}{1+z}\Delta t(M_\odot), \tag{4}$$

where Δt is the timescale of variability of the AGN, δ is the Doppler factor and z is the redshift. According to Xie et al. (1991b, 2001b, c, 2003 and 2004b), the Doppler factor, δ, is given by

$$\delta \geq \Big(\frac{5.0 \times 10^{-43}\Delta L_{\rm bol}}{0.057 \times \Delta t_{\rm ob}}\Big)^{\frac{1}{4+\alpha}}, \tag{5}$$

where α is the spectral index. For 3C 454.3, $\alpha = 1$ and $\log \Delta L_{\rm bol} = 46.80$ erg s^{-1} (Xie et al. 2004c).

A variability of 0.5 mag on a timescale of one day (Lloyd 1984) and a variability on a timescale of $1.7-2.6$ h (Vallata et al. 1997; Raiteri et al. 1998) have been reported in 3C 454.3. According to Equation (4), the mass estimated from the 1-day timescale is $M_K \sim 10^{9.04} M_\odot$, which is consistent with the result from Equation (3) ($M_K \approx M$). Thus, the variability on the timescale of 1-day may be caused by the primary black hole. We consider the variability on the timescale of $1.7 - 2.6$ h may be caused by the secondary black hole. The timescale of 2.6 h will be used to estimate the mass of the secondary black hole, because the light curve on the timescale of 2.6 hours is more complete than that on the timescale of 1.7 hours. The mass estimated with the 2.6-hour timescale is $m_K \sim 1.86 \times 10^8 M_\odot \approx 10^{8.27} M_\odot$, that is, the mass of the secondary black hole is $m = m_K \sim 10^{8.27} M_\odot$. Thus, the primary and secondary black holes differ in mass by less than one order of magnitude ($\frac{M}{m} = 10^{0.91}$). According to the traditional definition of merger, the binary black hole system may have been produced by a minor merger. Even so, there may still be an accretion disk surrounding the secondary black hole. However, further research is still needed on whether the shorter timescale variability is caused by the secondary black hole. The black hole mass estimated with the timescale of variability is an upper limit.

4.2 The Orbit of the Binary Pair

According to the Kepler's law, we can estimate the orbit of the binary pair,

$$T^2 = \left(\frac{P}{1+z}\right)^2 = \frac{4\pi^2 a^3}{G(M+m)}, \tag{6}$$

where T is the variability time scale in the rest reference frame, P the orbital periodicity in the observer reference frame, a the separation in the black hole binary, M and m the masses of the primary and secondary black holes. If $P = 6.15$ yr, $M = 1.53 \times 10^9 M_\odot$ and $m = 1.86 \times 10^8 M_\odot$, then $a \sim 5.88 \times 10^{16}$ cm $\approx 10^{16.77}$ cm.

4.3 The Lifetime of the Binary Black Hole System

According to Kraft et al. (1962), the orbit of a binary black hole system should evolve via gravitational radiation. Its lifetime should be

$$t_{\rm merge} = \frac{5}{256} \frac{c^5}{G^3} \frac{a^4}{(M+m)^2 \mu}, \tag{7}$$

where $\mu = \frac{Mm}{M+m}$. Thus $t_{\rm merge} \sim 2.37 \times 10^5 \approx 10^{5.37}$ yr for 3C 454.3.

4.4 Gravitational Radiation

In a close massive black hole binary, the luminosity of gravitational wave, $L_{\rm GR}$, is (Shapiro & Teukolsky 1983)

$$L_{\rm GR} = \frac{32}{5} \mu^2 \frac{(m+M)^3}{a^5} \frac{G^4}{c^5}, \tag{8}$$

and $L_{\rm GR} \sim 3.28 \times 10^{46} \approx 10^{46.52}$ erg s^{-1} for 3C 454.3.

The period of 1.57 ± 0.12 yr was found in our work. Even the period from the Jurkevich method is weak, we think the existence of the period is reliable, because the same result was found in radio light curves at two frequencies from two different methods (power spectrum and Jurkevich). If it is a real period, then a possible interpretation is the helical jet theoretics (Villata & Rarteri 1999). The model of helical jet provides a geometrical explanation for the emission variability in blazars. In this model the emission variability is due to the change of viewing angle: the source gets fainter as the viewing angle increases. As the viewing angle changes, the emission flux observed on the ground is varied. The reliability of the period of 1.57 ± 0.12 yr and the relation of the two periods of 6.15 ± 0.50 and 1.57 ± 0.12 yr need further study, and we would take more data to check them in the future.

5 CONCLUSIONS

We have presented the historical light curve of 3C 454.3 at 37 and 22 GHz and found there are two long-timescale periodic outbursts with periods of 1.57 ± 0.12 and 6.15 ± 0.50 yr in the radio light curve from two different methods of analysis. The period of 1.57 ± 0.12 yr is very weak, if it is a real one. It is, we think, caused by a helical jet, that is, the variable emission is due to viewing angle change and is not an intrinsic characteristic of the object. The other period of 6.15 ± 0.50 yr is a very strong period, and we think it is real. We propose that 3C 454.3 has a binary black hole in its nucleus surrounded by accretion disks and that outbursts are produced by tidal effects when the two black holes pass the pericenter point of their common orbit.

Through a very simple estimation, we obtain the parameters of the central structure of 3C 454.3 as follows. The masses of the primary and the secondary black holes are $1.53 \times 10^{9} M_{\odot}$ and $1.86 \times 10^{8} M_{\odot}$, respectively; the distance between the two black holes is 5.88×10^{16} cm and their life time is 2.37×10^{5} yr. In addition, the luminosity of gravitational wave emitted is $L_{\rm GR} \sim 3.28 \times 10^{46}$ erg s^{-1}. These results suggest that 3C 454.3 is a possible candidate of binary black hole system. However, the evidence at present is not strong and calls for more observations.

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