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Blazar 中央黑洞的变化特性和质量估计

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摘要

利用 blazar 的长期的光学和红外测光数据分析了其变化特性，并利用 Jurkevich 技术和分立相关函数 (DCF) 法在光学数据中寻找光变曲线中的周期性. 发现了 1.5 至 19yr 范围的周期. 利用短时间尺度来估计中央黑洞的质量，发现 γ 射线噪 blazar 的中心黑洞质量范围为 $(3.8\sim 130)\times 10^7 M_\odot$，并对结果作了讨论.

关键词 活动星系核 (AGNs)：变化性 — 周期性 — 耀变体

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Variability Properties and Masses of Central Black Hole for Blazars

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Abstract

In this paper, the compiled long-term optical and infrared measurements of some blazars are used to analyze the variation properties, and the optical data are used to search for periodicity evidence in the lightcurve by means of the Jurkevich technique and the discrete correlation function (DCF) method. The periods are found in the range of 1.5 to 19 years. The short time scales are used to estimate the central black hole masses which are found in the range of $(3.8\sim 130)\times 10^7 M_\odot$ for the gamma-ray loud blazars. Some discussions are presented.

Key words Active Galactic Nuclei (AGNs): variability— periodicity—blazar

1 Introduction

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

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Fan *et al.* 1998). The variations of AGNs are characterized by rapid variability superposed on the long-term variation. The intensive monitoring of the AGNs provides not only the rapid variability (or the so called short-term variability or intraday variability) but also the long-term tendency of variations. There are some groups working on such kind of monitoring in the radio bands: Michigan (Aller *et al.* 1999), Metsahovi (Terasranta *et al.* 1999; Valtaoja *et al.* 2000), and IRAM (Steppe *et al.* 1995). Assuming an intrinsic origin of IDV, the brightness temperature of the variable component can be derived using the Rayleigh-Jeans law and the light travel time argument: $T_{\rm B}(K) = 4.5 \times 10^{12} \times S[{\rm Jy}]\left(\frac{\lambda[{\rm cm}]D_{\rm L}[{\rm Mpc}]}{t_{\rm obs}[{\rm d}](1+z)}\right)^2$, Where S is the radio flux density at λ (cm) in unites of Jy, $D_{\rm L}$ is the cosmological distance in unites of Mpc, $t_{\rm obs}$is the variability time scale in unites of days, and z is redshift. For the strong variations seen within one day in most of the IDV-sources, above equation yields brightness temperature of up to $10^{17} \sim 10^{21}$K, far in excess of the inverse Compton limit of 10^{12}K. This fact seriously challenges existing models to explain AGN variability. Adopting an intrinsic origin for IDV, Qian *et al.* (1991) considered the propagation of a thin shock through the jet plasma in a cylindrical geometry with periodic boundaries. They found this model capable of explaining the variations and the apparent high temperature by $T_{\rm B}^{\rm app} = \gamma_{\rm s}^2\delta^3 T_{\rm B}^{\rm true}$, where $\gamma_{\rm s}$ is the Lorentz factor of the shock. δ is the Doppler factor and $T_{\rm B}^{\rm true}$ and $T_{\rm B}^{\rm app}$ are the intrinsic and observed brightness temprature. An alternative, collective emission (Benford 1992) caused by the scattering of an intense, relativistic electron beam from plasma waves, can avoid the violation of the inverse Compton limit. It is still unknown whether this process can produce broad-band (i.e. radio-optical) variations (see Kraus *et al.* 1999). Optical observations are made widely by

- American group (Miller *et al.* 1999; Balonek *et al.* 1998; Webb *et al.* 1988; 1998)
- Argentina group (Romero et *al.* 2000a, b, c)
- Chinese group(Fan *et al.* 1997a, 2000a; Bai *et al.* 1998, 1999; Xie *et al.* 1999; Qian *et al.* 2000)
- Finland group (Pursimo *et al.* 2000; Sillanpaa *et al.* 1996a,b; Katajainen *et al.* 1999; Takalo *et al.* 1996,1998,)
- Georgia group (Nikolashvili e*t al.* 1999a,b; Kurtanidz *et al.* 1999, Kurtanidze, O.M., & Nikolashvili, 1999, 2000)
- Germany group (Heidt & Wagner 1998)
- Italy groups (Villata, *et al.* 1999, 2000; Raiteri et *al.* 1998a,b; Nesci *et al.* 1999; Tosti *et al.* 1999)
- Russian group (Efimov & Shakhovskoy, 1998; Badzhanyants & Chernyshev 1999)

Some particular objects have been claimed to display periodicity in their lightcurves over a variety of timescales (e.g. and references therein), but, in general, the clear identification of periodic behavior has been very elusive due to the complexity of the optical lightcurves and the lack of databases large enough as to provide an adequate sampling over large periods.

Blazars are an extremely subclass of AGNs, characterized as rapid and high amplitude variations, high and variable polarization, superluminal radio components, nonthermal continuum (Cheng *et al.* 1999; Fan *et al.* 1999; Mei *et al.* 1999). Blazars have been monitored for a long time, compilations are available for optical (Fan & Lin 2000a; Fan *et al.* 2000b) and infrared (Fan & Lin 1999a; Fan 1999a) bands. The infrared data are available in http://xxx.lanl.gov/astro-ph/9908104 and http://xxx.lanl.gov/astro-ph/9910269. The long-term measurements make it possible for one to search for periodicities from the light curves and to discuss the long-term variability properties. Because the characteristic of the astronomical measurements, we adopted the Jurkevich (Jerkevich 1971) and DCF (Discrete Correlation Function) (see Fan & Lin 2000b) methods to the available data in searching for the periods. In the second section we will give the variation properties, in the third section, we present the results and finally in section 4, we give some discussions.

2 Variation Property

From the compilation (Fan *et al.* 2000b, Fan & Lin 2000a,b; Fan 1999a), we found that the largest variations are comparable in both the optical and infrared bands (see Table 1). Largest variations at different wavelengths increase with decreasing wavelength. The variations are also correlated with the observed maximum optical polarization, $P^{\rm ob}$ which can be explained using the beaming model

$$P^{\rm ob} = \frac{(1+f)\delta_{\rm o}^{\rm p}}{1+f\delta_{\rm o}^{\rm p}} P^{\rm in}, \tag{1}$$

where intrinsic polarization, P^{in} is defined by

$$P^{\rm in} = \frac{f}{1+f}\frac{\eta}{1+\eta}, \tag{2}$$

which is the polarization in the source frame, an indication of magnetism field in the source and $\delta_{\rm o}$ is the optical Doppler factor (see Fan *et al.* 1997a for details). Therefore, the observed polarization is associated with the magnetic field and the Doppler factor.

From beaming model, which gives $S^{\rm ob} = (1+f\delta^{\rm p})S_{\rm unb} \equiv S_0 10^{-0.4m^{\rm ob}}$ and relation (1), we can obtain the following the relation

$$\log P(\%) = 0.4(\lambda - 1)\Delta m + \log P_{\rm min}, \tag{3}$$

where $P(\%)$ is the polarization and λ is a parameter, and Δm is the optical variation.

Tab.1 The largest variations of Blazars

Name	Δm_{opt}	Δm_{IR}	$P_{opt}(\%)$	Name	Δm_{opt}	Δm_{IR}	$P_{opt}(\%)$
(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
0048-097	2.7	6.55	27.2	0109+244	3.07	1.58	17.3
0118-272	1.05	0.67	17.	0138-097	1.52	1.69	29.3
0215+015	5.0	2.69	20.	0219+428	2.0	1.61	18.0
0235+164	5.3	5.0	44.	0323+022	1.3	0.97	10.4
0420-014	2.8	2.88	20.	0422+004	2.2	3.25	22.
0521-365	1.4	1.25	11.	0537-441	5.4	3.0	18.8
0716+714	5.0		29.0	0735+178	4.6	2.47	36.
0736+017	1.35	2.71	6.	0754+100	3.16	1.88	26.
0818-128	3.78	2.14	36.	0823-223	1.41	2.32	11.
0829+046	3.58	2.15	12.	0851+202	6.0	3.87	37.2
0912+297	2.25	2.27	13.	1101+384	4.6	2.03	16.0
1144-379	1.92	3.46	8.5	1147+245	1.0	1.34	13.0
1156+295	5.0	4.47	28.	1215+303	3.3	1.05	14.
1219+285	3.13	2.46	10.	1253-055	6.7	4.57	44.
1308+326	4.17	5.55	28.	1418+546	4.8	1.59	24.
1510-089	5.4	1.25	14.	1514-241	3.0	2.64	8.0
1538+149	3.7	0.89	32.8	1641+395	3.0	3.16	35.
1652+398	1.30	2.37	7.0	1727+502	2.1	0.82	6.0
1749+096	2.7	2.21	32.	1807+698	2.0	1.02	12.
1921-293	2.64	3.06	17.	2005-489	0.53	0.31	2.0
2155-304	1.85	1.88	14.2	2200+420	5.31	2.93	23.
2223-052	5.0	3.96	17.3	2240-260		1.66	15.1
2251+158	2.5	1.57	19.	2254+074	3.27	1.36	21.

Notes to the table: Col. 1 The name of the source; Col. 2, The largest optical variation; Col. 3 The largest infrared variation; Col. 4, The largest optical polarization

3 Periodicity Analysis Methods

3.1 Jurkevich Method

The Jurkevich method (Jurkevich 1971, also Kidger *et al.* 1992; Fan *et al.* 1998a; Fan 1999b) is based on the expected mean square deviation and it is less inclined to generate spurious periodicity than the Fourier analysis used by other authors (e.g. Fan *et al.* 1997b). It tests a run of trial periods around which the data are folded. All data are assigned to m groups according to their phases around each trial period. 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 reduced variance relative to those given by other false trial periods and with almost constant values. 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 (Fan *et al.* 1998a).

3.2 DCF Method

The DCF (Discrete Correlation Function) method is intended for analysis of the correlation of two data set. It is described in detail by Edelson & Krolik (1988) (also Fan *et al.* 1998b). This method can indicate the correlation of two variable temporal series with a time lag, and can be applied to the periodicity analysis of a unique temporal data set. If there is a period, P, in the lightcurve, then the DCF should show clearly whether the data set is correlated with itself with time lags of $\tau = 0$ and $\tau = P$ (see Fan & Lin 2000b). We have implemented the method as follows.

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

$$UDCF_{ij} = \frac{(a_i - \bar{a}) \times (b_j - \bar{b})}{\sqrt{\sigma_a^2 \times \sigma_b^2}}, \tag{4}$$

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. Secondly, we average 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, and

$$DCF(\tau) = \frac{1}{M}\Sigma\, UDCF_{ij}(\tau), \tag{5}$$

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

$$\sigma(\tau) = \frac{1}{M-1}\{\Sigma\,[UDCF_{ij} - DCF(\tau)]^2\}^{0.5}. \tag{6}$$

4 SMBHs in the Centers of Active Galactic Nuclei

Although AGNs largely provide the motivation for searching for SMBHs, ironically,to be precise conventional techniques used in these objects to measure masses fail. The bright continuum emission of the active nucleus nearly always completely overpowers the stellar absorption lines near the center, and in many cases the narrow emission lines are significantly affected by non-gravitational forces.

An approach taken in the past attempts to utilize the broad $[(1\text{-few})\times10^3\text{km}\cdot\text{s}^{-1}]$ emission lines that are thought to arise from the so-called broad-line region (BLR), a tiny, dense region much less than a parsec from the central source. The mass follows from $\eta v^2 r_{\rm BLR}/G$, where $\eta \approx 1-3$ depending on the kinematic model adopted. The BLR radius has traditionally been estimated from photoionization arguments. $F = \eta ma = \eta\frac{v^2}{r} = GMm/r^2 \Longrightarrow M = \frac{\eta v^2 r_{\rm BLR}}{G}$. One of the uncertainties in the application of this simple formalism lies in the choice of v. One reasonable choice might be $v = (\sqrt{3/2}\text{FWHM})$, the width at half-maximum of a representative broad lines. Another ambiguity is which line to use, since not all broad emission lines have the same widths. Since the line width affects the mass quadratically, it is conceivable that some measure of the line profile other than the FWHM is more appropriate.

4.1 SMBHs from Fe Kα

The recent detection in AGNs of the broad iron Kα line at 6.4 KeV. This line has been known for some time to be a common feature in the hard X-ray spectra of AGNs, and it is thought to arise from fluorescence of the X-ray continuum off of cold material, persumably associated with the accretion disk around the SMBHs. The ASCA satellite provided the much high spectral resolution for the line, which perhaps imply the existence of SMBHs. In addition, detailed modeling of the line asymmetry has even the potential to measure the spin of the BHs, but this is still very much a goal of the future.

4.2 SMBHs from long-term variation period

Begelman *et al.* (1980) have considered binary black hole models for active galactic nuclei with orbit periods of the order of 10 yr. They pointed out that the precession period in a black hole binary system generally exceeds 10^4 yr. Thus it is impossible that the $\approx$10 yr period is caused by the precesion of a relativistic jet on and off the line of sight. In the binary black hole model of Sillanpaa *et al.* (1988), the tidal perturbations of sufficient strength create global disturbances in the disk and cause a flow of matter into the center of the disk. They consider that two mass points (black holes) are initially in an elliptic orbit. The larger mass point is surrounded by a self-gravitational disk of matter which is tidally perturbed by the smaller mass point. The disk lies in the orbital plane of the binary, and it rotates in the same sense as the binary. Using simulation (inputing the ratio of the masses of two black holes, M_1, M_2 and the disk mass, M_{d}, of the primary black hole, $\frac{M_2}{M_1+M_{\mathrm{d}}}$, the eccentricity e, the semimajor axis of the binary orbit a, and the radius of the main disk r, the last three parameters are correlated), one can get the variation pattern and the mass of the smaller black hole can also be estimated by the short time scale, $M \approx 10^6 M_{\odot}\Delta t(\mathrm{min})$. In this sense, one can estimate M_1. But the problem is why the short time scale is caused by the smaller black hole.

If the long-term variation period is caused by a slim disk, then the period can be expressed as $P = 9.0\mathrm{yr}\delta(\frac{\alpha}{0.1})^{-0.62}(\frac{M_{\mathrm{BH}}}{10^6 M_{\odot}})^{1.37}$. But this method gives less massive black hole mass ($\approx 10^7 M_{\odot}$) (Fan 1999b).

Abraham & Romero (1999) and Romero *et al.* (2000c) proposed a way to explain the long-term period. Assuming that the inner jet and the innermost parts of the accretion disk that surrounds the primary black hole are coupled in such a way that a precession of the disk induces a precession of the jet. A secondary black hole in a close non-coplanar orbit can exert a tidal perturbation on the disk that can result in the near-rigid body precession of its innermost region. But the masses can not be determined precisely.

4.3 SMBHs from short time scales

Short time scales are observed in many cases, which perhaps bring us the size information of the emission region, $R \le c\delta\frac{\Delta t}{1+z}$ where c, δ, z, and Δt are the speed of the light, the Doppler factor, the redshift, and the short time scale respectively. Therefore, if R is assumed to be *few* (3 for instance) Schwarzschild radii, one can estimate the masses of the central black hole

$$M \approx 2 \times 10^6 M_\odot \frac{\delta \Delta t(\mathrm{min})}{1+z}.$$

But the Doppler factor is usually unknown. In this sense, based on the variable time scale, we propose a method to estimate the masses of the central black hole, the Doppler factor, and the size of the emission region for gamma-ray loud blazars are estimated by Cheng, Zhang, & Fan (1999).

Therefore the γ-rays are focused in a small solid angle, $\Omega = 2\pi(1 - \cos \Phi)$, suggesting that the apparent observed luminosity should be expressed as $L_\gamma = \Omega D^2 (1+z)^{\alpha_\gamma - 1} F_\gamma^{\mathrm{obs}}(> 100\mathrm{MeV})$, where F_γ^{obs} is the observed energy flux of the γ-rays, D the distance to the AGN, and z the redshift. The observed γ-rays from the AGN require that the jet almost points to us and the optical depth $\tau \leq 1.0$. In this sense, both the absorption and beaming (boosting) effects should be considered when the properties of a γ-ray loud blazar are discussed.

Now we describe our method of estimating the basic parameters (M, δ, Φ and d) of the blazars with short timescale variabilities in the γ-ray band. As mentioned above, high energy γ-rays can escape only when the optical depth of γ-γ pair production is not larger than unity. Based on Becker & Kafatos (1995), we can obtain an approximate relation for the optical depth at an arbitrary angle, Φ,

$$\tau_{\gamma\gamma}(M_7, \Phi, d) = \frac{1}{3}(51 - 8\omega) \times \Phi^{2.5} \left(\frac{d}{R_\mathrm{g}}\right)^{-\frac{2\alpha_\mathrm{X}+3}{2}} + k M_7^{-1} \left(\frac{d}{R_\mathrm{g}}\right)^{-2\alpha_\mathrm{X}-3} , \tag{7}$$

where k is given by

$$\begin{aligned} k \ = \ & 4.50 \times 10^9 \frac{\Psi(\alpha_\mathrm{X})(2-\omega)(1+z)^{3+\alpha_\mathrm{X}} F_0'(1+z-\sqrt{1+z})^2}{(2\alpha_\mathrm{X}+4-\omega)(2\alpha_\mathrm{X}+3)} \times \\ & \left[\frac{(\frac{R_0}{R_\mathrm{g}})^{2\alpha_\mathrm{X}+4-\omega} - (\frac{R_\mathrm{ms}}{R_\mathrm{g}})^{2\alpha_\mathrm{X}+4-\omega}}{(\frac{R_0}{R_\mathrm{g}})^{2-\omega} - (\frac{R_\mathrm{ms}}{R_\mathrm{g}})^{2-\omega}}\right] \left(\frac{E_\gamma}{4 m_\mathrm{e} c^2}\right)^{\alpha_\mathrm{X}}. \end{aligned} \tag{8}$$

$\Psi(\alpha_\mathrm{X})$ is a function of the X-ray spectral index, α_X, F_0' the X-ray flux parameter in units of $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$, m_e the electron mass, c the speed of light, $R_\mathrm{g} = \frac{GM}{c^2}$ the Schwarzschild radius, E_γ the average energy of the γ-rays, and R_0 and R_ms are the outer and inner radii of the accretion disk, respectively. ω is a free parameter. $\omega = 3$ is for a two-temperature disk while $\omega = 0$ is for a uniformly bright disk.

From Eq. (7), the optical depth depends on d, Φ and M. At first, d can be determined if the variability timescale (ΔT_D) for a blazar is observed, it is given by

$$\frac{d}{R_\mathrm{g}} = 1.73 \times 10^3 \frac{\Delta T_\mathrm{D}}{1+z} \delta M_7^{-1}. \tag{9}$$

Furthermore, using the observed γ-ray flux, $F_\gamma^{\mathrm{obs}}(> 100\mathrm{MeV})$ in units of erg $\cdot\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$, the relationship among the intrinsic luminosity, L_in, the Doppler factor, δ, the mass of the central black hole, M, and the propagation angle, Φ, is given by $F_\gamma^{\rm obs}(>100{\rm MeV}) = (1+z)^{1-\alpha_\gamma}\delta^{\alpha_\gamma+4}L_{\rm in}/\Omega D^2$. We can define an isotropic luminosity as $L_{\rm iso} = 4\pi D^2(1+z)^{\alpha_\gamma-1}F_\gamma^{\rm obs}(>100{\rm MeV})$ in units of 10^{48} erg·s^{-1}, and it can be expressed as

$$L_{\rm iso}^{48} = \frac{\lambda 2.52\times10^{-3}\delta^{\alpha_\gamma+4}}{1-\cos\Phi}M_7, \tag{10}$$

where $L_{\rm in} = \lambda L_{\rm Edd} = \lambda 1.26\times10^{45}M_7$, and λ is a parameter depending on the specific γ-ray emission model.

Substituting Eqs. (9) and (10) into Eq. (7), we obtain a function of M and Φ. From this equation, a minimum value of $\tau_{\gamma\gamma}$ for a given mass, M, can be determined by $\frac{\partial\tau}{\partial\Phi}|_M = 0$, i.e. solving

$$\begin{aligned}&\tfrac{2.5}{3}(51-8\omega)\Phi^{1.5}(1-\cos\Phi) - \tfrac{1}{3}(51-8\omega)\times\tfrac{2\alpha{\rm x}+3}{2\alpha_\gamma+8}\Phi^{2.5}\sin\Phi - \\ &\tfrac{2\alpha{\rm x}+3}{\alpha_\gamma+4}kM_7^{-1}\times A^{-\frac{2\alpha{\rm x}+3}{2}}(1-\cos\Phi)^{-\frac{2\alpha{\rm x}+3}{2\alpha_\gamma+8}}\sin\Phi = 0\end{aligned} \tag{11}$$

where

$$A = 1.73\times10^3\frac{\Delta T_{\rm D}}{1+z}M_7^{-\frac{\alpha_\gamma+5}{\alpha_\gamma+4}}\left(\frac{L_{\rm iso}^{45}}{\lambda 2.52}\right)^{\frac{1}{4+\alpha_\gamma}}.$$

Finally, letting the minimum of $\tau(M_7,\Phi)$ equal to 1.0, we have

$$\frac{1}{3}(51-8\omega)\times\Phi^{2.5}(\frac{d}{R_{\rm g}})^{-\frac{2\alpha{\rm x}+3}{2}} + kM_7^{-1}(\frac{d}{R_{\rm g}})^{-2\alpha{\rm x}-3} = 1. \tag{12}$$

For a source with available data in the X-ray and γ-ray bands, the masses of the central black holes, M_7, the Doppler factor, δ, the distance (height), d, and the propagation angle with respect to the axis of the accretion disk, Φ, can be derived from Eqs. (9), (10), (11) and (12), where $R_{\rm ms} = 6R_{\rm g}$, $R_0 = 30R_{\rm g}$, E_γ= 1GeV and $\omega = 3$ (a two-temperature disk) are used. For gamma-ray loud objects with short time scales, the masses are in the range of $(3.8 \approx 130)\times10^7M_\odot$ (see Cheng *et al.* 1999).

5 Results and Discussions

Very recently, we compiled four data bases for BL Lac objects and OVV/HPQs in the optical and infrared bands (Fan & Lin 1999a; 2000a; Fan 1999a). The data bases can be used to discuss the long-term variability properties, the correlated variations and to search for periodicity signatures in the light curves. When both methods are adopted to those optical data, the both methods give consistent results. The results are presented in Table 2. It is interesting to notice that there is a common period of ≈ 1.0 yr, which is likely from the effect of the Sun on the measurements. The detail analysis is presented in the paper by Fan *et al.* (2000c). From the short time scale, the basic parameters are obtained.

Tab.2 Investigation Results of Periodicity of 13 Blazars

Name	P_1 (f)(year)	P_2 (f)(year)	P_3 (f)(year)
0219+428	2.14	2.93	4.52
0235+164	1.56	2.95±0.25	5.87±1.3
0735+178	14.39±0.51	18.58±0.52	28.62±0.58
0754+100	17.85±1.3	24.7±0.7	
0851+202	5.53	11.75±0.5	
1215+303	2.05±0.1	4.45±0.05	6.89±0.34
1219+285	1.97	9.0±0.1	14.84±1.55
1226+023	2.00	13.5±0.2	22.5±.02
1253-055	7.1±0.4		
1308+326	2.03	2.95	6.07±0.1
1514-241	2.01	4.09	9.35±0.1
1807+698	6.0	18.18	
2155-304	4.16	7.0	
2200+420	13.7±0.4	19.95±0.70	29.6±0.30

notes to the Table: P_1, P_2, and P_3 are the possible periods derived from the light curves

For the long-term periodicity of variations, there are several explanations: the double black hole model, the hectic jet model, the slim disk model, and the effect of external perturbations to the accretion disk. (e.g. Sillanpaa *et al.* 1988; Meyer & Meyer-Hofmeister 1984; Horiuchi & Kato 1990; Abraham & Romero 1999; Fan *et al.* 1997b, 1998a, 2000c; Villata & Raiteri 1999; Romero *et al.* 2000c).

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