Research in Astron. Astrophys. **2011** Vol. **11** No. **11**, 1311–1316
http://www.raa-journal.org *http://www.iop.org/journals/raa*

Research in Astronomy and Astrophysics

Rapid variability in S5 0716+714 *

Jun-Hui Fan[1,2], Jun Tao[3,4], Bo-Chen Qian[3,4], Yi Liu[1,2], Jiang-He Yang[5], Fei-Peng Pi[1,2] and Wei Xu[1,2]

[1] Center for Astrophysics, Guangzhou University, Guangzhou 510006, China; *jhfan_cn@yahoo.com.cn*
[2] Astronomy Science and Technology Research Laboratory of Department of Education of Guangdong Province, Guangzhou 510006, China
[3] Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China
[4] Joint Institute for Galaxies and Cosmology, Shanghai Astronomical Observatory and University of Science and Technology of China, Chinese Academy of Sciences, Shanghai 200030, China
[5] Department of Physics and Electronics Science, Hunan University of Arts and Science, Changde 415000, China

Received 2011 April 6; accepted 2011 August 27

Abstract S5 0716+714 is one of the targets in our long term blazar monitoring program carried out with the 1.56-m telescope at Sheshan Station of Shanghai Astronomical Observatory, China. We report a very rapid variability of $\Delta I = 0.611 \pm 0.102$ mag over 3.6 min detected in our monitoring program during the period from December 2000 to March 2007. The rapid variability suggests that the mass for the central black hole is $\log(M/M_{\odot}) = 7.68 - 8.38$.

Key words: galaxies: active-BL Lacertae objects: general-galaxies: jets

1 INTRODUCTION

Blazars consisting of BL Lacertae (BL Lac) objects and flat-spectrum radio quasars (FSRQs) are an extreme subclass of active galactic nuclei (AGNs). They show variability over the whole electromagnetic spectrum with time scales from 30 seconds to years (Fan 2005; Fan 2011, and references therein). The variability time scales can shed some light on the size of the emission region, the mass of the central black hole and even the mechanisms for the variability and the emissions (Fan 2010). However, the very rapid variability can only be detected using a large amount of monitoring time. If a variability is greater than three times the uncertainty, we can regard it as a real variability, and the corresponding time can be taken as the variability time scale (Fan et al. 2009b,c).

S5 0716+714, one of the best studied objects (See Raiteri et al. 2003; Gu et al. 2006; Villata et al. 2008; Gupta et al. 2009; Poon et al. 2009; Wu et al. 2009; Zhang et al. 2010) is located at a redshift of 0.31 (Nilsson et al. 2008). It is one of the blazars monitored in our program with the 1.56-m telescope at Sheshan Station, Shanghai Astronomical Observatory (ShAO), China (Qian et al. 2002;

* Supported by the National Natural Science Foundation of China.

Qian & Tao 2003, 2004; Tao et al. 2004; Fan et al. 2009b,c). It is a good object to search for rapid variation since it is variable and has a high latitude. Here, we present the rapid observational results of the BL Lacertae object S5 0716+714. The paper is arranged as follows. In Section 2, we describe the observations and results; in Section 3, we present discussion and a conclusion.

2 OBSERVATIONS AND RESULTS

2.1 Observations and Data Reduction

The present observations were obtained on the 1.56-m telescope at Sheshan, ShAO from 2000 through 2007. The standard Johnson-Cousins V, R and I filters were used. Typical integration times were 300 s for the I and R, and 600 s for the filter V, depending on sky conditions and the brightness of S5 0716+714. Sometimes, integration time as short as 35 s was also used in our observations of the I and R bands. The flat field images were taken at dusk and dawn. The bias images were taken at the beginning and the end of the observations, while the dark-field images were taken at the end. All observing data were processed using the IRAF software package. The seeing at the Sheshan Station of ShAO varied from $1.3''$ to $2.0''$ FWHM and we have discussed this elsewhere (see fig. 3 of Qian et al. 2002). We used comparison stars (Stars 2, 3, 5 and 6, see Table 1) from Villata et al. (1998) for the V, R and I-data (Stars A, B, C and D) from Ghisellini et al. (1997).

Table 1 Field Standard Stars of S5 0716+714

Star	V	R	I
A(2)	11.46 ± 0.01	11.12 ± 0.01	10.92 ± 0.04
B(3)	12.43 ± 0.02	12.06 ± 0.01	11.79 ± 0.05
C(5)	13.55 ± 0.02	13.18 ± 0.01	12.85 ± 0.05
D(6)	13.63 ± 0.02	13.26 ± 0.01	12.97 ± 0.04

Using differential photometry with respect to each comparison star, $c_i, i = 1 - n$, within the frame we obtain a magnitude m_i for the object of interest. Then the object's magnitude at that time is

$$\overline{m} = \frac{\sum m_i}{n}, \tag{1}$$

where n is the number of standard stars. In this case, it is 4. The uncertainty σ_1 is calculated as

$$\sigma_1 = \sqrt{\frac{\sum(m_i - \overline{m})^2}{n-1}}. \tag{2}$$

The difference between comparison stars is

$$\sigma_2 = (m_{\rm A} - m_{\rm B}) - \Delta m_{\rm AB}, \tag{3}$$

where $\Delta m_{\rm AB}$ is the magnitude difference of comparison stars A and B given by Ghisellini et al. (1997). The absolute value of σ_2 was used as an additional indicator of the observational uncertainty (Qian et al. 2002).

2.2 Results

During our monitoring period, the source was variable (Fan et al. 2011, in preparation). Using the criteria for a real variation, Δm can be taken as a real one if Δm is greater than three times the uncertainty. Namely, $\Delta m \geq 3\sqrt{\sigma_{m1}^2 + \sigma_{m2}^2}$, where σ_{m1} and σ_{m2} are the uncertainties for m_1 and

Table 2 Variability and Time Scales in the V Band

JD 2450000 (1)	V (2)	σ_V (3)	JD 2450000 (4)	V (5)	σ_V (6)	σ_V^M (7)	ΔT (8)	ΔV (9)	σ (10)	σ_M (11)	Vari (12)
3049.9939	12.967	0.064	3050.0092	12.456	0.071	0.105	22.0	–0.511 ± 0.096	5.3	3.4	Y
3072.995	12.819	0.041	3073.0236	13.404	0.014	0.087	41.2	0.585 ± 0.043	13.5	4.8	Y
3073.0236	13.404	0.014	3073.0541	12.438	0.087	0.087	43.9	–0.966 ± 0.088	11.0	7.9	Y
3073.0622	12.439	0.02	3073.0877	13.272	0.06	0.087	36.7	0.833 ± 0.063	13.2	6.8	Y
4166.9913	13.918	0.073	4167.0139	13.511	0.037	0.099	32.5	–0.407 ± 0.082	5.0	2.9	N
4167.0139	13.511	0.037	4167.0234	13.997	0.064	0.099	13.7	0.486 ± 0.074	6.6	3.5	Y
4167.0234	13.997	0.064	4167.0736	13.496	0.082	0.099	72.3	–0.501 ± 0.104	4.8	3.6	Y

Table 3 Variability and Time Scales in the R Band

JD 2450000 (1)	R (2)	σ_R (3)	JD 2450000 (4)	R (5)	σ_R (6)	σ_R^M (7)	ΔT (8)	ΔR (9)	σ (10)	σ_M (11)	Vari (12)
2934.3255	13.658	0.001	2934.3381	13.319	0.002	0.07	18.1	–0.339 ± 0.002	151.6	3.4	Y
2934.3381	13.319	0.002	2934.3502	13.49	0.032	0.07	17.4	0.171 ± 0.032	5.3	1.7	N
2934.3502	13.49	0.032	2934.3745	13.234	0.044	0.07	35.0	–0.256 ± 0.054	4.7	2.6	N
3050.988	12.433	0.022	3051.0152	13.086	0.113	0.113	39.2	0.653 ± 0.115	5.7	4.1	Y
3051.0152	13.086	0.113	3051.0526	12.3	0.016	0.113	53.9	–0.786 ± 0.114	6.8	4.9	Y
3387.1028	12.627	0.006	3387.1269	11.933	0.017	0.117	34.7	–0.694 ± 0.018	38.5	4.2	Y
3387.1269	11.933	0.017	3387.1432	12.632	0.088	0.117	23.5	0.699 ± 0.090	7.8	4.2	Y
3387.1586	12.601	0.066	3387.1673	11.983	0.004	0.117	12.5	–0.618 ± 0.066	9.3	3.7	Y
3388.1352	13.618	0.021	3388.138	13.019	0.059	0.114	4.0	–0.599 ± 0.063	9.6	3.7	Y
3388.138	13.019	0.059	3388.1499	13.574	0.103	0.114	17.1	0.555 ± 0.119	4.7	3.4	Y
4166.9804	13.166	0.031	4166.988	13.616	0.084	0.091	10.9	0.45 ± 0.090	5.0	3.5	Y

m_2 respectively. In this work, we will take the variation as a real one if $\Delta m \geq 3\sigma_m^M$, where σ_m^M is the largest uncertainty of a certain observing day. Therefore, the time corresponding to the real variation is the timescale. From our monitoring results, we can get the variabilities and the time scales in the V, R and I bands as shown in Tables 2, 3 and 4. In the table, Cols. 1 and 4 are JD time; Cols. 2 and 5 are the magnitudes corresponding to Cols. 1 and 4; Cols. 3 and 6 are the magnitude uncertainties corresponding to Cols. 2 and 5; Col. 7 is the largest uncertainty (σ_m^M) of the observing day; Col. 8 is time scale in minutes; Col. 9 is the variability, where a positive value means brightness is decreasing and a negative value means brightness is increasing. Col. 10 is the times of the uncertainty ($\sqrt{\sigma_{m1}^2 + \sigma_{m2}^2}$); namely it is equal to $\Delta m/\sqrt{\sigma_{m1}^2 + \sigma_{m2}^2}$; Col. 11 is the times of the uncertainty (σ_m^M); it is equal to $\Delta m/\sqrt{2}\sigma_m^M$; for Col. 12, 'Y' means the variability is real, 'N' means the variability is false.

In Table 2, we can clearly see the V variability of JD 2453072; the source brightness decreases by 0.585±0.043 mag over 41.2 min, then increases by 0.966±0.088 mag over 43.9 min; finally it decreases again by 0.833±0.063 mag over 36.7 min. The shortest time scale of 13.7 min was detected in the V band of JD 2454167.

In the R band, a brightness decrease of 0.653±0.115 over 39.2 min followed by a brightness increase of 0.786±0.114 over 53.9 min in JD 2453050 was observed. Rapid variabilities over time scales of 4, 10.9 and 12.5 min were also detected in JD 2450000+ 3388, +4166 and +3387 respectively (see Table 3).

In the I band, variability time scales of 3.6, 10.1 and 10.2 min were detected in JD 2450000+ 3388, 3438 and 3388 respectively (see Table 4). The shortest time variability of $\Delta I = 0.611 \pm 0.102$ mag over 3.6 min is shown in Figure 1.

Table 4 Variability and Time Scales in the I Band

JD 2450000 (1)	I (2)	σ_I (3)	JD 2450000 (4)	I (5)	σ_I (6)	σ_I^M (7)	ΔT (8)	ΔI (9)	σ (10)	σ_M (11)	Vari (12)
3385.1081	12.224	0.007	3385.1378	12.519	0.073	0.073	42.8	–0.418 ± 0.073	4.0	2.9	N
3388.1043	12.286	0.102	3388.1068	12.897	0.003	0.113	3.6	0.611 ± 0.102	6.0	3.8	Y
3388.1068	12.897	0.003	3388.1296	12.492	0.073	0.113	32.8	–0.405 ± 0.073	5.5	2.5	N
3388.1972	12.481	0.081	3388.2112	12.063	0.041	0.113	20.2	–0.418 ± 0.091	4.6	2.6	N
3388.2112	12.063	0.041	3388.2183	12.697	0.053	0.113	10.2	0.634 ± 0.067	9.4	4.0	Y
3438.0557	12.067	0.03	3438.0605	12.427	0.115	0.115	6.9	0.36 ± 0.119	3.0	2.2	N
3438.0605	12.427	0.115	3438.0625	12.15	0.011	0.115	2.9	–0.277 ± 0.116	2.4	1.7	N
3438.9797	12.592	0.048	3438.9867	13.043	0.03	0.086	10.1	0.451 ± 0.057	8.0	3.7	Y

3 DISCUSSION & CONCLUSIONS

Variability is one of the most common phenomena in blazars, which sheds lights on the emission mechanisms operating in those sources and the nature of the variability. Optical photometric observations are important for obtaining light curves of blazars (see Fan et al. 1998). S5 0716+714 is a well observed BL Lacertae object, whose host galaxy is found to have an R magnitude of 18.3±0.5 (Nilsson et al. 2008). It is a well known intraday variability (IDV) object; a typical variation rate of 0.02 mag hr^{-1} was detected (Nesci et al. 2002) and a 4-day period was found in its optical band (Wagner et al. 1996). Montagni et al. (2006) reported the fastest variability rate of $0.1-0.12$ mag hr^{-1}. In our previous work, a variability of ~ 0.87 mag in 9 min was detected in a monitoring program over 5 yr (Qian et al. 2002). Variabilities over 2 to 8 hr were reported in our recent work (Poon et al. 2009).

In our analysis, if the variation is greater than three times the uncertainty, then it is taken as a real variation. Very short time scale variability did not occur often during our several years of observations. We only detected a 3.6 min timescale case in JD 2453388, and the corresponding variation is about six times the uncertainty, therefore, we take this as a true variation. During the night, we also observed using the R filter. However, the source did not show clear variation over a period of 13.8 min between JD 2450000+3388.0999 and +3388.1095 in the R band when the source showed a 0.611 mag variation over 3.6 min between JD 2450000+3388.1043 and +3388.1068 in the I band. If the 3.6 min short variability is real, then we missed a variability in the R band between JD 2450000+3388.0999 and +3388.1095. This is quite possible since the very short time scale variability does not often occur. Both the I and R light curves are shown in Figure 1.

The short time scale is assumed to shed information on the emission size,

$$R \leq \delta c \Delta T/(1+z).$$

If R is the radius of the innermost stable orbit around a black hole, then we can get an upper limit for the mass of the central black hole (Fan 2005). Using the relations $R = \frac{6GM}{c^2}$ for thin accretion disks surrounding a Schwarzschild black hole, $R = \frac{4GM}{c^2}$ for thick accretion disks surrounding a Schwarzschild black hole, and the radius of the event horizon of a Kerr black hole with a mass M and an angular momentum parameter a gives $R = 1.2 \times \frac{GM}{c^2}$ for $a = 0.9982$ (Espaillat et al. 2008).

From a short time scale, we have $R \leq c\Delta T \delta/(1+z) \sim 1.8/(1+z) \times 10^{12} \Delta T(\mathrm{min})\delta$. Therefore, the central black hole masses are in the range of $[2/(1+z), 10/(1+z)]\Delta T(\mathrm{min})\delta$. When the shortest time scale of 3.6 min and the redshift of 0.31 are taken into account, we find that the upper limits for the central black hole masses are $5.5\delta \times 10^6 M_\odot$ for a thin accretion disk surrounding a Schwarzschild black hole, or $2.74\delta \times 10^7 M_\odot$ for a Kerr black hole with an extreme momentum parameter of $a = 0.9982$. So, the central black hole masses are $\sim (0.55 - 2.74)\delta \times 10^7 M_\odot$ for S5

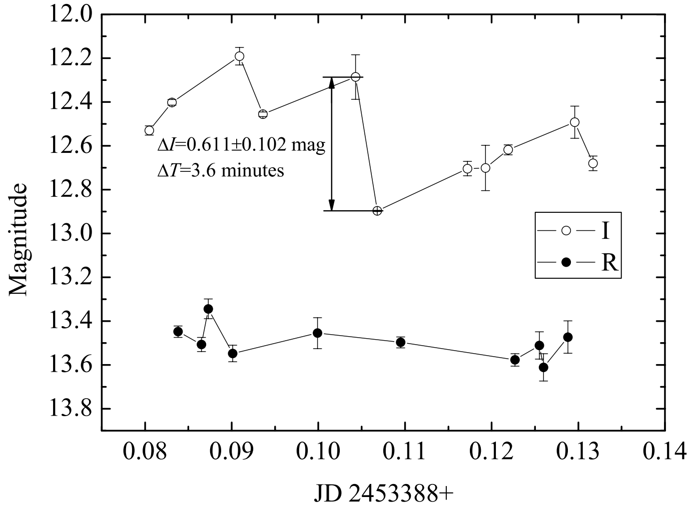

Fig. 1 Light curves of JD 2453388 for I (*open circles*) and R (*filled circles*) bands of S5 0716+714.

0716+714. In our previous work, a $\delta = 8.76$ was estimated (Fan et al. 2009a), then the masses for the central black hole are $\log(M/M_{\odot}) = 7.68 - 8.38$.

Its host galaxy is found to have an R magnitude of 18.3 (Nilsson et al. 2008), which suggests an absolute magnitude of $M_R = -22.66$ for $z = 0.31$. There is a correlation between the central black hole mass and the absolute magnitude, $\log M/M_{\odot} = -0.5 * M_R + 3.0$ (Urry et al. 2000). So, we have $\log(M/M_{\odot}) = 8.33$ for S5 0716+714, which is consistent with $\log(M/M_{\odot}) = 7.68 - 8.38$.

In our monitoring program, we detected a variability of ΔI = 0.611$\pm$0.102 mag over 3.6 min. The time scale is the shortest time scale for S5 0716+714, and it suggests a black hole mass of $M = 10^{7.68-8.38} M_{\odot}$ at the center of the object.

Acknowledgements The work is partially supported by the National Natural Science Foundation of China (Grant Nos. 10633010 and 11173009), the National Basic Research Program of China (973 program, 2007CB815405) and the Bureau of Education of Guangzhou Municipality (No.11 Sui-Jiao-Ke[2009]), Guangdong Province Universities and Colleges Pearl River Scholar Funded Scheme (GDUPS)(2009), Yangcheng Scholar Funded Scheme (10A027S) and the Joint Laboratory for Optical Astronomy of Chinese Academy of Sciences.

References

Espaillat, C., Bregman, J., Hughes, P., & Lloyd-Davies, E. 2008, ApJ, 679, 182

Fan, J.-H. 2005, ChJAA (Chin. J. Astron. Astrophys.) Supplement, 5, 213

Fan, J.-H., Huang, Y., He, T.-M., et al. 2009a, PASJ, 61, 639

Fan, J. H., Peng, Q. S., Tao, J., Qian, B. C., & Shen, Z. Q. 2009b, AJ, 138, 1428

Fan, J. H., Xie, G. Z., Pecontal, E., Pecontal, A., & Copin, Y. 1998, ApJ, 507, 173

Fan, J. H., Zhang, Y. W., Qian, B. C., et al. 2009c, ApJS, 181, 466

Fan, J. H. 2011, JAA, 32, 67

Fan, J. H. 2010, 10000 Selected Problems in Sciencs (Astronomy) (Science Press), 609

Ghisellini, G., Villata, M., Raiteri, C. M., et al. 1997, A&A, 327, 61

Gu, M. F., Lee, C.-U., Pak, S., Yim, H. S., & Fletcher, A. B. 2006, A&A, 450, 39

Gupta, A. C., Srivastava, A. K., & Wiita, P. J. 2009, ApJ, 690, 216

Montagni, F., Maselli, A., Massaro, E., et al. 2006, A&A, 451, 435
Nesci, R., Massaro, E., & Montagni, F. 2002, Publications of the Astronomical Society of Australia, 19, 143
Nilsson, K., Pursimo, T., Sillanpää, A., Takalo, L. O., & Lindfors, E. 2008, A&A, 487, L29
Poon, H., Fan, J. H., & Fu, J. N. 2009, ApJS, 185, 511
Qian, B., & Tao, J. 2003, PASP, 115, 490
Qian, B., & Tao, J. 2004, PASP, 116, 161
Qian, B., Tao, J., & Fan, J. 2002, AJ, 123, 678
Raiteri, C. M., Villata, M., Tosti, G., et al. 2003, A&A, 402, 151
Tao, J., Qian, B., & Fan, J. 2004, PASP, 116, 634
Urry, C. M., Scarpa, R., O'Dowd, M., et al. 2000, ApJ, 532, 816
Villata, M., Raiteri, C. M., Lanteri, L. et al. 1998, A&AS, 130, 305
Villata, M., Raiteri, C. M., Larionov, V. M., et al. 2008, A&A, 481, L79
Wagner, S. J., Witzel, A., Heidt, J., et al. 1996, AJ, 111, 2187
Wu, J., Zhou, X., Ma, J., Wu, Z., & Jiang, Z. 2009, in ASPC Series 408, The Starburst-AGN Connection, eds. W. Wang, Z. Yang, Z. Luo, & Z. Chen, 278
Zhang, B., Dai, B., Zhang, L., Liu, J., & Cao, Z. 2010, Publications of the Astronomical Society of Australia, 27, 296