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The masses of central supermassive black holes and the variability time-scales in gamma-ray loud blazars

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ABSTRACT

The central supermassive black hole (SMBH) masses and variability time-scales of completed EGRET positive γ-ray blazars loud were investigated. We generalized the Elliot–Shapiro relation to the Klein–Nishina regime and derived a corrected form of the relation by taking into account the Klein–Nishina effect, then compiled a small sample including 21 γ-ray loud blazars, the rapid variation time-scales of which in the optical band were well established, to examine whether or not they obey the corrected form of the relation. It is found that the γ-ray luminosity (assuming it is isotropically emitted) at low state (corresponding to the minimum γ-ray flux presented in the Third EGRET Catalog) and the variation time-scales for these sources obey the corrected Elliot–Shapiro relation well. This suggests that the measured variability time-scales are not short enough to require a beaming effect when the Klein–Nishina effect is considered. The γ-ray emissions at low state may be produced in a region close to the central SMBHs, and are unbeamed or weakly beamed. This is quite consistent with Dermer & Gehrels's argument. Thus, taking into account the Klein–Nishina effect, the central SMBH masses and variability time-scales of completed EGRET γ-ray loud blazars were derived with the γ-ray fluxes. The results show that the central SMBH masses range in $10^{6.5}$–$10^{10.2}\,\mathrm{M}_{\odot}$. The mean and the median of the masses are $10^{8.9}$ and $10^{9.1}\,\mathrm{M}_{\odot}$, respectively. The distribution of the masses exhibits a weak bimodal distribution with peaks at $10^{8.2}\,\mathrm{M}_{\odot}$ and $10^{9.2}\,\mathrm{M}_{\odot}$, and with a valley at $10^{8.5}\,\mathrm{M}_{\odot}$. This seems to present a signature for classifying these blazars into two groups. Most of the objects (75 per cent) belong to the group of $M \geqslant 10^{8.5}\,\mathrm{M}_{\odot}$, while only about 25 per cent objects are included in the group of $M \leqslant 10^{8.5}\,\mathrm{M}_{\odot}$. We also found that most of the BL Lac objects in the sample belong to the latter group, while most of the quasars belong to the former one. This likely indicates that the masses of the central SMBHs of BL Lac objects are significantly smaller than those of quasars. This is quite consistent with the argument proposed by Ozernoy. The variability time-scale is an observable indicator for examining the reliability of the mass estimate. Our results show that the variability time-scales for these sources range from $10^{1.6}$ s to $10^{5.6}$ s. The variation time-scales show a bimodal distribution too, with two peaks at $10^{3.2}$ s (corresponding to 0.44 h) and $10^{4.5}$ s (corresponding to 8.78 h), and a valley at $10^{4.0}$ s. About 25 per cent of the sources have rapid variability on time-scales of a fraction of an hour, and 75 per cent of the sources have variability on a time-scale of intranight or intraday. The time-scales derived in this work are significantly correlated with observed shortest time-scales. The linear correlation coefficient is 0.76 with a chance probability of 0.0001. These results might indicate that the mass estimate in this work is reliable.

Key words: black hole physics – galaxies: active – BL Lacertae objects: general – galaxies: nuclei – quasars: general – gamma-rays: observations.

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1 INTRODUCTION

The widely accepted working model of active galaxy nuclei (AGNs) is a 'central engine' that consists of a hot accretion disc surrounding a supermassive black hole (SMBH) with a relativistic jet or twin jet (Rees 1984; Peterson 1997). Among AGNs, blazars are the most powerful sources. They exhibit unusual observational phenomena, showing continuum variability at all wavelengths, from γ-rays to radio wavelengths. EGRET detected 66 blazars, which emit most of their bolometric luminosity at high γ-ray band ($E > 100$ MeV). Many of the sources are strongly variable in the γ-ray range on time-scales from days to a fraction of an hour (Gaidos et al. 1996; Mattox et al. 1997). The short variability time-scale indicates that the emission region is extremely compact (Kniffen et al. 1993). These energetic γ-ray emissions and rapid variability time-scales may shed light on the understanding of the nature of the central SMBHs in these objects.

The mechanism of γ-ray radiations from blazars is still not understood. Some models, such as inverse Compton process on external photons (e.g. Dermer et al. 1992; Coppi et al. 1993; Sikora et al. 1994; Blandford & Levison 1995) and synchrotron self-Compton model (Maraschi et al. 1992; Bloom & Marscher 1992, 1993, 1996; Zdziarski & Krolik 1993; Marscher & Travis 1996; Ghisellini et al. 1998), have been proposed for the interpretation of radiation mechanism of the γ-ray emission.

The emission region of these energetic γ-ray is also a mystery. Two contrary opinions have been proposed. The first one is that these γ-ray emissions are isotropic and are produced in a region close to the central SMBH (e.g. Dermer & Gehrels 1995). In this scenario the gamma-ray emission is unbeamed. Based on this assumption Dermer & Gehrels (1995) presented a formula to derive the masses of the central SMBHs, and got reasonable results without considering the beaming effect. The second one is that the emissions are beamed and are produced from a jet in a region far away from the central SMBHs (0.1 pc), in a relativistic jet pointing toward the observer (Dondi & Gissellini 1995).

The necessity of beaming in gamma-ray loud sources is now well established, mainly based on the gamma-ray transparency argument and correlation analysis between the emissions at the γ-ray and at lower energy bands (Dondi & Gissellini 1995; Ulrich, Maraschi & Urry 1997; Hartman et al. 1996; Ghisellini & Madau 1996; Zhou et al. 1997; Xie, Zhang & Fan 1997; Xie et al. 1998, 2001b; Zhang & Xie 1997; Müche et al. 1997; Celotti & Ghisellini 1998; Zhang et al. 1998; Fan et al. 1998).

Arguments for beaming can also be made by Elliot–Shapiro relation (Elliot & Shapiro 1974) on the basis of the time-scale of variation of the source luminosity. The relation presents a limit to luminosity for black hole accreting and isotropically emitting, i.e. $L_{48}/t_{\rm min}({\rm d}) < 1/(1+z)$, where $t_{\rm min}$ is the minimum time-scale of variation and L_{48} the bolometric luminosity for emission in the Thomson regime in unit of 10^{48} erg s^{-1}, z the redshift. The large luminosities and very short time-scales observed in γ-ray loud blazars violate the relation, indicating the γ-ray emissions are beamed.

Note that the Elliot–Shapiro relation is on the basis of the assumption that the photons interact with matter in the Thomson regime. However, the γ-ray emission measured by EGRET is well into the Klein–Nishina regime. The relation should be generalized to the Klein–Nishina regime. Thus, the conclusion drawn from the relation that γ-ray emissions are beamed is not very reliable. In this work, we first generalized the relation in the Klein–Nishina regime. A corrected form of the relation was derived by taking into account the Klein–Nishina effect. Then, we compiled a small sample of γ-ray loud blazars, whose rapid variation time-scales in optical band were well established, to examine whether or not they obey the corrected form of the relation. On the assumption that the γ-ray emissions are isotropic we found that the γ-ray luminosity at low state (corresponding to the minimum γ-ray flux presented in the Third Catalog) and the variation time-scales for the sources in the sample well obey the corrected Elliot–Shapiro relation. However, when the sources are at high state (corresponding to the maximum γ-ray flux presented in the Third EGRET Catalog), we found that most of them violate the corrected Elliot–Shapiro relation, suggesting that the beaming effect should be invoked. Thus, we suggested that the γ-ray emissions at low state are produced in a region close to the central SMBHs. They are umbeamed or weakly beamed. In this work we simply assumed that the γ-ray emissions at low state are produced in the innermost of central SMBHs by the steady and Eddington-limited accretion and are isotropic emitted, then calculated the masses of central SMBHs for all EGRET γ-ray blazars by Dermer & Gehrels method (Dermer & Gehrels 1995) with the γ-ray emissions at low state. The variation time-scale is an observable indicator to examine the reliability of the mass estimate. Based on the black hole accretion model we also computed the shortest variation time-scales of these objects and compared them with observational results.

In Section 2 we describe our samples. In Section 3 we generalize the Ellio–Shapiro relation in the Klein–Nishina regime and presented a corrected form of the Ellio–Shapiro relation for γ-ray loud blazars. The new corrected form of the relation was applied to a sample including 21 γ-ray loud sources, whose observed shortest time-scales of flux variations are well established. In Section 4, the masses of central SMBHs of completed EGRET positive γ-ray loud blazars (66 blazars) are presented. In Section 5, the shortest variation time-scales are computed and compared with observational results. The conclusions and discussion are presented in Section 6.

Throughout this paper $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ are adopted.

2 THE SAMPLES

The third EGRET Catalog contains 66 positive and 25 marginal detections of γ-ray loud blazars above 100 MeV (Hartman et al. 1999). Our sample (Sample 1) is consists of all the positive γ-ray loud blazars. They are listed in Table 1 with following headings: (1) source, (2) the redshift (z), (3) spectral indices at γ-ray band (α_γ), and (4) γ-ray fluxes (in units of 10^{-6} photon cm^{-2} s^{-1}) at low state.

For examining the relation between variation time-scales and γ-ray luminosity for γ-ray loud blazars, a small sample (Sample 2) including 21 γ-ray loud blazars, the shortest variation time-scales of which were well established, was compiled from literature. They are listed in Table 2 with following headings: (1) source; (2) and (3) the γ-ray fluxes (in units of 10^{-6} photon cm^{-2} s^{-1}) at low and high state, respectively; and (4) the shortest optical variation time-scales (in units of s).

3 THE RELATION BETWEEN GAMMA-RAY LUMINOSITY AND SHORTEST VARIATION TIME-SCALE

On the basis of black hole accretion model and the isotropic radiation produced by stray Eddington-limited accretion, the luminosity and the variation time-scale of an object should obey the Elliot & Shapiro relation,

Table 1. The observations and the results derived in present paper for completed EGRET positive blazars.

Source (1)	z (2)	α_γ (3)	F_γ (phs cm^{-2} s^{-1}) (4)	log M (M$_\odot$) (5)	log $t_{\rm min}$ (s) (6)
0202+149	1.202	1.23	2.36	9.6	5.0
0208−512	1.003	0.99	3.5	9.8	5.1
0219+428	0.444	1.01	1.21	8.6	3.8
0235+146	0.94	0.85	1.16	9.3	4.6
0336−019	0.852	0.84	1.31	9.3	4.6
0414−189	1.536	2.25	1.37	9.5	4.9
0420−014	0.915	1.44	0.93	8.9	4.2
0430−2859	0.97	0.9	1.6	9.5	4.7
0440−003	0.844	1.37	2.23	9.3	4.5
0446+112	1.207	1.27	0.63	9.0	4.4
0454−234	1.003	2.14	0.81	8.8	4.1
0454−463	0.858	1.75	0.55	8.5	3.8
0458−020	2.286	1.45	0.95	9.7	5.2
0459+060	1.106	1.36	1.19	9.2	4.5
0528+134	2.07	1.46	3.24	10.2	5.6
0537−441	0.896	1.41	1.65	9.2	4.4
0616−116	0.97	1.67	1.49	9.1	4.4
0716+714	0.3	1.19	0.93	8.1	3.2
0735+178	0.424	1.6	1.58	8.4	3.6
0738+5451	0.723	1.03	1.14	9.0	4.2
0827+243	2.05	1.42	1.56	9.8	5.3
0829+046	0.18	1.47	1.68	7.7	2.8
0836+170	2.172	1.62	0.86	9.6	5.1
0850−1213	0.566	0.58	1.4	9.2	4.4
0851+202	0.306	1.03	0.97	8.2	3.3
0954+556	0.901	1.12	0.65	8.9	4.2
0954+658	0.368	1.08	0.66	8.2	3.3
1101+384	0.031	0.57	0.9	6.7	1.7
1156+295	0.729	0.98	0.83	8.9	4.1
1219+285	0.102	0.73	0.69	7.4	2.5
1222+216	0.435	1.28	0.69	8.2	3.4
1226+032	0.158	1.58	0.85	7.3	2.3
1229−021	1.405	1.85	0.49	9.0	4.3
1243−072	1.286	1.73	0.6	9.0	4.3
1253−055	0.538	0.96	0.76	8.6	3.8
1331+170	2.08	1.41	0.94	9.6	5.1
1334−127	0.539	1.62	1.14	8.5	3.7
1406−076	1.494	1.29	1.04	9.4	4.8
1424−418	1.522	1.13	1.53	9.7	5.1
1510−089	0.361	1.47	1.26	8.2	3.4
1604+159	0.357	1.06	1.23	8.4	3.6
1606+106	1.227	1.63	2.1	9.5	4.8
1611+343	1.404	1.42	1.9	9.6	5.0
1622−253	0.786	1.07	1.01	9.0	4.2
1622−297	0.815	1.07	1.24	9.1	4.4
1633+382	1.814	1.15	3.18	10.1	5.6
1725+044	0.296	1.67	1.33	8.0	3.1
1730−130	0.902	1.23	1.81	9.3	4.6
1739+522	1.375	1.42	0.97	9.3	4.7
1741−038	1.054	1.42	1.76	9.3	4.6
1759−396	0.296	2.1	1.75	8.0	3.1
1830−210	1	1.59	1.78	9.2	4.5
1908−210	0.97	1.39	1.49	9.2	4.5
1933−400	0.966	1.86	1.4	9.0	4.3
1936−155	1.657	2.45	0.76	9.3	4.8
2022−077	1.388	1.38	2.18	9.7	5.0
2032+107	0.601	1.83	1.02	8.5	3.7
2052−474	1.489	1.04	1.13	9.6	4.9
2155−304	0.116	1.35	0.79	7.1	2.1
2200−420	0.069	1.6	0.88	6.5	1.6
2209+236	1	1.48	1.23	9.1	4.4
2230+114	1.037	1.45	1.21	9.1	4.4
2251+158	0.859	1.21	2.46	9.4	4.6
2320−035	1.411	1.36	0.82	9.3	4.6
2351−456	1.992	1.38	1.18	9.7	5.2
2356+196	1.066	1.09	1.28	9.3	4.6

$$\log t_{\rm min} > \log L - 43.1, \qquad (1)$$

where the luminosity is in units of erg s^{-1}, and $t_{\rm min}$ in seconds.

Note that the Elliot & Shapiro relation is based on the assumption that the photons interact with matter in the Thomson regime. However, the γ-ray emission measured by EGRET is well into the Klein–Nishina regime. The Klein–Nishina effect should be considered. For γ-ray loud blazars, the relation should be generalized to the Klein–Nishina regime.

In the Klein–Nishina regime the cross-section of photons interacting with matter is

$$\sigma_{\rm KN} \simeq \frac{3}{8\epsilon}\sigma_{\rm T}\left(\ln 2\epsilon + \frac{1}{2}\right), \qquad (2)$$

where $\sigma_{\rm T}$ is the Thomson cross-section, $\epsilon = \frac{h\nu_i}{m_{\rm e}c^2} \gg 1$, ν_i the frequency of the emergent photons. For EGRET sources, assuming $h\nu_i = 100$ MeV, the Eddington-limited luminosity of a SMBH hosted in the EGRET sources with mass of M should be

$$L_{\rm Edd}^{\rm KN} = \frac{4\pi G M m_{\rm p} c}{\sigma_{\rm KN}} = L_{\rm Edd}\frac{8\epsilon}{3\left(\ln 2\epsilon + \frac{1}{2}\right)} \simeq 10^{40}\frac{M}{{\rm M}_\odot}, \qquad (3)$$

where $m_{\rm p}$ is the proton mass, c the light velocity, G the gravitational constant, and $L_{\rm Edd}$ the Eddington luminosity in the Thomson regime.

For black hole accretion we expect the minimum variability timescales be greater than the light travel time across a distance equal to the gravity radius of the black hole. Thus one can deduce that

$$t_{\rm min} \geqslant 0.98 \times 10^{-5}\frac{M}{{\rm M}_\odot}(s). \qquad (4)$$

Combining the equations (3) and (4), we have

$$\log t_{\rm min} \geqslant \log L_{\rm Edd}^{\rm KN} - 44.2. \qquad (5)$$

Since $L_\gamma < L_{\rm Edd}^{\rm KN}$, thus

$$\log t_{\rm min} > \log L_\gamma - 44.2. \qquad (6)$$

Because γ-ray loud blazars emit most of their bolometric luminosity in the high γ-ray band ($E > 100$ MeV), we approximately took the γ-ray luminosity as their bolometric luminosity. Thus, equation (6) should be regarded as the corrected form of the Elliot–Shapiro relation in the Klein–Nishina regime for γ-ray loud blazars.

With the sources in Sample 2 we examined the relations between the luminosity at low and high state and observed optical $t_{\rm min}$ for γ-ray loud blazars, which are shown in Figs 1 and 2, respectively. In the two figures the solid line and the dotted line represent the original Elliot–Shapiro relation and its corrected form in Klein–Nishina regime, respectively.

From Fig. 1, one can find that 6 sources violate the Elliot–Shapiro limit. However, all of the objects in Sample 2 obey the corrected

Table 2. Sample 2.

Source (1)	$F_\gamma^{\rm L}$ (phs cm^{-2} s^{-1}) (2)	$F_\gamma^{\rm H}$ (phs cm^{-2} s^{-1}) (3)	log $t_{\rm obs}$ (s) (4)	log $t_{\rm min}$ (s) (5)
0219+428	2.36	5.28	3.73^a	3.8
0235+146	3.5	13.41	4.45^b	4.6
0420−014	1.16	6.51	4.65^c	4.2
0528+134	0.55	2.28	4.94^d	5.6
0537−441	0.95	6.82	4.66^e	4.4
0716+714	3.24	35.1	3.38^f	3.2
0735+178	1.65	9.11	3.63^a	3.6
0827+243	0.93	4.57	3.68^g	4.5
0851+202	1.68	3.35	3.36^e	3.3
1101+384	0.65	4.72	3.26^h	1.7
1156+295	0.66	1.8	4.40^c	4.1
1219+285	0.9	2.71	3.58^c	2.5
1226+032	0.69	5.36	4.57^e	2.3
1253−055	0.85	4.83	3.69^a	3.8
1406−076	0.76	26.70	4.76^i	4.8
1510−089	1.04	12.84	3.40^j	3.4
1622−297	1.9	6.89	4.24^k	4.4
1633+382	1.01	8.25	4.76^l	5.6
2155−304	1.02	3.59	2.95^m	2.1
2200−420	1.13	3.50	3.44^n	1.6
2230+114	0.88	3.99	4.59^e	4.4

Note: [a]Xie et al. (1999), [b]Moles et al. (1985), [c]Xie et al. (1991), [d]Wagner et al. (1997), [e]Bassani et al. (1983), [f]Qian, Tao & Fan (2002), [g]Xie et al. (2001a), [h]Gaidos et al. (1996), [i]Wagner, Mattox & Hopp (1995), [j]Xie et al. (2002a), [k]Mattox et al. (1997), [l]Fan, Xie & Bacon (1999), [m]Paltani et al. (1997), [n]Weistrop (1973).

form of the Elliot–Shapiro relation well. Although some observed minimum time-scales are as short as a quarter of an hour (e.g. 2155–304), they are not yet sufficiently short to argue in favour of beaming. This implies that the γ-ray emissions at low state are unbeamed or weakly beamed after taking into account the Klein–Nishina effect. This is quite consistent with the Dermer & Gehrels' arguments.

However, from Fig. 2, one can observe that most of the sources (about 70 per cent sources in the Sample 2) violate the original Elliot–Shapiro relation, and even 30 per cent of the sources violate

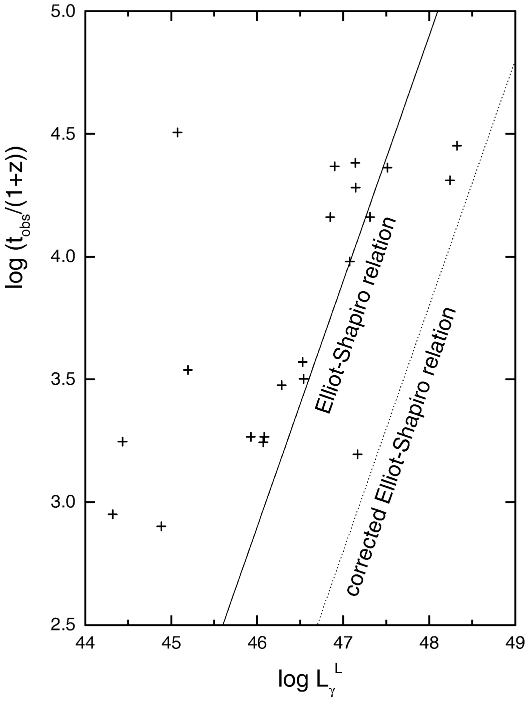

Figure 1. The observed shortest optical variation time-scale as a function of γ-ray luminosity at low state. The solid line and the dotted line represent the original Elliot–Shapiro relation and its corrected form in the Klein–Nishina regime, respectively.

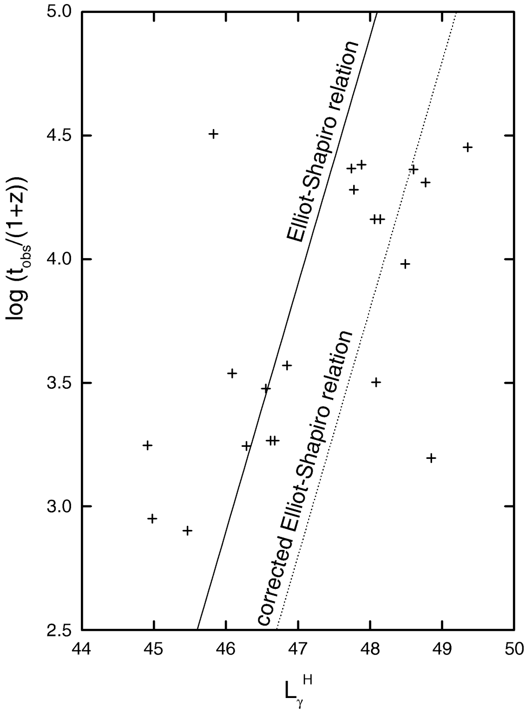

Figure 2. The observed shortest optical variation time-scale as a function of γ-ray luminosity at high state. The line styles are same as in Fig. 1.

the corrected Elliot–Shapiro relation. This suggests that the beaming effect should be considered for the γ-ray emissions at high state.

4 THE MASSES OF CENTRAL SMBHS

Based on the assumption that the γ-ray emissions in γ-ray loud blazars are isotropic radiation produced by the steady and Eddington-limited accretion without considering the beaming effect, Dermer & Gehrels (1995) took into account the Klein–Nishina effect and obtained an expression for minimum mass of central black hole, in unit of 10^8 M$_\odot$, given by

$$M_8^{\mathrm{KN}} \geqslant \frac{3\pi d_{\mathrm{L}}^2\left(m_{\mathrm{e}}c^2\right)}{2 \times 1.26 \times 10^{46}\,\mathrm{erg\,s^{-1}}} \cdot \frac{F(\varepsilon_l, \varepsilon_u)}{1+z} \cdot \ln[2\varepsilon_1(1+z)], \tag{7}$$

where $F(\varepsilon_l, \varepsilon_u)$ is the integrated photon flux between photon energies ε_l and ε_u in units of 0.511 MeV (the EGRET band is 100 MeV–5 GeV), d_{L} the luminosity distance, z the source redshift. For $q_0 = 0.5$, $d_{\mathrm{L}} = 2c[z + 1 - \sqrt{z+1}]/H_0$.

The k-correction should be made to the observed $F(\varepsilon_l, \varepsilon_u)$,

$$F(\varepsilon_l, \varepsilon_u) = F^{\mathrm{ob}}(\varepsilon_l, \varepsilon_u)(1+z)^{\alpha_\gamma - 1}, \tag{8}$$

where α_γ is the spectral index in γ-ray band.

The masses of 66 positive EGRET γ-ray blazars (the Sample 1) are derived by equation (7). They are listed in column 5 of Table 1. The masses range in $10^{6.5} - 10^{10.2}$ M$_\odot$. The mean and the median of the masses are $10^{8.9}$ and $10^{9.1}$ M$_\odot$, respectively. The distribution of the masses is shown in Fig. 3. It exhibits a weak bimodal distribution with peaks at $10^{8.2}$ M$_\odot$ and $10^{9.2}$ M$_\odot$, and a valley at $10^{8.5}$ M$_\odot$. This seems to present a signature for classifying these blazars into two groups. Most of the objects (75 per cent) belong to the group of $M \geqslant 10^{8.5}$ M$_\odot$. Only about 25 per cent objects are included in the group of $M \leqslant 10^{8.5}$ M$_\odot$. We also found that most of the BL Lac objects are included the latter group, while most of the quasars belong to the former group. This possibly indicates than the masses of the central SMBHs in BL Lac objects are significantly smaller that than in quasars. This is consistent with the argument proposed by Ozernoy (1986).

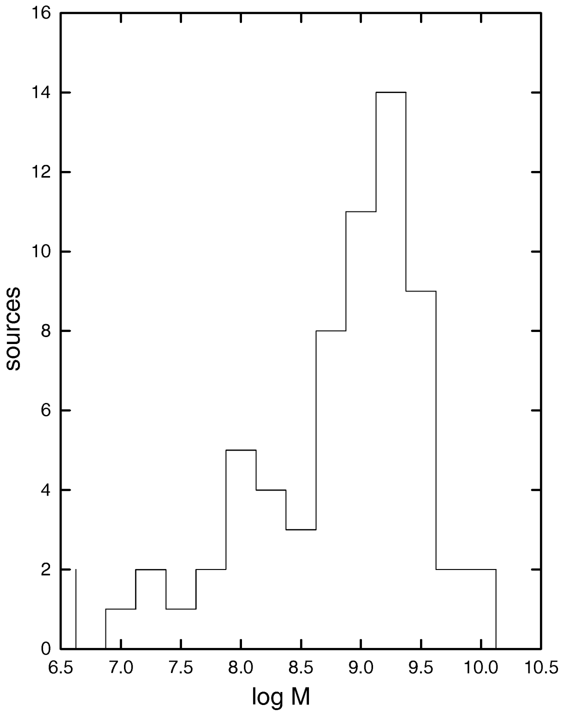

Figure 3. The distribution of the central SMBH masses.

5 THE SHORTEST VARIATION TIME-SCALES

Rapid variability is an identifying characteristic for blazars. Observations show that some γ-ray blazars exhibit significant variation on a time-scale of hours, even a small fraction of an hour. For example, the detected optical variability time-scale is 16 min for 2155–304 (Paltani et al. 1997), 30 min for 1101+384 (Gaidos et al. 1996), and about 40 min for PKS 1510 (Xie et al. 1999, 2002a,b; Dai et al. 2001). These very short variation time-scales might lead to a violation of the Elliot–Shapiro relation and present an indication of beaming. However, we have shown in Section 3 that the measured shortest time-scales we have found in literature are not short enough to violate the corrected form of the Elliot–Shapiro relation in the Klein–Nishina regime. This rapid variability is likely produced in the innermost of the SMBH in the centre of these objects (Abramowicz & Nobili 1982). Thus, the lower limits of the variation time-scales for these objects can be estimated by equation (4). Considering the time dilation effect, the observed variation time-scales should be multiplied a factor of (1 + z). The results are listed in Column 6 of Table 1. The time-scales range from $10^{1.6}$ s to $10^{5.6}$ s. The distribution of the time-scales is shown in Fig. 4. Similarly to the Fig. 3, Fig. 4 is a bimodal distribution with two peaks at $10^{3.2}$ s (corresponding to 0.44 h) and $10^{4.5}$ s (corresponding to 8.78 h), and a valley at $10^{4.0}$ s.

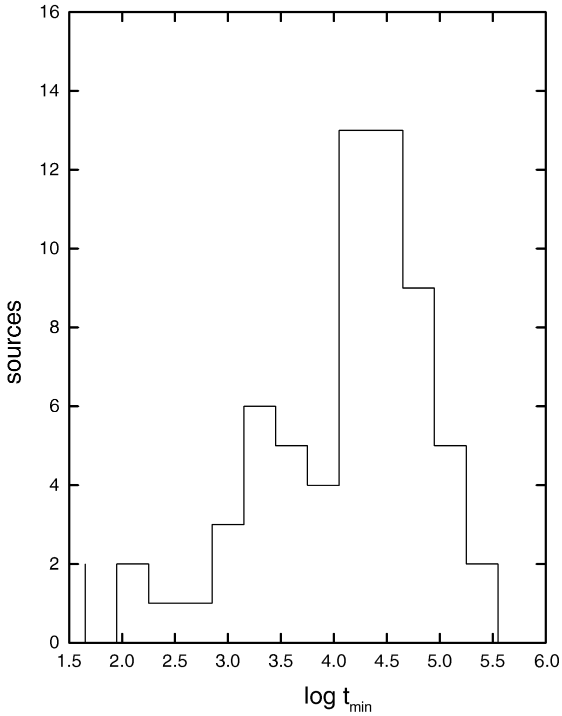

Figure 4. The distribution of the shortest variation time-scales derived in this work.

The variation time-scale is an observable indicator to examine the reliability of mass estimating. Our results show that the rapid variability on a time-scale of a fraction of an hour seems to be a rare phenomenon in these objects (about 25 per cent in Sample 1), while the variability on time-scale of intraday/intranight is quit common (about 75 per cent in Sample 1). This is quite consistent with

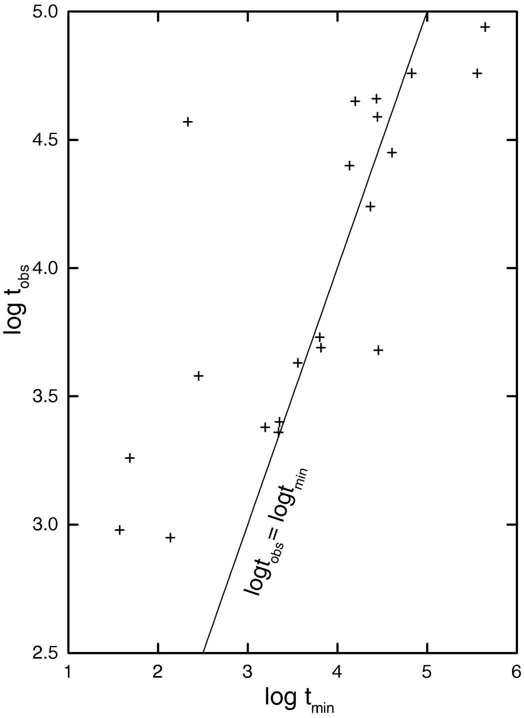

Figure 5. The plot of observed shortest variation time-scales versus the shortest variation time-scales derived in this work. The solid line is $\log t_{\rm obs} = \log t_{\rm min}$.

observational results. For further examining the reliability of the time-scales, we illustrated the observed shortest time-scales as a function of the theoretical time-scales derived in this work for the objects in Sample 2 in Fig. 5. From Fig. 5 one can find that the minimum time-scales derived in this work are quite consistent with observational results. A correlation analysis shows that two quantities are strongly correlated with a linear correlation coefficient of 0.76 and a chance probability of 0.0001.

6 CONCLUSIONS AND DISCUSSIONS

The central SMBH masses and variability time-scales of completed EGRET positive γ-ray blazars loud were investigated. We generalized the Elliot–Shapiro relation to the Klein–Nishina regime and derived a corrected form of the relation by taking into account the Klein–Nishina effect, then compiled a small sample including 21 γ-ray loud blazars, whose rapid variation time-scales in optical band were well established, to examine whether or not they obey the corrected form of the relation. It is found that the γ-ray luminosity at low state and the variation time-scales for these sources well obey the corrected Elliot–Shapiro relation. This suggests that the measured variability time-scales are not short enough to require beaming effect when the Klein–Nishina effect is considered. The γ-ray emissions at low state may be produced in a region close to the central SMBHs, and are unbeamed or weakly beam. This is quite consistent with Dermer & Gehrels's argument. Thus, taking into account the Klein–Nishina effect, the central SMBH masses and variability time-scales of completed EGRET γ-ray loud blazars were derived with the γ-ray fluxes. The results show that the central SMBH masses range in $10^{6.5}$–$10^{10.2}\,{\rm M}_{\odot}$. The mean and the median of the masses are $10^{8.9}$ and $10^{9.1}\,{\rm M}_{\odot}$, respectively. The distribution of the masses exhibits a weak bimodal distribution with peaks at $10^{8.2}\,{\rm M}_{\odot}$ and $10^{9.2}\,{\rm M}_{\odot}$, and a valley at $10^{8.5}\,{\rm M}_{\odot}$. This seems to present a signature for classifying these blazars into two groups. Most of the objects (75 per cent) belong to the group of $M \geqslant 10^{8.5}\,{\rm M}_{\odot}$, while only about 25 per cent objects are included in the group of $M \leqslant 10^{8.5}\,{\rm M}_{\odot}$. We also found that most of the BL Lac objects in the sample belong to the later group, while most of the quasars in the sample belong to the former group. This likely indicates that the masses of the central SMBHs of BL Lac objects are significantly smaller than that of quasars. This is quite consistent with argument proposed by Ozernoy. The variability time-scale is an observable indicator for examining the reliability of the mass estimate. Our results show that The variability time-scales for these sources range from $10^{1.6}$ s to $10^{5.6}$ s. the variation time-scales shows a bimodal distribution too, with two peaks at $10^{3.2}$ s (corresponding to 0.44 h) and $10^{4.5}$ s (corresponding to 8.78 h), and a valley at $10^{4.0}$ s. About 25 per cent of the sources have rapid variability on time-scale of a fraction of an hour, and 75 per cent of the sources have variability on a time-scale of intranight or intraday. The time-scales derived in this work are significantly correlated with observed shortest time-scales. The linear correlation coefficient is 0.76 with a chance probability of 0.0001. These results might indicate that the mass estimate in this work is reliable.

One of the most important properties of a SMBH is its mass, which is the key parameter determine most of the fundamental scales of an AGN and its determination can have a great impact on our comprehension of AGNs. Many unusual observational phenomenons of blazars may be directly related to their central engines, the SMBHs. Many works on searching for the evidence of SMBHs have been done, and dynamical evidence of dark compact objects of mass $\sim 10^{6.5}$–$10^{9.5}\,{\rm M}_{\odot}$ in galaxies has been accumulating rapidly in the last decade or so (see reviews in Kormendy & Richstone 1995; Richstone et al. 1998). SMBH with mass less than $10^{6}\,{\rm M}_{\odot}$ has not been measured (Magorrian et al. 1998, and references therein). Some methods for estimating SMBH mass, such as spatially resolved kinematic method (e.g. Kormendy 2001), reverberation mapping method (Blandford & McKee 1982; Netzer & Peterson 1997; Gebhardt et al. 2000), methods with variability in optical or X-ray wavebands (see e.g. Abramowicz & Nobili 1982; Ho 1999), have been proposed. It is well known that it is difficult and complicated to study SMBHs in AGNs by kinematic method because they are swallowed into the light and dust surrounding the AGNs. In the present work we evaluated the SMBH masses in γ-ray blazars with their γ-ray fluxes. The results are quite consistent with the measured masses of dark compact objects in galaxies. The variation time-scale is an observable indicator to examine the reliability of the mass estimates. The shortest time-scales derived in this work quite agree with the observational results. This suggests that the mass estimate in this work is reliable.

An important point that should be emphasized is that the results of this work are based on a controversial assumption that these γ-ray emissions are unbeamed. It is well known that the necessity of beaming in gamma-ray loud sources is now well established. However, in this paper we have shown that the gamma-ray emissions at low state are likely unbeamed or weakly beamed, while the gamma-ray emissions at high state are beamed. More efforts should be paid to justifying the beaming effect in detail for the different cases of such energetic radiation.

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