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Minimal variability time scale – central black hole mass relation of the γ-ray loud blazars
(Research Note)

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ABSTRACT

Context. The variability time scales of the blazar γ-ray emission contain the imprints of the sizes of their emission zones and are generally expected to be larger than the light-crossing times of these zones. In several cases the time scales were found to be as short as ~10 min, suggesting that the emission zone sizes are comparable with the sizes of the central supermassive black holes. Previously, these measurements also led to the suggestion of a possible connection between the observed minimal variability time scales and the masses of the corresponding black holes. This connection can be used to determine the location of the γ-ray emission site, which currently remains uncertain.
Aims. The study aims to investigate the suggested "minimum time scale – black hole mass" relation using the blazars, detected in the TeV band.
Methods. To obtain the tightest constraints on the variability time scales this work uses a compilation of observations by the Cherenkov telescopes HESS, MAGIC, and VERITAS. These measurements are compared to the blazar central black hole masses found in the literature.
Results. The majority of the studied blazars show the variability time scales which are at least comparable to the period of rotation along the last stable orbit of the central black hole – and in some cases as short as its light-crossing time. For several sources the observed variability time scales are found to be smaller than the black hole light-crossing time. This suggests that the detected γ-ray variability originates, most probably, from the turbulence in the jet, sufficiently far from the central black hole.

Key words. gamma rays: galaxies – galaxies: active – quasars: supermassive black holes – BL Lacertae objects: general

1. Introduction

Blazars are among the most powerful and variable γ-ray emitters in the Universe. Even though their output in the γ-ray domain often dominates the bolometric luminosity of these sources, the location of the region responsible for this intense γ-ray radiation remains unclear. The potential connection of this region to the vicinities of the central supermassive black hole (SMBH) is complicated by the fact that the multi-GeV gamma rays may be absorbed in the dense optical and UV photon fields (Jelley 1966), originating from the broad line region (BLR; Liu & Bai 2006; Poutanen & Stern 2010), jet, or accretion flow (Dermer et al. 1992; Maraschi et al. 1992; Bednarek 1993). A solution to this problem is found in the assumption that the gamma ray emission site is located at parsec-scale distances from the SMBH where the photon fields are less intense and the γ-ray emission can escape the source (Abdo et al. 2010; Tavecchio et al. 2011; Pacciani et al. 2012; Ghisellini et al. 2013).

However, the observed fast variability of the blazar γ-ray emission – down to (sub-)hour time scales (Aharonian et al. 2007; Albert et al. 2007; Neronov et al. 2008; Abramowski et al. 2010; Foschini et al. 2011; Neronov & Vovk 2011; Sbarrato et al. 2011; Vovk & Neronov 2013) – suggests that the gamma-ray emission region is very compact, much smaller than the transverse size of the jet at parsec distances from the SMBH. Although this compactness of the region is a strong argument in favour of the connection to the blazar central engine, alternative explanations to this phenomenon were also proposed that attributed the observed fast variability to the small-scale inhomogeneities in the jet structure (Begelman et al. 2008; Ghisellini & Tavecchio 2008; Ghisellini et al. 2009; Giannios et al. 2009; Barkov et al. 2012; Narayan & Piran 2012).

The choice between these two possibilities – the close vs. distant gamma-ray source – can be made based on statistical arguments. The relation of the emission site to the central SMBH invokes the connection between the minimal variability time scales and the size of the SMBH $t_{\rm min} \geq t_{\rm lc} = R_{\rm BH}/c \sim 10^4\,(M_{\rm BH}/10^9\,M_\odot)$ s. On the other hand, if the site of the gamma ray production is remote to the SMBH, the time scales of the variability are dictated by the characteristic spatial scales of the processes in the jet, where the information about the central black hole size is already lost. Thus, one can search for the presence of the relation between the minimal variability time scales of blazar γ-ray emission and the masses of their SMBHs. The presence of such a connection would be evidence for a strong link between the SMBH vicinities and the gamma ray emission site.

This relation has been already searched for in the GeV band (Vovk & Neronov 2013) using the data from the space-borne *Fermi*/LAT telescope (Atwood et al. 2009). Even though

Table 1. List of the sources used here together with the derived time scales.

Name	Type	$\log\left(\frac{t_{\rm GeV}}{1\ \rm s}\right)$	$\log\left(\frac{t_{\rm TeV}}{1\ \rm s}\right)$	$\log\left(\frac{M_{\rm BH}}{M_\odot}\right)$
1ES 1218+304	BL Lac	–	$5.4^{+0.1}_{-0.1}$(4)	8.5(16)
1ES 1959+650	BL Lac	–	$3.2^{+0.3}_{-0.7}$(8)	8.2(11)
4C +21.35	FSRQ	3.64	$3.0^{+0.1}_{-0.1}$(6)	8.9(14)
BL Lac	BL Lac	4.96	$2.9^{+0.1}_{-0.2}$(9)	8.6(16)
IC 310	Rad.gal	–	$2.7^{+0.2}_{-0.3}$(7)	8.5(7)
Mrk 421	BL Lac	–	$3.5^{+0.2}_{-0.1}$(12)	8.5(10)
Mrk 501	BL Lac	–	$2.2^{+0.1}_{-0.2}$(5)	8.9(10)
M 87	Rad.gal	–	$4.7^{+0.1}_{-0.1}$(2)	9.5(15)
W Com	BL Lac	–	$4.9^{+0.1}_{-0.2}$(3)	8.0(16)
PKS 2155-304	BL Lac	6.69	$2.0^{+0.1}_{-0.1}$(1)	8.9(13)

Notes. Column 3 shows the minimal variability time scale in the GeV band from Vovk & Neronov (2013), Col. 4 the variability time scales derived here. Column 5 lists the SMBH masses estimates selected for the analysis here (numbers in brackets indicate the corresponding reference; please see the discussion in Sect. 3 for the description of the particular $M_{\rm BH}$ choice).

References. (1) Abramowski et al. (2010); (2) Abramowski et al. (2012); (3) Acciari et al. (2008); (4) Acciari et al. (2010); (5) Albert et al. (2007); (6) Aleksić et al. (2011); (7) Aleksić et al. (2014); (8) Aliu et al. (2014); (9) Arlen et al. (2013); (10) Falomo et al. (2002); (11) Falomo et al. (2003b); (12) Galante & the VERITAS Collaboration (2011); (13) Ghisellini et al. (2010); (14) Shaw et al. (2012); (15) Walsh et al. (2013); (16) Wu et al. (2009).

the observed minimal variability time scales for several sources were found to be very close to the light-crossing times of their SMBHs, this study was very much limited by the sensitivity of the *Fermi*/LAT instrument, which prevented the detection of the variability on the $t \sim t_{\rm lc}$ time scales except for the brightest sources.

Ground-based Cherenkov γ-ray telescopes, operating in the energy band $\gtrsim$100 GeV, have much larger collection areas (typically $\sim 10^4$–10^5 m^2) than *Fermi*/LAT ($\approx$0.7 m^2, Atwood et al. 2009), and so have greater capabilities when it comes to the detection of fast variability. For this reason the presented study aims to collect the available observations of the short time scale variability from Cherenkov telescopes and compare them to the conclusions of Vovk & Neronov (2013).

2. Data selection and analysis

Observations of fast variability for a number of blazars have already been reported in the literature (Aharonian et al. 2007; Albert et al. 2007; Abramowski et al. 2010, 2012; Acciari et al. 2010, 2008; Arlen et al. 2013). As there is no unique way of measuring the variability, the time scales reported in the literature are often derived in different manners and have to be put into the same scale. Here they were all converted to the exponential rise/decay (e-folding) time scales by the fitting of the reported light curves wherever the authors defined the variability differently. The only exception was 4C +21.35, whose light curve is consistent with a simple linear growth. For this source the *e*-folding time scale was defined as $t(F_{\rm max})-t(F_{\rm max}/e)$, where $F_{\rm max}$ is the highest flux, observed in the light curve. All derived variability time scales are listed in Table 1. The results from the analysis of the *Fermi*/LAT data at ~1 GeV (Vovk & Neronov 2013) are also listed there for comparison.

The masses of the central SMBHs for the studied active galactic nuclei (AGNs) were collected from the literature, the corresponding reference(s) for each object is given below the table. For some of the sources several estimates of the SMBH mass were found. For such objects the mass estimates are discussed below to find the most reliable ones.

3. SMBH masses and corresponding time scales

The variability time scales derived here can be used to infer the information about the size of the γ-ray emission region. The presence of the relation between the lowest time scales and the masses of the central SMBHs would indicate a close connection between the SMBH and the gamma-ray production site. Its absence, on the other hand, would support an assumption about the "distant" γ-ray emission site.

A connection between the observed variability time scale and the size of the emission region usually involves a jet Doppler factor to account for the relativistic motion of the emitting plasma. However, if the observed variability of the γ-ray emission is related to certain inhomogeneities of the jet flow, which is driven by the central black hole, then these time scales can be directly compared to the size of the central engine without a correction for the uncertain value of the Doppler factor (Neronov et al. 2008).

Indeed, this last situation can be seen as a stationary source (blazar) emitting signals (blobs of relativistic particles) towards a stationary observer with a time separation of Δt. Because the source and observer are in the same frame of reference, the interval between the detected signals $\Delta t_{\rm obs}$ will not change – $\Delta t_{\rm obs} = \Delta t$ even though the signals are carried by the relativistic flow (jet). In this way the only correction needed to relate the observed and true variation time scales, provided that the emission region is local to the SMBH, is the correction for the redshift of the source $z - \Delta t = \Delta t_{\rm obs}/(1+z)$.

In this way the variability time scales derived from the data can be compared to the light-crossing times $\Delta t_{\rm lc} = 2(R_{\rm g} + \sqrt{R_{\rm g}^2 - a^2})/c$ of the corresponding SMBHs:

$$t_{\rm lc} \simeq \begin{cases} 2\times 10^3 \left(\dfrac{M_{\rm BH}}{10^8 M_\odot}\right) s, & a = 0 \\ 10^3 \left(\dfrac{M_{\rm BH}}{10^8 M_\odot}\right) s, & a = R_{\rm g}. \end{cases} \quad (1)$$

Here $R_{\rm g} = GM_{\rm BH}/c^2$, and $a = J_{\rm BH}/M_{\rm BH}c^2$ is the reduced angular momentum $J_{\rm BH}$ of the black hole.

The variability induced by the central engine might be also related to the inhomogeneities in the accretion disk, resulting in the non-stable feeding of the relativistic jet. In this case one can expect that the characteristic time scales of the variability would be connected to the orbital period around the central SMBH:

$$P(r) = 2\pi \frac{r^{3/2} \pm aR_{\rm g}^{1/2}}{cR_{\rm g}^{1/2}}. \quad (2)$$

In case of the last stable prograde orbit (which has the shortest period), this equation gives:

$$P(r_{\rm min}) \simeq \begin{cases} 6\times 10^3 \left(\dfrac{M_{\rm BH}}{10^8 M_\odot}\right) s, & a = R_{\rm g} \\ 5\times 10^4 \left(\dfrac{M_{\rm BH}}{10^8 M_\odot}\right) s, & a = 0. \end{cases} \quad (3)$$

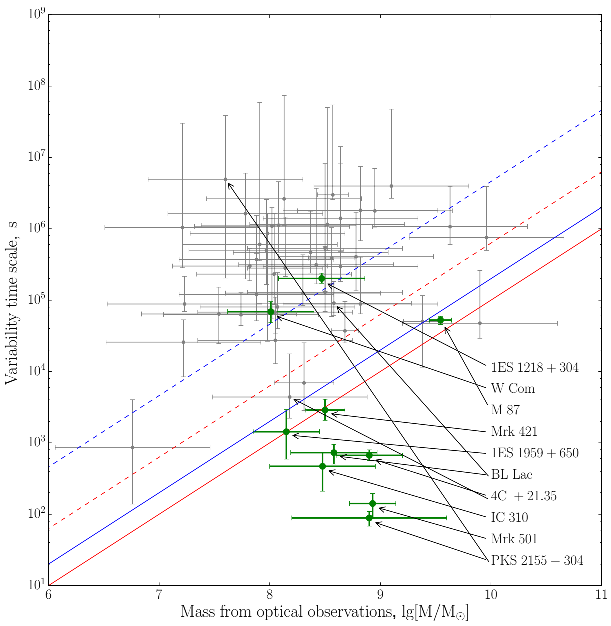

Fig. 1. Summary of the minimal variability time scales derived from the GeV data (in grey, Vovk & Neronov 2013) and TeV data (in green, this work). The arrows indicate the variability estimates for the specific sources from Table 1. The black hole light-crossing times $t_{\rm lc}$ are shown by the solid blue ($a = 0$) and red ($a = R_{\rm g}$) lines. The last stable orbit periods for the $a = 0$ and $a = R_{\rm g}$ cases are indicated by the blue and red dashed lines, respectively.

In principle, a potentially complicated structure of the jet launching region might result in a somewhat smaller intrinsic size of the particle acceleration site. Still, one can expect that the time scale of the large-amplitude variability of the source should not be much smaller than the limiting values given by Eqs. (1) and (3). A test of this assumption on real sources can then be used to establish its validity.

To accomplish this it also important to have accurate measurements of the SMBH masses. Because of the distance and presence of the beamed non-thermal emission, for blazars (which constitute the majority of the sources in Table 1) the dynamical measurements of the black hole mass are usually not feasible, and black hole masses are inferred from a range of estimators. Whenever they were available, we used the $M_{\rm BH}$ estimates based on the established correlations of the black hole mass with the host galaxy properties (Kormendy & Richstone 1995; Magorrian et al. 1998; Gebhardt et al. 2000a; Ferrarese & Merritt 2000; Wandel 2002; Marconi & Hunt 2003). In addition, we also used the estimators calibrated from reverberation mapping technique (Gebhardt et al. 2000b; Kaspi et al. 2000; Vestergaard & Peterson 2006) and, in some cases, the estimates based on spectral energy distribution (SED) modelling (Ghisellini et al. 2010). In cases where more than one estimate was found, we adopted the most direct one or the one based on the relation with the least intrinsic scatter.

1ES 1218+304. Two $M_{\rm BH}$ measurements were found for this blazar. The value of $\log(M_{\rm BH}/M_\odot) = 8.69$, given by Falomo et al. (2003a), is based on the correlation with the host galaxy bulge luminosity in R-band ($M_R - M_{\rm BH}$, McLure & Dunlop (2002)). Based on the same galaxy property correlation $M_R - M_{\rm BH}$, a value of $\log(M_{\rm BH}/M_\odot) = 8.5$ was reported by Wu et al. (2009). Another estimate of $\log(M_{\rm BH}/M_\odot) = 8.0$ (Wu et al. 2002) is based on the bulge velocity dispersion – black hole mass relation ($\sigma - M_{\rm BH}$; Ferrarese & Merritt 2000; Gebhardt et al. 2000a), with the velocity dispersion inferred from the fundamental plane relation. Because it is based on the application of two correlations, each with its own intrinsic scatter, this estimate was considered to be less reliable. Here we adopted the most recent value from Wu et al. (2009).

1ES 1959+650. The mass of the central black hole of this BL Lac object was estimated by several authors. Based on the measured host velocity dispersion, Falomo et al. (2003b) give the value $\log(M_{\rm BH}/M_\odot) = 8.15 \pm 0.17$. Based on the host galaxy luminosity relation, Falomo et al. (2003a) give a somewhat higher value of $\log(M_{\rm BH}/M_\odot) = 8.53$. Based on the fundamental plane and velocity dispersion correlation, Wu et al. (2002) give the value $\log(M_{\rm BH}/M_\odot) = 8.22$ or 8.33, depending on the adopted $\sigma - M_{\rm BH}$ relation. Wu et al. (2009) reported $\log(M_{\rm BH}/M_\odot) = 8.2$ using the $M_R - M_{\rm BH}$ relation. An interesting estimate comes from the SED modelling, by assuming that the putative accretion disk emission does not contribute to the continuum, which is dominated by the non-thermal jet emission (Ghisellini et al. 2010). Using this method the authors found an estimate $\log(M_{\rm BH}/M_\odot) = 8.3$. Since most estimates are consistent with it, the original estimate from Falomo et al. (2003b) is used here.

4C +21.35. For this object, we found two black hole mass estimates, both based on the reverberation-mapping calibrated virial mass estimator, $\log(M_{\rm BH}/M_\odot) = 8.17$ (Wang et al. 2004), based on Hβ line width and extrapolated continuum luminosity, and two values, $\log(M_{\rm BH}/M_\odot) = 8.91 \pm 0.29$ and $\log(M_{\rm BH}/M_\odot) = 8.89 \pm 0.15$, based on Mg II and H$\beta$ lines, respectively (Shaw et al. 2012). Here we adopt a more recent estimate of Shaw et al. (2012), conservatively taking $\log(M_{\rm BH}/M_\odot) = 8.9 \pm 0.3$.

BL Lac. For this object four $M_{\rm BH}$ estimates were found in the literature. Two of them are based on the correlation with the host galaxy bulge luminosity and give similar values: Falomo et al. (2003a) give $\log(M_{\rm BH}/M_\odot) = 8.77$, with host luminosity derived from the HST images, while Wu et al. (2009) give a similar value of $\log(M_{\rm BH}/M_\odot) = 8.58$, based on the luminosity found in previous publications. Using the fundamental plane derived velocity dispersion, Woo & Urry (2002) find a lower value of $\log(M_{\rm BH}/M_\odot) = 8.23$. Based on the SED and accretion disk modelling, Ghisellini et al. (2010) find a value of $\log(M_{\rm BH}/M_\odot) = 8.7$, in agreement with the values reported by Falomo et al. (2003a) and Wu et al. (2009). Here we keep the "closest to average" value from Wu et al. (2009).

Mrk 421. This source has several $M_{\rm BH}$ estimates based on various approaches. Here we will only list the two estimates based on the $\sigma - M_{\rm BH}$ relation as the more reliable ones. Falomo et al. (2002) measured the velocity dispersion of the source and obtained an estimate $\log(M_{\rm BH}/M_\odot) = 8.50 \pm 0.18$. The authors also comment that applying the $M_R - M_{\rm BH}$ relation they would obtain a similar result $\log(M_{\rm BH}/M_\odot) = 8.65$. Barth et al. (2003) report a lower value of $\log(M_{\rm BH}/M_\odot) = 8.28 \pm 0.11$. Since the two values are consistent within the quoted uncertainties, we retained the original estimate from Falomo et al. (2002).

Mrk 501. We found two velocity-dispersion-based mass estimates for this source: $\log(M_{\rm BH}/M_\odot) = 8.93 \pm 0.21$ (Falomo et al. 2002) and $\log(M_{\rm BH}/M_\odot) = 9.21 \pm 0.13$ (Barth et al. 2003). Based on the SED and accretion disk modelling, Ghisellini et al. (2010) report an estimate of $\log(M_{\rm BH}/M_\odot) = 8.84$, in agreement with the value from Falomo et al. (2002), which we therefore choose to adopt for our analysis.

M87. For this source, we found two reliable black hole mass measurements based on stellar and gas dynamics, respectively: $\log(M_{\rm BH}/M_\odot) = 9.82 \pm 0.03$ (Gebhardt et al. 2011) and $\log(M_{\rm BH}/M_\odot) = 9.5 \pm 0.1$ (Walsh et al. 2013). For the present analysis we adopt the more recent estimate from Walsh et al. (2013).

W Comae. The two $M_{\rm BH}$ measurements for this source come from the $M_R - M_{\rm BH}$ relation, $\log(M_{\rm BH}/M_\odot) = 8.0$ (Wu et al. 2009) and from the SED modelling, $M_{\rm BH} = 5 \times 10^8\ M_\odot$ (Ghisellini et al. 2010). Because of the disagreement between the two values, the reason for which is not clear, we adopt the value arising from the correlation with the galaxy luminosity.

PKS 2155-304. For this source, we found only one $M_{\rm BH}$ estimate, $\log(M_{\rm BH}/M_\odot) = 8.9$ (Ghisellini et al. 2010), based on modelling the observed SED, which we adopt in this work.

A comparison of the expected limiting values from Eqs. (1) and (3) with the observed variability time scales for the sources in Table 1 is shown in Fig. 1.

4. Discussion

Figure 1, which summarizes the variability time scales and the SMBH masses estimates compiled here, clearly demonstrates the advantages of the Cherenkov instruments over the satellite measurements when it comes to the studies of the fast variability in the high-energy γ-ray domain: they provide more precise measurements, at the same time probing smaller time scales. From the *Fermi*/LAT data alone, the majority of AGNs showed the variability on the time scales significantly larger than the light-crossing times of their central black holes. However, even though they are limited by the sensitivity of *Fermi*/LAT, they were still found to be variable on the time scales comparable to the periods of rotation around the last stable orbit of the corresponding SMBH (Vovk & Neronov 2013).

We note that the estimates of variability time scales obtained from the TeV data come from observational campaigns dedicated to each source, with inhomogeneous time sampling – as opposed to much more homogeneous light curves based on the *Fermi*/LAT data. This implies that the time scales listed in Table 1 should be considered as upper limits to the minimal variability time scales; they are likely to be decreased in the future with new observations.

All ten sources in Table 1 are clearly variable on the time scales $t_{\rm TeV}$, which are at least comparable with the period of rotation at the last stable orbit; at the same time five blazars (4C +21.35, BL Lac, IC 310, Mrk 501, and PKS 2155-304) demonstrate the variability with $t_{\rm TeV} < t_{\rm lc}(M_{\rm BH})$ for the corresponding SMBH masses $M_{\rm BH}$.

The variability of the studied blazars that is apparently too fast is in disagreement with the $t_{\rm TeV} \gtrsim R_{\rm g}/c$ constraint, expected if the emission region is connected to the central SMBH. Some of the investigated objects (e.g. Mrk 501) demonstrate $t_{\rm TeV}$ values that are an order of magnitude smaller than the corresponding SMHB light-crossing time even accounting for the uncertainties on $M_{\rm BH}$, suggesting a weak connection to the SMBH size, if any.

The absence of the apparent connection between the minimal variability time scales and the SMBHs masses is generally expected if the source of the γ-ray emission is distant, located at parsec-scale distances from the central black hole. For the typical opening angles of the AGN jets of $\sim 10°$, this means that the transverse extension of the jet is $\gtrsim 0.1$ parsec, which is definitely too large to explain the observed variability time scales, even taking into account the necessary correction for the bulk Lorentz-factor of the jet Γ. The observed variability in this case – and the γ-ray emission itself – should be attributed to the presence of the small-scale inhomogeneities in the jet. These inhomogeneities can be in the form of subregions moving randomly at relativistic (Marscher 2014) or even ultra-relativistic velocities with respect to the jet (Ghisellini & Tavecchio 2008; Giannios et al. 2009; Narayan & Piran 2012), streams of the relativistic particles moving along the jet magnetic field lines (Ghisellini et al. 2009), or even compact clouds created by the stars traversing the jet (Barkov et al. 2012).

Fast variability can be produced even at hundreds of $R_{\rm g}$ from the black hole, provided that the jet is able to accelerate up to $\Gamma \gtrsim 50$ at such distances (Begelman et al. 2008); however, the observations of $t_{\rm TeV} < t_{\rm lc}(M_{\rm BH})$ make this interpretation less likely. It is still possible that the apparent variability is induced by the presence of the small-scale blobs in the accretion disk, which results in inhomogeneous matter supply to the jet. If this supply is fed from a specific region in the accretion disk – for example, as a result of the difference in orientation of the accretion disk magnetic field and the rotation axis of the central black hole (Neronov et al. 2009) – then the blobs crossing it would cause an abrupt injection of particles to the jet, which may result in flares.

It is also possible that blazars as a class do not have a uniquely located region of gamma ray production – or even have several of them. In this case different sources may or may not demonstrate a connection to the SMBH size depending on the location of the primary γ-ray emission region.

Further interpretation of the fast variability would clearly benefit from the more precise estimations of the SMBH masses for the γ-ray loud blazars. Such measurements would allow us to clearly confirm or disprove the observed relation $t_{\rm TeV} < t_{\rm lc}(M_{\rm BH})$ and, probably, clarify the properties of the gamma-ray emitting region(s). Combined with the detailed studies of the jet structure in the vicinities of the central SMBHs, which are now becoming possible with radio interferometers (Doeleman et al. 2012), this will help to better understand the processes leading to the particle acceleration in AGNs.

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