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Rapid VHE variability in blazars

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Active Galactic Nuclei (AGN) are known to show significant variability over a wide frequency range. We review observational results on the variability characteristics of blazars in the very high energy (VHE) domain, focusing on recent findings of rapid VHE variability and evidence for an underlying multiplicative driving process in PKS 2155-304. We explore a physical scenario where the variability is assumed to arise due to accretion disk fluctuations transmitted to the jet, and discuss its implications for the central powerhouse.

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1. Introduction

Active Galactic Nuclei (AGN) show significant variability over a large range of timescales and with different amplitudes [1, 2, 3]. At the time when this paper is written, despite the limited temporal coverage of Atmospheric Cherenkov Telescopes (ACTs) half of the AGN detected in the TeV domain by these experiments have shown variability. For the majority of them, variability timescales above one month have been found. In about a quarter of them there is clear evidence for short-term VHE variability on observed timescales of less than one day. The class of the high-frequency peaked BL-Lac objects currently reveals the most rapid VHE gamma-ray flux variability (observed VHE variability timescales of a few minutes), as found by the H.E.S.S. and MAGIC experiments in PKS 2155-304 [4] and Mkn 501 [5], respectively. The latter findings suggest that one of the most constraining requirements on the jet kinematics and the high-energy emitting region may actually come from VHE variability studies.
Perhaps the most prominent example concerns the TeV blazar PKS 2155-304 at redshift of $z = 0.116$. In July 2006, the H.E.S.S. telescope array detected a dramatic VHE outburst in PKS 2155-304 [4], with flux level varying between 1 and 15 Crab units and clear evidence for minute-timescale ($t_v \sim 200$ sec) VHE variability (see Fig. 1, left panel).
Apart from the extreme minimum variability timescale, Fourier analysis of the VHE light curve also revealed a red-noise-type PSD (power spectra density) with an exponent close to ~ 2 within the frequency range $[10^{-4}$-10^{-2}Hz$]$ (see Fig. 1 right panel). Similarly to results in the X-ray domain, a correlation between (absolute) rms (root mean square) variability amplitude and mean VHE flux has been observed [6]. This is known to be characteristic of a non-linear, log-normal stochastic process where the relevant, normally distributed variable is the logarithm of the flux $\log(X)$, and not just the flux X itself [7, 8]. The process driving the VHE variability in PKS 2155-304 is therefore expected to satisfy a log-normal distribution.
In most currently-proposed scenarios for extreme short-term variability in blazars, this second finding is not discussed and this still leaves us with a challenge to coherently explain both facts. In the present paper, we discuss a model (explained in more detail in [9]), where fluctuations in accretion disk rate feeding the jet are ultimately responsible for the observed PSD (Fig. 2).

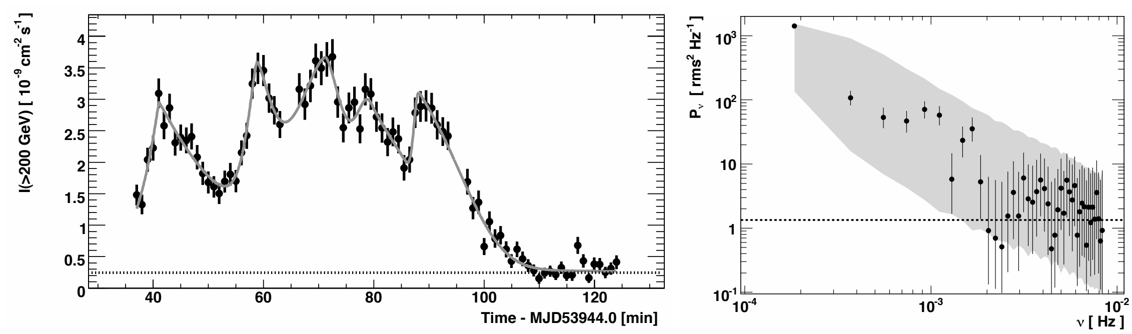

Figure 1: Left: H.E.S.S. integral flux above 200 GeV observed from PKS 2155-304 on MJD 53944 vs. time. The data are binned in 1 minute intervals. Taken from [4]. Right: The Fourier power spectrum of the light curve aside. The area corresponds to the 90% CL for a power-law spectrum of index -2 [4].

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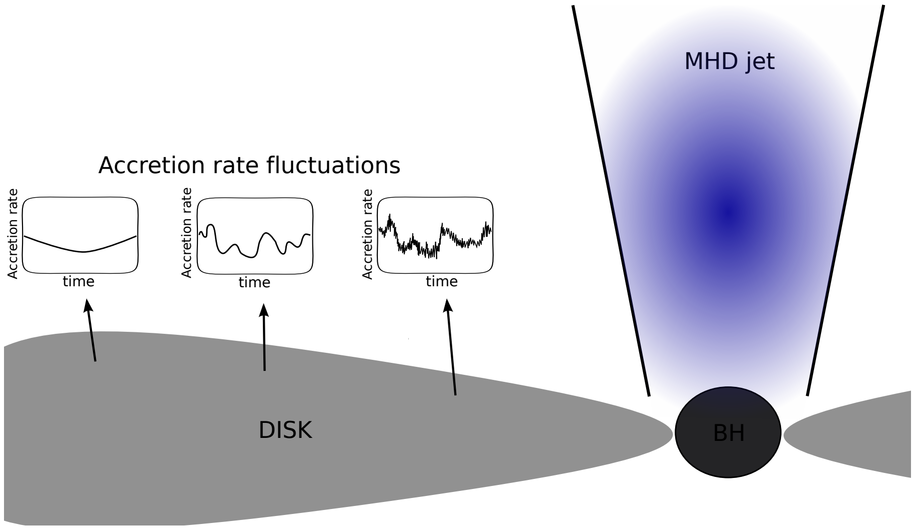

Figure 2: Sketch of the considered model, where the VHE variability is driven by variations in the accretion rate: Small, independent fluctuations of the accretion rate on local viscous timescale $t_{\rm visc}(r)$ are assumed to occur over a range of disk radii $r \gg r_i$ large compared to the inner radius r_i of the disk. If not damped, these fluctuations can propagate inwards and couple together to produce log-normal accretion rate variability close to r_i of the flicker or red-noise-type. Any emission process linked to this region (e.g., plasma injected into the jet) may then eventually be modulated over a frequency interval ranging from the inverse accretion time near the outer to the one at the innermost disk radius, respectively.

2. On the log-normal VHE behavior in PKS 2155-304

In principle, log-normal variability, as found in PKS 2155-304, can be considered as a statistical property of variable objects which is generated by a stationary random process by taking the exponential of a Gaussian time series. In such a case, the average fluxes is strongly correlated with the higher moments of the time series and thus with the rms. The correlation then signifies that the stochastic process driving this variability is multiplicative (not additive).
The log-normal VHE flux distribution in PKS 2155-304 can thus be thought of as the results of many multiplicative random effects as in a cascade. Variations on short timescales (determining the rms) will then obviously decrease in amplitude when the long timescales variations (determining the mean flux) decrease [8].
In the context of accretion disk variability, Lyubarskii [10] has shown that fluctuations of the disk parameters at some radius, occurring on local viscous timescale, can lead to log-normal-type variations in the accretion rate at smaller radii that are of the flicker- or red-noise-type (cf. Fig. 2).

3. The origin of the VHE variability in PKS 2155-304

Suppose that these variations in the accretion rate are efficiently transmitted to the jet, resulting in red-noise fluctuations in the injection rate for Fermi-type particle acceleration. To successfully reproduce the variability characteristics in PKS 2155-304, one would then (at least) require the following:

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1. First, the observed minimum variability timescale of ~ 200 sec, sets constraints on the size of the jet-emitting black hole dominating the VHE emission viz. $t_v \sim (1+z)r_g/c$, where $r_g = Gm/c^2$ is the gravitational radius of the black hole. The allowed maximum black hole mass would then be
$$m_v \lesssim 4 \times 10^7 \left(\frac{t_v}{200\ \mathrm{sec}}\right) M_\odot \,, \tag{3.1}$$
which is about an order of magnitude smaller than the anticipated central black hole mass inferred for PKS 2155-304 based on the known host galaxy luminosity relation [9]. A rather small black hole mass also appears consistent with the X-ray variability properties observed from PKS 2155-304 [11, 12]. Such apparently divergent mass estimates inferred from high energy emission properties and host galaxy observations, could possibly indicate the presence of a close binary BH system [13, 14], where the jet that dominates the high energy emission originates from the less massive (secondary) BH (see Fig. 3).

2. Secondly, we will only be able to observe rapid VHE emission (occurring on timescales as short as 200 sec) with red noise-characteristics if these signatures do not get blurred by processes occurring on longer timescale within the source. As flux changes for an observer will always appear to be convolved and thus dominated by the longest timescale, this requires that the (observed) timescales for photons traveling across the radial width of the source and for the relevant radiative processes still remains smaller than t_v. As shown in [9], this seems feasible in the case of PKS 2155-304.

4. A possible binary black hole scenario for PKS 2155-304

Suppose that the different mass estimates are indeed due to the presence of a close binary system (separation $d \ll 1$ pc), where the VHE emission is dominated by the jet from the less massive black hole. Such a binary system may be the outcome of the underlying hierarchical merging process shaping the host galaxy. There are a variety of reasons (e.g., observations of longterm periodicity) to take this to be of particular relevance for radio-loud AGN, e.g., see [15] for a review. Such a binary scenario for PKS 2155-304 may involve the following:

1. While the observed short-term variability implies an upper limit on the secondary black hole mass, a lower limit can be derived based on the observed VHE luminosity during the outburst, i.e., the secondary mass m_2 cannot be too small if one also wishes to account for the required jet power. The analysis suggests that $m_2 \sim 10^7 M_\odot$ [9].

2. There are indications for an optical longterm periodicity of $\sim (4-7)$ yr in PKS 2155-304 [18]. If true, this may fit nicely into a binary framework and suggest an upper limit on the intrinsic Keplerian orbital period of the binary of
$$P_k \leq \frac{2}{(1+z)} P_{\mathrm{obs}}^{\mathrm{opt}} \simeq 13 \left(\frac{P_{\mathrm{obs}}^{\mathrm{opt}}}{7\ \mathrm{yr}}\right) \mathrm{yr} \,, \tag{4.1}$$
if one assumes e.g. that the observed optical longterm periodicity is caused by the secondary crossing the disk around the primary twice per orbital period, or similarly, that time-dependent gas streams are periodically feeding the central binary [16].

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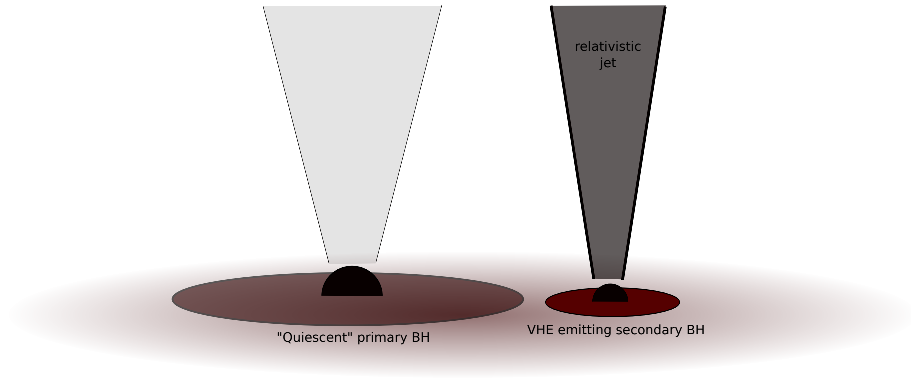

Figure 3: Sketch of a possible binary black hole scenario for PKS 2155-304: Two black holes orbit each other on quasi-coplanar orbits, with the binary surrounded by a circumbinary disk. Jet emission from the less massive, secondary black hole dominates the observed VHE radiation spectrum. Once the secondary becomes embedded in the outer disk around the primary, it starts clearing up an annular gap. Numerical simulations, e.g. [16, 17], show however, that mass supply from the circumbinary disk to the central binary continues through tidal, time-dependent gas streams that penetrate the disk gap, periodically approaching and preferentially feeding the secondary (disk). The numerical results particularly evince a reversal of mass accretion rates can occur (i.e., $\dot{m}_2 > \dot{m}_1$ despite $m_2 < m_1$), acting towards equal-mass binaries and suggesting that the secondary may become more luminous than the primary. If so, then applying variability constraints based on observed high emission properties can lead to a spurious identification of the secondary mass with the (total=primary+ secondary) central black hole mass.

3. The residual life-time of the binary system due to gravitational wave emission (assuming quasi-circular orbits) is then expected to be below $\sim 10^8$ yrs [9], providing phenomenological support to the notion that supermassive binary black hole systems are able to coalescence within a Hubble time.

4. If the jet launched from the black hole is wrapped by a sufficiently strong magnetic field, its overall path can become curved (at least on small, sub-VLBA scales) due to the orbital motion of the supporting black hole. Then, the need for high minimum-bulk-Lorentz-factors of the outflow (as inferred from VHE SED modelling) might be somewhat relaxed because the effective Doppler factor becomes time-dependent [9]. This (and the possibility that the primary may also produce a slower, radio-emitting wind) could help to explain why on larger (radio VLBA) scales only modest Doppler boosting appears to be present [19].

5. High-resolution VLBI images for PKS 2155-304 indicate strong jet bending within the inner milli-arcsecond (i.e., on parsec-scales) [20]. This could possibly be caused by precessional and/or orbital driving in a binary black hole system [21].

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5. Conclusions

The observed extreme VHE variability characteristics of PKS 2155-304 provide strong constraints on the physical parameters of its engine. We have suggested that the putative presence of a close supermassive binary binary system could allow to, e.g.,

- reconcile central mass estimates based on host galaxy observations (indicative of the total primary and secondary mass) with those based on VHE gamma-ray variability (possibly only indicative of the jet-emitting secondary),
- account for the observed log-normal variability characteristics via accretion disk fluctuations,
- relax constraints on the jet flow velocity.

Obviously, an increased instrumental sensitivity in the TeV domain (with a CTA-type instrument) that may allow us to search for even faster variability and, complementary, an advanced QPO analysis in the optical could be particularly valuable to assess the plausibility of such a scenario for PKS 2155-304.

References

[1] A.A. Abdo et al. (Fermi Collaboration) 2010, *ApJ*, **722**, 520

[2] A.C. Gupta et al. 2008, *AJ*, **135**, 1384

[3] J.H. Fan et al. 2007, *A&A*, **462**, 547

[4] F. Aharonian et al. (H.E.S.S. Collaboration) 2007, ApJ, **664**, L71

[5] J. Albert et al. (MAGIC Collaboration) 2007, *ApJ*, **664**, 71

[6] A. Abramowski et al. (H.E.S.S. Collaboration) 2010, *A&A*, **A83**, 16

[7] P. Uttley et al. 2005, *MNRAS*, **359**, 345

[8] I. McHardy 2008, *PoS(BLAZARS2008)*, **14**

[9] F.M. Rieger & F. Volpe 2010, *A&A*, **520**, A23

[10] Y.E. Lyubarskii 1997, *MNRAS*, **292**, 679

[11] B. Czerny et al. 2001, *MNRAS*, **325**, 865

[12] P. Lachowicz et al. 2009, *A&A*, **506**, L17

[13] F.M. Rieger & K. Mannheim 2003, *A&A*, **397**, 121

[14] C. Dermer, J. Finke, G. Menon 2008, *PoS*(Blazar2008) 019

[15] F.M. Rieger 2007, *Ap&SS* **309**, 1

[16] P. Artymowicz & S.H. Lubow 1996, *ApJ*, **467**, L77

[17] K. Hayasaki, S. Mineshige, & H. Sudou 2007, *PASJ* **59**, 427

[18] J.H. Fan & R.G. Lin 2000, *A&A*, **355**, 880

[19] B.G. Piner & P.G. Edwards 2004, *ApJ*, **600**, 115

[20] B.G. Piner, N. Pant & P.G. Edwards 2010, *ApJ*, **723**, 1150

[21] A. Zensus 1997, *ARA&A*, **35**, 607

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