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Scenarios for ultrafast gamma-ray variability in AGN

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We compare the energy requirements of different scenarios that allow addressing ultrafast gamma-ray variability recently reported by the MAGIC collaboration from two extragalactic sources, IC 310 and NGC 1275. Currently, the following three models are accepted as feasible explanation for minute-scale variability: (i) external cloud in the jet, (ii) relativistic blob propagating through the jet material, and (iii) production of high-energy gamma rays in the magnetosphere gaps. Our analysis shows that the first two scenarios are not constrained by the flare luminosity. On the other hand, there is a robust upper limit on the luminosity of flares generated in the black hole (BH) magnetosphere (MSph). The maximum luminosity of magnetosphere flares depends weakly on the mass of the central BH and is determined by the accretion disk magnetization, viewing angle, and the pair multiplicity. For the most favorable values of these parameters, the luminosity for 5-minute flares is limited by $2\times10^{43}\,\mathrm{erg\,s^{-1}}$, which excludes a BH MSph origin of the flare detected with MAGIC from IC 310, and NGC 1275. In the scopes of scenarios (i) and (ii), the jet power, which is required to explain the flares detected from these sources, exceeds the jet power estimated based on the radio data. To resolve this discrepancy in the framework of the scenario (ii), it is sufficient to assume that the relativistic blobs are not distributed isotropically in the jet reference frame. A realization of scenario (i) demands that the jet power during the flare exceeds by a large factor, $\sim10^2$, the power of the radio jet relevant on a timescale of $\sim10^8$ years.

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1. Introduction

It is natural to compare the non-thermal emission variability timescale to the shortest time that characterizes a black hole (BH) system as an emitter, namely, the light-crossing time of the gravitational radius of the BH:

$$\tau_0 = r_g/c \approx 5\times 10^2 M_8\,\mathrm{s}, \tag{1.1}$$

where $M_8 = M_{\rm BH}/(10^8 M_\odot)$ is mass of the central BH, and $r_g = GM_{\rm BH}/c^2 = 1.5\times 10^{13} M_8\,\mathrm{cm}$ is the gravitational radius of extreme Kerr BH. For the mass range of BHs $M \geq 10^8 M_\odot$, gamma-ray emission variable on a minute scale has a potential to explore the physics of active galactic nuclei (AGN) on the shortest timescale. Such ultrafast gamma-ray flares have previously been detected from four AGN: PKS 2155−304 [1], Mkn 501 [2], and IC 310 [3] at TeV energies, and 3C 279 at GeV energies [4]. In addition, a flare with a duration comparable to the BH horizon light-crossing time, $\sim 2\tau_0$, was observed from a missaligned radio galaxy M87, in which the jet Doppler factor is expected to be small [5]. Finally, recently the MAGIC collaboration reported detection of a gamma-ray flare from NGC 1275 with properties apparently incompatible to any suggested scenario [6]. Based on arguments suggested in Ref.[7], one concluded that, similarly to the case of IC 310, the magnetosphere (MSph) gaps provides the most feasible interpretation for the gamma-ray emission detected from NGC 1275 [6]. Here we consider these two cases in the frameworks of the approach elaborated in Ref.[8].

Following the approach of Ref.[8] we discuss in three possible scenarios for the production of ultrafast variability in AGNs:

(i) The source of the flare is a magnetospheric gap occupying a small volume in the proximity of the BH close to the event horizon [9, 10].

(ii) The emitter moves relativistically in the jet reference frame. The most feasible energy source for this motion is magnetic field reconnection in a highly magnetized jet [11, 12, 13].

(iii) Flares are initiated by penetration of external objects (stars or clouds) into the jet [14, 15].

Any model designed to explain the ultrafast variability should satisfy some key criteria. In particular, the required overall energy budget should be feasible, the source should be optically thin for gamma-rays, and of course, the proposed radiation mechanism(s) should be able to explain the reported spectral features of gamma-ray emission.

2. Flare luminosity limitation for different scenarios

In this section we summarize the energy constraints obtained for different scenarios [8], and discuss the limitation of this analysis. We focus on AGNs, which were considered as feasible sources for production of detectable MSph gamma-ray emission: M87 [10], IC 310 [3], and NGC 1275 [6].

Vacuum gaps in MSph of the central super-massive BHs (SMBHs) in AGN can be efficient particle accelerators where the electron energy is boosted to multi-PeV energies [16, 17, 9, 18, 10]. These electrons may generate non-thermal emission with spectra extending to very-high energy energies. The variability of this radiation component might be very short as the size of the gap is much smaller than the gravitational radius. Since the accretion flow is an important source of soft photons, the vacuum gap scenario can be realized only in the case of relatively small accretion rate [10, 8]. If the accretion rate exceeds some threshold value, the density of photons emitted by the accretion flow appears to be sufficient to screen vacuum gaps in MSph.

Because of both the low accretion rate and the lack of Doppler boosting, the gamma-ray luminosities of such objects are expected to be quite modest when compared to blazers. Therefore the detectability of the BH magnetospheric radiation is moslty limited to a few nearby objects. In particular, the radio galaxy M87, as well as the compact radio source Sgr A* in the center of our Galaxy, can be considered as suitable candidates for the realization of such a scenario [10].

The energy release in the entire magnetosphere is limited by the Blandford – Znajek (BZ) luminosity:

$$L_{\rm BZ} = \frac{1}{24} f(a_{\rm BH}) B_{\rm BH}^2 r_g^2 c\,. \tag{2.1}$$

Below we follow a simplified treatment that allows us to estimate the energy release in a thin vacuum gap formed in the SMBH magnetosphere. The rotation of a magnetized neutron star or BH in vacuum induces an electric field, $\mathbf{E_0}$, in the surrounding space [19, 20]. If a charge enters this region, the electric field should accelerate it. In an astrophysical context the unscreened electric field is usually strong enough to boost the particle energy to the domain where the particle starts to interact with the background field and thus initiates an electron-positron pair cascade. The secondary particles move in the magnetosphere in a way that tends to screen the electric field [21, 22]. Eventually, an electric-field-free configuration of the magnetosphere can be formed. However, one should note that there are differences between the structures of the pulsar and BH magnetospheres, and consequently, the theoretical results obtained for pulsar magnetospheres cannot be directly applied to the BH magnetosphere. In particular, while in the case of the pulsar magnetosphere the source of the magnetic field is well defined, in the BH magnetosphere the magnetic field is generated by currents in the disk and magnetosphere. The configuration of the field is determined by the structure of the accretion flow. Thus, a change of the accretion flow can result in the formation of charge-starved regions (gaps) in the BH magnetosphere.

For a thin spherical gap, $R < r < R + h$, the luminosity upper limit is

$$L_\gamma < 4\pi R^2 h e n_{\rm e} c E_0\,, \tag{2.2}$$

where the electrons are assumed to emit outward. The particle density can be expressed as a fraction of the Goldreich-Julian density: $en_{\rm e} = \kappa\rho_{\rm GJ}$, where κ is the multiplicity. The condition for the electric field screening, $e|n_{\rm e} - n_{\rm e^+}| = \rho_{\rm GJ}$, allows charge configurations with high multiplicity and still non-screened electric field.

Following the procedure described in the [8], for sake of simplicity below it is adopted that $R^3 B_{\rm g}^2 \simeq r_g^3 B_{\rm BH}^2$, where $B_{\rm BH}$ is the magnetic field at the BH horizon. Thus, one obtains

$$L_\gamma < \frac{1}{8} B_{\rm BH}^2 r_g \kappa h c \sin^2\theta\,. \tag{2.3}$$

We should note that for $h \to r_g$, the luminosity estimate provided by Eq. (2.3) (after averaging over the polar angle θ) exceeds the BZ luminosity [20, 23] by a factor of 2.

Thus, Eq. (2.3) can be considered as a safe upper limit for the luminosity of magnetospheric flares. A similar estimate has been obtained by [24] and [10]. However, the numerical expression in [10] contains some uncertain geometrical factor (η in the notations of [10]). Eq. (2.3) allows us to estimate its value: this geometrical factor should be small, $\sim 10^{-2}$ (see also Eq. 52 in [24]).

Finally, the thickness of the gap, h, in Eq. 2.3 is constrained by the variability time scale, $h \sim t_{\rm var} c$. To produce the emission variable on a 5-minute time-scale, $t_{\rm var} = 5 t_{\rm var,5}$ min, the gap thickness, $h = 10^{13} t_{\rm var,5}$ cm, should be smaller than the gravitational radius of the SMBH with a mass $M_8 > 1$. Thus, the estimated gamma-ray luminosity cannot exceed the following value:

$$L_\gamma < 5 \times 10^{43} \kappa B_4^2 M_8 t_{\rm var,5} \sin^2\theta \, {\rm erg\, s^{-1}}\,, \tag{2.4}$$

where $B_{\rm BH} = 10^4 B_4$ G.

Eq. 2.4 contains two parameters that are determined by properties of the advection flow in the close vicinity of the BH: pair multiplicity, κ, and the magnetic field strength, B. Importantly, these parameters are essentially defined by the same property of the flow, more specifically, by the accretion rate. The magnetic field at the BH horizon needs to be supported by the accretion flow. Therefore the field strength is directly determined by the accretion rate. The accretion rate also defines the intensity of photon fields in the magnetosphere, and consequently, the density of electron-positron pairs produced through gamma-gamma interaction (see, e.g., [10, 8]). If the multiplicity parameter, κ, approaches unity, the gap electric field vanishes (see, e.g., [25]). This sets an upper limit on the accretion rate, and consequently on the magnetic field strength.

The upper limit of the γ-ray luminosity can be estimated as:

$$L_\gamma < 2 \times 10^{43} \beta_{\rm m}^{8/7} \kappa t_{\rm var,5} M_8^{-1/7} \sin^2\theta \ \ {\rm erg\ s^{-1}}\,. \tag{2.5}$$

This estimate is obtained for the thick-disk accretion (in the ADAF-like regime). For higher accretion rates, $\dot{m} \geq 0.1$, the accretion flow is expected to converge to the thin-disk solution [26, 27]. In this regime, the temperature of the disk is expected to be significantly below 1 MeV, thus the pair creation by photons supplied by the accretion disk should cease. This effectively mitigates the constraints imposed by the accretion rate. However, the change of the accretion regime also significantly weakens the strength of the magnetic field at the BH horizon [28], and consequently decreases the available power for acceleration in the gap.

To derive Eq. 2.5, we assumed that the gap thickness is determined by the variability timescale; this corresponds to the energetically most feasible configuration. In a more realistic treatment, one should also take into account the interaction of the particles that are accelerated in the gap with the background radiation field. For high and ultrahigh energies of electrons, $E > 1$ TeV, the characteristic time of the inverse Compton scattering appears to be shorter than the minute-scale typical for the short TeV flares. For the hot target photon field, as expected from a thick accretion disk, the pair-production process should also be very efficient, $\lambda_{\gamma\gamma} \leq \lambda_{\rm IC}$. Thus, computation of the TeV emission requires a detailed modeling of the electromagnetic cascade (see, e.g., [29, 30, 31]). Furthermore, the production and evacuation of the cascade-generated pairs may follow a cyclic pattern and the inductive electric field may become comparable to the vacuum field [32]. A detailed consideration of this complex dynamics is beyond the scope of this paper, but we note that the characteristic length of such a cascade-moderated gap should be small, $\sim \sqrt{\lambda_{\rm IC}\lambda_{\gamma\gamma}}$, resulting in a reduction of the available power (see also [16, 31]).

The similar to the Eq. 2.5 upper limit of the γ-ray luminosity for long lasting variability $t_{\rm var} \gg r_g/c$ takes a form:

$$L_\gamma < 4\times 10^{43}\beta_{\rm m}^{8/7}\kappa M_8^{6/7}\sin^2\theta \ \ {\rm erg\ s^{-1}}\,. \tag{2.6}$$

The dominant contribution to the photon field comes from plasma located at distances $r \sim 2r_g$, and the characteristic viscous accretion time (density decay time in the flow) is

$$t_{\rho,{\rm decay}} \simeq \frac{2r_g}{c\alpha_{\rm ss}} \simeq 10^4\alpha_{{\rm ss},-1}^{-1}M_8\,{\rm s}\,. \tag{2.7}$$

When the accretion fades, the decay of the magnetic field is determined by the magnetic field reconnection rate [33]:

$$t_{\rm B,decay} \simeq \frac{\pi r_g}{0.3c} \sim 10^4 M_8\,{\rm s}\,. \tag{2.8}$$

Since these two time-scales are essentially identical, it is natural to expect that the field strength and the disk density will decay simultaneously. Thus, Eq. 2.5 should also be valid for the time-dependent accretion regime.

2.1 Relativistically Moving Blobs

The properties of radiation generated in jets may be significantly affected if some jet material moves relativistically with respect to the jet local comoving frame. For example, the magnetic field reconnection may be accompanied by the formation of slow shocks (see, e.g., [11]) that in the magnetically dominated plasma produce relativistic flows [34]. If such a process is realized in AGN jets, it can lead to gamma-ray flares in blazar-type AGN with variability timescale significantly shorter than r_g/c [12]. Another implication of this scenario is related to short gamma-ray flares detected from missaligned radio galaxies [35]. Indeed, the conservation of momentum requires that for each plasmoid directed within the jet-opening cone, there should exist a counterpart that is directed outside the jet-beaming cone. While the radiation of the plasmoid directed along the jet appears as a short flare, the emission associated with its counterpart outflow can be detected as a bright flare by an off-axis observer. The latter process may have a direct implication on the interpretation of flares from nearby missaligned radio galaxies, e.g., M87 [35].

If the viewing angle is small, the mini-jet Lorentz factor can be expressed as $\Gamma_{\rm em} = 2\Gamma_{\rm j}\Gamma_{\rm co}/(1+\alpha^2)$ where $\alpha = \theta\Gamma_{\rm j}$ is the viewing angle expressed through the jet-opening angle, (here $\Gamma_{\rm j}$ and $\Gamma_{\rm co}$ are Lorentz factors of the jet and mini-jet, respectively). Thus, comparing the energy density in the plasmoid and the energy density in the jet we can derive a limitation on the power for one plasmoid as [12, 8]:

$$L_{\rm j} = \frac{L_\gamma}{\Gamma_{\rm co}^6\Gamma_{\rm j}^6}\frac{\left(1+\alpha^2\right)^6}{256}\frac{\pi r^2}{\xi c^2\Delta t^2} \tag{2.9}$$

or

$$L_{\rm j} = 1.4\times 10^{-5}L_\gamma\left(\frac{1+\alpha^2}{4}\right)^6\Gamma_{{\rm co},1}^{-6}\Gamma_{{\rm j},1}^{-6}\xi_{-1}^{-1}r_2^2M_8^2t_{{\rm var},5}^{-2}\,. \tag{2.10}$$

Here it was assumed that the flare originates at a distance $r_2 = 100r_g$ from the central BH with mass $M_{\rm BH} = 10^8 M_\odot M_8$.

The above estimate describes the jet luminosity requirement to generate a single short flare of duration $t_{\rm var}$. Observations in the HE and VHE regimes show that AGNs often demonstrate a rather long period of activity (as compared to the duration of a single peak): $T \gg t_{\rm var}$. If the mini-jets are isotropically distributed in the jet comoving frame, the probability for an observer to be in the mini-jet beaming cone depends weakly on the observer viewing angle[1], and this probability can be estimated as $P \simeq (2\Gamma_{\rm co})^{-2}$ [35]. If the mini-jet formation is triggered by some *spontaneous* process, then the comoving size of the region responsible for the flare is $l'_0 = \delta_{\rm j} T c$, and the energy contained in this region is $E' = S l'_0 e'_{\rm j}$ (here S is the jet cross-section). The energy of a single mini-jet in the comoving frame is

$$E'_{\rm mj} = \frac{L_\gamma t_{\rm var} \Gamma_{\rm co}}{4\xi \Gamma_{\rm em}^3}\,. \tag{2.11}$$

The total number of mini-jets during a flaring episode can be estimated as $N \approx \Phi T / P t_{\rm var}$, where Φ is the so-called filling factor.

The total dissipated energy for the flare should be smaller than the energy that is contained in the dissipation region:

$$\frac{E'_{\rm mj} \Phi T}{P t_{\rm var}} < L_{\rm j} T \frac{\delta_{\rm j}}{\Gamma_{\rm j}^2}\,. \tag{2.12}$$

This implies a requirement for the jet luminosity

$$L_{\rm j} > 0.006\Phi \left(1+\alpha^2\right)^4 \Gamma_{\rm j,1}^{-2} L_\gamma \xi_{-1}^{-1}\,, \tag{2.13}$$

where the small viewing angle limit was used for the ratio of Lorentz and beaming factors: $\zeta = \Gamma_{\rm j}/\delta_{\rm j} \simeq (1+\alpha^2)/2$. The requirement imposed by Eq. 2.13 significantly exceeds the limit related to the shortest variability time, Eq. 2.10.

On the other hand, this requirement can be somewhat relaxed if the velocity direction of the plasmoids is not random, e.g., is controlled by the large-scale magnetic field [12, 36], or is triggered by some perturbation propagating from the base of the jet. In the former case the mini-jet detection probability, P, may be higher, and in the latter case, the comoving distance between the mini-jets may be larger. Let us assume that the flare trigger propagates with Lorentz factor $\Gamma'_{\rm tr}$ in the jet comoving frame, then the comoving region size is larger by a factor of $\Gamma'_{\rm tr}$.

2.2 Cloud-in-Jet Model

In the framework of the cloud-in-jet scenario, we deal with the nonthermal emission generated at the interaction of a jet with some external obstacle, e.g., a BLR cloud or a star (see, e.g., [37, 38, 14, 39, 40]). Debris of the obstacle matter, produced at such an interaction, can be caught by the jet flow. This debris should form dense blobs or clouds in the jet, and the emission generated during their acceleration may be detected as a flare [15, 41]. If this interpretation is correct, each peak of the light curve can be associated with emission produced at the acceleration of some individual blob. The peak profile and its duration are determined by the condition of how quickly this blob can be involved into the the jet motion.

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[1] If $\Gamma_{\rm co} > \Gamma_{\rm j}$, this statement is correct for observers located in $\theta_{\rm view} < \pi/2$, otherwise for $\tan\theta_{\rm view} < v_{\rm co}/\sqrt{1/\Gamma_{\rm co}^2 - 1/\Gamma_{\rm j}^2}$.

If the cloud dynamics determines the variability, then the luminosity of the emission appears to be independent of the mass of the cloud [15, 8]:

$$L_\gamma \simeq cP_0\pi R_{\rm c}^2 \frac{\xi\delta_{\rm j}^4}{4\Gamma_{\rm j}^2}\,. \tag{2.14}$$

Since $L_{\rm j} > cP_0\pi R_{\rm c}^2$, the above equation allows us to obtain a lower limit on the jet luminosity required for the operation of the star-jet interaction scenario:

$$L_{\rm j} > 0.025\left(1+\alpha^2\right)^4\Gamma_{\rm j,1}^{-2}L_\gamma\xi_{-1}^{-1}\,, \tag{2.15}$$

which is a factor of $4/\Phi$ larger than the estimate for the jet-in-jet scenario (see Eq. 2.13).

The first dynamical limitation is related to the ability of a cloud to penetrate the jet and become involved in the jet motion. According to the estimates given by [15] and [41], for the typical jet parameters these constraints do not impose any strong limitations. The heaviest blobs that can be accelerated by a jet with luminosity $10^{43}\,{\rm erg\,s^{-1}}$ can result in flares with a total energy release of 10^{54} erg.

If the cloud is light enough to be caught by the jet, then one should consider two main processes: the cloud expansion, and its acceleration. At the initial stage, the cloud cross-section is not sufficiently large to provide its acceleration to relativistic velocities. On the other hand, the intense jet-cloud interaction at this stage leads to a rapid heating and expansion of the cloud. The cloud size-doubling time can be estimated as

$$t_{\rm exp} \approx A\left(\frac{M_{\rm c}}{\gamma_g R_{\rm c} P_{\rm j}}\right)^{1/2}\,. \tag{2.16}$$

here $P_{\rm j}$ and $R_{\rm c}$ are the jet ram pressure and the cloud radius, respectively, $\gamma_g = 4/3$ is the adiabatic index and A is a constant of about a few [42, 43, 44, 45, 46]. When the size of the cloud becomes large enough for acceleration to relativistic energies, the intensity of the jet-cloud interaction fades away, and the cloud expansion proceeds in the linear regime. Since the time scale for acceleration to relativistic velocity is

$$t_{\rm ac} \simeq \frac{M_{\rm c}c^2}{\pi R_{\rm c}^2 c P_{\rm j}}\,, \tag{2.17}$$

the size of the cloud relevant for the flare generation can be obtained by balancing Eqs. 2.16 and 2.17:

$$R_{\rm c} = A_{\rm exp}\left(\frac{M_{\rm c}c^2}{P_{\rm j}}\frac{\gamma_{\rm g}}{\pi^2 A^2}\right)^{1/3}\,. \tag{2.18}$$

Here the constant $A_{\rm exp}$ accounts for the cloud expansion in the linear regime.

The dynamical limitation given by Eq. 2.18 together with Eq. 2.15 allows determination of the jet ram pressure:

$$P_{\rm j} = \frac{\pi A^4}{\xi\gamma_{\rm g}^2 A_{\rm exp}^6}\left(2\zeta\right)^6\frac{E_\gamma}{t_{\rm var}^3 c^3}\,. \tag{2.19}$$

The actual value of the coefficient in the above equation, in particular the value of $A_{\rm exp}$, can be revealed only through the numerical simulations given the complexity of the jet-cloud interaction.

Comparison of models for different sources

Source	IC 310^a	M87^b	NGC 1275^c
$M_{\rm BH,8}$	3	60	8
t_5	1	175	120
τ_0	0.2	2	10
L_γ, erg s^{-1}	2×10^{44}	10^{42}	10^{45}
Φ	0.1	0.3	0.1
$\Gamma_{\rm j}$	10	10	1.5
$\Gamma_{\rm co}$	10	10	10
α	2	2	0.2
$L_\gamma/L_{\gamma,ms}$	10	5×10^{-4}	5
$L_{\rm ed}$, erg s^{-1}	4×10^{46}	10^{48}	10^{47}
$L_{\rm j,jj}$, erg s^{-1}	10^{44}	10^{42}	4×10^{44}
$L_{\rm j,cj}$, erg s^{-1}	3×10^{45}	2×10^{43}	2×10^{46}

Table 1: ^{a}[3] ^{b}[5], [51], [52]. ^{c}[6], [53] $M_{\rm BH,8} = M_{\rm BH}/10^8 M_\odot$ is the SMBH mass, $t_5 = t/300$ s is the variability time, $\tau_0 = tc/r_g$ is the nondimensional variability time in units of gravitation radius light-crossing time, L_γ is the maximum luminosity in gamma-rays, $\Gamma_{\rm j}$ is the jet Lorentz factor, $\Gamma_{\rm co}$ is the Lorentz factor of the mini-jet, $\alpha = \theta/\Gamma_{\rm j}$ is the normalized viewing angle, $L_{\gamma,ms}$ is the upper limit of the gamma-ray luminosity for a magnetospheric model, $L_{\rm j,jj}$ is the minimal jet power for the jet-in-jet model, $L_{\rm j,cj}$ is the minimum jet power for cloud-in-jet model.

However, if one assumes that the expansion proceeds very efficiently, i.e., the cloud size achieves a value close to the light-crossing limit, $R_{\rm c} \simeq \delta_{\rm j} t_{\rm var} c$, then the expression for the jet ram pressure becomes

$$P_{\rm j} = \left(\frac{2\zeta}{\delta_{\rm j}^2}\right)^2 \frac{E_\gamma}{\pi \xi t_{\rm var}^3 c^3}\,. \tag{2.20}$$

Since each flaring episode should correspond to specific jet parameters[2], the above equation implies that the energy emitted in an individual peak of a flare should be proportional to the cube of its duration: $E_\gamma \propto t_{\rm var}^3$ (or $L_\gamma \propto t_{\rm var}^2$). Obviously, the study of individual peaks in a statistically meaningful way requires a detailed light curve that can be obtained with future observations, in particular with CTA (see, e.g., [50]).

2.3 Energetic Constraints for Detected Exceptional Flares

So far, several super-fast gamma-ray flares have been detected in the VHE or HE regimes from different types of AGNs. The peculiarity of the signal is related both to the duration of the flare and to the released energy. Below we consider several cases that are summarized in Table 2.2.

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[2] We note, however, that across a magnetically driven jet one may expect strong gradients of the jet ram pressure (see, e.g., [47, 48, 49]).

2.3.1 IC 310

In 2012 November, the MAGIC collaboration detected a bright flare from IC 310 [3]. The flare consisted of two sharp peaks with a typical duration of $\sim 5\,\mathrm{min}$. The measured spectra were hard, with a photon index $\lesssim 2$, extending up to ~ 10 TeV. The energy released during this event has been estimated to be at a level of $2\times10^{44}\,\mathrm{erg\,s^{-1}}$.

The mass of the BH powering activity of IC 310 has been estimated to be $M_{IC\ 310} = \left(3^{+4}_{-2}\right)\times 10^{8}M_{\odot}$ [3], i.e., the measured variability time scale is as short as 20% of τ_0.

According to the estimate provided by Eq. 2.5, the luminosity of flares generated in the BH magnetosphere depends weakly on the mass of the BH and is determined by the disk magnetization, the viewing angle, and the pair multiplicity[3]. Since all these parameters are smaller than unity, from Eq. 2.5 we have

$$L_{\gamma,\mathrm{ms}} < 2\times10^{43}\,\mathrm{erg\,s^{-1}} \tag{2.21}$$

This upper limit is an order of magnitude below the required value [3]. Thus, we conclude that the ultrafast flare detected from this source cannot have a magnetospheric origin.

Assuming that mini-jets are distributed isotropically in the jet frame and that the detection of two pulses is not a statistical fluctuation, one can estimate the true jet luminosity using Eq. 2.13. For the relevant flare parameters (i.e., $t_{\mathrm{var}} = 4.8\,\mathrm{min}$, $L_\gamma = 2\times10^{44}\,\mathrm{erg\,s^{-1}}$) and $M_8 = 3$

$$L_{\mathrm{j,jj}} > 10^{44}\Phi_{-1}\left(\frac{1+\alpha^2}{5}\right)^4\Gamma_{\mathrm{j},1}^{-2}\xi_{-1}^{-1}\,. \tag{2.22}$$

If the mini-jets are not distributed isotropically, the requirement on the jet power can be a few orders of magnitude weaker; see Eq. 2.10.

The cloud-in-jet scenario requires a higher jet luminosity; from Eq. 2.15 it follows that

$$L_{\mathrm{j,cj}} > 3\times10^{45}\Gamma_{\mathrm{j},1}^{-2}\left(\frac{1+\alpha^2}{5}\right)^4\xi_{-1}^{-1}\,\mathrm{erg\,s^{-1}}\,. \tag{2.23}$$

2.3.2 M87

In 2010, a bright flare has been recorded during a multi-instrument campaign in the VHE energy band [52]. The variability time during the VHE transient was about 0.6 day and the flux level achieved $10^{42}\,\mathrm{erg\,s^{-1}}$. This source is characterized by a large jet-viewing angle of $\theta_{\mathrm{j}} \approx 15^{o}$ and a Lorentz factor of about $\Gamma_{\mathrm{j}} \approx 7$ [51], and the SMBH mass is $\sim 6\times10^{9}M_{\odot}$ [5].

Given the heavy central BH and the relatively long duration of the VHE flare, which allows high values of the gap size, the energy constraint in the magnetosphere scenario is quite modest:

$$L_{\gamma,\mathrm{ms}} < 2\times10^{45}\,\mathrm{erg\,s^{-1}}\,. \tag{2.24}$$

M87 might be an interesting candidate for a detection of magnetosphere flares.

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[3] Eq. 2.5 does not account for relativistic effects that should be small unless the gap is formed close to the horizon. However, if the vacuum gap is close to the horizon, then the gravitational redshift should make more robust the constraints imposed by the variability time.

For the flare parameters (i.e., $t_{\rm var} = 0.6\,{\rm d}$, $L_\gamma = 10^{42}\,{\rm erg\,s^{-1}}$) and $M_8 = 60$, Eq. 2.13 constrains the required jet true luminosity at the level

$$L_{\rm j,jj} > 10^{42}\Phi_{-0.5}\left(\frac{1+\alpha^2}{5}\right)^4\Gamma_{\rm j,1}^{-2}\xi_{-1}^{-1}\,. \tag{2.25}$$

On the other hand, the mulitwavelength properties of the gamma-ray flares detected from M87 seem to be quite diverse, with no detected robust counterparts at other wavelengths. Thus, if the VHE emission is produced by a single mini-jet, then a much weaker constraint, provided by Eq. 2.10, is applied. In this case, the variability detected with imaging atmospheric Cherenkov telescope should correspond to the mini-jet variability, thus the mini-jet comoving size should be

$$\tilde{l}_{\rm em} = \Delta t c\Gamma_{\rm em} = \frac{2\Delta t c\Gamma_{\rm j}\Gamma_{\rm co}}{1+\alpha^2} \sim 10^{17}\,{\rm cm}\,, \tag{2.26}$$

which is about the jet cross-section at a parsec distance from the central BH. We should also note that the typical spectra emitted by plasmoids are dominated by synchrotron radiation, which seems to be inconsistent with the multi-wavelength observations of M87. Moreover, the peculiar light curve that has been detected with H.E.S.S. has not yet been explained in the framework of the jet-in-jet scenario.

Formally, for the parameters of the flare detected from M87, the minimum jet luminosity required by the cloud-in-jet scenario is

$$L_{\rm j,cj} > 2\times10^{43}\Gamma_{\rm j,1}^{-2}\left(\frac{1+\alpha^2}{5}\right)^4\xi_{-1}^{-1}\,{\rm erg\,s^{-1}}\,. \tag{2.27}$$

However, it has been argued that the light curve and the VHE spectrum is best explained if the TeV is produced through p-p interactions induced by the jet collision with a dense cloud. In this case, the required jet power is about $L_{\rm j} \approx 5\times10^{44}\,{\rm erg\,s^{-1}}$ [40].

2.4 NGC 1275

The nature of recently observed by MAGIC collaboration of the TeV flare from NGC 1275 was discussed in the paper [6]. The flare has $10^{45}\,{\rm erg\,s^{-1}}$ flux in the gamma and gamma-ray flux doubling time is about 10 hours which is 10 times larger compare to the light crossing time of the central black hole with mass about $\sim 8\times10^8 M_\odot$ [53]. Compare this luminosity and the limit $2\times10^{44}\,{\rm erg\,s^{-1}}$ from Eq. 2.6, we can't explain such power in the frame work of the magnetosphere model.

The current hydrodynamical jet power of NGC 1275 is difficult to estimate and it can vary in the range $6\times10^{43} \le L_{\rm j} \le 10^{47}\,{\rm erg\,s^{-1}}$ [54]. So, we can't share the critics in [6] for jet-in-jet ($L_{\rm j,jj} \approx 4\times10^{44}\,{\rm erg\,s^{-1}}$) or even cloud-jet ($L_{\rm j,cj} \approx 2\times10^{46}\,{\rm erg\,s^{-1}}$) models. Following the paper [55] the jet in the NGC 1275 did not show relativistic motions and upper limits on the jet power can't be derived from the paper [8] which was used in the paper [6].

3. Discussion and Conclusions

In this paper (which is based on the [6]) we considered three scenarios for the production of ultrafast AGN flares with variability times shorter than the Kerr radius light-crossing time: gamma-ray emission of gaps in the SMBH magnetosphere [9, 10], the jet-in-jet realization [12], and the emission caused by penetration of external dense clouds [15].

The production of gamma rays in the BH magnetosphere has several unique properties. In particular, this scenario can be invoked to explain emission from off-axis AGNs and orphan gamma-ray flares. On the other hand, the luminosity of the magnetospheric gap has a robust upper limit that depends weakly on the SMBH mass. Moreover, the magnetospheric emission is not enhanced by the Doppler-boosting effect, and this seems to be crucial for explaining short flares from distant AGN. On the other hand, some nearby SMBHs[10], e.g., the Sagittarius A star or M87, might be very promising candidates to produce gamma-ray flares (see, however, [56, 10, 57] for the discussion of gamma-gamma attenuation in magnetosphere).

In general terms, there can be little doubt that the nonthermal radiation of powerful AGN is related, in one way or another, to relativistic jets. The ultrafast gamma-ray flares might be linked to the formation of relativistically moving features (plasmoids or mini-jets) inside the major outflow, the jet originating from the central BH. Depending on the orientation of the mini-jets to the jet axis, the radiation of the mini-jet can be focused within the jet cone or outside. This scenario has been suggested to interpret the variable emission from AGN [12, 35]. It has been shown that under certain conditions, magnetic field reconnection can result in the formation of relativistic outflows [11, 58]. We note, however, that formation of a relativistic outflow is not an indispensable feature of reconnection. Thus, ejection of relativisitcally moving plasmoids may require a specific configuration of the magnetic field. Independently, to form outflows with large Lorentz factors, $\Gamma_{\rm co} \geq 10$, an initial configuration with high magnetization, $\sigma \simeq \Gamma_{\rm co}^2 \geq 100$, is required. Such a high magnetization of the jet at the flare production site requires an even higher initial jet magnetization, $\sigma_{\rm init} \gg 10^3$. Jets with such a high magnetization should have an extremely low mass load, which seems to be inconsistent with the properties of AGN jets at large distances (see, however, [59, 60, 61] and references therein).

Finally, the SED of the emission produced by plasmoids formed at reconnection contains a dominating synchrotron component that peaks in the UV energy band [13]. This feature is not consistent with the SEDs obtained from AGNs during the ultrafast flares. The presence of a guiding magnetic field can significantly enhance the magnetization of plasmoids, resulting in a further enhancement of the synchrotron component and perhaps in the extension of the synchrotron component to the gamma-ray band. The examination of this scenario requires detailed modeling, since the guiding field impacts on the Lorentz factor of plasmoids.

The jet-in-jet scenario quantitatively implies a modest requirement for the jet intrinsic luminosity, however; it can be even further relaxed if one assumes that the mini-jets are not distributed isotropically in the major jet comoving frame. Such an anisotropy can be realized, for example, by focusing the outflow along the direction of the reconnecting magnetic field.

The star-in-jet scenario, the third possibility considered in the paper, requires significantly higher jet luminosity than the jet-in-jet scenario. In many cases, the jet luminosity, needed to realize the star-in-jet scenario, exceeds the Eddington limit. It was also shown that some details of the GeV light curve obtained from 3C 454.3 with *Fermi*, e.g., the plateau phase, can be readily interpreted in the framework of the star-in-jet scenario [41]. It is also important to note that the emission produced by the interaction of a cloud with the AGN jet should be characterized by a universal relation between the luminosity and the duration of individual peaks of the flare: $L^{1/2} \propto \Delta t$. To verify this relation observationally, a high photon statistics is required, which may possibly be achieved with future observations with CTA.

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