Particle acceleration close to the supermassive black hole horizon: the case of M87

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The radio galaxy M87 has recently been found to be a rapidly variable TeV emitting source. We analyze the implications of the observed TeV characteristics and show that it proves challenging to account for them within conventional acceleration and emission models. We discuss a new pulsar-type scenario for the origin of variable, very high energy (VHE) emission close to the central supermassive black hole and show that magneto-centrifugally accelerated electrons could efficiently Compton upscatter sub-mm ADAF disk photons to the TeV regime, leading to VHE characteristics close to the observed ones. This suggests, conversely, that VHE observations of highly under-luminous AGNs could provide an important diagnostic tool for probing the conditions prevalent in the inner accretion disk of these sources.

Keywords: Active galaxies; Black hole physics; Particle acceleration; Non-thermal radiation: gamma-rays; M87.

1. Introduction

The advance in modern imaging atmospheric Cherenkov technologies has opened up a new window on the non-thermal Universe, providing a unique diagnostic tool to study the physical conditions in violent regions of galactic and extragalactic sources. Until recently, blazars have been the only extragalactic sources known to emit TeV (10^{12} eV) radiation. Although comprising only a small fraction of radio-loud active galactic nuclei (AGNs), the favourable orientation of their jets at small viewing angles $i$ to the line of sight ($i < 10^\circ$), combined with the bulk relativistic motion of the plasma in their jets, makes them a privileged source class on the TeV sky. The H.E.S.S. detection of variable TeV emission from the non-blazar ($i > 19^\circ$) radio galaxy M87 (redshift $z = 0.0043$, distance $d \sim 16$ Mpc) during a campaign in 2003-2006 [1], may thus come surprising. Although some detectable TeV emission has been anticipated based on simple homogeneous SSC model extrapolations [2], the observed rapid $\gamma$-ray flux variations and the hard TeV spectrum comes quite unexpected.

The giant elliptical galaxy M87 is known to host one of the most massive black holes $M_{BH} \simeq 3 \times 10^9 M_\odot$ in the Universe, and a prominent, non-aligned jet detectable from radio to X-ray wavelengths. As we show below, the VHE results may point to a new acceleration process occurring in the vicinity of the central supermassive black hole (BH).

2. Observed VHE characteristics in M87 and implications

The H.E.S.S. observations of M87 in 2005 [1] show a gamma-ray spectrum that reaches beyond 10 TeV and is consistent with a relatively hard power-law (with spectral index $\alpha \sim 1.2$, where $S_\nu \propto \nu^{-\alpha}$). The detected VHE output is quite moderate, with an isotropic TeV luminosity of $\sim 3 \times 10^{40}$ erg/s. During the 2005 high state, significant variability (flux doubling) on time scales of $\Delta t_{\text{obs}} \sim 2$ days was found, the fastest variability observed in any waveband from M87 so far.

Several scenarios for the origin of VHE emission from M87 have been discussed in the literature, ranging from the vicinity of the central supermassive BH [3, 4] and the innermost part of the jet [5-7] to the superluminal feature HST-1 at a de-projected distance of $\sim 100$ pc from the central BH [8, 9]. The latter has some interesting features including the fact that the TeV flux maximum in 2005 seems to coincide with a Chandra X-ray flux maximum from HST-1. On the other hand, the same observations [1, 10] also indicate that the TeV and HST-1 X-ray flux evolutions from 2003 to 2004 are not correlated, yet the TeV spectral shape does not change (i.e., same power index within errors) from 2004 to 2005, so that an HST-1 origin of the TeV emission in 2005 seems to require some sort of cosmic conspiracy. Note further, that the observed spectrum of HST-
1 appears synchrotron cooling dominated above the break at \( \nu_b \simeq 10^{15} \) Hz, where the spectrum steepens to \( \alpha \simeq 1.0 \) \( (3\nu \propto \nu^{-\alpha}) \) [10], corresponding to an average radiating particle distribution \( n(\gamma') \propto \gamma'^{-3} \). In order to Compton upscatter lower energy photons to the observed TeV regime, the presence of energetic electrons with Lorentz factors up to \( \gamma' \sim 10^7 / \delta \) is required within the source region, where \( \delta \) is the bulk Lorentz factor of the source. If scattering in a single SSC-type scenario occurs in the Thomson limit, the target photon field, and thus the observed TeV flux, is expected to vary on time scales larger than implied by a source limit inferred from the cooling break, i.e., the total source size would be at most comparable to \( R \sim c \Delta t_{\text{obs}} / \delta \). If, on the other hand, the relevant scattering occurs in the Klein-Nishina regime, the resultant TeV spectrum would be very steep, contrary to the observed one. Further studies are required to assess whether current HST-1 models are flexible enough to overcome these issues.

A similar consideration seems to hold for leptonic scenarios that assume Compton scattering in a decelerating relativistic inner jet flow [5]. Radio features in the inner jet, for example, seem to be at most mildly relativistic [11, 12], yet significantly relativistic on larger scale [8], the jet thus more resembling an accelerating than a decelerating flow, although matters may be more complicated if an internal velocity structure (e.g., spine plus sheath) is present.

Note also, that the predicted spectral shapes for the TeV regime in simple model applications are much steeper than observed, although again, an internal jet structure may help by introducing additional acceleration and radiation effects [7, 13].

Here we consider an alternative scenario assuming particle acceleration and TeV \( \gamma \)-ray production to take place close to the event horizon of the central supermassive black hole. We show that such a model can successfully reproduce the observed VHE characteristics and introduce an important link between accretion disk physics and jet formation theory.

3. Particle acceleration close to the central black hole

Today, magneto-hydrodynamical models are widely considered to represent the most promising class for the formation and collimation of relativistic astrophysical jets. According to this picture, magnetic flux dragged inward and amplified by dynamo actions in the inner accretion disk can build up a rigidly rotating, dipolar magnetosphere. Along open flux surfaces the bulk of the plasma is centrifugally accelerated to relativistic speeds \( (\Gamma \sim 10) \) and collimated outside the light cylinder \( r_L \simeq (5-10) \) \( r_s \), e.g., see [14, 15]. It has been realized for quite a while [16–18], that such a MHD field structure could also allow for efficient centrifugal acceleration of test particles, i.e., a test particle co-rotating with the field line (bead-on-wire motion) will experience the centrifugal force and gain rotational energy while moving outwards [19, 20]. The radial motion of such a particle is most conveniently analyzed in the framework of Hamiltonian dynamics [4, 17]. Consider an idealized two-dimensional model topology: since the Lagrangian \( L \) for a particle with rest mass \( m_0 \) on a relativistically, rigidly rotating wire (angular velocity \( \Omega = c / r_L = \) constant) is not explicitly time-dependent, i.e.,

\[
L = -m_0 c^2 \sqrt{1 - r^2 / r_L^2} - \dot{r}^2 / c^2, \tag{1}
\]

the associated Hamiltonian

\[
H = \gamma m_0 c^2 (1 - r^2 / r_L^2) = \text{constant}, \tag{2}
\]

with \( \gamma = (1 - r^2 / r_L^2 - \dot{r}^2 / c^2)^{-1/2} \) the Lorentz factor, is a constant of motion. Thus, as a particle approaches \( r_L \), the term in brackets of Eq. (2) gets smaller and has to be compensated by an increase in \( \gamma \), which implies that the Lorentz factor increases dramatically for a particles approaching the light cylinder. In reality, unlimited growth will be prohibited by radiative energy losses (e.g., inverse Compton in the ambient photon field), the breakdown of the bead-on-the-wire (BW) approximation or the bending of the field line with increasing inertia [16, 17]. In particular, validity of the BW approximation requires, that the characteristic acceleration time scale, which can be easily derived from Eq. (2), i.e.,

\[
t_{\text{acc}} = \frac{\gamma}{\dot{\gamma}} \simeq \frac{1}{2 \Omega \tilde{m}^{1/4} \gamma^{1/2}}, \tag{3}
\]

is always larger than the inverse of the relativistic gyro-frequency \( \omega = eB / \gamma m_0 c \). Here \( \tilde{m} \) is determined by the initial conditions, i.e. \( \tilde{m} = 1 / (\gamma_0^2 (1 - \dot{r}_0^2 / r_L^2)^2) \). This constrains achievable Lorentz factors to

\[
\gamma_{\text{BB}}^{1/3} \leq \frac{1}{\tilde{m}^{1/6}} \left( \frac{qB}{2m_0 c^2} r_L \right)^{2/3}, \tag{4}
\]

which is formally equivalent to the requirement that the Coriolis force must not exceed the Lorentz force
[17]. For parameter relevant to M87 (i.e., $B(r_L) \sim 10$ G, $r_L \sim 5 \times 10^{15}$ cm), one finds $\gamma_{\text{max}}^{BB} \sim 5 \times 10^8$ for electrons. In general, centrifugal acceleration is less favourable for protons in the sense that $\gamma_{\text{max}}^{BB} \propto m^{-2/3}$, indicating that accelerated protons will not be able to interact efficiently with the ambient photon field.

4. Inverse Compton upscattering of Comptonized disk photons

In realistic astrophysical environments, radiative energy losses will always compete with acceleration and introduce additional constraints on the maximum achievable particle energies. Given its very low bolometric luminosity output, mass accretion in M87 is likely to occur in a two-temperature, advection-dominated (ADAF) mode [14, 21, 22]. For the estimated Bondi accretion rate of $\dot{m} \approx 1.6 \times 10^{-3} \dot{m}_{\text{edd}}$ [21], the characteristic ADAF spectrum close to $r_L$ peaks at around $\nu'_1 \sim 10^{11}$ Hz with an associated (radio) luminosity $L_R \sim 10^{40}$ erg/s. Inverse Compton interactions with the ambient photon field are thus not expected to lead to a much stronger constraint on the electron Lorentz factors compared with $\gamma_{\text{max}}^{BB}$, suggesting that electron Lorentz factors up to $\gamma \sim (10^7 - 10^8)$ could well be achieved via the proposed acceleration mechanism [4]. Hence, Compton (Thomson) upscattering of sub-mm ($\nu' \sim 10^{13}$ Hz) accretion disk photons can easily result in VHE photons with energies extending up to $\sim 10$ TeV and beyond. Note that this is different from the case of luminous AGN sources, where severe inverse Compton losses tend to limit achievable electron Lorentz factors to be below one thousand [16, 17]. Yet, even for the latter sources, centrifugal acceleration could operate as a promising pre-acceleration mechanism, possibly along with electrostatic wave surfing [23], and thus provide the energetic seed particles required for efficient Fermi acceleration on larger scales.

For the inferred Bondi accretion rate $\dot{m}_{B}$ in M87, comptonization of cyclosynchrotron soft photons in an ADAF is expected to add a power law-like tail to the disk spectrum above $\nu'_1$ with spectral index close to $\alpha_c \sim 1.2$ [4, 24]. Suppose that energetic electrons, after being released from the acceleration process with high Lorentz factors, encounter such a comptonized disk photon field. In general, the shape of the emergent (singly, Thomson) scattered inverse Compton spectrum $j_{\text{IC}}(\nu)$ will depend on both the seed photon spectrum $F(\nu')$ and the differential electron distribution $n(\gamma)$, e.g.,

$$j_{\text{IC}}(\nu) \propto \nu^{-p/2} \int_{\nu'_1}^{\nu'_2} d\nu' F(\nu') \nu'^{(p-1)/2} \times \int_{\min\{x_1,1\}}^{\min\{x_2,1\}} dx x^{(p-1)/2} f_{\text{IC}}(x),$$

assuming a power law electron distribution $n(\gamma) \propto \gamma^{-p}$ in the interval $\gamma_1 \leq \gamma \leq \gamma_2 \sim 5 \times 10^7$, with $x_i := \nu'/(4\gamma_i^2 \nu')$ and $f_{\text{IC}}(x) = 2r \ln x + x + 1 - 2x^2$. Far away from the endpoints, i.e., for $\nu \leq 4\gamma_2^2 \nu'_2 \sim 5$ TeV, we obtain the common $j_{\text{IC}}(\nu) \propto \nu^{-(p-1)/2}$ power law evolution, independent of the incident photon spectrum. Yet, closer to the endpoints, i.e., for $4\gamma_2^2 \nu'_2 < \nu < 4\gamma_1^2 \nu'_1$, we become again sensitive to the seed photon distribution so that the resultant inverse Compton VHE spectrum will be power law-like with spectral index $\alpha \simeq \alpha_c$. This is illustrated in Fig. 1 for $p = 2$.

5. Discussion

Taking the detected TeV emission in M87 to arise via inverse Compton scattering by centrifugally accelerated electrons close to the central black hole, requires to examine whether, amongst others, the model can self-consistently account for the observed variability and luminosity output:
(1) The observed flux doubling time scale is of order $\sim 2$ days. Centrifugal acceleration, on the other hand, occurs on a characteristic time scale $r_L/c$. The observed variability thus implies a light cylinder radius of order $r_L \sim 6 r_s$, which is indeed consistent with expectations from relativistic MHD jet formation models [14, 15].

(2) The detected TeV luminosity is of order $L_{\text{TeV}} \simeq 3 \times 10^{40}$ erg/s (if assumed isotropic). It can be shown [4] that the test particle number density $n_e$, required to account for $L_{\text{TeV}}$, does not violate the presumed quasi force-free MHD condition in the sense that the corresponding kinetic energy density $\sim n_e c^2 m_e c^2$ is still much smaller than the allowed particle energy density of the background plasma.

(3) Is it possible that TeV photons, produced via inverse Compton upscattering, can escape from the vicinity of the central black hole? In principle, photons of energy $E$ [TeV] will interact most efficiently with target photons in the infrared regime, i.e., with energy $\epsilon \simeq (1 \text{TeV}/E)$ eV. If the estimated, observed infrared luminosity $L_{\text{IR}} \sim 10^{41}$ erg/s [25] is produced on characteristic scale $R_{\text{IR}}$, the optical depth for $\gamma \gamma$ absorption becomes $\tau_{\gamma \gamma} \simeq 0.2 (L_{\text{IR}}/10^{41}\text{erg/s}) (r_1/R_{\text{IR}}) (E/1 \text{TeV})$, indicating that TeV photons can escape even if a non-negligible percentage of the observed infrared flux would originate in the innermost region of the accretion flow $r_1 \sim 60 r_s$. In particular, assuming all of the observed flux in M87 to arise in an ADAF (which is perhaps over-restrictive given its jet) constraints transparent radii of 10 TeV photons to scales between 5 and 13 Schwarzschild radii [26], consistent with the scenario presented here.

6. Conclusion

VHE gamma-ray observations of low-luminous, non-blazar AGN jet sources like M87 could provide an ideal test laboratory for particle acceleration close to the supermassive black hole horizon and serve as a fundamental diagnostic tool for the conditions prevalent in the innermost part of the accretion flow. In blazars, these effects are likely to be swamped by relativistically beamed jet emission, while in luminous quasar sources interactions with the ambient photon field will severely limit the efficiency of centrifugal acceleration.

Using a simple toy model, we have shown that efficient centrifugal acceleration of electrons in the vicinity of the central supermassive black hole could naturally account for the observed VHE characteristics in M87, including variability on time scales of about two days and a hard TeV spectrum. The strength of the considered scenario is not only that it success-fully reproduces the VHE characteristics, but also that it allows substantial corroboration of facts by drawing on insight gained in accretion disk physics and jet formation theory. Generalizing the approach suggests that (i) similar to M87 other low luminous AGN jet sources such as, for example Cen A, may as well be TeV $\gamma$-ray emitting sources, and that (ii) efficient centrifugal acceleration may lead to the onset of energetic particle beams in BL Lac-type objects, responsible for X-ray and TeV radiation on larger ($\gtrsim 10 r_L$) distances [27].

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