PROCEEDINGS OF SCIENCE

Gamma-ray emission from the black hole's vicinity in AGN

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Non-thermal magnetospheric processes in the vicinity of supermassive black holes have attracted particular attention in recent times. Gap-type particle acceleration accompanied by curvature and Inverse Compton radiation could in principle lead to variable gamma-ray emission that may be detectable with current instruments. We shortly comment on the occurrence of magnetospheric gaps and the realisation of different potentials. The detection of rapid variability becomes most instructive by imposing a constraint on possible gap sizes, thereby limiting extractable gap powers and allowing to assess the plausibility of a magnetospheric origin. The relevance of this is discussed for the radio galaxies Cen A, M87 and IC 310. The detection of magnetospheric gamma-ray emission generally allows for a sensitive probe of the near-black-hole region and is thus of prime interest for advancing our understanding of the (astro)physics of extreme environments.

7th Fermi Symposium 2017
15-20 October 2017
Garmisch-Partenkirchen, Germany

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1. Introduction

The non-thermal processes occurring in the vicinity of supermassive black hole have attracted particular attention in recent times, e.g. [9, 12, 4, 11, 7, 10]. The strong electromagnetic fields around rotating black holes are often thought to facilitate efficient (one-shot) particle acceleration to very high energies, in the case of hadrons even up to the highest cosmic ray energies ($\sim 10^{20}$ eV), cf. [12] for a review. This process is naturally accompanied by gamma-ray production via curvature emission (the radiation of charged particles following curved magnetic fields) and inverse Compton up-scattering of ambient (accretion disk) soft photons. Provided suitable conditions are present, the close black hole environment could enable high power extraction and account for rapid variability on timescales of $\sim r_g/c = 1.4\ (M_{BH}/10^9 M_\odot)$ hr and shorter [2]. A characteristic feature in this context is the occurrence of magnetospheric gaps close to the black hole.

2. The Occurrence of Magnetospheric Gaps

Unscreened parallel (magnetic-field-aligned) electric field components $E_{||}$ (so-called "vacuum gaps") could occur in at least two places, the *null surface* (NS) and the *stagnation surface* (SS), e.g. [6, 7, 10], see Fig. 1. The former (NS) designates the (potentially quasi-spherical) region where the generalised Goldreich-Julian charge density ρ_{GJ} vanishes, changing sign across it. This happens close to the location where the field line rotation frequency Ω_F equals the Lense-Thirring angular frequency $\omega(r)$, i.e. usually on radial scales $r \sim r_g \equiv GM/c^2$. In order for the black hole magnetosphere to be force-free (vanishing $E_{||}$) the real charge density ρ_e should corresponds to ρ_{GJ}. As ρ_{GJ} changes signs across the null surface, ρ_e is required to have opposite signs on opposite sites, hence a parallel electric field component could easily arises around the null surface [7]. The stagnation surface, on the other hand, naturally occurs in an MHD outflow driven by a rotating (Kerr) black hole and designates the surface that separates plasma motion inwards (inflows) due to the gravitational field from plasma motion outwards (outflows) above it. Plasma would need to be continuously replenished to maintain a charge density $\rho_e \geq \rho_{GJ}$ and allow for a general (time-averaged) force-free MHD description. The stagnation surface is in general non-spherical (with a prolate shape) and located inside the (outer) light cylinder, typically on radial scales of some r_g.

3. The Conceptual Relevance of Magnetospheric Gaps

It is usually believed that the magnetospheric structure of astrophysical black holes can be reasonably approximated (at least in a time-averaged sense) by an electromagnetic force-free solution. Such a configuration is known to facilitates an efficient electromagnetic extraction of the rotational energy of the black hole [3]. For this to be possible, however, some quasi-steady electric currents that pervade the magnetospheres as sources of the magnetic field and that are carried by charged particles flowing through them, need to be sustained despite the presence of inflows and outflows. If we suppose, to the contrary, that under-dense ($\rho_e < \rho_{GJ}$) regions (gaps) are formed in which a parallel electric field is established, see Sec. 2 above, this does not necessarily invalidate overall force-freeness. In fact, if the potential is sufficiently strong as expected around supermassive black holes, a single particle entering the gap can be accelerated to very high energy (up to Lorentz

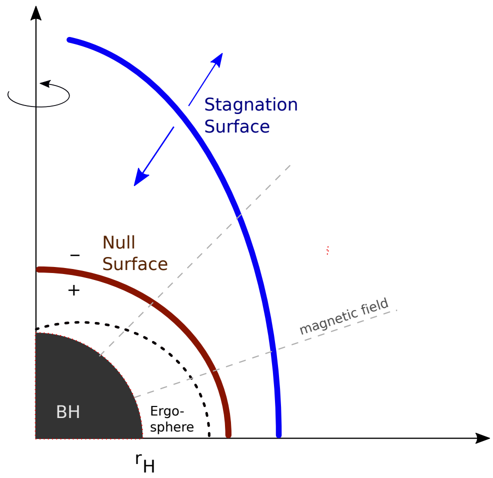

Figure 1: Illustration of the possible location and structure of magnetospheric "vacuum" gaps in rotating black hole magnetospheres. The brown line denotes the null surface across which the charge density changes sign, and the blue line gives the stagnation surface from which stationary MHD flow starts.

factors $\gamma \sim 10^{10}$) in the parallel field $E_{||}$, emitting curvature and inverse Compton gamma-ray photons on its way. In the presence of an ambient photon field, an electron-positron pair production ($\gamma\gamma \rightarrow e^+e^-$) cascade is triggered, that leads to vacuum breakdown and the formation of highly conducting pair plasma, i.e. to enough charges ($\rho_e = \rho_{GJ}$) to annihilate the parallel electric field component and ensure gap closure ($\vec{E} \cdot \vec{B} = 0$), e.g. [9]. As a consequence, the magnetic field lines can be considered as nearly orthogonal to the $\vec{E}$ field lines, with just enough $\vec{E} \cdot \vec{B}$ remaining to produce sparks of electron-positron pairs and keep the magnetosphere filled with plasma [16]. This suggests that an electromagnetic force-free solution provides a reasonable approximation to the time-averaged structure of such a magnetosphere [3].
While the qualitative picture seems evident, the resulting non-thermal emission features (e.g., maximum particle energy, dominant emission mechanism, radiative window, gap power) will depend on the details of the magnetospheric set-up (boundary conditions), and different realisations of the electric field and potential are in principle conceivable (and actually encountered, see e.g. [8]) as motivated below.

3.1 Gap Potential Realisations

In its simplest (one-dimensional, non-relativistic) form the gap electric field along s in the presence of a non-zero charge charge density ρ_e can be determined from Gauss' law

$$\frac{dE_{||}}{ds} = 4\pi(\rho_e - \rho_{GJ})\,, \tag{3.1}$$

and the electrostatic potential from

$$\frac{d\Phi_e}{ds} = -E_{||}\,, \tag{3.2}$$

so that the relevant voltage drop becomes $\Delta\mathscr{V}_{gap} = \Phi_e(s=h) - \Phi_e(s=0)$, where h denotes the characteristic gap height. Different solutions are however obtained dependent on which boundary conditions are considered to be realised as shown in ref. [8]: if $\rho_e \ll \rho_{GJ}$ (*case a*), for example, then

$$\Delta\mathscr{V}_{gap,a} = \Phi_0 \left(\frac{h}{r_g}\right)^2 , \tag{3.3}$$

with $\Phi_0 \simeq \Omega_F r_g^2 B_H/c$, where B_H corresponds to the strength of the normal magnetic field component threading the horizon, while for $\rho \sim \rho_{GJ}$ (*case b*) one instead finds

$$\Delta\mathscr{V}_{gap,b} \simeq \frac{1}{6}\Phi_0 \left(\frac{h}{r_g}\right)^3 , \tag{3.4}$$

i.e. a scaling $\propto h^3$ where the power index is increased by one compared to the previous one.

3.2 Associated Gap Luminosities

Given the anticipated potential strengths around supermassive black holes, a significant amount of the non-thermal emission of magnetospheric gaps is expected to occur in the high and very high energy (VHE) gamma-ray domain, e.g. [12, 9, 7, 11]. The different gap potential noted above, however, result in different expectations for the maximum gap luminosity $L_{gap} \simeq n_c\, V_{gap}\, dE_e/dt$ (with characteristic gap volume $V_{gap} \propto r_g^2 h$) for a gap of height h. As we show in ref. [8] the maximum extractable gap power is in general proportional to the classical Blandford-Znajek jet power, $L_{BZ} \propto r_g^2 B_H^2 \propto \dot{m} M_{BH}$ (with $B_H \propto \dot{m}^{1/2}$), and a sensitive function of the gap height h,

$$L_{gap} \simeq \eta_\beta L_{BZ} \left(\frac{h}{r_g}\right)^\beta , \tag{3.5}$$

where the power index $\beta \geq 1$ is dependent on the respective gap-setup, i.e. $\beta = 2$ with $\eta_2 = 1$ for the noted *case a* and $\beta = 4$ with $\eta_4 = 1/6$ for the *case b* above.

4. The Phenomenological Relevance of Magnetospheric Gaps

The detection of magnetospheric γ-ray emission features in principle allows for a fundamental probe of the near black hole environment including accretion physics and jet formation. In reality, however, this may be more difficult to achieve. On the one hand, to allow for the escape and detectability of VHE gamma-rays the inner accretion flow needs to be radiatively inefficient as otherwise severe $\gamma\gamma$-absorption in the disk photon field will occur. On the other hand, for classical blazar-type sources (with small jet inclination) magnetospheric emission is likely to be overpowered by the strongly Doppler-boosted emission of their jets. Only if the jet is sufficiently misaligned such that Doppler effects are modest may we expect to see it. This has made misaligned and under-luminous AGN, in particular *nearby radio galaxies*, to the most promising targets, see e.g. [14] for review and further references. The occurrence of magnetospheric emission in these sources could possibly account for the spectral hardening at GeV energies seen in some sources [15, 5] and under suitable conditions for rapid VHE γ-ray variability on horizon crossing-times and shorter [2, 7]. For a moderately massive and rather weak gamma-ray source such as, e.g., *Centaurus A* (at $d \simeq 3.7$ Mpc), with $M_{BH} \simeq (0.5-1)\times 10^8 M_\odot$ and characteristic (isotropic equivalent) $L_{VHE} \sim 3\times 10^{39}$ erg/s, variability on timescales $\Delta t_H \sim r_g/c = 8.3\ (M_{BH}/10^8 M_\odot)$ min is unlikely to become detectable given current sensitivities, i.e. the source may appear as quasi-steady on the required instrumental integration times (no evidence for significant short-term variability has in fact been reported so far, neither in the HE nor the VHE domain), with magnetospheric emission probably only becoming apparent as an additional contribution towards higher energies. The situation can be different for more massive (larger r_g) and/or more luminous gamma-ray sources. For the radio galaxy *M87* (at $d \simeq 16.7$ Mpc) with a black hole mass of $M_{BH} \simeq (2-6)\times 10^9 M_\odot$, corresponding to crossing times of $\Delta t_H \simeq r_g/c \simeq (3-9)$ hr, day-scale VHE variability has been detected during several TeV high states (where $L_{VHE} \sim 10^{41}$ erg/s). There are indications that the TeV emission is accompanied by delayed radio core flux enhancements supporting the conclusion that the VHE emission may originate at the jet base very close to the black hole, e.g., [1]. One typically expects magnetospheric gaps to possess maximum heights of $h \lesssim r_g$ (if efficient pair production takes place, screening may well occur earlier, cf. [9]). The (so far) observed day-scale variability in M87 thus does not impose severe constraints on h, cf. eq. 3.5. However, to ensure transparency to VHE photons the accretion flow needs to be radiatively inefficient (of ADAF- type) and this on average constrains inner accretion rates to satisfy $\dot{m}_c \lesssim 0.01$, see e.g. [8] for details. When this is put in context, extractable gap powers are such as to allow accommodation of the gamma-ray emission seen from M87, see Fig. 2. A magnetospheric contribution could also account for the apparent VHE excess above a simple Fermi-LAT power law extrapolation, cf. [13] for details and discussion. The situation is different for the Perseus Cluster radio galaxy *IC 310* (at $d \sim 80$ Mpc), believed to host a black hole of $M_{BH} \simeq 3\times 10^8 M_\odot$. The minute-scale VHE variability that has

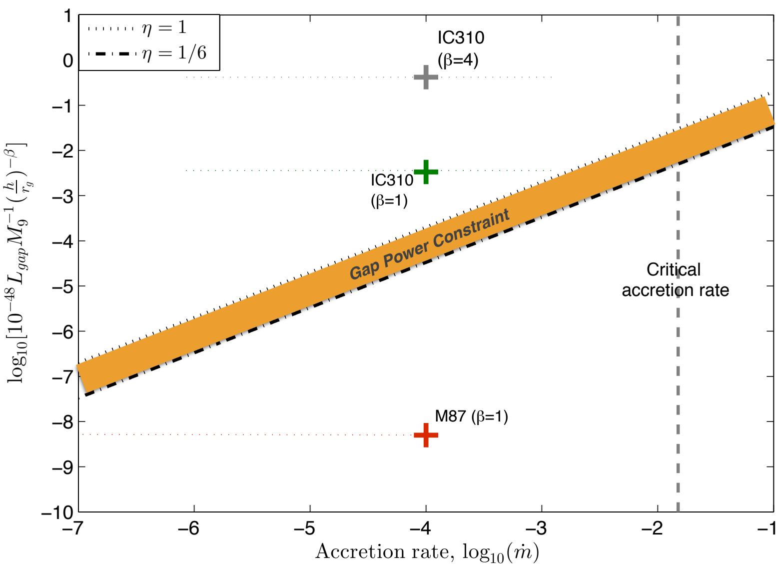

Figure 2: Maximum possible gamma-ray power (orange band) of a magnetospheric gap as a function of accretion rate, cf. eq. (3.5). Different assumptions on the gap potential, eqs. (3.3)-(3.4), lead to a difference in extractable powers. The required transparency of the accretion environment to VHE photon introduce an upper limit $\dot{m}_c \simeq 0.01$ on possible rates. If the observed VHE variability is used to constrain the gap height h, the extractable power is in principle sufficient to account for the gamma-ray emission seen from M87, yet under-predicts the VHE emission seen from IC 310. See ref. [8] for further details.

been seen during a strong VHE flare in Nov. 2012 (with isotropic $L_{VHE} \sim 2 \times 10^{44}$ erg/s) would imply a gap height $h \lesssim c\,\Delta t \simeq 0.2 r_g$ [2]. When this is employed in eq. 3.5 along with the ADAF constraint $\dot{m}_c \simeq 0.01$, extractable powers tend to becomes too small to account for the observed VHE emission, see Fig. 2, thus disfavouring conventional magnetospheric scenarios for its origin.

5. Conclusions

Non-thermal magnetospheric processes could in principle lead to a non-negligible contribution at gamma-ray energies that could vary on horizon crossing times and introduce specific spectral features (e.g. hardening in the overall source spectrum). As this contribution is non-boosted, potential targets would need to be close enough and possess jets sufficiently misaligned for this emission to become detectable by current instruments. The extractable gap power is a sensitive function of the gap height h, $L_{gap} \propto L_{BZ}\,(h/r_g)^{\beta}$, where L_{BZ} denotes the characteristic Blandford-Znajek jet power and $\beta \geq 1$ defines the gap potential that is realised. Detection of rapid variability on timescales smaller than r_g/c thus becomes most constraining and could allow to probe different gap descriptions. When put in context of recent observations, this suggests that the gamma-ray emission seen from M87 may have a magnetospheric origin, while such a scenario appears rather disfavoured in the case of IC 310. The detection of magnetospheric emission generally allows for a sensitive probe of the near black hole environment and is thus of prime interest for advancing our understanding of the physical processes in extreme environments.

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