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# Injection of leptonic matter above accreting black holes

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**Resumen** / El origen de la materia de los jets relativistas lanzados por agujeros negros es desconocido. En este trabajo establecemos un modelo de inyección de materia leptónica sobre agujeros negros acretantes basado en cascadas electromagnéticas. El modelo supone la existencia de un gap electrostático: una región de aceleración de partículas a muy altas energías en la zona polar de la magnetósfera del agujero negro. Calculamos la emisión gamma allí producida debido a las interacciones de las partículas aceleradas con el campo magnético y el campo de radiación del disco de acreción. Esos rayos gamma, al propagarse con el flujo de Poynting lanzado por la ergosfera del agujero, dan lugar a las cascadas electromagnéticas que finalmente cargan el flujo de materia y reducen su magnetización. Por último, simulamos las cascadas con un código Monte Carlo y calculamos el decaimiento de la magnetización a lo largo del jet.

**Abstract** / The origin of matter in black hole-driven relativistic jets is unknown. In this work we set up a leptonic matter injection model above accreting black holes based on electromagnetic cascades. The model assumes the existence of an electrostatic gap: a high energy particle acceleration region in the polar zone of the black hole magnetosphere. We calculate the gamma emission produced therein through the interactions of the accelerated particles with the magnetic field and the radiation field of the accretion disk. Those gamma rays propagate through the Poynting flux launched by the hole's ergosphere and trigger the electromagnetic cascades which eventually load the flux with matter and reduce its magnetization. Finally, we simulate the cascades in detail using a Monte Carlo code and calculate the magnetization along the jet.

*Keywords* / black hole physics — acceleration of particles — radiation mechanisms: non-thermal

## 1. Introduction

Jets are highly collimated fluxes of matter and electromagnetic fields present in an amazing variety of astrophysical objects. Despite this remarkable ubiquity, many aspects of their physics remain poorly understood even six decades after their discovery. Blandford & Znajek (1977) showed that the rotation of a black hole in a magnetic field produces a Poynting flux along the rotation axis. But this flux is purely electromagnetic, while the observations show the signature of a population of relativistic particles. The origin of matter in these fluxes is a yet unsolved problem. These jets, which are highly magnetized at their bases, must enter into a magnetohydrodynamic regime through some other process.

Here we focus on jets of active galactic nuclei (AGNs), the most energetic persistent jets in the universe. Our purpose is to investigate the injection of leptonic matter via electromagnetic cascades above the black hole in Blandford & Znajek jets. We assume there is a gap in the polar region of the magnetosphere where the electric field can accelerate particles up to very high energies. These accelerated particles emit gamma rays due to the interactions with the magnetic field and the radiation field of the accretion disk. After reaching the base of the jet, the gamma rays can trigger the electromagnetic cascades of interest here. We study the cascades by detailed simulations of the interactions with the Monte Carlo code UTOPIA (Pellizza et al., 2010).

## 2. Physical processes in the gap

The potential difference across the gap is of the form

$$\Delta V \sim 4.4 \times 10^{19} \left(\frac{M_{\rm BH}}{10^8\ {\rm M}_\odot}\right)\left(\frac{B}{10^4\ {\rm G}}\right)\left(\frac{h}{r_{\rm g}}\right)^2 {\rm V}, \quad (1)$$

where $M_{\rm BH}$ is the black hole mass, $r_{\rm g}$ the gravitational radius, $B$ the ambient magnetic field and $h$ the gap length (Thorne et al., 1986). We assume that the gap lies on the black hole rotation axis, at a height $z = 2r_{\rm g}$ (Ford et al., 2018), and we set $M_{\rm BH} = 10^8$ $\rm M_\odot$ and $B = 10^4$ G. For these parameters, typical of AGNs, the potential difference can accelerate particles up to very high energies.

The accelerated particles interact with the magnetic field and the radiation field of the accretion disk. To characterize the latter we use the results of a radiatively inefficient accretion model presented in Gutiérrez et al. (2019). It is a two-temperature highly-ionized plasma that radiates via inverse Compton, synchrotron and *Bremsstrahlung* processes.

The electrons in the gap, which move along the magnetic field lines, emit curvature radiation and comptonize the low energy background photons. Other processes are not taken into account as their effect is negligible. There is one issue that one must take care of. The gamma rays produced can annihilate with the background photons thus creating electron-positron pairs. If

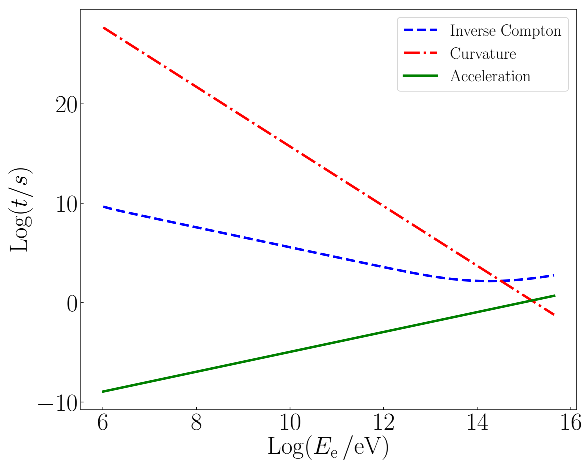


Figure 1: Cooling and acceleration times with $h \simeq 0.36\, r_{\rm g}$. The equilibrium energy is $\sim 2.1 \times 10^{15}$ eV.

this process is efficient the charge density increases until it screens the electric field and closes the gap, neutralizing the acceleration mechanism. This efficiency is controlled by the balance between acceleration and cooling, which in turn depends on $h$. Hence, the adoption of a criterion to ensure the gap sustainability translates into a condition on $h$. Here we follow the criterion suggested by Hirotani & Pu (2016), according to which the amount of pairs created per acclerated lepton must be one. We find the corresponding $h$ value iteratively, solving in each step the evolution equation

$$\frac{dE_{\rm e}}{dl} = \frac{e\Delta V}{h} - \frac{1}{c}\frac{dE_{\rm e}}{dt}\bigg|_{\rm curv} - \frac{1}{c}\frac{dE_{\rm e}}{dt}\bigg|_{\rm IC}, \qquad (2)$$

integrating the emitted photon spectrum along the trajectory and then calculating the amount of pairs according to the annihilation probabilities. The result is $h \simeq 0.36\, r_{\rm g}$.

In Fig. 1 we show the acceleration and cooling times in the gap. The equilibrium energy is $\sim 2.1 \times 10^{15}$ eV. At lower energies the acceleration strongly outpowers the losses. In consequence, the electrons rapidly reach the equilibrium energy and cross virtually the entire gap with that energy. Supposing that the electron number density corresponds to 10 % of the Goldreich-Julian charge density, the gap luminosity results $\sim 1.5 \times 10^{36}$ erg s$^{-1}$. The emitted spectrum is essentially monochromatic, with $\epsilon_\gamma \simeq 6.9 \times 10^{10}$ eV. Besides, given the high energy of the electrons, the photons are emitted in a collimated beam along the $z$-axis.

## 3. Injection of leptonic matter

The gamma rays that escape the gap reach the base of the jet and propagate until annihilating with the background photons, thus producing electron-positron pairs. The created leptons begin to move under the influence of the magnetic field, losing energy while comptonizing the background photons, and producing even more gamma rays. If these gamma rays have enough energy they may annihilate just like the first generation, restarting the chain and triggering a cascade. If the setting is favourable, after some generations the cascades end up injecting leptonic matter in the jet at the expense of the initial photon energy. This is a highly non-linear problem, so only a numerical implementation is possible. We performed detailed Monte Carlo simulations of the cascades using the code UTOPIA (Pellizza et al., 2010).

The simulations require a complete prescription of the magnetic field in the jet. As little is known about that, we propose a paraboloidal magnetic field model obtained from the magnetic flux function

$$\psi = \frac{\psi_0\, r^2}{z} \qquad (3)$$

in cylindrical coordinates, where $\psi_0$ is a parameter that can be fixed in terms of the magnetic field intensity at the base. As to the toroidal component, we take $B_\varphi = \alpha B_r$, being $\alpha$ another parameter. The field intensity decays approximately as $z^{-1}$, times a factor weakly dependent on $r/z$.

Finally, from the base of the jet we launch a collimated photon beam with energy $\epsilon_\gamma \simeq 6.9 \times 10^{10}$ eV. For simplicity we locate the base at $z = 2\, r_{\rm g}$. We simulate three scenarios with different magnetic fields at the base of the outflow: one with (a) $B_0 = 10^4$ G, another with (b) $B_0 = 10^3$ G, and another with (c) $B_0 = 10^2$ G. In case (a) we launch a hundred photons, and in cases (b) and (c), ten photons. The statistics is relatively low because the computational cost is high and the resources scarce.

In case (a) we did not find a big scale cascade. The initial photons annihilate creating a first generation of leptons near the base, but the synchrotron cooling quickly thermalizes them, dominating largely over the inverse Compton cooling. Besides, both for leptons and photons, most of the interactions take place with the synchrotron background photons. As these have low energies, scattering proceeds in the Thomson regime, where only low energy photons are produced. I.e., the few second generation photons do not have enough energy to carry on the cascade. Nevertheless, the initial photons create leptons wherever they interact, and the jet is loaded with matter anyway.

In cases (b) and (c) the prospect improves. While lowering the magnetic field the synchrotron cooling becomes less dominant, and new generations of photons appear. Even so, most of the leptons are still created near the base.

In summary, synchrotron cooling is what eventually cuts off the cascades, depending on its degree of dominance. However, in all three cases leptons are created along the jet, which rapidly cool and are thermalized practically *in situ*.

Specifically, the result we extract from the simulations is the amount of leptons deposited in the flux along the jet per photon launched, as shown in Fig. 2. Then we normalize the quantities according to the gap luminosity calculated in Sec. 2. The injected lepton mass densities are (a) $\rho_{\rm e} = 5.47 \times 10^{-27}$ g cm$^{-3}$, (b) $\rho_{\rm e} = 3.29 \times 10^{-26}$ g cm$^{-3}$ and (c) $\rho_{\rm e} = 1.09 \times 10^{-25}$ g cm$^{-3}$.

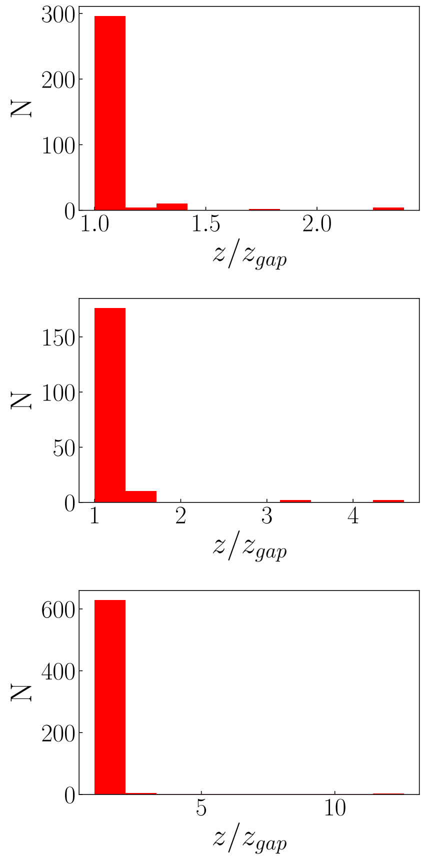


Figure 2: Amount of leptons deposited in the jet per photon launched. From top to bottom: $B_0 = 10^4$ G, $10^3$ G and $10^2$ G. In all cases, although at different degrees, most of the leptons are thermalized near the base.

With this information we can calculate the magnetization along the jet, as $\sigma = B^2/(8\pi\rho c^2)$, using the continuity and induction equations. The ratio $\sigma/B$ is found to be constant over the magnetic surfaces as the injection occurs mainly at the base. In Fig. 3 we show the magnetization on the $z$-axis in all three scenarios. The magnetization is determined by the value it takes there, and then decays as $z^{-1}$. In any case, the jet becomes matter dominated at a certain height, and what changes is the height at which that happens.

## 4. Conclusions

We have investigated the injection of leptonic matter in the context of a particular accretion model. Having simulated three scenarios we found that even in the most favourable case the cascades cease after a few generations. The created leptons are thermalized practically *in situ* by synchrotron cooling, which strongly outpowers inverse Compton cooling. No place is left then for the continuation of the cascades.

Nonetheless, leptons are created wherever photons annihilate, and the jet is loaded with matter anyway. The magnetization decays as $z^{-1}$. The lower the magnetic field at the base, the smaller the height at which

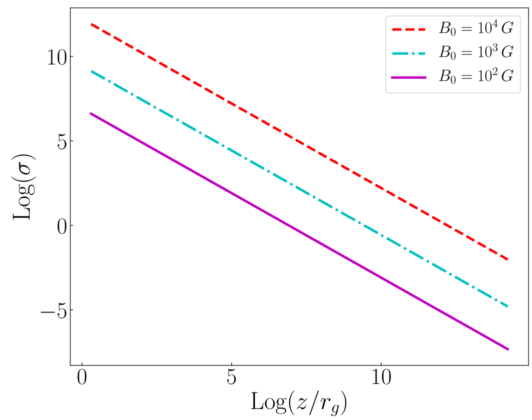


Figure 3: Magnetization along the $z$-axis. It is determined by the value it takes at the jet base, and then decays as $z^{-1}$. As the field intensity decreases, the flux becomes matter-dominated at a smaller height, both because the field decreases and because the injected mass density increases.

the flux becomes matter-dominated, not only because the magnetic field decreases, but also because the injected mass density increases.

As a concluding remark, the accretion model used does not seem to be favourable for the development of cascades, at least if the magnetic fields are as high as $B_0 = 10^4$ G at the base. A more luminous accretion disk would be needed for synchrotron cooling to not overwhelm inverse Compton cooling, and to let many photon generations be created.

In this work we did not take into account the emission corresponding to protons in the gap. Although these stray particles may have a much lower density than the magnetospheric plasma electrons, the former could produce much more energetic photons than the latter. We will investigate the effect of a hadronic component in the gap.

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