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The brightest blazar flares require Eddington-power jets

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In cases where sub -TeV observations of powerful blazar flares are available, pair opacity arguments point to the flare taking place beyond the ~ 0.1 pc size broad line region (BLR). Still, the GeV emission of powerful blazars has been argued to take place in an environment rich in external photons. These two requirements suggest that the blazar GeV emission comes from within the 1-few pc molecular torus region (MTR). Adopting this as our working hypothesis, we show that jets presumed to carry only their radiating electrons will strongly decelerate before they escape the MTR, contrary to VLBI observations of highly superluminal motions at comparable scales. This means that for flaring within the MTR, jets need to carry additional power. We show that a factor of at least few more than the beaming-corrected bolometric luminosity L_{rad} is needed to ensure that the jet will not decelerate strongly. For flares for which L_{rad} is a non-negligible fraction of Eddington luminosity L_{Edd}, events which we term Eddington-class flares, this requires that the flaring jet carries at least the Eddington luminosity, as we demonstrate for the June 2010 flare of PKS 1222+21.

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1. Introduction

A small fraction of accreting supermassive black holes produce jets that may reach a jet power L_{jet} comparable to or higher than the accretion disk luminosity L_{acc} - see [1] for a connection between L_{acc} and time-averaged L_{jet} and [2] for a connection between L_{acc} and the instantaneous L_{jet}. The jet power is an important quantity, as it is directly related to the work that the expanding lobes of radio-loud quasars do on the host galaxy cluster X-ray emitting gas, potentially solving the problem of the missing cooling flows (for a recent review see [3]). Also, its relation to the accretion luminosity and mass accretion rate can be used to understand the jet formation mechanism (jets powered by accretion only, or with the contribution of the black hole spin [4, 5]).

Here we focus on Eddington-class flares, major blazar flares for which the beaming-corrected bolometric luminosity L_{rad} is a non-negligible fraction of the Eddington power L_{Edd} and we show that during such flares jets can carry power larger than L_{Edd}. We start by arguing that in many cases the γ-ray flares must be taking place within the MTR. We then show that a lower limit on L_{jet} can be set by the fact that a jet transversing the MTR photon field will experience a Compton drag that will decelerate it, if it does not carry sufficient power in non-radiating agents (this issue has been previously examined by [7], under the assumption that the blazar emission is produced inside the sub-pc size BLR through external Compton scattering (ECS) of the BLR seed photons [8]). We then use the requirement that jets reach distances of several pc with highly superluminal speeds (e.g. [9]) to argue that $L_{jet} \gtrsim L_{Edd}$. As we discuss these considerations we use as an example the 2010 *Fermi* flare of PKS 1222+21 [17].

2. The case for blazar emission within the MTR

Since the seminal paper of [8], the idea that the blazar emission takes place within the BLR has been widely accepted. Against the BLR blazar location, however, argues the sub-TeV detection of a handful of blazars such as 3C 279 [10] and PKS 1222+21 [11]: the high pair-production optical depth of the BLR to multi-GeV photons disfavors the production of the γ-rays in the BLR.

Alternatively the emission may take place further out at 1-few pc scales where IR seed photons of the dusty MTR dominate the ECS process (e.g. [12]). In favor of ECS, without discriminating between BLR and MTR, [13] showed that, for a sample of powerful blazars, the Compton dominance (the ratio of the γ-ray to synchrotron power) increases for more aligned jets (as the increasing radio core dominance, the ratio of core to extended radio power, suggests). This increase of the Compton dominance with alignment is the trademark of ECS [15, 14]. Combining this with the pair production opacity argument that requires that blazar flares take place outside the BLR, we are led to adopt as our working hypothesis that γ-ray flaring takes place within the MTR.

3. Eddington-class flares within the MTR and a lower limit on the jet power

We will call a flare an Eddington-class flare when its L_{rad} is a non-negligible fraction of L_{Edd}. In the case of EC γ-ray emission [7]:

$$L_{rad} = L_{iso} \frac{\int_{4\pi} \delta^6 d\Omega}{4\pi\delta^6} = L_{iso} \frac{16}{5} \frac{\Gamma^4}{\delta^6}, \tag{3.1}$$

where Γ is the bulk motion Lorentz factor, δ is the usual Dopper factor, L_{iso} is the observationally derived luminosity assuming isotropic emission, and the last equation holds for $\Gamma \gg 1$. This is also a first lower limit on the power that the jet needs to carry to produce the observed flare, requiring $L_{jet} > L_{rad}$.

In the case of of our example source, the blazar PKS 1222+21 (also known as 4C 21.35) at $z = 0.432$, the source was detected at sub-TeV energies by *MAGIC* on 17 June 2010 [11]. During the time of the TeV detection, the source was undergoing a major GeV flare [17] and it was heavily dominated by the high energy component. As we discussed above, this clearly argues that the flare took place outside the BLR. To find L_{iso}, we note that the high energy spectral energy distribution (SED) can be described by a broken power law with photon index 2 between 100 MeV to 2 GeV. Above 2 GeV the *Fermi* photon index is 2.44 ± 0.1 while the 70-400 GeV *MAGIC* index is 2.7 ± 0.3. We adopt a photon index 2.5 above 2 GeV, with our subsequent work not being sensitive to the particular choice. The *LAT* - *MAGIC* Gamma-ray luminosity, assuming isotropic emission, is $L_{iso} \approx 3 \times 10^{48}$ erg s^{-1}, with $\approx 2/3$ of it below the 2 GeV break. The beaming-corrected luminosity from equation (3.1) is $L_{rad} \approx 2.4 \times 10^{46}$ erg s^{-1}, where we set $\Gamma = \delta = 20$, satisfying pair opacity constraints [19] and in agreement with *VLBI pc-scale* superluminal speeds $\beta_{app} \sim 10-26$ [18, 9]. With a black hole mass of $M_{BH} \approx 6 \times 10^8 M_\odot$ [6], $L_{Edd} \approx 8 \times 10^{46}$ erg s^{-1} and $L_{rad} \approx 1/3 L_{Edd}$, The flare, therefore, is an Eddington-class flare. L_{rad} is a lower limit for the jet electron power L_e of the electrons producing the 100 MeV - 400 GeV emission during the flare, and therefore a lower limit to L_{jet}.

4. Compton drag on an external photon field

A more stringent lower limit on the jet power is imposed but the fact that if the flaring emission is dominated by ECS, as is the case for emission within the MTR, the power transfer from relativistic electrons to γ-ray photons is also a momentum transfer to the up-scattered seed photons, because, unlike synchrotron, ECS is anisotropic in the comoving frame [15, 14] and, as we show below, this will strongly decelerate the flow if the jet does not carry a sufficient amount of power/momentum in non-radiating particles. Strong deceleration, however, is incompatible with the highly superluminal apparent speeds ($\beta_{app} \sim 10-40$) observed at the few-pc VLBI scales ([9]) and requiring $\Gamma \geq \beta_{app}$. The jet producing an Eddington-class flare, therefore, must carry a sufficient amount of power/momentum in non-radiating particles.

To calculate the degree of deceleration for a given composition of radiating and non-radiating particles, we present here an economic set-up of the Compton drag problem that captures the essential physics and it is an extension of the one given by [16] to include adiabatic energy changes: a relativistic jet with bulk Lorentz factor $\Gamma(z)$ (speed $\beta(z)$ in units of the speed of light c) and constant opening angle, propagates through an isotropic external photon field of energy density U. Here, z measures the distance of propagation from a fiducial point z_0. The flow is composed of a non-thermal electron energy distribution (EED), and a non-radiating component, including protons, thermal electrons, and magnetic field, with total comoving energy density ρ. The EED at injection (z_0) is constrained between electron Lorentz factors $\gamma_{min,0}$ and $\gamma_{max,0}$ and is assumed, but not required, to be a power law. As the jet propagates, the jet electrons up-scatter the external field photons to GeV energies, transferring to them energy and, importantly, momentum in the forward direction.

For electrons of Lorentz factor γ in the comoving frame and with an isotropic distribution, the solid angle averaged component of momentum along the z-axis in the galaxy frame is

$$\langle\tilde{\gamma}^2\rangle_z = \frac{1}{2}\int_{-1}^{+1} \mu\tilde{\gamma}^2 d\mu', \tag{4.1}$$

where $\tilde{\gamma}$ is the electron Lorentz factor in the galaxy frame, θ' is the angle between the electron and the flow direction of motion in the comoving frame and $\mu' = \cos\theta'$, with θ, μ referring to the same quantities in the galaxy frame. Note that equation (4.1) corrects equation (9) of [16] in projecting the momentum of the electrons on the galaxy and *not* on the comoving frame. This results to a factor of two higher deceleration rate than that of [16] and it is important, as manifested by the fact that the factor of two ends up in the exponent of the analytically solvable case we present below, causing significantly faster deceleration. Integrating equation (4.1) and assuming $\gamma >> 1$, relevant when efficient Compton drag is anticipated, we obtain

$$\langle\tilde{\gamma}^2\rangle_z = \frac{\gamma^2\Gamma^2}{3\beta^2}[-6(1-\beta^2)(1-\beta')^2\tanh^{-1}(\beta)+\beta\{3+\beta'(2\beta^2(3-\beta')-3(2-\beta'))\}] = \frac{4}{3}\beta\gamma^2\Gamma^2, \tag{4.2}$$

where the last equation holds for $\gamma >> 1$, relevant to the Compton drag problem.

Using the last approximate expression, the coupled equations governing the radiative deceleration of the flow and cooling of the electrons are:

$$\frac{d\Gamma}{dz} = -\frac{16\sigma_T U}{9m_e c^2}\frac{\beta\Gamma^2\langle\gamma^2\rangle}{\frac{\rho/c^2}{N_e m_e}+\langle\gamma\rangle} \tag{4.3}$$

$$\frac{d\gamma}{dz} = -\frac{16\sigma_T U}{9m_e c^2}\frac{\gamma^2}{\beta\Gamma}\left(\Gamma^2-\frac{1}{4}\right)-\frac{2}{3}\frac{\gamma}{z}-\frac{1}{3}\frac{\gamma}{\beta^2\Gamma}\frac{d\Gamma}{dz}, \tag{4.4}$$

where m_e is the electron mass, σ_T is the Thomson cross-section, N_e is the comoving electron number density and $\langle\gamma\rangle$ and $\langle\gamma^2\rangle$ are averages over the EED. The first term in equation (4.4) is the electron radiative energy losses, assumed to be dominated by external Compton losses, the second is the adiabatic losses assuming a constant opening angle jet, and the third is the adiabatic gains from the compression of the fluid element along the z-axis as it decelerates. Eq. (4.4) is used to follow the evolution of γ, and through this, using particle conservation, the evolution of the EED along z. This is in turn used to evaluate $\langle\gamma^2\rangle$ and $\langle\gamma\rangle$ that are then used in equation (4.3).

An analytic solution can be found in the case of a monoenergetic EED injection, assuming $\Gamma >> 1$, neglecting the adiabatic process, and assuming a purely leptonic jet, equations (4.3) and (4.4) become a system of autonomous differential equations

$$\frac{d\Gamma}{dz} = -\frac{16\sigma_T U}{9m_e c^2}\Gamma^2\gamma, \quad \frac{d\gamma}{dz} = -\frac{16\sigma_T U}{9m_e c^2}\gamma^2\Gamma, \tag{4.5}$$

that through a substitution $\chi = \Gamma\gamma$ has the following analytic solution, useful for testing numerical work (see Figure 1):

$$\Gamma(z) = \Gamma_0(1+z/l_{dec})^{-1/2}, \quad \gamma(z) = \gamma_0(1+z/l_{dec})^{-1/2},$$
$$l_{dec} = \frac{9m_e c^2}{32\sigma_T U\Gamma_0\gamma_0} \approx 10^{-2}\times(U_{-3}\Gamma_0\gamma_{0,4})^{-1}\ \mathrm{pc}$$

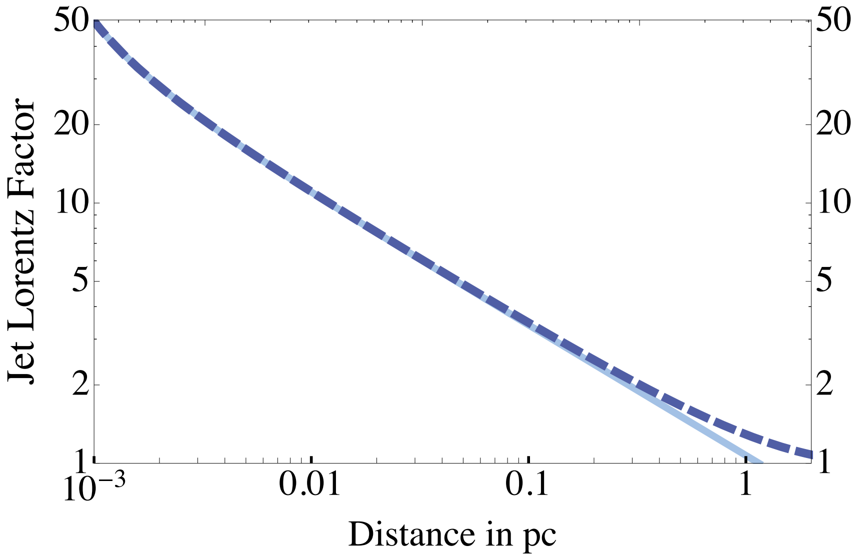

Figure 1: Solid line: the analytic solution for the radiative deceleration of a purely leptonic jet with $\Gamma_0 = 50$ and $\gamma_0 = 10^4$ in an external photon field $U = 5\times10^{-4}$ erg cm^{-3}. Dashed line: The numerical solution where, instead of a monoenergetic injection, a narrow power-law EED with $\gamma_{min} = 9\times10^3$, $\gamma_{max} = 1.1\times10^4$ and electron index $p = 2.5$ is injected. Note that the two lines agree very well, except close to $\Gamma\sim1$, where the analytical aproximation $\Gamma >> 1$ breaks down.

where Γ_0 and γ_0 are the initial bulk and individual electron Lorentz factor and l_{dec} is the characteristic deceleration length, with $U_{-3} = U/10^{-3}$ and $\gamma_{0,4} = \gamma/10^4$, appropriate for GeV emission from within the MTR.

We can now apply the above discussed formalism and in particular the numerical solution for the jet deceleration equations (4.3) and (4.4) to the 2010 Eddington-class flare of PKS 1222+21. The energy density of the MTR, where we assume the flaring is taking place, is $U = L_{IR}/(4\pi c R^2_{MTR})$ $= 5\times10^{-4}$ erg cm^{-3} (with $L_{IR} = 8\times10^{45}$ erg s^{-1}, MTR size $R_{MTR}\sim2$ pc [20]). We assume that the cooling of all the electrons responsible for the $E > 100$ MeV emission takes place in the fast cooling regime. This is the most conservative assumption for estimating the jet power, because it minimizes the injected electron power required to produce the observed SED. Under the assumption of fast cooling, the injected EED required to explain the SED above 100 MeV self-consistently will have $L_e = L_{rad} \approx L_{Edd}/3$ and slope 2 between $\gamma = (100\,\mathrm{MeV}/0.3\,\mathrm{eV})^{1/2}(1+z)^{1/2}/\delta \approx 2.1\times10^4/\delta$ and $\gamma = (2\,\mathrm{GeV}/0.3eV)^{1/2}(1+z)^{1/2}/\delta \approx 9.6\times10^4/\delta$, breaking to a slope of 3 above that and up to $\gamma = (400\,\mathrm{GeV}/0.3\,\mathrm{eV})^{1/2}(1+z)^{1/2}/\delta \approx 1.3\times10^6/\delta$. In the fast cooling case this break is intrinsic to the injected EED and we attribute it to the particle acceleration mechanism.

In addition to $L_e \approx L_{Edd}/3$, the power carried by the EED responsible for the 100 MeV - 400 GeV SED, the jet may carry power in low energy leptons, protons, and a comoving magnetic field. The degree of jet deceleration depends on the degree of jet loading with these non-radiating agents. One possible configuration we want to examine is that $L_{jet} = L_{acc}$, which in the case of PKS 1222-21 is $L_{acc} \approx 5\times10^{46}$ erg s^{-1} [20], and so $L_{jet} = L_e + L_{nr} = L_{acc}$, where L_{nr} is the power of the non-radiating agents. Because $L_e = L_{rad} \approx 2.4\times10^{46}$ erg s^{-1}, in this case $L_{nr} \approx 2.6\times10^{46}$ erg s$^{-1} \approx L_e$. Another possibility is $L_{jet} = L_{Edd}$, which requires $L_{nr} = L_{jet} - L_e \approx 2L_{Edd}/3 \approx 2L_e$.

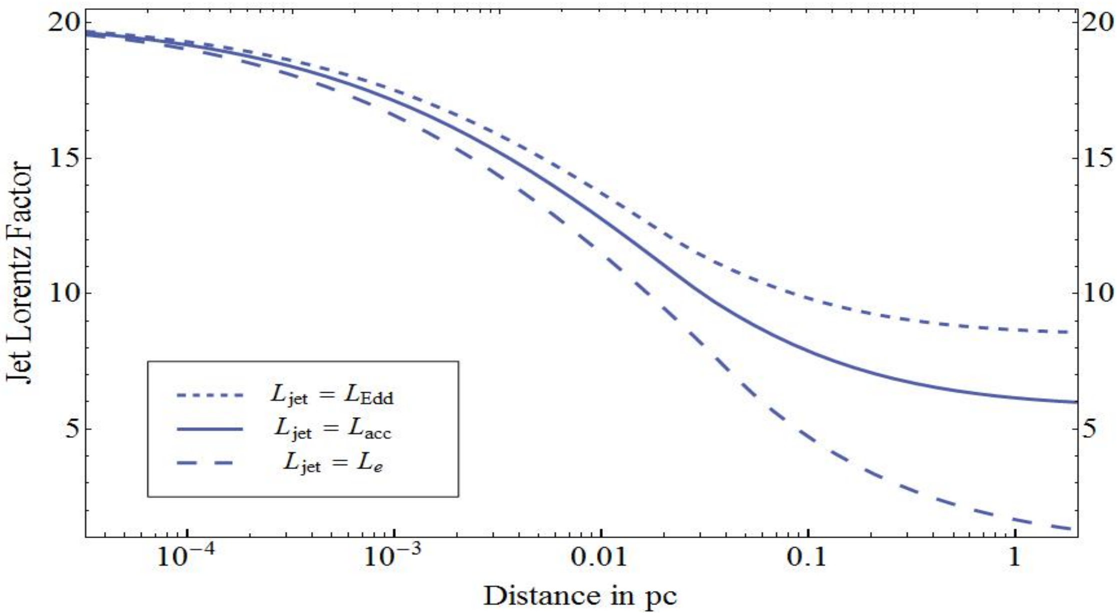

Figure 2: The jet bulk Lorentz factor Γ deceleration profile for the three cases discussed in the text: $L_{jet} = L_e$, $L_{jet} = L_{acc}$, $L_{jet} = L_{Edd}$. It is assumed that the jet propagates in the MTR and that starts with $\Gamma_0 = 20$. The x-axis is the propagation length from the starting point somewhere in the MTR.

We plot the numerical solution of equations (4.3) and (4.4) for the three cases for the jet power, $L_{let} = L_e$, $L_{let} = L_{acc}$, $L_{let} = L_{Edd}$ in figure 2. In all three cases the jet starts with $\Gamma = 20$. The case where the jet carries only the radiating leptons is strongly disfavored, as the flow decelerates down to sub-relativistic speeds before exiting the MTR. The case where $L_{jet} = L_{acc}$ reduces Γ by a factor of ~ 4 before the jet covers a distance comparable to that required for exiting the MTR. This means that to retain a Lorentz factor $\Gamma \sim 20$ beyond the MTR, as required by VLBI observations [9], the jet would need a starting $\Gamma \sim 80$. Similarly, for $L_{jet} = L_{Edd}$, the flow decelerates down to $\Gamma \sim 9$, which indicated that for an exit Lorentz factor $\Gamma \sim 20$ the jet would need a starting $\Gamma \sim 45$. While a starting Lorentz factor of $\Gamma \approx 45$ is within what is expected for the γ-ray emitting region of the source [21], a value of $\Gamma \approx 80$ is in not anticipated and disfavored by blazar sample studies [22]. We therefore conclude that the jet must carry a luminosity at least equal to the Eddington luminosity otherwise it will decelerate substantially, requiring implausibly high starting Lorentz factors. Note that for $L_{jet} \gtrsim 2L_{Edd}$ (not plotted) the flow deceleration is small, as the radiating leptons carry only a small fraction of the jet power and momentum.

5. Conclusions

During Eddington-class flares, major blazar flares that have a beaming-corrected luminosity that is a significant fraction of L_{Edd}, the requirement that the emitting plasma does not decelerate below Lorentz factors $\Gamma \sim 20$ seen in VLBI studies, requires that blazar jets, beyond the radiating leptons, must carry additional power that brings the total jet power at or above the Eddington luminosity of the source. We demonstrated this of a 2010 flare of PKS 1222+21. The same line of argument may be applied to other Eddington-class blazar flares.

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