Compton rockets and the minimum power of relativistic jets

G. Ghisellini* and F. Tavecchio

INAF – Osservatorio Astronomico di Brera, via E. Bianchi 46, I–23807 Merate, Italy

ABSTRACT

The power of a relativistic jet depends on the number of leptons and protons carried by the jet itself. We have reason to believe that powerful γ-ray flat spectrum radio sources emit most of their radiation where radiative cooling is severe. This helps us to find the minimum number of emitting leptons needed to explain the radiation we see. The number of protons is more uncertain. If there is one proton per electron, they dominate the jet power, but they could be unimportant if the emission is due to electron–positron pairs. In this case, the total jet power could be much smaller. However, if the γ-ray flux is due to inverse Compton scattering with seed photons produced outside the jet, the radiation is anisotropic also in the comoving frame, making the jet recoil. This Compton rocket effect is strong for light, electron–positron jets, and negligible for heavy, proton-dominated jets. No significant deceleration, required by fast superluminal motion, requires a minimum number of protons per lepton, and thus a minimum jet power. We apply these ideas to the blazar 3C 454.3 to establish a robust lower limit to its total jet power: if the viewing angle $\theta_v \approx 1/\Gamma$, the jet power is larger than the accretion luminosity L_d for any bulk Lorentz factor Γ. For $\theta_v = 0°$, instead, the minimum jet power can be smaller than L_d for $\Gamma < 25$. No more than $\sim$10 pairs per proton are allowed.

Key words: radiation mechanisms: non-thermal – galaxies: active – galaxies: individual: 3C454.3 – galaxies: jets.

1 INTRODUCTION

The high-quality data of the Large Area Telescope (LAT) onboard the *Fermi* satellite, together with the simultaneous observations performed by the *Swift* satellite in the optical–UV and X-ray bands and by ground-based telescopes, allowed a new era in the study of blazar jets. Detailed modelling of these sources allows the estimation of the physical parameters of the jet emitting region, such as its magnetic field, particle density, size and bulk Lorentz factor. Therefore, we can estimate the power that the jet carries in the form of particles and fields, and compare it with the accretion luminosity, at least in flat spectrum radio quasars (FSRQs), where the disc component is visible. In our previous studies of γ-ray loud FSRQs (Ghisellini et al. 2010a,b), we found that the jet power can be even larger than the accretion luminosity, and that it correlates with it (also when accounting for the common redshift dependence).

When estimating the jet power in this way, there are two crucial uncertainties: (i) the total number of leptons that depends on the low-energy end of the particle distribution (as those are most numerous) yet – this number is difficult to observe because of synchrotron self-absorption; and (ii) the number of protons per lepton. For the first concern, evidence is accumulating that in FSRQs the radiative

cooling is severe, so that leptons of almost all energies do cool in one light crossing time, and the presence of low-energy particles is often required to reproduce the observed X-ray spectrum, interpreted as inverse Compton radiation with photons originating externally to the jet (i.e. external Compton, hereinafter EC).

The second concern (how many pairs per proton) has been discussed, among others, by Ghisellini et al. (1992), Celotti & Fabian (1993), Sikora & Madejski (2000), Celotti & Ghisellini (2008) and Ghisellini et al. (2010a). If pairs are created in the γ-ray emission region, we should see a clear break in the spectrum, and the absorbed luminosity should be reprocessed at lower energies, especially in the X-ray band, where instead the spectral energy distribution (SED) of FSRQs has a minimum. If the pairs are created very close to the black hole, there is a maximum number of them surviving annihilation, corresponding to a local pair scattering optical depth $\tau_\pm \sim 1$ (Ghisellini et al. 1992). At the parsec scale [i.e. the sizes measurable by very long baseline interferometry (VLBI)], the corresponding pair density is less than the lepton density required to produce the synchrotron flux we see. On the other hand, the γ-ray-emitting zone is much smaller and closer to the black hole than the VLBI zone, and the number density of the surviving pairs might be enough to account for the radiation produced in this region. We have found in our earlier works (Celotti & Ghisellini 2008; Ghisellini et al. 2010a,b) that the power spent by the jet to produce its radiation is often greater than the power in the Poynting flux and

*E-mail: gabriele.ghisellini@brera.inaf.it

the bulk kinetic energy of the emitting leptons, requiring an additional form of jet power, that is, protons. The simplest hypothesis of one proton per electron leads to jet powers systematically larger than the accretion luminosity. Thus it is crucial to evaluate how many protons per emitting lepton there are in the jet. To this end we introduce here a new argument that can be applied when most of the radiation is produced through Compton scattering with external radiation (EC). In this case, the emission pattern is anisotropic in the comoving frame of the emitting region that must recoil. This is the 'hot version' of the Compton drag effect (the emitting particles are relativistic in the comoving frame) and is called the 'Compton rocket' (hereinafter CR) effect. First studied in the 1980s (O'Dell 1981) as a way to accelerate jets using the accretion disc photons as seeds, it has been used as a tool to limit the jet bulk Lorentz factor Γ assuming, as seed photons, those re-isotropized by the broad line region (BLR) or by a relatively distant torus (e.g. Sikora et al. 1996). More recently, it has been used as a decelerating agent for very fast jet 'spines' moving inside slower jet 'layers' (Ghisellini, Tavecchio & Chiaberge 2005), or for large-scale jets interacting with the cosmic microwave background (Tavecchio et al. 2006).

We use the CR effect to limit the number of pairs, assuming that the jet is moving with a given Γ and that requiring it does not significantly decelerate due to the CR effect, in order to be consistent with observations of fast superluminal motion at the VLBI scales. Light jets (i.e. pair dominated) can be decelerated more effectively than heavier jets (i.e. with an important proton component). Therefore, requiring no significant deceleration fixes the minimum number of protons per lepton, one of the most important numbers for finding out a limit on the total jet power. Furthermore, if the (energetically dominant) γ-ray flux is EC emission, we can in a rather straightforward way evaluate the jet power in its different forms: magnetic, leptonic, radiative and protonic, and how these different jet powers change by changing Γ (similarly to what done in Ghisellini & Celotti 2001). Doing this, one finds a *minimum* power, approximately where the Poynting flux equals the other dominant form of power (i.e. bulk motion of leptons, or protons or radiative), and a corresponding Γ.

We apply these arguments to 3C 454.3, one of the best-studied blazars, used as a test case. It is an FSRQ at $z = 0.859$ (Jackson & Browne 1991), superluminal (Jorstad et al. 2005; Lister et al. 2009) with components moving with β_{app} from a few to more than 20, resulting in estimated bulk Lorentz factors from 10 to 25. It is one of the brightest and most variable FSRQs. In 2005 April–May, it underwent outburst, dramatic in optical (Villata et al. 2006) and visible also at X-ray energies (Giommi et al. 2006; Pian et al. 2006). The *AGILE* satellite detected 3C 454.3 as one of the brightest and most variable sources in the γ-ray band (Vercellone et al. 2007, 2010). After the launch of the *Fermi* satellite, 3C 454.3 was seen to flare several times (Tosti et al. 2008; Abdo et al. 2009), with a climax in 2009 December (Bonnoli et al. 2010).

2 THE COMPTON ROCKET EFFECT AND THE PAIR CONTENT OF THE JET

If the main emission process of blazars is synchrotron and self-Compton radiation, then the emitted luminosity is isotropic in the comoving frame. This means that the jet loses mass, but not velocity. The lost mass is at the expenses of the 'relativistic' (i.e. $\gamma m_e c^2$) mass of the emitting leptons. Instead, if powerful blazars produce most of their emission by scattering *external* radiation, then the produced

radiation is anisotropic even in the comoving frame, and the jet must decelerate (i.e. it recoils in the comoving frame). The amount of this deceleration depends on the produced EC luminosity and the inertia of the jet, that is, if the jet is 'heavy' or 'light'. Therefore, this CR effect (i.e. the 'hot' version of Compton drag, because the leptons are relativistic) can give some limit on the minimum number of protons present in the jet, requiring that it does not decelerate significantly. We present here a simple derivation of the relevant formulae that agree with the more detailed and complex derivation of Sikora et al. (1996).

Let us remain in the observer frame. There we measure an external and isotropic radiation energy density U_{ext}. The total Lorentz factor ($\tilde{\gamma}$) of the electrons is the superposition of the bulk (Γ) and random (γ) Lorentz factors (β_{bulk} and β are the corresponding velocities). Assuming that the bulk motion occurs along the x-axis, and that the random velocity forms an angle θ' with respect to that axis, in the comoving frame, we have (e.g. Rybicki & Lightman 1979):

$$\beta_x = \frac{\beta' \cos\theta' + \beta_{bulk}}{1 + \beta_{bulk}\beta' \cos\theta'}; \quad \beta_y = \frac{\beta' \sin\theta'}{\Gamma(1 + \beta_{bulk}\beta' \cos\theta')}. \tag{1}$$

The total $\tilde{\gamma}^2$ is

$$\tilde{\gamma}^2 = \left(1 - \beta_x^2 - \beta_y^2\right)^{-1} = (1 + \beta_{bulk}\beta' \cos\theta')^2 \gamma^2 \Gamma^2. \tag{2}$$

If the particle distribution is isotropic in the comoving frame, the average over angles gives

$$\langle \tilde{\gamma}^2 \rangle = \frac{\int 2\pi \sin\theta' \tilde{\gamma}^2(\theta') d\theta'}{4\pi} = \left[1 + \frac{(\beta_{bulk}\beta')^2}{3}\right] \gamma^2 \Gamma^2, \tag{3}$$

which gives the factor (4/3) for ultrarelativistic speeds.

Now assume that a portion of the jet carries a total number N_p of protons and N_e leptons (including pairs). The 'cooling time' of the jet (i.e. the time for halving Γ) is

$$t_{cool} = \frac{E}{\dot{E}} = \Gamma \frac{N_p m_p c^2 + N_e \langle\gamma\rangle m_e c^2}{(4/3)\sigma_T c N_e U_{ext} \langle\tilde{\gamma}^2\rangle}$$

$$= \frac{9}{16} \frac{(N_p/N_e)m_p c^2 + \langle\gamma\rangle m_e c^2}{\sigma_T c U_{ext} \langle\gamma^2\rangle \Gamma}. \tag{4}$$

In the cooling time t_{cool}, the jet travels a distance $R_{cool} = \beta c t_{cool}$. The corresponding interval of time as measured by the observer is Doppler-contracted by the factor $(1 - \beta\cos\theta_v) \equiv 1/(\Gamma\delta)$ (θ_v is the viewing angle and δ is the beaming factor). The time $t_{cool}(1 - \beta\cos\theta_v)$ has to be compared with the time-scale for which the particles are indeed described by an energy distribution with the value of $\langle\gamma^2\rangle$ used, provided that, during this time, the radiation density remains U_{ext}. This time-scale is approximately the variability time-scale. The CR effect is unimportant if

$$t_{cool} > \frac{t_{var}}{(1+z)(1-\beta\cos\theta_v)} = \frac{t_{var}\Gamma\delta}{(1+z)} \rightarrow$$

$$\Gamma^2\delta < \frac{9(1+z)}{16} \frac{(N_p/N_e)m_p c^2 + \langle\gamma\rangle m_e c^2}{\sigma_T c U_{ext} \langle\gamma^2\rangle t_{var}}. \tag{5}$$

This limit becomes very severe if the jet is dominated by hot pairs, and if $U_{ext} = U_{BLR}$ the radiation energy density is dominated by radiation from the BLR. In this case, jets with $\Gamma \gtrsim 10$ are bound to decelerate. They do not decelerate if they contain a proton component that increases their inertia. We can rewrite equation (5) to find the minimum ratio N_p/N_e compatible with halving Γ in t_{var}:

$$\frac{N_p}{N_e} > \max\left[0, \left(\frac{16}{9}\frac{\Gamma^2\delta t_{var}}{1+z}\frac{\sigma_T c U_{ext}\langle\gamma^2\rangle}{m_p c^2} - \frac{\langle\gamma\rangle m_e}{m_p}\right)\right]. \tag{6}$$

Since $N_e = N_{\pm} + N_p$ (pairs plus electrons associated with protons), we have $N_{\pm}/N_p = (N_e/N_p) - 1$.

3 THE POWER OF THE JET

The most robust estimate on the jet power is the power P_r spent to produce the radiation as measured with a '4π' detector surrounding the source in the observer frame. If the luminosity L' is isotropic in the comoving frame, then we would derive $P_r = L'/(4\pi) \int \delta^4 d\Omega = (4/3)\Gamma^2 L'$. However, if the EC process is important, the emission is not isotropic in the rest frame, and the observed flux, instead of being boosted by δ^4, follows a pattern given by $\delta^4(\delta/\Gamma)^2$ (see Dermer 1995; Georganopoulos, Kirk & Mastichiadis 2001). Setting $\langle L' \rangle$, the angle averaged luminosity, in the comoving frame, we then have

$$P_r = \frac{\langle L' \rangle}{4\pi} \int_{4\pi} \frac{\delta^6(\theta)}{\Gamma^2} d\Omega \sim \frac{16}{5}\Gamma^2 \langle L' \rangle \approx \frac{16\,\Gamma^4 L_{obs}}{5\,\delta^6(\theta_v)}. \quad (7)$$

The power in bulk motion of leptons, protons and magnetic fields are calculated as

$$P_e = \pi R_{blob}^2 \Gamma^2 \beta c\, m_e c^2 \int_{\gamma_{cool}}^{\gamma_{max}} N(\gamma)\gamma\, d\gamma$$
$$= \pi R_{blob}^2 \Gamma^2 \beta c\, n_e \langle \gamma \rangle m_e c^2,$$
$$P_p = \pi R_{blob}^2 \Gamma^2 \beta c\, n_p m_p c^2,$$
$$P_B = \pi R_{blob}^2 \Gamma^2 \beta c\, U_B, \quad (8)$$

where R_{blob} is the size of the emitting source. We are assuming that protons are cold and that n_e is the total number density of leptons, including pairs (if present), so that $n_e = n_{\pm} + n_p$. We also assume that *all* leptons are relativistic and are described by the energy distribution $N(\gamma)$. Neglecting cold leptons minimizes the power requirement. The total jet power is $P_{jet} = P_r + P_e + P_p + P_B$.

As long as the scattering is in the Thomson regime, the observed luminosity in the EC component of the SED is

$$L_{EC}^{obs} \sim \frac{16\pi R_{blob}^3}{9} \sigma_T c n_e \langle \gamma^2 \rangle U_{ext}' \frac{\delta^2}{\Gamma^2}\delta^4. \quad (9)$$

We can then find the number density n_e of the emitting leptons:

$$n_e = \frac{9 L_{EC}}{16\pi R_{blob}^3 \sigma_T c \langle \gamma^2 \rangle U_{ext}\delta^6}. \quad (10)$$

The averages $\langle \gamma \rangle$ and $\langle \gamma^2 \rangle$ are calculated assuming that the emitting particle distribution is a broken power law, extending from γ_{cool} to γ_{peak} with slope $N(\gamma) \propto \gamma^{-2}$, as appropriate for radiative cooling, and breaking above γ_{peak}, where we assume $N(\gamma) \propto \gamma^{-p}$ up to γ_{max}. The slope p is related to the observed energy spectral index α above the synchrotron and the EC peaks as $p = 2\alpha + 1$. The values of γ_{cool} and γ_{peak} will depend on Γ and δ (see equations 15 and 16). In general, both $\langle \gamma \rangle$ and $\langle \gamma^2 \rangle$ decrease by increasing Γ and δ: this is because the external photon field is seen more boosted in the comoving frame, inducing a stronger Compton cooling (and so γ_{cool} decreases); at the same time, a smaller γ_{peak} is required to produce the high energy peak.

The magnetic energy density U_B can be derived in terms of the 'Compton dominance', namely the γ-ray to synchrotron luminosity ratio L_γ/L_{syn}:

$$\frac{L_\gamma}{L_{syn}} = \frac{U_{ext}'(\delta/\Gamma)^2}{U_B} \rightarrow U_B = \delta^2 U_{ext} \frac{L_{syn}}{L_\gamma}. \quad (11)$$

4 THE MINIMUM JET POWER

We now show how the different forms of jet power change by changing the bulk Lorentz factor. These estimates depend on the following parameters: $L_\gamma \sim L_{EC}$; L_γ/L_{syn}; ν_c (the νF_ν peak frequency of the γ-ray spectrum); θ_v (the viewing angle); $t_{var} = (1+z)R_{blob}/(c\delta)$; α_γ (the energy spectral index of the γ-ray spectrum above the peak), and z. Of these seven parameters, all but one (the viewing angle) are observables. Note that the external radiation energy density is not a free parameter if the typical radius of the BLR (or the reprocessing torus) depends on the disc luminosity as $R_{ext} \propto L_d^{1/2}$. In this case, $U_{ext} \propto L_d/R_{ext}^2$ is constant.

The viewing angle θ_v is in general unknown. We can assume $\theta_v = 1/\Gamma$, in order to always have $\Gamma = \delta$. Alternatively, we can assume $\theta_v = 0$, that is, $\delta = 2\Gamma$. Maximizing the Doppler boosting, this choice will minimize the derived powers but the probability to observe any source with $\theta_v = 0$ is vanishingly small. There might be an exception: consider the case for which the velocity vectors of the emitting flow are not parallel, but somewhat radial within the jet aperture angle θ_{jet}. Thus, if θ_v is finite, but smaller than θ_{jet}, there is a *portion* of the jet exactly pointing at us. On the other hand, the corresponding emitting volume of this portion is small, and the flux we see is mostly contributed for by those parts of the jet moving with $\theta_v \sim 1/\Gamma$, because they have a larger volume.

We are led to conclude that the case $\theta_v = 1/\Gamma$ is favoured. It is also the angle for which the superluminal motion is maximized, but this implies that the jet does not change direction between the γ-ray-emitting region and the VLBI scale, which is not guaranteed.

We now rewrite the different forms of jet power in order to make more transparent their dependencies on the bulk Lorentz factor and the parameters listed above:

$$P_B = \frac{\pi c^3 t_{var}^2}{(1+z)^2} \frac{L_{syn}}{L_\gamma} U_{ext}\beta\Gamma^4\delta^2$$
$$P_e = \frac{9}{16} \frac{\langle \gamma \rangle}{\langle \gamma^2 \rangle} \frac{m_e c^2}{\sigma_T c U_{ext}} \frac{(1+z)L_\gamma}{t_{var}}\delta^{-5}$$
$$P_p = P_e \frac{m_p}{\langle \gamma \rangle m_e}; \qquad n_p = n_e$$
$$P_p \sim L_\gamma\,\Gamma^4\delta^{-6} \sim P_r; \quad n_p \text{ from equation (6).} \quad (12)$$

The last approximate equality assumes that the second term in round brackets in equation (6) is negligible with respect to the first. Note that, as expected, the minimum P_p limited by the CR effect is of the order of the power spent in radiation (given in equation 7). Be aware that $\langle \gamma \rangle$ and $\langle \gamma^2 \rangle$ do depend on Γ (see equations 15 and 16 below).

4.1 Application to the blazar 3C 454.3

In order to find a lower limit to the jet power of 3C 454.3, we make the following assumptions.

(i) In Bonnoli et al. (2010), we have shown that during the big flare of 2009 November–December the γ-ray, X-ray and optical fluxes of 3C 454.3 were correlated with one another, with the γ-ray flux varying more than linearly with the flux in the other two bands. We take this as a very robust indication that most of the non-thermal flux received from 3C 454.3 above the far-infrared band is produced in the same region of the jet.

(ii) The size of the emitting region R_{blob} is assumed to be associated with the minimum variability time-scale t_{var} of the source. In the γ-ray, Tavecchio et al. (2010), Foschini et al. (2010) and Ackermann et al. (2010) found significant variations in 3–6 h.

Therefore,

$$R_{\text{blob}} = ct_{\text{var}} \frac{\delta}{1+z} \sim 7 \times 10^{15} \left(\frac{t_{\text{var}}}{6 \, \text{hr}} \right) \left(\frac{\delta}{20} \right) \quad \text{cm.} \quad (13)$$

(iii) We assume an accretion disc luminosity $L_{\text{d}} \sim 6.7 \times 10^{46}$ erg s^{-1}, based on direct detection of the Lyman α line (Bonnoli et al. 2010) and on the flattening of the optical–UV SED when the source is in low state.

(iv) We assume that the BLR reprocesses 10 per cent of L_{d} and that the BLR size is given by $R_{\text{BLR}} = 10^{17} L_{\text{d},45}^{1/2}$ cm. This choice (in rough agreement with Bentz et al. 2006 and Kaspi et al. 2007) implies that the radiation energy density within the BLR is constant:

$$U_{\text{BLR}} = \frac{0.1 L_{\text{d}}}{4\pi R_{\text{BLR}}^2 c} = \frac{1}{12\pi} \quad \text{erg cm}^{-3}. \quad (14)$$

The small t_{var} suggests that dissipation takes place within the BLR, so we assume $U_{\text{ext}} = U_{\text{BLR}}$.

(v) After one light crossing time, $R_{\text{blob}}/c = t_{\text{var}}\delta/(1+z)$, the cooling energy γ_{cool} is

$$\gamma_{\text{cool}} \sim \frac{3(1+z)m_{\text{e}}c^2}{4\sigma_{\text{T}} c t_{\text{var}} \delta \left[U'_{\text{BLR}} + U_B + U'_{\text{syn}} \right]} \propto \frac{1}{\Gamma^2 \delta} \quad (15)$$

with the EC mechanism (with BLR photons as seeds) being the dominant cooling agent.

(vi) The soft slope of the γ-ray spectrum and the hard slope of the X-ray spectrum constrain the peak of the high-energy component $h\nu_{\text{c}}$ of the SED to lie close to 100 MeV. For the EC process, the peak is made by electrons at γ_{peak} scattering the Lyman α seed photons with frequency $\nu_{\text{Ly}\alpha}$. γ_{peak} is then given by

$$\nu_{\text{c}} = 2\gamma_{\text{peak}}^2 \nu_{\text{Ly}\alpha} \frac{\Gamma\delta}{1+z} \rightarrow \gamma_{\text{peak}} = \left[\frac{\nu_{\text{c}}(1+z)}{2\nu_{\text{Ly}\alpha} \, \delta \, \Gamma} \right]^{1/2}. \quad (16)$$

For all reasonable parameters appropriate for 3C 454.3, $\gamma_{\text{peak}} > \gamma_{\text{cool}}$, implying that most of the energy injected in the form of relativistic leptons is radiated away in one light crossing time.

The top panel of Fig. 1 shows the different jet powers as a function of Γ, assuming that $\theta_{\text{v}} = 1/\Gamma$. The two dashed lines are the total P_{jet} derived, assuming one proton per electron (i.e. no pairs) or instead the minimum number of protons given by equation (6). In both cases, $P_{\text{jet}} > L_{\text{d}}$ for all values of Γ. The minimum P_{jet} is set by the equipartition between P_{p} and P_B. This occurs at $\Gamma \sim 55$ for the 'no pairs' case, and $\Gamma \sim 40$ for the case of the minimum number of protons ('no decel.' case).

The bottom panel of Fig. 1 shows the maximum ratio $n_{\pm}/n_{\text{p}}$ required not to decelerate significantly for the CR effect, as a function of Γ. To understand the behaviour of this curve, consider equation (6). If we neglect the second term, we have $n_{\pm}/n_{\text{p}} \propto (\Gamma^2 \delta \langle \gamma^2 \rangle)^{-1}$. For illustration, consider a particle distribution extending only between γ_{cool} and γ_{peak} with slope $N(\gamma) \propto \gamma^{-2}$. In this case, $\langle \gamma^2 \rangle \sim \gamma_{\text{cool}} \gamma_{\text{peak}} \propto [\Gamma^2 \delta (\Gamma\delta)^{1/2}]^{-1}$ as can be seen through equations (15) and (16). Therefore, $n_{\pm}/n_{\text{p}} \propto (\Gamma\delta)^{1/2} \propto \Gamma$. This behaviour ends when γ_{cool} becomes unity, that is, for large values of Γ. In this case, $n_{\pm}/n_{\text{p}} \propto \Gamma^{-1} (\Gamma\delta)^{-1/2} \sim \Gamma^{-2}$. The maximum in $n_{\pm}/n_{\text{p}}$ therefore occurs when γ_{cool} becomes unity.

The top panel of Fig. 2 shows the powers assuming $\theta_{\text{v}} = 0°$. In this case, the minimum P_{jet} occurs for $\Gamma \sim 18$ (no pairs) or $\Gamma \sim 16$ (with $N_{\text{p}}/N_{\text{e}}$ given by equation 6). In the case of no pairs, $P_{\text{jet}} \sim L_{\text{d}}$, and is a factor of 4 smaller than L_{d} for the minimum number of protons allowed by equation (6). The ratio $n_{\pm}/n_{\text{p}}$ behaves approximately as in Fig. 1.
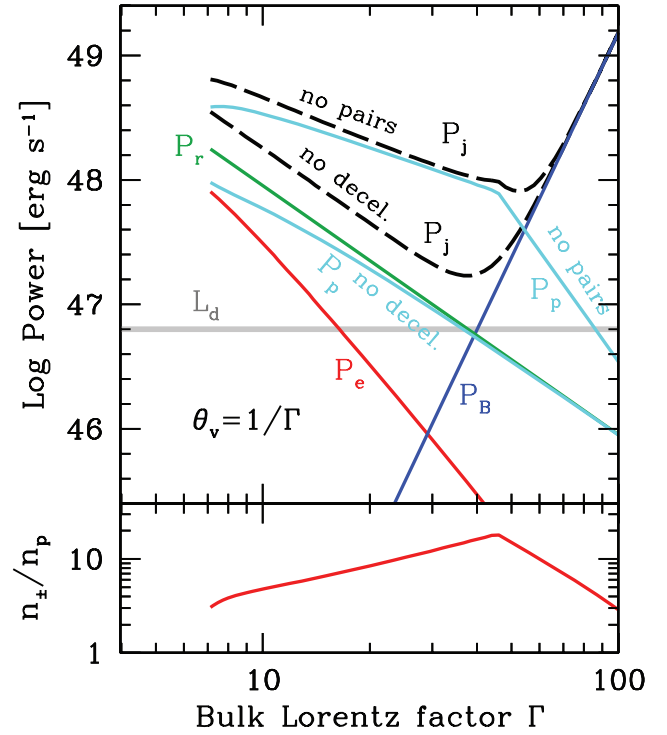

Figure 1. Different forms of jet power as a function of the bulk Lorentz factor Γ, as labelled. For this particular example, we have assumed $L_\gamma = 9 \times 10^{49}$ erg s^{-1}, $\nu_{\text{c}} = 10^{22}$ Hz, $t_{\text{var}} = 6$ h and $L_\gamma/L_{\text{syn}} = 20$, appropriate for the blazar 3C 454.3, at $z = 0.859$. We have further assumed that $\delta = \Gamma$, implying $\theta_{\text{v}} = 1/\Gamma$. The horizontal grey line indicates the accretion disc luminosity. The long dashed lines correspond to P_{jet} assuming one proton per emitting electron (i.e. no pairs) or instead assuming the minimum number of protons per electron consistent with no strong jet deceleration for the Compton rocket effect. We can see that $P_{\text{jet}} > L_{\text{d}}$ for all Γ. The bottom panel shows the maximum pair-to-proton ratio allowed by the CR effect.

5 CONCLUSIONS

It is very likely that the γ-ray-emission region in powerful FSRQs is within their BLR, with broad line photons being the seeds for the inverse Compton scattering process. We base this assumption on the observed fast variability, difficult to explain in models where dissipation takes place at much larger distances in the jet, as in the models by Marscher et al. (2008), Sikora, Moderski & Madejski (2008) and Sikora et al. (2009). This implies that the radiation is anisotropic in the comoving frame, making the jet recoil. The observer would then see a deceleration of the jet, important for pure electron–positron light jets and becoming less significant if the jet is heavier due to the presence of protons. Therefore, the requirement of no or only modest deceleration translates in a requirement on the amount of protons in the jet. This then gives a lower limit on the total jet power.

Within the framework of synchrotron and external Compton models, the only parameters that remain somewhat free (namely, not accurately given by observational data) for calculating the minimum P_{jet} are the viewing angle θ_{v} and the bulk Lorentz factor Γ. We can, however, see how the minimum P_{jet} values change as a function of Γ, assuming a given viewing angle. Doing so, we find at which Γ the jet power is minimized. We can then compare this minimum $P_{\text{jet}}^{\text{min}}$ ('minimum of the minimum values') with the accretion disc luminosity.
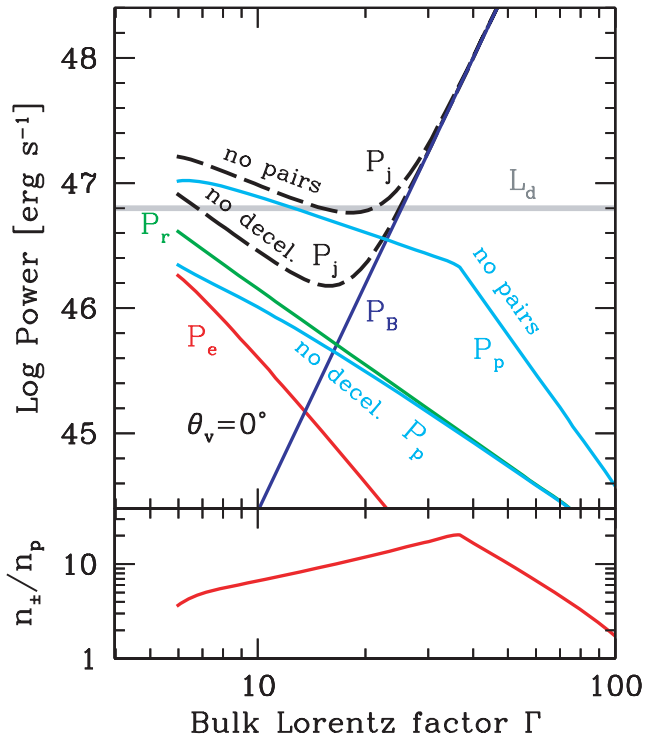
Figure 2. Same as Fig. 1, but assuming $\theta_v = 0$. Note the different range of the *y*-axis. In the bottom panel, the function $n_\pm / n_p$ is similar, but not identical to the one shown in Fig. 1.

Applying these arguments to 3C 454.3, one of the best-studied γ-ray blazars, we found that if $\theta_v = 1/\Gamma$ then $P_{\text{jet}}^{\min} > L_d$, while it becomes a factor of 4 smaller than L_d if $\theta_v = 0°$. The key question of if the jet power can be larger than the accretion disc luminosity remains therefore open, but with a narrower range of possibilities than before. We can exclude pure electron–positron jets, but we can allow for ~ 10 pairs per proton. This value is in agreement with what was found by Sikora & Madejski (2000) using a different argument. Be aware that all these estimates are based on the assumption that *all* leptons present in the source participate in the emission. If cold leptons were present, they would increase our estimate of the jet power.

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