

Estimating jet power in proton blazar models

R.J. Protheroe

*Department of Physics and Mathematical Physics, The University of
Adelaide, Adelaide, SA 5005, Australia*

A. Mücke

*Université de Montréal, Département de Physique, Montréal, H3C 3J7,
Canada*

Abstract. We discuss the various contributions to the jet luminosity in proton blazar models of active galactic nuclei and describe a method of estimating the jet luminosity from the observed spectral energy distribution (SED) and the fitted model parameters. We apply this to a synchrotron proton blazar (SPB) model for Markarian 501.

1. Introduction

The mechanical luminosity of an AGN jet of cross-sectional area A with Lorentz factor $\Gamma = 1/\sqrt{1-\beta^2}$, containing jet-frame (primed variables) matter density ρ' , energy density u' and pressure p' is given by

$$L_{\text{jet, mech}} = \Gamma^2 \beta c A [\rho' c^2 (\Gamma - 1) / \Gamma + u' + p'].$$

(see e.g. Leahy 1991). To calculate the total jet luminosity L_{jet} , measured in the rest frame of the galaxy, we adapt the formulae of Bicknell (1994) and Bicknell & Dopita (1997), given for the synchrotron self-Compton model, to apply for the case of proton blazar models. In this paper we shall apply the formula adapted for proton blazar models to a synchrotron proton blazar (SPB) model for Markarian 501 described by Mücke & Protheroe (2000).

2. Proton blazar models

In proton blazar models, the high energy part of the SED is due to interaction of protons accelerated along with electrons in the AGN jet. The interactions are pion photoproduction on either low energy photons of the low energy part of the SED produced as synchrotron radiation by electrons in the jet (e.g. Mannheim 1993), or on direct or scattered UV bump radiation from an accretion disk (e.g. Protheroe 1997), and direct synchrotron emission by protons, muons and charged pions (e.g. Mücke & Protheroe 2000). To accelerate protons to sufficiently high energies that they can produce the high energy part of the SED, a large magnetic field is required.

Proton blazars would contain relativistic plasma of electrons and protons, and a non-negligible magnetic field. For a $n'_e(\gamma_e') = n_{e0}\gamma_e'^{-2}$ power-law ($\gamma_{e1}' <$

$\gamma_e' < \gamma_{e2}'$) for the jet-frame number density of electrons, the total number density of (relativistic) electrons is $n_e' = n_{e0}/\gamma_{e1}'$, and the energy density of (relativistic) electrons is $3p_e' = u_e' = n_e' m_e c^2 \langle \gamma_e' \rangle = n_{e0} m_e c^2 \ln(\gamma_{e2}'/\gamma_{e1}')$. Similarly, for a $n_p'(\gamma_p') = n_{p0} \gamma_p'^{-2}$ power-law ($\gamma_{p1}' < \gamma_p' < \gamma_{p2}'$) for the jet-frame number density of protons, the total number density of (relativistic) protons is $n_p' = n_{p0}/\gamma_{p1}'$, and the energy density of (relativistic) protons is $3p_p' = u_p' = n_p' m_p c^2 \langle \gamma_p' \rangle = n_{p0} m_p c^2 \ln(\gamma_{p2}'/\gamma_{p1}')$, giving

$$n_e' m_e c^2 \approx \frac{3p_e'}{\gamma_{e1}' \ln(\gamma_{e2}'/\gamma_{e1}')}, \quad n_p' m_p c^2 \approx \frac{3p_p'}{\gamma_{p1}' \ln(\gamma_{p2}'/\gamma_{p1}')}$$

Assuming that the number of relativistic electrons will be greater than the number of relativistic protons, and applying charge conservation, i.e. the number of ‘cold’ (non-relativistic) protons equals the number of ‘hot’ (relativistic) electrons minus the number of hot protons, one obtains

$$\begin{aligned} L_{\text{jet, mech}} &= \\ &= \Gamma^2 \beta c A \left[\left(\frac{m_p}{m_e} \frac{3p_e'}{\gamma_{e1}' \ln(\gamma_{e2}'/\gamma_{e1}')} - \frac{3p_p'}{\gamma_{p1}' \ln(\gamma_{p2}'/\gamma_{p1}')} \right) \frac{(\Gamma - 1)}{\Gamma} + 4p_e' + 4p_p' + 4p_B' \right] \\ &= 4p_p' \Gamma^2 \beta c A \left[\chi_p \frac{(\Gamma - 1)}{\Gamma} + 1 + \frac{p_B'}{p_p'} + \frac{p_e'}{p_p'} \right] \end{aligned}$$

since for a tangled magnetic field $u_B' = 3p_B'$, and where

$$\chi_p = \frac{3}{4} \left(\frac{m_p p_e'}{m_e p_p' \gamma_{e1}' \ln(\gamma_{e2}'/\gamma_{e1}')} - \frac{1}{\gamma_{p1}' \ln(\gamma_{p2}'/\gamma_{p1}')} \right).$$

We now consider how to apply these formulae to proton blazar models. First, consider the radiation efficiency of protons which depends on their effective energy loss rates r' for synchrotron radiation (syn), photoproduction leading to electromagnetic radiation (EM) or anything (any), and adiabatic losses (adiab),

$$\zeta_p'(\gamma_p') = \frac{r'_{\text{syn,p}}(\gamma_p') + r'_{\text{p}\gamma \rightarrow \text{EM,p}}(\gamma_p')}{r'_{\text{syn,p}}(\gamma_p') + r'_{\text{p}\gamma \rightarrow \text{any,p}}(\gamma_p') + r'_{\text{adaib}}}$$

Averaging over the input *energy* spectrum gives the total radiation efficiency

$$\zeta_p = \frac{\int \zeta_p'(\gamma_p') \gamma_p' \gamma_p'^{-2} d\gamma_p'}{\int \gamma_p' \gamma_p'^{-2} d\gamma_p'}$$

For electrons, we assume the radiation efficiency to be $\zeta_e = 1$.

If we assume that the low energy part of the observed SED is due to electrons, and the high energy part is due to protons, then we may infer values of p_e' and p_p' directly from the observed bolometric flux in the two parts of the SED for an assumed Doppler parameter and emission region size. The bolometric luminosities for the two parts of the SED (in any frame since they are Lorentz

invariant) are then $L_{\text{bol}}^{\text{low}} = \zeta_e \Gamma^2 \beta c A 4 p'_e$ and $L_{\text{bol}}^{\text{high}} = \zeta_p \Gamma^2 \beta c A 4 p'_p$. These bolometric luminosities are related to the observed bolometric fluxes (corrected for relativistic beaming) from the two parts of the SED by $L_{\text{bol}}^{\text{low}} = 4\pi d_L^2 S_{\text{obs}}^{\text{low}} / D^2$ and $L_{\text{bol}}^{\text{high}} = 4\pi d_L^2 S_{\text{obs}}^{\text{high}} / D^2$ with $D = [\Gamma(1 - \beta \cos \theta)]^{-1}$ the Doppler factor and d_L the source's luminosity distance. Hence, we obtain

$$L_{\text{jet, mech}} = \frac{L_{\text{obs}}^{\text{high}}}{D^2 \zeta_p} \left[\chi_p \frac{(\Gamma - 1)}{\Gamma} + 1 + \frac{p'_B}{p'_p} + \frac{\zeta_p S_{\text{obs}}^{\text{low}}}{\zeta_e S_{\text{obs}}^{\text{high}}} \right]$$

where $p'_B = [B'^2 / (2\mu_0)] / 3$, and

$$p'_p = \frac{L_{\text{obs}}^{\text{high}}}{4D^2 \zeta_p \Gamma^2 \beta c A}, \quad \chi_p = \frac{3}{4} \left(\frac{m_p \zeta_p S_{\text{obs}}^{\text{low}}}{m_e \zeta_e S_{\text{obs}}^{\text{high}}} \frac{1}{\gamma_{e1}' \ln(\gamma_{e2}' / \gamma_{e1}')} - \frac{1}{\gamma_{p1}' \ln(\gamma_{p2}' / \gamma_{p1}')} \right).$$

3. Application to SPB model for Markarian 501

We use these formula to estimate the total jet power of Mrk 501 during its 1997 flare to be $\sim 10^{46}$ erg/s, and find the contributions to the total jet power of cold protons, magnetic field, and accelerated electrons, relative to that of accelerated protons. Fig. 1 shows the dependence of the total jet luminosity on the Doppler factor D for a fixed variability time scale $t_{\text{var}} = 12$ hours, and with B , n'_p and a target photon density appropriate to Mrk 501 during flaring. Clearly visible is the fact that in hadronic models the proton kinetic energy and the poynting flux dominate the total jet luminosity, while the electron kinetic energy is only of minor importance. At high Doppler factors the emission region becomes so large that one needs only relatively small magnetic fields and proton densities to fit the observations. In addition, adiabatic losses become small resulting in a decrease of the required kinetic proton luminosity. For example, $B \approx 5$ G and $n'_p \approx 10^{-2} \text{ cm}^{-3}$ are sufficient to fit the Mrk 501 flare for $D = 50$, while for $D = 8$ magnetic fields of over 30 G and proton densities of $n'_p \approx 10^4 \text{ cm}^{-3}$ are needed. The total jet luminosity exhibits a minimum of $\sim 10^{46}$ erg/s at $D \approx 12$.

In the framework of the jet–disk symbiosis (e.g. Falcke & Biermann 1995), the jet luminosity should not exceed the total accretion power Q_{accr} for the equilibrium state. Accretion theory relates the disk luminosity to the accretion power. Page & Thorne (1974) give $L_{\text{disk}} \approx (0.05 - 0.3) Q_{\text{accr}}$. Disk luminosities for ‘typical’ radio-loud AGN lie in the range $L_{\text{disk}} \approx 10^{44} - 10^{48}$ erg/s with BL Lac objects tending to the lower end on average. Specifically, for Mrk 501 there are no emission line measurements available, and this complicates the evaluation of its disk luminosity. However, any observed UV-emission in the flaring stage may put an upper limit on it. Historical data give $L_{\text{disk}} \approx 10^{43} - 10^{44}$ erg/s (Mufson et al 1984, Pian et al 1998), and we obtain for the accretion power, $Q_{\text{accr}} \approx (3 - 200) \times 10^{43}$ erg/s, at least a factor 5 below the value necessary to comply with the constraint of the disk–jet symbiosis. Note, however, that the estimate of Q_{accr} is based on archival non-flaring data from Mrk 501, and we could speculate that either the disk has pushed more energy into the jet during TeV-flaring, or that the flaring stage can not be considered as a steady state. Also, accretion theory might predict larger conversion efficiencies of the accretion power into disk radiation than actually might occur in BL Lac objects.

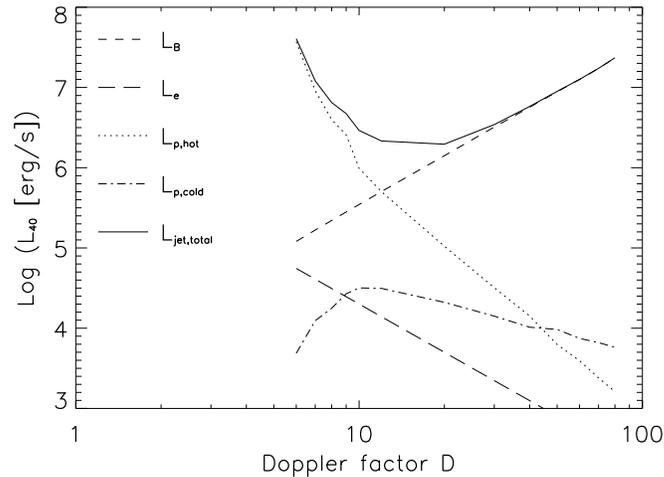


Figure 1. Dependence of total jet luminosity L_{jet} and its contributions (L_B – magnetic field, $L_{p,\text{hot}}$ and $L_{p,\text{cold}}$ – hot and cold protons, L_e – electrons) on D for model parameters which reasonably fit the Mrk 501 1997 flare SED (see Mücke & Protheroe 2000 for details). $L_{40} = L/10^{40}$ erg/s.

References

- Bicknell G.V. 1994, ‘On the relationship between BL Lacertae objects and Fanaroff-Riley I radio galaxies’, *ApJ*, 422, 542–561
- Bicknell G.V. & Dopita M.A. 1997, ‘Relativistic Jets in FR1 and FR2 Radio Galaxies and Seyfert Galaxies’, in *Relativistic Jets in AGNs*, Proc. Int. Conf., Cracow, eds. Ostrowski M. et al., 1–12.
- Falcke H. & Biermann P.L. 1995, ‘The jet-disk symbiosis. I. Radio to X-ray emission models for quasars’, *A&A*, 293, 665–682
- Leahy, J.P. 1991, ‘Interpretation of Large Scale Extragalactic Jets’, in *Beams and Jets in Astrophysics*, ed. P.A. Hughes (Cambridge: Cambridge University Press), 141–142
- Mannheim K. 1993, ‘The proton blazar’, *A&A*, 269, 67–76.
- Mücke, A., & Protheroe, R.J. 2000, ‘A Proton Synchrotron Blazar Model for Flaring in Markarian 501’, *Astropart. Phys.*, in press
- Mufson S.L. et al. 1984, ‘Coordinated multifrequency observations of the BL Lacertae objects MRK 180 and MRK 501’, *ApJ*, 285, 571–579
- Page D.N. & Thorne K.S. 1974, ‘Disk-Accretion onto a Black Hole. Time-Averaged Structure of Accretion Disk’, *ApJ*, 191, 499–506
- Pian E. et al. 1998, ‘BeppoSAX Observations of Unprecedented Synchrotron Activity in the BL Lacertae Object Markarian 501’, *ApJ*, 492, L17–L20
- Protheroe, R.J. 1997, ‘High Energy Neutrinos from Blazars’ in *Accretion Phenomena and Related Outflows*, IAU Colloq. 163. ASP Conf. Ser. Vol. 121, ed. D. T. Wickramasinghe et al., 585–588