Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRASL **444,** L16–L19 (2014) doi:10.1093/mnrasl/slu101

Possible proton synchrotron origin of X-ray and gamma-ray emission in large-scale jet of 3C 273

Esha Kundu[1★] and Nayantara Gupta[2★]

[1] *Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005, India*
[2] *Raman Research Institute, Sadashiva Nagar, Bangalore 560080, India*

Accepted 2014 June 20. Received 2014 May 19

ABSTRACT

The large-scale jet of quasar 3C 273 has been observed in radio to gamma-ray frequencies. Earlier the X-ray emission from knot A of this jet has been explained with inverse Compton scattering of the cosmic microwave background radiations by the shock accelerated relativistic electrons in the jet. More recently it has been shown that this mechanism overproduces the gamma-ray flux at GeV energy and violates the observational results from *Fermi* LAT. We have considered the synchrotron emission from a broken power-law spectrum of accelerated protons in the jet to explain the observed X-ray to gamma-ray flux from knot A. The two scenarios discussed in our work are (i) magnetic field is high, synchrotron energy loss time of the protons is shorter than their escape time from the knot region and the age of the jet and (ii) their escape time is shorter than their synchrotron energy loss time and the age of the jet. These scenarios can explain the observed photon spectrum well for moderate values of Doppler factor. The required jet luminosity is high $\sim 10^{46}$ erg s^{-1} in the first scenario and moderate $\sim 10^{45}$ erg s^{-1} in the second, which makes the second scenario more favourable.

Key words: quasars: general – gamma-rays: galaxies – X-rays: galaxies.

1 INTRODUCTION

The large-scale jet of the quasar 3C 273 has been observed in radio to gamma-ray frequencies by different ground-based and space-based detectors. The optical image taken by *HST* (Bahcall et al. 1995) showed the presence of bright knots in the kpc jet of 3C 273. The first knot, called knot A (knot nomenclature according to Jester et al. 2006), is the most luminous one in X-rays.

The emission in the radio to optical frequencies from knot A is consistent with synchrotron radiation of relativistic electrons in the jet (Sambruna et al. 2001) whereas the X-ray emission has been modelled by the inverse Compton scattering of the cosmic microwave background photons (IC/CMB) by the relativistic electrons (Sambruna et al. 2004). It has been shown that the synchrotron self-Compton mechanism cannot explain the observed X-ray flux (Sambruna et al. 2001).

The IC/CMB model requires the jet to be highly collimated up to the location of the X-ray knot pointing close to our line of sight or the Lorentz factor has to be high. The small angle subtended by the jet to our line of sight may require the length of the jet to be Mpc in some cases. The electron spectrum in the jet has to extend down to 1–10 MeV. Also sometimes this model requires huge jet kinetic power exceeding the Eddington power of the source (Dermer & Atoyan 2004; Uchiyama et al. 2006) to explain the observed X-ray fluxes. X-ray emission could also be possible from synchrotron emission from an additional shock accelerated electron population (Hardcastle 2006; Jester et al. 2006; Uchiyama et al. 2006). Although the synchrotron emission mechanism is far more efficient than IC/CMB without requiring high Lorentz factors, extreme jet lengths, high jet kinetic powers to explain the observed X-ray fluxes, it is not yet known which physical mechanism might produce the second population of electrons or additional electron energy distribution. Meyer & Georganopoulos (2014) have analysed more than four years of *Fermi* LAT gamma-ray data from knot A and ruled out the IC/CMB process as a possible mechanism of X-ray radiation as IC/CMB overproduces the GeV gamma-ray flux.

The observed energy spectrum of radio, optical and X-ray photons at 1 keV has an overall spectral index 0.75 which deviates to 0.6 for the local X-ray photons according to Marshall et al. (2001). The synchrotron power per unit frequency having a spectral index 0.75 originates from a shock accelerated electron spectrum $\frac{dN_e}{dE_e} \propto E_e^{-1.5}$, which steepens to $E_e^{-2.5}$ due to synchrotron losses. The high-energy electrons are expected to lose energy very fast due to synchrotron cooling before moving far from their production site. Due to this reason unless the electron acceleration is taking place throughout the entire knot or there are many compact acceleration sites inside the knot it is hard to explain the X-ray emission by synchrotron radiations of high-energy electrons. Aharonian (2002) proposed synchrotron emission by accelerated protons to be the origin of the

★ E-mail: esha.kundu@gmail.com (EK); nayan@rri.res.in (NG)

radio to X-ray or only the X-ray emission observed from knot A of 3C 273 to overcome the problem of fast cooling of the high-energy electrons. The age of the jet (3×10^7 yr), the escape time of the accelerated protons after diffusion and the time for their synchrotron energy loss are the crucial parameters in determining the spectral index of the proton spectrum in this model.

In this Letter, we revisit the proton synchrotron model to identify the possible common origin of the X-ray and gamma-ray emission from knot A of 3C 273.

AGN jets have been speculated earlier to be one of the potential sites of accelerating protons up to 10^{20} eV (Hillas 1984; Cesarsky 1992; Rachen & Bierman 1993; Henri et al. 1999). Rachen & Bierman (1993) showed that with size of about 1 kpc and ambient magnetic field of 0.5 mG the jet terminal shock can accelerate proton up to 10^{20} eV in the hotspot of Fanaroff–Riley type II radio galaxy. In this case, the jet can be moderately relativistic. Proton acceleration to extremely high energy can also take place at the jet shear boundary layer as demonstrated by Ostrowski (1998). Protons can be accelerated to 10^{19} eV (Murase, Inoue & Dermer 2014) by *Fermi* acceleration mechanism in the inner jets of radio-loud AGN. Ebisuzaki & Tajima (2014) has recently proposed that the plasma wakefield, formed by intense electromagnetic field, can accelerate protons/nuclei beyond 10^{21} eV in the AGN jet over an extended region. In this case, the particles are accelerated by the Lorentz invariant pondermotive force. The proton synchrotron models discussed in our work requires the maximum energy of the protons to be close to 10^{20} eV.

2 PROTON SYNCHROTRON SPECTRA

2.1 Radio to X-ray emission

The X-ray emission from knot A[1] of the large-scale jet of 3C 273 has been explained earlier (Aharonian 2002) with synchrotron emission from a relativistic proton population. In this work, the author has considered three different scenarios to explain the observed spectral energy distribution in radio to X-ray frequencies. The first model (Model I) uses a broken power-law spectrum of protons with a spectral index of 2.4 and 3.4 below and above the break energy at $E_{\rm brk} = 3 \times 10^{17}$ eV, respectively. If a proton of energy $E_{\rm p}$ is trapped in a region of homogeneous magnetic field B and size R, then the escape time-scale from that region is given by equation 2 of Aharonian (2002) as

$$t_{\rm esc} \simeq 4.2 \times 10^5 \eta^{-1} B_{\rm mG} R^2_{\rm kpc} E^{-1}_{19}\ {\rm yr}, \tag{1}$$

where η is known as gyrofactor. In the Bohm diffusion limit $\eta = 1$ and in other cases the value of η is more than one. Here, $E_{19} = E_{\rm p}\ {\rm eV}/10^{19}$, $B_{\rm mG} = \frac{B}{10^3}$ G and $R_{\rm kpc} = \frac{R\ {\rm cm}}{3.08\times10^{21}}$. Observational pieces of evidence suggest that the size of the knot should be $\leq$1 kpc. The age of the jet is nearly 3×10^7 yr. For this model, the author has assumed that the magnetic field $B = 5$ mG and the size of the emission region $R = 1$ kpc. In the Bohm limit, equation (1) gives $t_{\rm esc} = 2.1 \times 10^6$ yr for $E_{\rm p} = 10^{19}$ eV. The synchrotron cooling time is calculated according to equation 1 of Aharonian (2000) as

$$t_{\rm sync} \simeq 1.4 \times 10^7 B^{-2}_{\rm mG} E^{-1}_{19}\ {\rm yr}. \tag{2}$$

[1] Aharonian (2002) called it knot A1 according to the nomenclature used in Marshall et al. (2001). Note that knot A and knot A1 define the same region of the jet. So hereafter we call it knot A.

For maximum proton energy of $E_{\rm max} = 10^{19}$ eV, the synchrotron energy loss time $t_{\rm sync} = 5.6 \times 10^5$ yr. For protons of energy $E_{\rm p} = 3 \times 10^{17}$ eV, $t_{\rm esc}$ and $t_{\rm sync}$ are ($t_{\rm esc} = 7 \times 10^7$ yr and $t_{\rm sync} = 2 \times 10^7$ yr) comparable to the age of the jet. Above this energy, the synchrotron loss dominates over escape loss which makes the injected proton spectrum steeper by $E_{\rm p}^{-1}$. In this model, the required luminosity in cosmic ray protons is $L_{\rm j,p} = 1.2 \times 10^{47}$ erg s^{-1} and in the magnetic field it is $L_{{\rm j},B} = 1.3 \times 10^{44}$ erg s^{-1} for a jet lifetime of 3×10^7 yr. This inequality of jet luminosities in protons and the magnetic field implies equipartition of energy does not hold in this case. It is noted that the contribution of low-energy protons to the jet luminosity is huge although the protons in the low-energy regime are incapable of producing the observed photon fluxes in the radio to X-ray frequencies.

To reduce the energy budget, Aharonian (2002) has considered another proton spectrum with a low-energy cut off at $E_{\rm brk} = 10^{13}$ eV. It has also been suggested that the energy requirement can be reduced by assuming (Model II) an energy dependent escape time-scale which is

$$t_{\rm esc} = \frac{1.4 \times 10^7}{(E/10^{14}\ {\rm eV})^{0.5}}\ {\rm yr}. \tag{3}$$

In this model, the spectral index of the shock accelerated proton spectrum is 2 below the break energy ($E_{\rm brk}$). At the break energy $t_{\rm esc} = 4.4 \times 10^7$ yr, using equation (3), and $t_{\rm sync} = 1.4 \times 10^{10}$ yr. In this case, beyond the break energy the escape loss dominates over the synchrotron loss. Thus, the injected proton spectrum $E_{\rm p}^{-2}$ becomes $E_{\rm p}^{-2.5}$ above the break energy due to energy-dependent losses due to escape.

The upper cut-off energy of the protons in this model is $E_{\rm cut} = 10^{18}$ eV. At the cut-off energy the rate of escape of the protons is 10 times higher than their synchrotron cooling rate ($t_{\rm esc} = 1.4 \times 10^5$ yr, $t_{\rm sync} = 1.4 \times 10^6$ yr). The value of the ambient magnetic field is assumed to be 10 mG in this model. Accelerated protons in the energy window of $10^{13}-10^{18}$ eV are mainly responsible for the synchrotron emission in radio to X-ray regime. For the time period of 1.4×10^7 yr, the cosmic ray energy budget required for Model II is $W_{\rm j,p} = 4.9 \times 10^{60}$ erg which results in cosmic ray luminosity of $L_{\rm j,p} = 1.1 \times 10^{46}$ erg s^{-1}. The total energy in magnetic field is $W_{{\rm j},B} = 4.9 \times 10^{59}$ erg corresponding to a jet luminosity in magnetic field $L_{{\rm j},B} = 1.1 \times 10^{45}$ erg s^{-1}. Thus, in Model II the jet luminosity in magnetic field is one tenth of that in cosmic ray protons.

In comparison to Model I, the required luminosity in Model II is less but it is still large. To further reduce the energy requirement, Aharonian (2002) proposed another model (Model III) where the cosmic ray proton spectrum is a power law with a spectral index 2 and an exponential cut off at $E_{\rm cut} = 10^{18}$ eV. The magnetic field inside knot A is assumed to be $B = 3$ mG and the size of the emission region is $R = 2$ kpc. In this model, $t_{\rm sync}$ and $t_{\rm esc}$ are larger than the age of the jet for all protons of energy below $E_{\rm cut}$. At $E_{\rm cut}$ the two time-scales $t_{\rm sync} = 1.6 \times 10^7$ yr and $t_{\rm esc} = 5.1 \times 10^7$ yr (using equation 1) are comparable to the age of the jet. Due to this reason, the spectral index of the shock accelerated proton spectrum is not affected by escape or synchrotron losses up to $E_{\rm cut}$ and remains 2. In Model III, the luminosities in cosmic ray protons and in magnetic field are $L_{\rm j,p} = 10^{45}$ erg s^{-1} and $L_{{\rm j},B} = 3.7 \times 10^{44}$ erg s^{-1}, respectively, assuming a jet age of 3×10^7 yr. We note that in this model the synchrotron emission by the relativistic proton population is only capable of producing the observed X-ray flux. The low-energy radiation is the synchrotron emission from the shock accelerated electrons. Fig. 3 of Aharonian (2002) shows the synchrotron spectra produced in Model I, II and III discussed above. The different

Table 1. t_{sync} and t_{esc} values in year for three models of Aharonian (2002). *Using equation (1). **Using equation (3).

Model	R_{kpc}	B_{mG}	E_p(eV)	t_{sync}(yr)	t_{esc}(yr)
I	1	5	3×10^{17}	2×10^7	$7 \times 10^7*$
I	1	5	10^{19}	5.6×10^5	$2.1 \times 10^6*$
II	1	10	10^{13}	1.4×10^{10}	$4.4 \times 10^7**$
II	1	10	10^{18}	1.4×10^6	$1.4 \times 10^5**$
III	2	3	10^{18}	1.6×10^7	$5.04 \times 10^7*$

time-scales for the three models are tabulated in Table 1 for different proton energies.

2.2 X-ray and gamma-ray spectra

Meyer & Georganopoulos (2014) have provided the photon fluxes in the three energy windows (100–300 MeV, 300–1000 MeV and 1–3 GeV) after analysing the *Fermi* LAT data from knot A of 3C 273. For the highest two energy bins, 3–10 GeV and 10–100 GeV, only upper limits are available due to poor statistics. The observed flux and the upper limits are shown in Fig. 1 with triangle symbols. This observed flux cannot be explained by extrapolating the IC/CMB curve to gamma-ray energy. We propose two models where proton synchrotron emission by extremely relativistic protons can explain the observed X-ray and gamma-ray fluxes. In our first model (Model I), we assume a proton population, in the jet rest frame, with spectral indices of $p1 = 1.2$ and $p2 = 2.2$ before and after the break energy E_{brk} as follows:

$$\frac{dN_p}{dE_p} = \begin{cases} K\ E_p^{-p1}, & E_p < E_{brk} \\ K\ E_{brk}^{(p2-p1)}\ E_p^{-p2}, & E_p \geq E_{brk}, \end{cases} \tag{4}$$

where K is the normalization constant of the proton spectrum. We have assumed that the knot region is spherical with radius $R = 1$ kpc and the uniform magnetic field (B) within this region is 30 mG.

In the case of Bohm diffusion using equation (1), the escape time of protons is found to be greater than their synchrotron cooling time

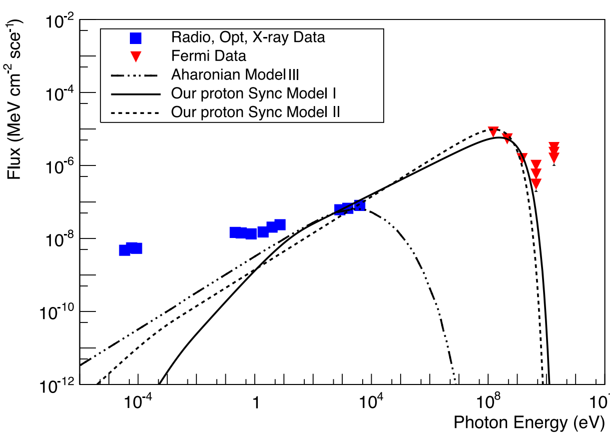

Figure 1. Spectral energy distribution of knot A of 3C 273 shown, radio to X-ray data (Jester et al. 2005; Uchiyama et al. 2006), gamma-ray data and upper limits (Meyer & Georganopoulos 2014). Solid line: synchrotron radiation from broken power-law proton spectrum corresponding to our Model I, dashed line: our Model II, triple-dot–dashed line: proton synchrotron spectrum corresponding to Model III of Aharonian (2002). Our work uses the code from Krawczynski, Hughes & Horan (2004).

for the entire range of proton energy taken into consideration for $B = 30$ mG.

For both of our models, the age of the jet is assumed to be 1.4×10^7 yr. For $E_p \geq 10^{16}$ eV, the synchrotron cooling time becomes smaller than the age of the jet (for example at $E_p = 10^{17}$ eV, $t_{esc} = 1.3 \times 10^9$ yr and $t_{sync} = 1.6 \times 10^6$ yr), which makes the proton spectrum steeper by E_p^{-1}. Thus above the break energy, the proton spectrum is proportional to $E^{-2.2}$.

The photons emitted in synchrotron emission of the accelerated protons can be visible from earth only if the beamed radiation is along the observer's line of site in observer's rest frame. If the radiated photons in the jet frame are at an angle of θ_{ob} with respect to an observer on earth, then the Doppler factor δ_D of the jet frame is calculated as

$$\delta_D = \frac{1}{\Gamma_j(1 - \beta_j \cos\theta_{ob})}, \tag{5}$$

where Γ_j and β_j are the Lorentz factor and dimensionless velocity of jet rest frame with respect to us.

In our model, the jet is moving with a Lorentz factor $\Gamma_j = 3.0$ and the viewing angle of emitted photons with respect to an observer on earth is $\theta_{ob} = 45^\circ$ which give $\delta_D = 1.0$. The synchrotron radiation emitted by protons is shown in Fig. 1 with black solid line which shows that the proton synchrotron spectrum can explain the observed X-ray as well as the gamma-ray flux.

In this model, the total energies in the magnetic field and in cosmic ray protons are $W_{j,B} = 4.9 \times 10^{60}$ erg and $W_{j,p} = 6.9 \times 10^{57}$ erg which give jet powers $L_{j,B} = 1.1 \times 10^{46}$ erg s^{-1} and $L_{j,p} = 1.6 \times 10^{43}$ erg s^{-1}, respectively. The maximum proton energy required to explain the observed gamma-ray flux is 5×10^{19} eV.

We propose a second model where the injected proton spectrum has a spectral index of 1.5 (Model II). In this model, the ambient magnetic field is much less than that in Model I. In our Model II, the magnetic field (B) is assumed to be 10 mG and the size of the knot region (R) is 0.8 kpc. Escape time-scale calculated using equation (3) shows that the loss due to escape of protons from the emission region is dominant over the loss due to synchrotron cooling. The escape time-scale become shorter than the age of the jet for proton energy $E_p \geq 10^{14}$ eV (at 10^{14} eV, $t_{esc} = 1.4 \times 10^7$ yr and $t_{sync} = 1.4 \times 10^{10}$ yr). Above this break energy, the proton spectrum has a spectral index of 2.0 as $t_{esc} \propto E_p^{-0.5}$ in equation (3). The synchrotron flux in Model II is shown in our Fig. 1 with dashed line and compared with the observed fluxes. The observed X-ray and gamma-ray fluxes are well explained by our Model II.

The values of the bulk Lorentz factor and jet angle are assumed to be the same as in our Model I which give the Doppler factor $\delta_D = 1.0$. The jet energy in magnetic and cosmic ray protons are $W_{j,B} = 2.6 \times 10^{59}$ erg and $W_{j,p} = 4.6 \times 10^{58}$ erg, respectively. Therefore, the required jet luminosity in the magnetic field is $L_{j,B} = 5.9 \times 10^{44}$ erg s^{-1} and in cosmic ray protons it is $L_{j,p} = 1 \times 10^{44}$ erg s^{-1}. Thus, the energies in the magnetic field and in the cosmic ray protons are in 6: 1 ratio. The parameters of both the models are listed in Table 2.

In both of our models, we require a hard proton acceleration spectrum, for Model I $p1 = 1.2$ and for Model II $p2 = 1.5$ before the break energy. We note that to explain the gamma-ray emission from *Fermi* detected gamma-ray blazars by proton synchrotron radiation, Böttcher et al. (2013) have considered a quite hard injection spectrum of protons. They have taken spectral index of 1.3 for the accelerated proton spectrum to justify the gamma-ray emission from PKS 0420−01 by synchrotron radiation from relativistic protons. For PKS 1510−089, an accelerated proton spectrum with a spectral

Table 2. Parameter values for our Model I and Model II.

Parameter	Symbol	Our Model I	Our Model II
Knot A size(cm)	R	3.2×10^{21}	2.5×10^{21}
Jet Lorentz factor	Γ_j	3	3
Doppler factor	δ_D	1.0	1.0
Jet angle	θ_{ob}	45°	45°
Magnetic field(mG)	B	30	10
Low-energy proton spectral index	$p1$	1.2	1.5
High-energy proton spectral index	$p2$	2.2	2.0
Minimum proton Lorentz factor	γ_{min}	10^5	10^3
Maximum proton Lorentz factor	γ_{max}	5×10^{10}	6.3×10^{10}
Break proton Lorentz factor	γ_{brk}	1.1×10^7	10^5
Jet power in proton (erg s^{-1})	$L_{j,p}$	1.6×10^{43}	1.04×10^{44}
Jet power in magnetic field (erg s^{-1})	$L_{j,B}$	1.1×10^{46}	5.9×10^{44}

index of 1.7 has been used which is consistent with the observed gamma-ray flux.

3 DISCUSSION

The proton synchrotron models discussed in our work show that the X-ray and gamma-ray fluxes from knot A of 3C 273 may have a common origin in synchrotron emission of the accelerated protons. We require a flat proton injection spectrum with spectral index of 1.2 (Model I) and 1.5 (Model II) before the break energy. In our Model I, the protons are assumed to diffuse in the Bohm limit while for our Model II an energy-dependent escape time has been used. In our Model I, the synchrotron loss dominates over the escape loss and t_{sync} is shorter than the age of the jet above the break energy at 10^{16} eV resulting in a steeper spectrum of $E_p^{-2.2}$ above this energy. In our Model II, the escape time of the cosmic ray protons is shorter than their synchrotron cooling time. Above the break energy, the escape time becomes shorter than the age of the jet as a result the spectrum steepens to E_p^{-2} from $E_p^{-1.5}$.

The maximum energies of the cosmic ray protons required in our models are 5×10^{19} and 6.3×10^{19} eV, respectively. If cosmic ray protons are accelerated in the jets of AGN (Ebisuzaki & Tajima 2014; Murase et al. 2014) up to $\sim 10^{20}$ eV their synchrotron radiation could be the origin of the X-ray and gamma-ray emissions observed from knot A of 3C 273. An important aspect of the proton synchrotron model is the acceleration site of the protons does not have to be located within the emission site of the synchrotron photons. As the accelerated protons lose energy at a much slower rate compared to the electrons, they can travel long distances from their acceleration site/sites before losing energy significantly.

In our Model I, the total luminosity required to explain the observed X-ray and gamma-ray fluxes by the synchrotron radiation of protons is 10^{46} erg s^{-1} which is about 10 per cent of the Eddington luminosity of 3C 273. For Model II, the total jet luminosity required is $\sim 10^{45}$ erg s^{-1}. In our Model I, the jet power in magnetic field is about three orders of magnitude higher than that in cosmic ray protons and this factor reduces to 6 in our Model II.

REFERENCES

Aharonian F. A., 2000, New Astron., 5, 377
Aharonian F. A., 2002, MNRAS, 332, 215
Bahcall J. N., Kirhakos S., Schneider D. P., Davis R. J., Muxlow T. W. B., Garrington S. T., Conway R. G., Unwin S. C., 1995, ApJ, 452, L91
Böttcher M., Reimer A., Sweeney K., Prakash A., 2013, ApJ, 768, 54
Cesarsky C., 1992, Nucl. Phys. B, 28, 51
Dermer C., Atoyan A., 2004, ApJ, 611, L9
Ebisuzaki T., Tajima T., 2014, Astropart. Phys., 56, 9
Hardcastle J. M., 2006, MNRAS, 366, 1465
Henri G., Pelletier G., Petrucci P. O., Renaud N., 1999, Astropart. Phys., 11, 347
Hillas A. M., 1984, ARA&A, 22, 425
Jester S., Röser H.-J., Meisenheimer K., Perley R., 2005, A&A, 431, 477
Jester S., Harris D. E., Marshall H. L., Meisenheimer K., 2006, ApJ, 648, 900
Krawczynski H., Hughes S. B., Horan D., 2004, ApJ, 601, 151
Marshall H. L. et al., 2001, ApJ, 549, L167
Meyer E. T., Georganopoulos M., 2014, ApJ, 780, L27
Murase K., Inoue Y., Dermer C. D., 2014, Phys. Rev. D, 90, 023007
Ostrowski M., 1998, A&A, 335, 134
Rachen J. P., Bierman P. L., 1993, A&A, 272, 161
Sambruna R. M., Urry C. M., Tavechhio F., Maraschi L., Scarpa R., Chartas G., Muxlow T., 2001, ApJ, 549, L161
Sambruna R. M., Gambill J. K., Maraschi L., Tavecchio F., Cerutti R., Cheung C. C., Urry C. M, Chartas G., 2004, ApJ, 608, 698
Uchiyama Y. et al., 2006, ApJ, 648, 910

This paper has been typeset from a TEX/LATEX file prepared by the author.