FUELING LOBES OF RADIO GALAXIES: STATISTICAL PARTICLE ACCELERATION AND THE EXTRAGALACTIC $\gamma$-RAY BACKGROUND

F. MASSARO$^1$ AND M. AJELLO$^2$

$^1$ Harvard-Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge, MA 02138, USA
$^2$ SLAC National Laboratory and Kavli Institute for Particle Astrophysics and Cosmology, 2575 Sand Hill Road, Menlo Park, CA 94025, USA

Received 2010 October 26; accepted 2011 January 6; published 2011 February 10

ABSTRACT

The recent discovery of the $\gamma$-ray emission from the lobes of the closest radio galaxy Centaurus A by Fermi implies the presence of high-energy electrons at least up to $\gamma \sim 10^5$–$10^6$. These high-energy electrons are required to interpret the observed $\gamma$-ray radiation in terms of inverse Compton emission off the cosmic microwave background (IC/CMB), the widely accepted scenario to describe the X-ray emission of radio galaxy lobes. In this Letter, we consider the giant radio lobes of FR II radio galaxies showing that it is possible to maintain electrons at energies $\gamma \sim 10^5$–$10^6$, assuming an acceleration scenario (driven by turbulent magnetic fields) that compensates radiative losses. In addition, we consider the contribution to the diffuse extragalactic $\gamma$-ray background due to the IC/CMB emission of FR IIs’ lobes, showing its relevance in the keV to MeV energy range.

Key words: galaxies: active – gamma rays: diffuse background – radiation mechanisms: non-thermal

1. INTRODUCTION

Radio galaxies exhibit several extended components on the kpc scale, namely, jets, hot spots, and lobes. The lobes are double structures extended over large scales, roughly symmetrical and ellipsoidal lying on both sides of the active nuclei of radio galaxies.

It was first noticed by Fanaroff & Riley (1974) that the relative positions of regions of high and low surface brightness in the extended components of extragalactic radio sources are correlated with their radio luminosity. It was found that nearly all sources with luminosity $L_{1.5\text{GHz}}$ $\leq 2 \times 10^{25} \ h_{70}^{-2} \ W \ Hz^{-1} \ str^{-1}$ were of Class I (i.e., FR I) while the brighter sources were nearly all of Class II (i.e., FR II). FR Is have a surface brightness that is larger toward their cores, while FR IIs have it larger toward their edges.

The morphology of radio galaxies turns out to reflect the method of energy transport in the radio source. FR I radio galaxies typically have bright jets in the center, while FR IIs have faint jets but bright hot spots at the ends of their lobes (e.g., Baum et al. 1995).

The radio emission arising from the lobes is widely interpreted as being due to synchrotron radiation, while the high-energy radiation has been successfully described as inverse Compton emission off the cosmic microwave background (IC/CMB). Moreover, because of the low electron densities in the large lobe volumes, the synchrotron self-Compton (SSC) mechanism produces a negligible contribution both at X-rays and at $\gamma$-rays (e.g., Hardcastle & Looney 2008), and recently, the Wilkinson Microwave Anisotropy Probe (WMAP) and Fermi observations of the Centaurus A lobes (Hardcastle et al. 2009; Abdo et al. 2010a). In addition, the Chandra, XMM-Newton, and Suzaku observations of radio galaxy lobes (Isobe et al. 2002, 2005, 2009; Kataoka et al. 2003; C05) show that their IC/CMB spectral energy distribution (SED) is rising in the X-rays, and consequently a significant fraction of their high-energy emission is expected to be radiated in the hard X-rays and at low-energy $\gamma$-rays.

Following the idea of Bergamini et al. (1967), the IC/CMB process of extended structures in radio galaxies could provide a significant contribution to the diffuse extragalactic $\gamma$-ray background (EBG) in the keV to MeV energy range.

The contribution to the EGB of kpc-scale jets in the case of FR Is, from IC scattering of starlight photons by the ultrarelativistic electrons, has been estimated by Stawarz et al. (2006). These estimates show that this emission contributes $\sim 1\%$ of the EGB at GeV energies, and it is less relevant at MeV energies, where the contribution of the IC/CMB emission peaks.

In this Letter, we adopt a statistical acceleration scenario for lobes in FR IIs, due to turbulent magnetic fields, that balances the radiative cooling and keeps electron energies up to $\gamma \sim 10^5$–$10^6$ (e.g., Pacholczyk & Scott 1976; Eilek & Shore 1989), in agreement with the recent Fermi observations. A similar mechanism has been proposed by Hardcastle et al. (2009) and O'Sullivan et al. (2009) to identify radio galaxy lobes as possible accelerators for the ultra high-energy cosmic rays (e.g., Hillas 1984).

Finally, we consider a template SED of the emission from the FR IIs’ lobes to estimate their contribution to the EGB.

We use cgs units and a flat cosmology with $H_0 = 72 \ \text{km s}^{-1} \ \text{Mpc}^{-1}$, $\Omega_M = 0.26$, and $\Omega_{\Lambda} = 0.74$ (Dunkley et al. 2009).

2. PARTICLE ENERGY LOSSES IN RADIO GALAXY LOBES

The relativistic electrons in radio galaxy lobes are subject to two main radiative loss processes: the synchrotron radiation and the IC/CMB. The first mechanism is responsible for the lobe radio emission, while the latter describes their observed
high-energy emission in the X-rays, and, recently, also in the γ-rays as in the nearby case of Centaurus A (Abdo et al. 2010a).

To clarify these radiative processes it is interesting to consider the case of a single relativistic electron of Lorentz factor γ. The total power emitted via synchrotron and IC/CMB radiation is

\[ P_{\text{rad}} = 1.05 \times 10^{-15} \gamma^2 (B^2 + B_{\text{IC}}^2) \text{ erg s}^{-1}, \]

where \( B \) is the lobe magnetic field while \( B_{\text{IC}} = 3.26 \times 10^{-6} (1 + z)^2 \) G, the value of the magnetic field that has the same energy density of the CMB at redshift \( z \) (e.g., Murgia et al. 1999). The \( B/B_{\text{CMB}} \) ratio identifies which emission process, synchrotron or IC/CMB, is more relevant for the electron radiative cooling.

In Figure 1(a), we report the \( B/B_{\text{CMB}} \) ratio and \( R_{\text{lobe}} \), the equivalent spherical radius of the lobe volume, with respect to \( z \), for the sample of FR II lobes detected in the X-rays (C05), where \( B \) has been estimated by fitting the radio-to-X-ray lobe SEDs.

We note that the ratio \( B/B_{\text{CMB}} \) is of the order of a few, in particular for sources with larger \( R_{\text{lobe}} \) at low redshift (i.e., \( z \leq 0.5 \)), for which the CMB energy density exceeds the estimate of the magnetic field energy density (Figure 1(b)). Seventy-five percent of the considered FR II lobes have \( B/B_{\text{CMB}} \) in the range 0.7–2 (Figure 1(a)), suggesting that in these sources the radiative losses for synchrotron and for IC/CMB have similar importance. This strongly suggests that the luminosity ratio of the two SED components \( L_{\text{syn}}/L_{\text{ic}} \) is \( \sim 1 \).

However, these estimates of the \( B/B_{\text{CMB}} \) ratio for radio galaxy lobes are dependent on the choice of the particle energy distribution (PED) adopted. The restricted energy ranges, where lobe emission is detected, do not allow us to estimate the PED shape and to constrain the \( L_{\text{syn}}/L_{\text{ic}} \) accurately, introducing uncertainties in the estimates of the \( B/B_{\text{CMB}} \).

Another relevant process for particle energy losses in lobes is adiabatic expansion. These losses could play a significant role during the evolution of radio lobes (e.g., Longair et al. 1973). Assuming a self-similar expansion scenario (e.g., Matthews & Scheuer 1990; Kaiser & Alexander 1997), the adiabatic losses are relevant in the initial phase of the lobe evolution, as in the case of young, compact radio galaxies.

During the final phase of the lobe expansion, when the lobe pressure is in equilibrium with that of the external medium, losses are dominated by radiative processes, e.g., via IC/CMB or synchrotron emission (if \( B/B_{\text{CMB}} \) is still \( \gg 1 \)). FR IIs, with lobe size \( \geq 30–50 \text{ kpc} \), can be considered at the end of their evolution, when the adiabatic expansion losses are negligible (e.g., Pacholczyk & Scott 1976).

3. STATISTICAL ACCELERATION SCENARIO

Acceleration by turbulent magnetic fields (due to electron scattering with magnetized plasma irregularities) via second-order Fermi mechanisms, could be considered as a possible mechanism to compensate both the synchrotron and the IC radiative losses (e.g., Eilek & Shore 1989; O’Sullivan et al. 2009; Hardcastle 2010).

Adopting this scenario, the acceleration timescale via a statistical mechanism can be written as \( \tau_{\text{acc}} \sim l/(c\beta_A^2) \), where \( l \) is the characteristic length scale of the magnetic field inhomogeneities (i.e., the mean free path of the electrons between collisions) and \( \beta_A = u_A/c \) is the ratio of the Alfvén velocity \( u_A \) and the speed of light \( c \). Consequently, according to Kardashev (1962), the energy gain by systematic statistical acceleration for a single relativistic electron in a turbulent magnetic field \( B \) is

\[ \left( \frac{dE}{dt} \right)_{\text{acc}} = \frac{u_A^2}{l c} E = \frac{m_e c u_A}{l} \gamma, \]

(2)

where \( \rho_p u_A^2/2 \sim B^2/8\pi \) is the energy density of the turbulent magnetic field, \( n \sim \rho_p/m_e \) is the plasma density, and \( m_e \) and \( m_p \) are the electron mass and the proton mass, respectively (e.g., Tsytovich 1966; Eilek & Shore 1989).

We can estimate the maximum Lorentz factor of the electrons in the lobes, balancing the acceleration energy gain (Equation (2)) with the radiative losses (Equation (1)):

\[ \gamma_{\text{max}} = 1.24 \times 10^{21} \left( \frac{1}{n l} \right) \left( \frac{B^2}{B_{\text{CMB}}^2 + B^2} \right), \]

(3)

that is only dependent on the length scale, \( l \), on the plasma density, \( n \), and on the \( B/B_{\text{CMB}} \) ratio.

Lobes are usually assumed to be close to the equipartition condition between the magnetic field and electrons, implying \( B \sim B_{\text{eq}} \sim 10^{-5} \) G (e.g., Hardcastle et al. 2002). However, the recent case of Pictor A (Migliori et al. 2007) or similar FR IIs (e.g., Brunetti et al. 2002; Isobe et al. 2005; C05) suggests that this requirement is not very tight, indicating that for a lobe with \( z \) between 0.5 and 1, as the majority of FR II lobes are detected in X-rays, \( B/B_{\text{CMB}} \) is of the order of unity (see Figure 1(a)).

The mean free path, until an electron collides with a magnetic inhomogeneity, in a turbulent plasma must be smaller than the source size and it has been estimated to be of the order of \( \sim 1 \) kpc (e.g., Lacombe 1977).

Consequently, substituting \( l \sim 10^{-2} R_{\text{lobe}} \sim 10^{21} \text{ cm} \) into Equation (3), and assuming \( B/B_{\text{CMB}} \sim 1 \), \( \gamma_{\text{max}} \) is of the order of \( 10^8 \), as required to interpret the γ-ray emission of Centaurus A lobes as IC/CMB and in agreement with the estimate of O’Sullivan et al. (2009). This is consistent with the radio/millimeter observations of radio galaxies (e.g., Hardcastle & Looney 2008) that imply the presence of a population of high-energy electrons in their lobes (i.e., \( \gamma \sim 10^{10} \)).

Our scenario is also in agreement with that proposed by Pacholczyk & Scott (1976) for the in situ re-acceleration of extended structures in radio galaxies.

We note that electrons with energies \( \gamma \sim 10^7–10^9 \) have synchrotron cooling times \( \tau_{\text{syn}} \sim 10^3–10^4 \text{ yr} \) and are not

![Figure 1](image-url)
expected to be present in radio lobes at the epochs of about few Myrs (which is the typical lobe age). This is in agreement with the non-detection of lobes at IR and optical frequencies (i.e., \( v \sim 10^{14} \) Hz), where the synchrotron emission in a magnetic field of about \( 10^{-5} \) to \( 10^{-6} \) G of electrons with \( \gamma \sim 10^{5} \)–\( 10^{10} \) should be seen.

### 4. THE RADIO LOBE SPECTRAL ENERGY DISTRIBUTION

The CMB is a blackbody exhibiting the peak frequency of the SED at \( v_{\text{CMB}} \sim 1.6 \times 10^{11} \) Hz (adopting the Wien law). Consequently, the expected peak frequency of the IC emission in the Thomson regime is \( v_{\text{IC}} \sim v_{\text{CMB}} \gamma^{2}(1 + z) \). Low-energy electrons at \( \gamma \sim 10^{3} \) radiate via IC/CMB in the X-ray band, while electrons with \( \gamma \sim 10^{8} \)–\( 10^{10} \) emit in the MeV–GeV energy range. The emission arising from highest energy electrons produces the tail of the IC/CMB SED component and as such its intensity is not expected to be extremely large, making the source undetectable by \textit{Fermi} unless the radio galaxy lies at very low redshift.

As previously anticipated this high-energy radiation could contribute to the diffuse EGB. To take this contribution into account, we built a template SED of the lobe emission from the radio to \( \gamma \)-rays. The template has been evaluated assuming a smooth log-normal PED: \( N(\gamma) = N_{0}(\gamma/\gamma_{p})^{-2 - r \log(\gamma/\gamma_{p})} \) (Massaro et al. 2004). This distribution has been suggested to be the intrinsic shape of lobes and hot spots (e.g., Katz-Stone & Rudnick 1994). The parameters considered to calculate our SED template are reported in Table 1 and it is shown in Figure 2(a).

We did not assume that the IC/CMB emission is beamed, since there is no evidence of relativistic bulk motion in lobes. We chose the value of \( R_{\text{lobe}} \) to be consistent with the typical value of the C05 sample (see Figure 1(b)) and \( \gamma_{p} \) to have the peak of the synchrotron emission in the radio band at ~10 GHz. This is justified by the case of 3C 219 at \( z = 0.1744 \) (Comastri et al. 2003), for which high-frequency radio observations are available. The predicted IR flux of the template at 3.6 \( \mu \)m is \( \gtrsim 7 \times 10^{-13} \) erg s\(^{-1}\) cm\(^{-2}\), in agreement with the non-detected emission at infrared and optical frequencies.

The template is in agreement with the observed radio-to-X-ray luminosities measured in the lobe sample of C05 (see Figure 2(b)) and with the models adopted for the X-ray-detected lobes of other FR IIs (e.g., 3C 219, Comastri et al. 2003; 3C 207, Brunetti et al. 2002; 3C 452, 3C 98, 3C 326, Isobe et al. 2002, 2005, 2009; Pictor A, Migliori et al. 2007).

We calculate the SED template with the luminosity ratio between the synchrotron and the IC/CMB component \( L_{\text{syn}}/L_{\text{IC}} \) of the order of unity (Figure 2(a)). This corresponds to the assumption that the energy losses for the radiative processes considered are equivalent—the similarity condition \( B/B_{\text{CMB}} \sim 1 \)—in agreement with the observations of FR IIs (see Section 2). In addition, the X-ray spectral index is consistent with the typical slope observed for the few lobes for which a detailed spectral analysis exists (Hardcastle et al. 2002; C05; Isobe et al. 2002, 2005, 2009).

### 5. THE CONTRIBUTION TO THE EGB

The estimate of the total diffuse flux arising from the FR II radio galaxy population can be evaluated adopting the following relation, as reported in Ajello et al. (2008, 2009):

\[
F_{\text{EGB}}(E_{0}) = \int dz \int dL \Phi(L, z) \frac{dV}{dz} \frac{dN}{dz} \frac{dE_{0}}{dz}(E_{0}(1 + z)),
\]

where \( F_{\text{EGB}}(E_{0}) \) is the diffuse flux in units of photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) MeV\(^{-1}\), \( \Phi(L, z) \) is the luminosity function (LF), \( \frac{dN}{dE_{0}} \) is derived from our SED template of the lobes in the observer’s frame at energy \( E_{0} \), and \( dV/dz \) is the comoving volume element per unit redshift and unit solid angle (Hogg 1999).

The knowledge of the source LF is crucial to correctly estimate this contribution. Indeed, it gives the space density of objects with luminosity \( L \) at redshift \( z \). We adopt the FR II radio galaxy LF at 15 GHz (Cara & Lister 2008).

The SED template used in Equation (4) is re-normalized such that at a given redshift \( z \) the luminosity in the native radio band of the LF is \( L \). Moreover, the IC component is multiplied by an additional factor \( (1 + z)^{\delta}(1 + 0.2)^{\delta} \) to account for the fact that the energy density of the CMB scales like \( \propto (1 + z)^{4} \).

The luminosity of the LF of Cara & Lister (2008) refers to the luminosity of the FR II core, while our SED template applies to the lobe emission. To convert the core luminosity into a proxy for the lobe luminosity at 15 GHz we have used the available observations of FR II (C05). We have found that rescaling the core luminosity by a factor \( K \approx 0.03 \) (and re-normalizing the SED template as described above) produces SEDs that reproduce well the available data on FR IIs for the range of source luminosities and redshifts reported in C05. We randomly extracted sources from our model and selected only those with flux at 1 keV \( \gtrsim 10^{-15} \) erg cm\(^{-2}\) s\(^{-1}\) and \( z \lesssim 1 \).
As shown in Figure 2, our LF model is able to reproduce successfully the range of radio and X-ray luminosities of the C05 sample (see Figure 2(b)). Moreover, we performed an additional test integrating the LF coupled to our SED model over luminosity and redshift and we counted how many objects would be detectable in an all-sky survey above a flux of $10^{-15}$ erg cm$^{-2}$ s$^{-1}$ in the X-ray band. The number of detectable sources is $\sim 100$ and they display a typical (average) X-ray luminosity of $5 \times 10^{32}$ erg cm$^{-2}$ s$^{-1}$. These numbers appear to be consistent with the Chandra and XMM-Newton observations (e.g., C05). As an example, adopting a value for $K$ of $10^{-1}$ or $10^{-3}$ would produce $\sim 4000$ or $\sim 1$ observable sources in the entire sky. Both these scenarios seem very unlikely given the observations described above. We estimated the uncertainties on $K$ adopting the following approach. To set a lower limit on $K$, we required that the number of all-sky detectable lobes (estimated through Equation (4)) at 1 keV, with flux $\geq 10^{-15}$ erg cm$^{-2}$ s$^{-1}$, matches (within 1σ) the number of sources in the C05 sample. This condition is satisfied for $K \approx 0.016$. Then, to set the upper limit, we request that the density of sources observable at X-rays (same criteria as above) matches the FR II density at 178 MHz in the complete sample of Mullin et al. (2008). This condition is satisfied for $K \approx 0.06$.

Figure 3 shows the contribution to the diffuse EGB emission arising from the extended structures of FR II lobes and its uncertainty. It is apparent that lobes give a significant, $\sim 10\%$, contribution to the EGB in the MeV energy range.

6. SUMMARY AND CONCLUSIONS

In this Letter, we adopted a statistical acceleration scenario based on the turbulent magnetic fields to show that balancing the particle energy gain with the radiative losses, the expected Lorentz factor is of the order of $\gamma \sim 10^6$--$10^8$ for electrons in the FR II lobes, in agreement with the radio/millimeter observations of lobes in radio galaxies (e.g., Hardcastle & Looney 2008). This has been estimated assuming that the acceleration length scale is comparable to the mean free path in the lobe not far from the equipartition condition, supported by the recent X-ray analyses of C05.

The above scenario is able to justify the presence of high-energy electrons responsible for the $\gamma$-ray emission arising from the radio galaxy lobes, via IC/CMB, as the Fermi observations of the nearby Centaurus A (Abdo et al. 2010a).

Considering the IC/CMB scattering as the main radiative process for the emission in the MeV energy range, we estimated the contribution of the FR IIs to the diffuse EGB. We found that the peak of this diffuse emission lies at $\sim 1$ MeV and the radiation arising from lobes could contribute $\sim 10\%$ of the EGB close to this energy.

So far, the lobes in radio galaxies were only observable at radio frequencies and at high energies in the X-rays. This implies that the shape of the emitting PED is uncertain. Consequently, the estimates of the lobe magnetic field and the possibility of identifying which is the most relevant radiative process, synchrotron or IC emission, are not well constrained. However, current models adopted to describe the SED of lobes in FR IIs assume the presence of high-energy electrons up to $\gamma \sim 10^5$--$10^8$ (e.g., C05).

To test this hypothesis, very deep infrared and/or hard X-ray observations, with sufficient spatial resolution are necessary. If Fermi will detect $\gamma$-ray emission arising from nearby FR II radio galaxies, these observations will be crucial to confirm the presence of high-energy electrons in radio lobes and to constrain their SED.

We thank the anonymous referee for the constructive suggestions that have improved and strengthened the manuscript. We are grateful to M. Murgia, D. Harris, and A. Cavaliere for fruitful suggestions, and to J. Finke, L. Stawarz, and T. Cheung for their comments. F.M. acknowledges the Foundation BLANCEFLOR Boncompagni-Ludovisi, n’ée Bildt for the grant awarded him in 2010. The work at SAO is supported by the NASA grant NNX10AD50G. M.A. acknowledges support by NASA grant NNH09ZDA001N.

REFERENCES

Abdo, A. A., et al. 2010a, Science, 328, 725
Abdo, A. A., et al. 2010b, ApJ, 720, 435
Ajello, M., et al. 2008, ApJ, 689, 666
Ajello, M., et al. 2009, ApJ, 699, 603
Baum, S. A., Zirbel, E. L., & O’Dea, C. P. 1995, ApJ, 451, 88
Bergamini, R., Londrillo, P., & Setti, G. 1967, Nuovo Cimento B, 52, 495
Blundell, K. M., & Rawlings, S. 2000, ApJ, 119, 1111
Brunetti, G., Bondi, M., Comastri, A., & Setti, G. 2002, A&A, 381, 795
Cara, M., & Lister, M. L. 2008, ApJ, 674, 111
Comastri, A., Brunetti, G., Gallaccia, D., Bondi, M., Pedani, M., & Setti, G. 2003, MNRAS, 340, L52
Croston, J. H., Hardcastle, M. J., Harris, D. E., Belsole, E., Birkinshaw, M., & Worrall, D. M. 2005, ApJ, 626, 733
Dunkley, J., et al. 2009, ApJ, 701, 1804
Eilek, J. A., & Shore, S. N. 1989, ApJ, 342, 187
Fanaroff, B. L., & Riley, J. M. 1974, MNRAS, 167, 31
Fukada, et al. 1975, Nature, 254, 398
Hardcastle, M. J. 2010, MNRAS, 405, 2810
Hardcastle, M. J., Birkinshaw, M., Cameron, R. A., Harris, D. E., Looney, L. W., & Worrall, D. M. 2002, ApJ, 581, 948
Hardcastle, M. J., Cheung, C. C., Feain, I. J., & Stawarz, L. 2009, MNRAS, 393, 1041
Hardcastle, M. J., & Looney, L. W. 2008, MNRAS, 388, 176
Hill, S. A. M. 1984, ARA&A, 22, 425
Hogg, D. W. 1999, arXiv:astroph/9905116v4
Isose, N., Makishima, K., Tashiro, M., & Hong, S. 2005, ApJ, 632, 781
Isobe, N., Tashiro, M. S., Gandhi, P., Hayato, A., Nagai, H., Hada, K., Seta, H., & Matsuta, K. 2009, ApJ, 706, 454
Isobe, N., Tashiro, M., Makishima, K., Iyomoto, N., Suzuki, M., Murakami, M. M., Mori, M., & Abe, K. 2002, ApJ, 580, L111
Kaiser, C. R., & Alexander, P. 1997, MNRAS, 286, 215
Kardashev, N. S. 1962, SvA, 6, 317
Kataoka, J., Leahy, J. P., Edwards, P. G., Kino, M., Takahara, F., Serino, Y., Kawai, N., & Martel, A. R. 2003, A&A, 410, 833
Katz-Stone, D. M., & Rudnick, L. 1994, ApJ, 426, 116
Lacombe, C. 1977, A&A, 54, 1
Longair, M. S., Ryle, M., & Scheuer, P. A. G. 1973, MNRAS, 164, 243
Massaro, E., Perri, M., Giommi, P., Nesci, R., & Verrecchia, F. 2004, A&A, 422, 103
Matthews, A. P., & Scheuer, P. A. G. 1990, MNRAS, 242, 616
Migliori, G., Grandi, P., Palumbo, G. C., Brunetti, G., & Stanghellini, C. 2007, ApJ, 668, 203
Mullin, L. M., Riley, J. M., & Hardcastle, M. J. 2008, MNRAS, 390, 595
Murgia, M., Fanti, C., Fanti, R., Gregorini, L., Klein, U., Mack, K.-H., & Vigotti, M. 1999, A&A, 345, 769
O’Sullivan, S., Reville, B., & Taylor, A. M. 2009, MNRAS, 400, 248
Pacholczyk, A. G., & Scott, J. S. 1976, ApJ, 203, 313
Stawarz, L., Kneiske, T. M., & Kataoka, J. 2006, ApJ, 637, 693
Tsytovich, V. N. 1966, Sov. Phys. Usp., 9, 370
van der Laan, H., & Perola, G. C. 1969, A&A, 3, 468
Watanabe, K. 1997, in AIP Conf. Ser. 410, Proc. Fourth Compton Symposium, ed. C. D. Dermer, M. S. Strickman, & J. D. Kurfess (Melville, NY: AIP), 1223
Weidenspointner, G., et al. 2000, in AIP Conf. Ser. 510, The Fifth Compton Symposium, ed. M. L. McConnell & J. M. Ryan (Melville, NY: AIP), 467