ORIGIN OF THE X-RAYS AND POSSIBLE GeV–TeV EMISSION FROM THE WESTERN HOT SPOT OF PICTOR A

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ABSTRACT

PICTOR A is a nearby Fanaroff–Riley class II (FR II) radio galaxy with a bright hot spot, the western hot spot. Observation of high polarization in the optical emission of the hot spot indicates that the optical emission could be synchrotron radiation of relativistic electrons in the hot spot. These electrons may be able to produce high-energy γ-ray photons through inverse Compton scattering. We use single-zone and multizone synchrotron + synchrotron self-Compton models to fit the observed spectral energy distribution (SED) from the radio to the X-ray band of the hot spot. Our results show that in the case of a much weaker magnetic field strength than the equipartition magnetic field, both the single-zone and multizone models can fit the SED, but the multizone model significantly improves the fit. The two models predict the hot spot as a GeV–TeV source, which might be marginally detectable with Fermi/LAT and H.E.S.S. The inverse Compton scattering of cosmic microwave background is also considered, but its contribution to GeV–TeV emission is negligible. Note that under the equipartition condition, the SED can also be fitted with the multizone model, but the predicted flux at $>10^{22}$ Hz is too weak to be detectable. The detection of TeV γ-rays from this FR II radio galaxy, if confirmed, would establish a new subclass of extragalactic sources in this energy regime since most of the active galactic nuclei detected to date at TeV energies are high-energy-peaked BL Lac objects.

Key words: galaxies: individual (PICTOR A) – gamma rays: theory – radiation mechanisms: non-thermal – X-rays: galaxies

1. INTRODUCTION

Blazars, which include both BL Lac objects and flat spectrum radio quasars (FSRQs), are typically characterized by a relativistic jet with a small angle between the jet axis and the line of sight. Their radiations are dominated by the jet. In the unified schemes (Urry & Padovani 1995), FR I radio galaxies are the parent population of BL Lac objects, and FR II radio galaxies are of FSRQs. Up to now, more than 20 blazars have been identified as TeV sources (De Angelis et al. 2008; Aharonian et al. 2008a). Most of them are X-ray bright, high-energy-peaked BL Lac (HBL) objects, with the exceptions of one low-energy-peaked BL Lac object (LBL/BL Lacertae; Albert et al. 2007), one FSRQ (3C 279; Albert et al. 2008), two intermediate-energy-peaked BL Lac Objects (IBL/W Comae, Acciari et al. 2008; IBL/3C 66A, Acciari et al. 2009), and one blazar with uncertain classification (S5 0716+71; Teshima 2008). Interestingly, Bai & Lee (2001) predicted that M87 and Centaurus A, two FR I radio galaxies, are TeV emission sources, and they were confirmed with the observations of H.E.S.S. (Aharonian et al. 2003, 2009).

Hot spots are found mostly at the end of the lobes in FR II radio galaxies. They are thought to be the location of the jet termination and are characterized by both high surface brightness and a prominent location near the outmost boundaries of radio lobes (Fanaroff & Riley 1974; Blandford & Rees 1974; Begelman et al. 1984; Bicknell 1985; Meisenheimer et al. 1989). Hot spots are believed to be the accelerated sites of relativistic electrons. Furthermore, the high-polarization observation of some optical hot spots indicates that the optical emission is from synchrotron radiation of relativistic electrons in the hot spots (Roeseer & Meisenheimer 1987; Lähteenmäki & Valtaoja 1999). Assuming a magnetic field strength $B \sim 10^{-5}$ G, one can estimate the energy of relativistic electrons $\gamma \sim 10^6$, which contribute optical emission by synchrotron process. If the observed X-rays also come from the synchrotron process, the energy of relativistic electrons is even higher. These electrons may interact with the synchrotron photons to produce very high energy (VHE) $\gamma$-ray photons by inverse Compton (IC) scattering. This motivates us to investigate the X-ray emission from the hot spots and to examine whether their VHE emission can be detectable with H.E.S.S. and Fermi.

The origin of X-ray emission is highly debated. The observed spectral energy distributions (SEDs) from the radio to X-ray band of some hot spots are explained as a single synchrotron radiation (Harris et al. 1998; Worrall et al. 2001; Hardcastle et al. 2004). However, an IC component is required to model the X-ray emission for most of the hot spots (e.g., Zhang et al. 2009). Although the synchrotron self-Compton (SSC) model can be used to explain the X-ray emission of some hot spots, the equipartition condition would be enormously violated (Hardcastle et al. 2002, 2004; Kataoka et al. 2003; Kino & Takahara 2004; Tavecchio et al. 2005). It was also proposed that X-ray emission may be contributed by an electron population different from that for the radio-optical emission (Harris et al. 2004), and that the relativistic beaming effect in the hot spots may also be taken into account (Georganopoulos & Kazanas 2003; Tavecchio et al. 2005).

PICTOR A is the prototype of an FR II radio galaxy at redshift $z = 0.035$ with a remarkable primary hot spot, the western hot spot (WH). It was first discovered and named by Stanley & Slee (1950). Its basic double structure was reported by Malby & Moffet (1962), and some hot spots located at the lobes were resolved by Schwarz et al. (1974). The WHS is located at 4.2 arcmin from the nucleus. It is much brighter
than the eastern one, and is a remarkable object with its high radio brightness and observed optical polarization (Roese & Meisenheimer 1987; Thomson et al. 1995) among the brightest radio hot spots in radio galaxies and quasars (Wilson et al. 2001). Perley et al. (1997) resolved the WHS in much higher resolution with their observation with the Very Large Array (VLA). The observations in the infrared band were reported by Meisenheimer et al. (1997). The X-ray observations of the WHS were first made with the Einstein telescope (Roese & Meisenheimer 1987), and then significantly improved by the Chandra X-ray Observatory, which derived an X-ray spectral index $\alpha = 1.07 \pm 0.11$ and luminosity $1.7 \times 10^{42}$ erg s$^{-1}$ in the $2$–$10$ keV band in 2000 January (Wilson et al. 2001). Aharonian et al. (2008b) observed Pictor A with the H.E.S.S. telescope, but some bright subcomponents embedded in a diffuse emission region with the Very Long Baseline Array (VLBA), and suggested that X-ray emission of the WHS may come from the synchrotron process of some compact subcomponents. In this paper, we focus on the physical origin of the X-rays and possible high-energy $\gamma$-rays from the hot spot. The synchrotron + SSC model for the two cases where the radiations from the radio to X-ray band are from the same region (single-zone model) and the X-rays are from a region different from that of the radio/optical emission (multizone model) are used to fit the observed SED. Our model is described in Section 2, and the results are reported in Section 3. Conclusions and a discussion are present in Section 4. Throughout, a concordance cosmology with parameters $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.30$, and $\Omega_\Lambda = 0.70$ is adopted.

2. MODEL

The observed SEDs of blazars are characterized with a double-peak structure, generally being responsible for the synchrotron emission of the relativistic electrons and the inverse Compton scattering of the synchrotron photons by the same electron population (SSC; Maraschi et al. 1992; Bloom & Marscher 1996). Although the double-peak structure of the SED for the WHS is not well established, some signatures were observed. The observation of polarization indicates that the radio and optical fluxes of the WHS should be produced by synchrotron radiation (Roese & Meisenheimer 1987; Thomson et al. 1995; Perley et al. 1997), and the sed from the radio to the X-ray band shows that X-rays are not a simple extension of radio and optical emission. We fit the broadband SED of the WHS with single- and multizone synchrotron + SSC models.

We assume that the emitting region is a homogeneous sphere with radius $R$, and the electron distribution as a function of energy ($\gamma$) is assumed to be a broken power law,

$$N(\gamma) = \begin{cases} N_0 \gamma^{-\alpha_1} & \gamma \leq \gamma_b, \\ N_0 \gamma_b^{-\alpha_1} \gamma^{-\alpha_2} & \gamma > \gamma_b, \end{cases}$$

(1)

where $\alpha_1 = 2\alpha_1 + 1$ and $\alpha_2 = 2\alpha_2 + 1$ are the indices below and above the break energy $\gamma_b m_ec^2$, respectively, and $\alpha_1, \alpha_2$ are the observed spectral indices. $\gamma_b$ is determined by the peak frequency of the synchrotron radiation

$$\nu_b = \frac{4}{3} \frac{\nu_0 \gamma_b^2 \delta}{1 + \epsilon}. \quad (2)$$

where $\nu_b = 2.8 \times 10^9$ Hz is the Larmor frequency of electrons in magnetic field $B$ and $\delta$ is the Doppler factor. Although the detection of one-sidedness in X-rays may indicate that the relativistic beaming effect should play a role (Tavecchio et al. 2005) and a mean outward velocity of $0.11 \pm 0.013c$ was also obtained for some hot spots (Arshakian & Longair 2000), the relativistic beaming effect is still quite uncertain. Thus, we do not consider this effect for the WHS in our model and take $\delta = 1$.

The total luminosity of the synchrotron emission in the comoving frame is calculated by

$$L_{\text{syn}}' = \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} N(\gamma) \tilde{P}(\gamma) V d\gamma.$$   

(3)

where $V = 4\pi R^3/3$ is the volume of the radiation region and $P(\gamma)$ is the single electron synchrotron emission power averaged over an isotropic distribution of pitch angles. It is given by

$$\tilde{P}(\gamma) = \frac{4}{3} \sigma_T c \beta^2 \gamma^2 U_B.$$   

(4)

Here $\beta = v/c$ can approximately be taken for 1, $\sigma_T = 8\pi e^4/(3m_e^2c^4)$ is the Thomson cross section, and $U_B = B^2/8\pi$ is the magnetic energy density. According to the equations mentioned above, we can obtain the electron density parameter $N_0$ by

$$N_0 = \frac{2L_{\text{syn}}' \gamma_b^{(p_1-3)}}{4\sigma_T c \beta^2 U_B f(\alpha_1, \alpha_2) V \delta^4},$$

(5)

where $L_{\text{syn}} = L_{\text{syn}}' \delta^4$ is the observed total luminosity of the synchrotron emission, and $f(\alpha_1, \alpha_2)$ is given by

$$f(\alpha_1, \alpha_2) = \frac{1}{1 - \alpha_1} + \frac{1}{\alpha_2 - 1}. \quad (6)$$

The observed total luminosity of the synchrotron emission is derived from

$$L_{\text{syn}} = f(\alpha_1, \alpha_2) \nu_0 L_\nu(\nu_0),$$

(7)

where $L_\nu(\nu_0)$ is the peak luminosity of the synchrotron radiation at the peak frequency $\nu_0$.

The equipartition magnetic field is calculated with the formula given in Brunetti et al. (1997). With these approximations, the synchrotron + SSC model can be completely specified by seven parameters (Tavecchio et al. 1998): the magnetic field intensity $B$, the emission region radius $R$, the Doppler factor $\delta$, the slopes $p_1$ and $p_2$, the Lorentz factor of the electrons at the break $\gamma_b$, and the electron density parameter $N_0$. In our calculations, the synchrotron self-absorption to the low-frequency part of the spectrum is also taken into account. In the GeV–TeV regime, the Klein–Nishina effect could be significant. We consider this effect using the following approximation (Zdziarski 1986),

$$\sigma = \begin{cases} \sigma_T & \gamma \nu \lesssim \frac{3}{4}, \\ 0 & \gamma \nu > \frac{3}{4}, \end{cases}$$

(8)

where $x = h\nu/m_ec^2$. This effect makes the IC spectrum show a high-energy cutoff.

The observed flux derived from the model can be calculated using the same numerical method given by Chiaberge & Ghisellini (1999). The frequency of the synchrotron radiation
can be calculated by Equation (2). The synchrotron emissivity \( \epsilon_s(v) \) is given by

\[
\epsilon_s(v) = \frac{1}{4\pi} \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} d\gamma N(\gamma) P_s(\gamma, \nu),
\]

(9)

where \( P_s(\gamma, \nu) \) (see, e.g., Crusius & Schlickeiser 1986; Ghisellini et al. 1988) is the single electron synchrotron emissivity averaged over an isotropic distribution of pitch angles. According to the transfer equation, the synchrotron radiation field \( I_s(\nu) \) is derived by

\[
I_s(\nu) = \frac{\epsilon_s(\nu)}{k(\nu)} [1 - e^{-k(\nu)R}],
\]

(10)

where \( k(\nu) \) is the absorption coefficient (e.g., Ghisellini & Svensson 1991).

In the SSC scenario, the IC emissivity is calculated by

\[
\epsilon_{\gamma}(v_c) = \frac{\sigma_T}{4} \int_{\nu_{\text{min}}}^{\nu_{\text{max}}} \frac{d\nu}{\nu} \int_{\gamma_l}^{\gamma_r} d\gamma \frac{d\gamma}{\gamma^2 \beta^2} N(\gamma) f(v_i, v_c) \frac{\nu_c}{\nu} I_s(v_i),
\]

(11)

where \( v_i \) is the frequency of the incident photons emitted by the synchrotron radiation between \( \nu_{\text{min}} \) and \( \nu_{\text{max}} \), \( \gamma_l \) and \( \gamma_r \) are the lower and upper limits of the scattering electrons, and \( f(v_i, v_c) \) is the spectrum produced by scattering monochromatic photons of frequency \( v_i \) with a single electron (e.g., Rybicki & Lightman 1979, p. 204). The medium is transparent for the IC radiation field, so we simply derived \( I_{\gamma,c}(\nu_c) = \epsilon_{\gamma}(v_c)R \). Assuming that \( I_{\gamma,c} \) is an isotropic radiation field, then the observed flux density is given by

\[
F(v_{\text{obs}}) = \frac{4\pi^2 R^2 I_{\gamma,c}(\nu_c) \delta^3 (1+z)}{4 \pi D^2}.
\]

3. RESULTS

The observed SED of the WHS is shown in Figures 1 and 2. The data are taken from Meisenheimer et al. (1997), Wilson et al. (2001), and Tingay et al. (2008). The upper limit made with H.E.S.S., \( 2.45 \times 10^{-12} \) photons cm\(^{-2}\) s\(^{-1}\) above 320 GeV from Aharonian et al. (2008b), is also presented in the figures.

3.1. Single-Zone Synchrotron + SSC Model

The Hubble Space Telescope resolved the WHS with a diameter of 1.4 arcsec and the brightest region is \( \sim 0.3 \) arcsec (FWHM; Thomson et al. 1995). Therefore, the radiation region radius of the WHS is taken as \( R = 209 \) pc (0.3 arcsec), which is slightly smaller than that given in Wilson et al. (2001), \( R = 250 \) pc. As shown in Figure 1, the radio–optical–ultraviolet SED appears as a perfect synchrotron peak, but the X-ray emission neither is the simple extension of the synchrotron radiation nor the IC component. We consider the X-ray emission to be contributed by both the synchrotron radiation and the SSC component. In order to match the observed X-ray spectrum, the fit with this model requires a magnetic field that is smaller than the equipartition magnetic field strength. Our good fit is shown in Figure 1 and the fitting parameters are \( v_s = 4.32 \times 10^{13} \) Hz, \( \alpha_1 = 0.69, \alpha_2 = 1.45, \) and \( B = 4.4 \times 10^{-5} \) G. The model predicts a VHE emission in the GeV–TeV band, which is even over the observed upper limit given by Aharonian et al. (2008b).

However, we should note that the fit cannot well describe the ultraviolet data.

3.2. Multizone Synchrotron + SSC Model

Based on the observation by Tingay et al. (2008) with VLBA, the WHS is resolved into some bright subcomponents embedded in a diffuse emission region. We thus consider a multizone synchrotron + SSC model.

According to the observations in the radio (Perley et al. 1997; Tingay et al. 2008), optical (Thomson et al. 1995), and X-ray (Wilson et al. 2001) bands, the radiation region is thought to contain a diffuse region of \( R = 975 \) pc (1.4 arcsec) and five compact subcomponents. We assume that the compact subcomponents have the same luminosity and size \( R = 60 \) pc (average value of their sizes resolved by VLBA). We first fit the SED with a multizone model under the equipartition condition. We take the same magnetic field strength as the average value
of the equipartition magnetic field $B_{eq} = 4.0 \times 10^{-4}$ G for both the diffuse region and the subcomponents. Our fit derives $v_{s} = 7.32 \times 10^{13}$ Hz, $\alpha_{1} = 0.71$, $\alpha_{2} = 1.72$ for the diffuse region and $v_{s} = 2.42 \times 10^{17}$ Hz, $\alpha_{1} = 0.75$, $\alpha_{2} = 1.3$ for the subcomponents. The result is shown in Figure 2. The observed SED is well fit by this model. In this scenario, the emission in the radio–optical–ultraviolet band is produced by the relativistic electrons through the synchrotron process in the diffuse region, and the X-ray emission mainly comes from the synchrotron radiation of the subcomponents. The IC component in the GeV–TeV band predicted by this model is very weak, which is much lower than the sensitivities of H.E.S.S. and Fermi/LAT.

The assumption of the energy equipartition condition has seldom been possible to be tested, and there is no strong a priori reason why it should be true (Hardcastle et al. 1998). Migliori et al. (2007) suggested that the X-ray emission of the lobes in Pictor A is due to cosmic microwave background (IC/CMB) and derived $B_{eq}/B_{IC} \sim 3$. Fan et al. (2008) argued that the ratio should be higher in hot spots than in lobes. They suggested that the relativistic electrons not only experience radiative loss but also are subjected to the adiabatic expansion loss from hot spots to radio lobes same as the magnetic field. Therefore, we take a small value of $B = 1.5 \times 10^{-5}$ G, under which the predicted flux should not exceed the upper limit derived with H.E.S.S., and try to fit the SED with the multizone model by letting the other parameters not change. The result is also shown in Figure 2. In this case, the model predicts a VHE emission component in GeV–TeV band (dashed line in Figure 2), similar to the single-zone model.

3.3. Comparison of the SEDs Between the WHS and the Nucleus

Since the space resolutions of Fermi and H.E.S.S. are inadequate to resolve the WHS region, one prominent issue regarding the GeV–TeV emission is that these high-energy photons are from the nucleus of the galaxy or from the WHS. Therefore, we fit the SED of the nucleus with the single-zone synchrotron + IC (SSC + EC) model and then compare the result with the WHS. In this scenario, we also consider the contribution of IC scattering of photon field of broad-line region (EC/BLR) though it is very weak. The total luminosity of BLR is estimated by the luminosities of the broad emission lines Hα and Hβ (Sulentic et al. 1995) according to Equation (1) given in Celotti et al. (1997). The BLR size is calculated with formula (23) given in Liu & Bai (2006). The radiation of BLR is assumed to be a blackbody spectrum.

The observed SED of the nucleus is taken from Perley et al. (1997) and Singh et al. (1990). The observations of Very Long Baseline Interferometry indicate that the parsec-scale jet components of Pictor A are likely subluminal motion (Tingay et al. 2000), so the beaming effect is considered for fitting the SED of the nucleus. Tingay et al. (2000) suggested that the jet angle $\theta$ of Pictor A to our line of sight is less than 51° within 10 $\mu$m as of the core. We take the apparent velocity $\beta_{app} = 1.1$ (the average value of the three components in Tingay et al. 2000) and $\theta = 40°$, and obtain the beaming effect factor $\delta = 1.6$. The emission-region radius is taken as $R = 10^{16}$ cm. The model fit derives $v_{s} = 4.0 \times 10^{13}$ Hz, $\alpha_{1} = 0.18$, $\alpha_{2} = 2.2$, and $B = 7$ G. The fitting result is shown in Figure 3 with comparison to that of the WHS. The synchrotron self-absorption is significant for the nucleus and the radio emission should come from the more extended region. As shown in Figure 3, the high-energy emission above 1 GeV is dominated by the WHS, indicating that the WHS should be a GeV–TeV source, if the detection is confirmed.

4. CONCLUSIONS AND DISCUSSION

We have fit the observed SED of the WHS with the single- and multizone synchrotron + SSC models. Our results show that the X-ray emission of the WHS may be the contribution of both the synchrotron and the SSC radiations in the single-zone model, but it may be only the synchrotron radiation of relativistic electrons in the compact subcomponents of the WHS in the multizone model. Comparing the fits of the two models, the multizone model greatly improves the fit, and the single-zone model needs a magnetic field strength much smaller than the equipartition field strength in order to fit the observed X-ray spectrum. The single-zone model also cannot describe the ultraviolet data well. The multizone model may be more reasonable than the single-zone model as Tingay et al. (2008) reported.

Georganopoulos & Kazanas (2003) reported that the bulk flow of the material in radio galaxy hot spots may be mildly relativistic. The energy density of the CMB in the jet frame is $U_{\text{CMB}} = 4 \times 10^{-13}$ erg cm$^{-3}$, which rapidly increases with the bulk Lorentz factor $\Gamma$ and the redshift $z$ of the sources. The synchrotron radiation energy density is $U_{\text{syn}} = L_{\text{syn}}/(4\pi R^{2}c\delta^{4})$ erg cm$^{-3}$. We examine whether the contribution of the IC scattering of CMB photons by the relativistic electrons (IC/CMB) becomes significant compared with the SSC. In the single-zone model, we get $U_{\text{CMB}} = 4.6 \times 10^{-13}$ erg cm$^{-3}$, which is smaller than $U_{\text{syn}} = 6.8 \times 10^{-11}$ erg cm$^{-3}$ by 2 orders of magnitude. Therefore, the contribution of IC/CMB to VHE emission can be neglected compared with the SSC, as shown in Figure 1. In the multizone model, we have $U_{\text{syn}} = 1.9 \times 10^{-12}$ erg cm$^{-3}$ for the diffuse region and $U_{\text{syn}} = 3.1 \times 10^{-11}$ erg cm$^{-3}$ for the subcomponents, which are much higher than $U_{\text{CMB}}$.

Both the single- and the multizone models predict a VHE emission component in the GeV–TeV band when the magnetic field strength is smaller than the equipartition magnetic field by an order of magnitude. The predicted VHE emission is above the sensitivities of Fermi and H.E.S.S. Furthermore, we show that the GeV–TeV emission from Pictor A is dominated by the WHS, but not the nucleus, suggesting that the WHS should be a
GeV–TeV emitter, if the GeV–TeV detection is confirmed. The detection of the TeV emission from Pictor A would establish a new subclass of extragalactic source in this energy regime since most of the active galactic nuclei detected to date at TeV energies are high-energy-peaked BL Lac (HBL) objects. The predicted GeV–TeV flux by the models requires a smaller magnetic field strength than the equipartition magnetic field. The GeV–TeV observations can also be used to test the equipartition condition for this source.

We notice that Pictor A was observed with the H.E.S.S. TeV γ-ray telescope between 2005 January and 2007 July, with 7.9 hr live time (Aharonian et al. 2008b), but no significant TeV emission was detected during that observation. This may be due to the sensitivity of H.E.S.S. decreasing at larger zenith angle (Aharonian et al. 2008b). As shown in Figures 1 and 2, the predicted GeV–TeV flux of the WHS is slightly over the sensitivities of Fermi and H.E.S.S. Longer exposure time may be needed in order to catch the TeV emission for the large zenith angle and the low fluxes of the WHS. We should note that under the equipartition condition, the SED also can be fit with the multizone model. In this scenario, the predicted flux in the range of $>10^{22}$ Hz is too weak to be detected.

Pictor A is the list of 206 “Very Important AGN/blazar” targets of Fermi for a simultaneous multifrequency analysis campaign. The detection of the high-energy emission and the broadband SEDs observed quasisimultaneously would place much stronger constraints on the radiation mechanism and on the physical parameters of the source.

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REFERENCES

Acciari, V. A., et al. 2008, ApJ, 684, L73
Acciari, V. A., et al. 2009, ApJ, 693, L104
Aharonian, F., et al. 2003, A&A, 403, L1
Aharonian, F., et al. 2008a, A&A, 481, L103
Aharonian, F., et al. 2008b, A&A, 478, 387
Aharonian, F., et al. 2009, ApJ, 695, L40
Albert, J., et al. 2007, ApJ, 666, L17
Albert, J., et al. (The MAGIC Collaboration) 2008, Science, 320, 1752
Arshakian, T. G., & Longair, M. S. 2000, MNRAS, 311, 846

Bai, J. M., & Lee, M. G. 2001, ApJ, 549, L173
Begelman, M. C., Blandford, R. D., & Rees, M. J. 1984, Rev. Mod. Phys., 56, 255
Bicknell, G. V. 1985, PASA, 6, 130
Blandford, R. D., & Rees, M. J. 1974, MNRAS, 169, 395
Bloom, S. D., & Marscher, A. P. 1996, ApJ, 461, 657
Brunetti, G., Setti, G., & Comastri, A. 1997, A&A, 325, 898
Celotti, A., Padovani, P., & Ghisellini, G. 1997, MNRAS, 286, 415
Chiaberge, M., & Ghisellini, G. 1999, MNRAS, 306, 551
Cruisius, A., & Schlickeiser, R. 1986, A&A, 164, L16
de Angelis, A., Mansutti, O., & Persic, M. 2008, Nuovo Cimento Riv. Ser., 31, 187
Fan, Z.-H., Liu, S., Wang, J.-M., Fryer, C. L., & Li, H. 2008, ApJ, 673, L139
Fanaroff, B. L., & Riley, J. M. 1974, MNRAS, 167, 31P
Georganopoulos, M., & Kazanas, D. 2003, ApJ, 589, L5
Ghisellini, G., & Svensson, R. 1991, MNRAS, 252, 313
Ghisellini, G., Guilbert, P. W., & Svensson, R. 1988, ApJ, 334, L5
Hardcastle, M. J., Birkinshaw, M., Cameron, R. A., Harris, D. E., Looney, L. W., & Worrall, D. M. 2002, ApJ, 581, 948
Hardcastle, M. J., Birkinshaw, M., & Worrall, D. M. 1998, MNRAS, 294, 615
Hardcastle, M. J., Harris, D. E., Worrall, D. M., & Birkinshaw, M. 2004, ApJ, 612, 729
Harris, D. E., Leighly, K. M., & Leahy, J. P. 1998, ApJ, 499, L149
Harris, D. E., Messman, A. E., & Walker, R. C. 2004, ApJ, 615, 161
Kataoka, J., Edwards, P., Georganopoulos, M., Takahara, F., & Wagner, S. 2003, A&A, 399, 91
Kino, M., & Takahara, F. 2004, MNRAS, 349, 336
Lahteenmäki, A., & Valtaoja, E. 1999, AJ, 117, 1168
Liu, H. T., & Bai, J. M. 2006, ApJ, 653, 1089
Malby, P., & Moffet, A. T. 1962, ApJS, 7, 141
Maraschi, L., Ghisellini, G., & Celotti, A. 1992, ApJ, 397, L5
Meisenheimer, K., Roser, H.-J., Hiltnner, P. R., Yates, M. G., Longair, M. S., Chini, R., & Perley, R. A. 1989, A&A, 219, 63
Meisenheimer, K., Yates, M. G., & Roser, H.-J. 1997, A&A, 325, 57
Migliori, G., Grandi, P., Palumbo, G. G. C., Brunetti, G., & Stanghellini, C. 2007, ApJ, 668, 203
Perley, R. A., Roser, H.-J., & Meisenheimer, K. 1997, A&A, 328, 12
Roeser, H.-J., & Meisenheimer, K. 1987, ApJ, 314, 70
Rybicki, G., & Lightman, A. P. 1979, Radiative Process in Astrophysics (New York: Wiley Interscience)
Schwarz, U. J., Whiteoak, J. B., & Cole, D. J. 1974, Aust. J. Phys., 27, 563
Singh, K. P., Rao, A. R., & Vahia, M. N. 1990, MNRAS, 246, 706
Stanley, G. J., & Slee, O. B. 1950, Aust. J. Sci. Res., 3, 234
Sulentic, J. W., Marziani, P., Zwitter, T., & Calvani, M. 1995, ApJ, 438, L1
Tavecchio, F., Cerutti, R., Maraschi, L., Sambruna, R. M., Gambill, J. K., Cheung, C. C., & Urry, C. M. 2005, ApJ, 630, 721
Tavecchio, F., Maraschi, L., & Ghisellini, G. 1998, ApJ, 509, 608
Teshima, M. (The MAGIC Collaboration) 2008, ATel, 1500, 1
Thomson, R. C., Crane, P., & Mackay, C. D. 1995, ApJ, 446, L93
Tingay, S. J., Lenc, E., Brunetti, G., & Bondi, M. 2008, AJ, 136, 2473
Tingay, S. J., et al. 2000, AJ, 119, 1695
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
Wilson, A. S., Young, A. J., & Shopbell, P. L. 2001, ApJ, 547, 740
Worrall, D. M., Birkinshaw, M., & Hardcastle, M. J. 2001, MNRAS, 326, L7
Zdziarski, A. A. 1986, ApJ, 305, 45
Zhang, J., Bai, J.-M., & Chen, L. 2009, ApJ, submitted

4 http://glastweb.pg.infn.it/blazar/