COORDINATED MULTIWAVELENGTH OBSERVATIONS AND SPECTRAL VARIABILITY MODELING OF GAMMA-RAY BLAZARS

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ABSTRACT

Our recent progress on time-dependent modeling of the multiwavelength spectra and variability of blazars with leptonic and hadronic jet models is reviewed. Special emphasis is placed on X-ray spectral variability of low-frequency peaked (LBLs) and intermediate BL Lac objects (IBLs). As an example, recent observational and modeling results of an extensive multiwavelength campaign of BL Lacertae in 2000 are presented. It is demonstrated how combined spectral and variability modeling of LBLs and IBLs can significantly constrain emission models and potential variability scenarios. In the case of BL Lacertae, the variability appears to be driven primarily by fluctuations in the spectral index of the non-thermal, ultrarelativistic electron population in the jet. Such constraints allow us to refine predictions of the intrinsic GeV γ-ray emission and the dominant electron cooling mechanism in these objects.

Key words: Active galactic nuclei; blazars; BL Lacertae; jets; gamma-rays; multiwavelength observations; theory.

1. INTRODUCTION

Blazars are the most extreme class of active galaxies known to date. They have been observed in all wavelength bands — from radio through very-high energy (VHE) γ-ray frequencies. 66 blazars have been identified as sources of > 100 MeV emission detected by the EGRET telescope on board the Compton Gamma-Ray Observatory (CGRO; Hartman et al. 1999), and 6 blazars (Mrk 421: Punch et al. 1992; Petry et al. 1996; Mrk 501: Quinn et al. 1994; Bradbury et al. 1997; PKS 2155-314: Chadwick et al. 1999; 1ES 2344+514: Catanese et al. 1998; 1H 1426+428: Horan et al. 2002; Aharonian et al. 2002; Nishimura et al. 1999; Holder et al. 2003; Aharonian et al. 2003) have now been detected at VHE γ-rays (> 350 GeV) by ground-based air Čerenkov telescopes. Many of the EGRET-detected γ-ray blazars appear to emit — at least temporarily — the bulk of their bolometric luminosity at γ-ray energies. Blazars exhibit variability at all wavelengths on time scales — in some cases — down to less than an hour. VLBI radio observations and monitoring often reveal one-sided kpc-scale jet structures, exhibiting apparent superluminal motion. The radio through optical emission from blazars often shows linear polarization, pointing towards a synchrotron origin.

1.1. Blazar Spectra

The broadband continuum spectra of blazars are dominated by non-thermal emission and consist of at least two clearly distinct, broad spectral components. A sequence of sub-classes of blazars can be defined through the peak frequencies and relative $\nu F_\nu$ peak fluxes of those components, which also appear to be correlated with the overall bolometric luminosity of the sources (Fossati et al. 1998): In the case of flat-spectrum radio quasars (FSRQs), the low-frequency (synchrotron) component extends from radio to optical/UV frequencies, with a peak frequency generally in the mm or IR band; the high-frequency component extends from X-rays through GeV γ-ray energies, with a $\nu F_\nu$ peak frequency corresponding to $\sim 10$ MeV — 1 GeV. No FSRQ has so far been detected by ground-based air Čerenkov telescope facilities at energies $> 100$ GeV, although in flaring states the $\gamma$-ray $\nu F_\nu$ peak flux of FSRQs dominates over the low-frequency emission by up to $\sim 1$ order of magnitude. In the case of high-frequency peaked BL Lac objects (HBLs), the low-frequency component often extends far into the X-rays, with peak frequencies ranging from the UV/soft X-ray to the hard X-ray regime (Pian et al. 1998), depending on the source and its state of activity; the high-energy component of HBLs extends from hard X-rays far into the VHE γ-ray regime. All blazars detected at VHE γ-ray energies to date are HBLs. In spite of extending to extremely high photon energies, the $\nu F_\nu$ peak flux of the γ-ray component of HBLs is generally at most comparable to the spectral output in the low-frequency component. In terms of their overall bolometric luminosity, FSRQs appear to be...
1.2. Blazar Variability

Fig. 3 already illustrates that in particular the high-energy emission from blazars can easily vary by more than an order of magnitude between different observing epochs. However, variability has been observed on much shorter time scales, in some extreme cases less than an hour (Gaidos et al. 1996). Fig. 2 shows examples of light curves of the LBL BL Lacertae, taken during a broadband observing campaign carried out in the second half of 2000 (Böttcher et al. 2003; Villata et al. 2002). While the radio emission of blazars is generally variable on time scales of weeks – months (Fig. 2a), the optical light curve shows significant variability on time scales down to $\sim$1.5 hr (Fig. 2b).

Often, both the optical and X-ray emission show characteristic hardness-intensity correlations. Fig. 4 illustrates this for BL Lacertae in 2000. Some HBLs (e.g., Mrk 421 and PKS 2155-304) have been observed to exhibit characteristic, clockwise loop structures (“spectral hysteresis”; Takahashi et al. 1994; Kataoka et al. 2000), which can be interpreted as the synchrotron radiation signature of gradual injection and/or acceleration of ultrarelativistic electrons into the emitting region, and subsequent radiative cooling (Kirk et al. 1998; Georganopoulos & Marscher 1998; Kataoka et al. 2000; Kusunose et al. 2002; Li & Kusunose 2000).

In LBLs, the soft X-ray emission is also sometimes dominated by the high-energy end of the synchrotron emission component, so similar spectral hysteresis phenomena should in principle be observable. However, those objects are generally much fainter at X-ray energies than their high-frequency peaked counterparts, making the extraction of time-dependent spectral information an observationally very challenging task. Fig. 3 clearly illustrates that the BeppoSAX observations of BL Lacertae in 2000 revealed evidence for spectral variability, but lacked the sensitivity to clearly establish or rule out spectral hysteresis. Such a measurement might require the new generation of X-ray telescopes such as Chandra or XMM-Newton.

2. OVERVIEW OF LEPTONIC JET MODELS OF BLAZARS

The high apparent bolometric luminosity combined with the short variability time scales and the apparent superluminal motions of individual jet components observed in many blazars, provide compelling evidence that the nonthermal continuum is produced in emission regions of a typical size scale of $\sim$ a few light days or less, moving relativistically along a jet structure which is directed at a small angle with respect to our line of sight. The jets are most likely powered by accretion of circumnuclear matter onto a supermassive black hole of $10^8 M_\odot \lesssim M_{BH} \lesssim 10^{10} M_\odot$. The emission regions are characterized by the presence of an ultrarelativistic population of nonthermal electrons. Several scenarios have been proposed concerning the acceleration of such ultrarelativistic electrons, including impulsive injection near the base of the jet (Dermer & Schlickeiser 1993; Böttcher et al. 1997), individual shock waves propagating along
the jet [Marscher & Gear 1985], relativistic particle acceleration at shear layers between a fast-moving inner jet and a slower moving outer jet (e.g., Stawarz & Ostrowski 2003) or internal shocks from the collisions of multiple shells of material ejected into the jet structure (Spada et al. 2001). Because of the difficulty of constraining the acceleration mechanism and the composition and spectral characteristics of the injected particle distribution (see, e.g., Sikora & Madejski 2000; Ostrowski & Bednarz 2002; Stawarz & Ostrowski 2003), the time profile of injection and injected particle spectra of ultrarelativistic electrons are generally treated as free parameters in blazar modeling.

The nonthermal electrons are emitting synchrotron radiation, which is responsible for the low-frequency emission from radio to UV or even X-ray frequencies. Higher-frequency (X-ray and \( \gamma \)-ray) emission is produced via Compton scattering processes. Possible target photon fields for Compton scattering are the synchrotron photons produced within the jet (the SSC process; Marscher & Gear 1985; Maraschi et al. 1992; Bloom & Marscher 1996), or external photons (the EC process). Sources of external seed photons include the UV – soft X-ray emission from the disk — either entering the jet directly (Dermer et al. 1993; Dermer & Schlickeiser 1993) or after reprocessing in the broad line region (BLR) or other circumnuclear material (Sikora et al. 1994; Blandford & Levinson 1995; Dermer et al. 1997). Non-continuous energy loss processes (such as Compton scattering) and energy gain due to acceleration processes, \( p_e \) and \( q_e \), are the terms describing the population and de-population of a given electron energy interval due to non-continuous energy loss processes (such as Compton scattering, in particular in the Klein-Nishina regime), \( Q_e \) describes the electron injection function, and \( t_{e,\text{esc}} \) is the escape time scale of nonthermal electrons. The evolution of the photon population in the emission region has to be solved simultaneously with the electron distribution, and is determined through

\[
\frac{\partial n_e(\gamma, t)}{\partial t} = - \frac{\partial}{\partial \gamma} \left( \frac{d\gamma}{dt} \right) \text{acc/loss,cont.} - \frac{\partial}{\partial \gamma} \left( \frac{Q_e(\gamma, t) - n_e(\gamma, t)}{t_{e,\text{esc}}} \right),
\]

where \( (d\gamma/dt)_{\text{acc/loss,cont.}} \) denotes the continuous energy losses due to radiative and adiabatic cooling and energy gain due to acceleration processes, \( p_e \) and \( q_e \).
Various versions of the generic leptonic jet model described in the previous section have been used very successfully to model simultaneous broadband spectra of several FSRQs, LBLs, and HBLs. As more detailed spectral information has become available, the results of such broadband spectral modeling have now converged towards a rather consistent spectral sequence HBLs → LBLs → FSRQs. As detailed spectral variability of blazars. Studies of blazar spectral variability have been done in great detail for the case of pure SSC models with electron cooling dominated by synchrotron losses, e.g., by Kirk et al. (1998); Georganopoulos & Marscher (1998); Kataoka et al. (2000); Kusunose et al. (2000); Li & Kusunose (2000). In those papers, the spectral hysteresis observed in several HBLs was reproduced, significantly constraining model parameters beyond constraints obtainable from pure spectral modeling. More recently, Sikora et al. (2001) have extended these studies to an inho-

average electron energies and lower magnetic fields than LBLs and FSRQs. In most cases, the required Doppler boosting factors $D$ seem to be comparable for all types of objects, although there have also been some results indicating an extraordinarily high value of $D \gtrsim 40$ for the HBL Mrk 501 (Krawczynski et al. 2002). Typical examples of broadband spectral fits consistent with this sequence of leptonic jet model parameters are shown in Fig. 1. The occasional finding of very high Doppler factors, in particular in some HBLs, has prompted Georganopoulos & Kazanas (2003) to propose their model of a decelerating, stratified jet in which synchrotron photons from slower regions of the jet would serve as seed photons for Compton scattering, appearing slightly blue shifted in the rest frame of the faster high-energy emission region further upstream. Such a scenario could remove the need for bulk Lorentz factors largely in excess of $\sim 10$ for HBLs.

2.2. Leptonic-Jet Modeling of Blazar Spectral Variability

The generic blazar model described above is inherently time-dependent and facilitates the modeling not only of the broadband SEDs, but also the detailed spectral variability of blazars. Studies of blazar spectral variability have been done in great detail for the case of pure SSC models with electron cooling dominated by synchrotron losses, e.g., by Kirk et al. (1998); Georganopoulos & Marscher (1998); Kataoka et al. (2000); Kusunose et al. (2000); Li & Kusunose (2000). In those papers, the spectral hysteresis observed in several HBLs was reproduced, significantly constraining model parameters beyond constraints obtainable from pure spectral modeling. More recently, Sikora et al. (2001) have extended these studies to an inho-

\[
\frac{\partial n_{\text{ph}}(\epsilon, t)}{\partial t} = \dot{n}_{\text{ph,em}}(\epsilon, t) - \dot{n}_{\text{ph,abs}}(\epsilon, t) + q_{\text{ph}}(\epsilon, t) - p_{\text{ph}}(\epsilon, t) - \frac{n_{\text{ph}}(\epsilon, t)}{t_{\text{ph,esc}}} \tag{2}
\]

where now $\dot{n}_{\text{ph,em}}$ and $\dot{n}_{\text{ph,abs}}$ describe the fundamental emission and absorption processes, $q_{\text{ph}}$ and $p_{\text{ph}}$ describe the scattering rates into and out of a given photon energy bin, and $t_{\text{ph,esc}}$ is the photon escape time scale.

2.1. Leptonic-Jet Spectral Modeling Results for Different Blazar Classes

Various versions of the generic leptonic jet model described in the previous section have been used very successfully to model simultaneous broadband spectra of several FSRQs, LBLs, and HBLs. As more detailed spectral information has become available, the results of such broadband spectral modeling have now converged towards a rather consistent picture (Ghisellini et al. 1998; Kubo et al. 1998). The spectral sequence HBLs → LBLs → FSRQs appears to be related to an increasing contribution of the external Comptonization mechanism to the $\gamma$-ray spectrum. While most FSRQs are successfully modelled with external Comptonization models (e.g., Dermer et al. 1997; Sambruna et al. 1997; Mukherjee et al. 1998; Hartman et al. 2001a), the broadband spectra of HBLs are consistent with pure SSC models (Mastichiadis & Kirk 1997; Pian et al. 1998; Petry et al. 2000; Krawczynski et al. 2002). BL Lacertae, a LBL, appears to be intermediate between these two extremes, requiring an external Comptonization component to explain the EGRET spectrum (Madejski et al. 1992; Böttcher & Bloom 2000). One generally finds that HBLs require higher

Figure 3. Left panel (a): Optical color-magnitude relation observed during the multiwavelength campaign on BL Lacertae in 2000 (Villata et al. 2002; Böttcher et al. 2003; Böttcher & Reimer 2004). Right panel (b): X-ray hardness-intensity diagram extracted from BeppoSAX observations. The curves indicate the spectral variability patterns from the best-fit leptonic model of Böttcher & Reimer (2004).
mogeneous jet model, also including an external Compton component, so that the model would now also be applicable to LBLs and quasars. They have applied their model to the special case of 3C 279. Based on their results, they interpreted the lack of a measurable time lag between the γ-ray and X-ray emission in that object as evidence that X-rays and γ-rays might be produced co-spatially by electrons of similar energies. This, in turn, provides evidence for two separate emission components being dominant at X-rays and γ-rays. Most plausibly, this might indicate that the X-ray emission is dominated by SSC emission, while the γ-rays are dominated by external Compton emission.

Time-dependent, homogeneous leptonic jet models in which radiation mechanisms other than synchrotron may dominate have recently been investigated in an analytical approach by Chiang & Böttcher (2002), and with detailed numerical simulations by Böttcher & Chiang (2002). Chiang & Böttcher (2002) pointed out that a dominant contribution from SSC to the electron cooling will produce a characteristic time-averaged synchrotron spectral index of $\alpha = 3/2$ (energy spectral index), independent of the injection index of relativistic electrons in the jet. In this case, the cooling time scale of electrons radiating at a synchrotron photon energy $E_{\text{sy}}$ is expected to scale as $\tau_{\text{cool,SSC}} \propto E_{\text{sy}}^{q-4/2}$, where $q$ is the electron injection spectral index (Böttcher et al. 2003). This differs characteristically from the synchrotron or EC dominated case in which $\tau_{\text{cool,ne}} \propto E_{\text{sy}}^{-1/2}$, independent of the electron injection index $q$.

Detailed numerical simulations of the time-dependent emission characteristics of homogeneous jet models with parameters specifically chosen to be appropriate for low-frequency peaked and intermediate BL Lac objects have been done by Böttcher & Chiang (2002). A key result of their study was that a dominant SSC component would leave very obvious imprints in the X-ray spectral variability of these objects, as illustrated in Fig. 4. In contrast, they found that a moderate and even slightly dominant contribution from external Compton scattering will have virtually no effect on the X-ray spectral variability patterns. This might be a consequence of the fact that the beaming pattern of external Compton emission is more strongly peaked in the forward direction than the synchrotron and SSC components (which are assumed to be isotropic in the co-moving frame of the emission region). Thus, even if the EC component is dominating the γ-ray emission at MeV – GeV energies, it may only make a moderate contribution to the electron cooling rate. The results of Böttcher & Chiang (2002) have been applied in detail to simultaneous multiwavelength observations of W Comae in 1998 (Böttcher et al. 2002) and BL Lacertae in 2000 (Böttcher & Reimer 2004).

3. OVERVIEW OF HADRONIC BLAZAR MODELS

While leptonic models deal with a relativistic $e^\pm$ plasma in the jet, in hadronic models the relativistic jet consists of a relativistic proton ($p$) and electron ($e^-$) component. In the following, a brief summary of the Synchrotron-Proton Blazar (SPB-) model (Mücke et al. 2003) is given, as an example of a hadronic model that takes into account all the salient features of hadronic blazar jet models in general.

Like in the leptonic model, the emission region in an AGN jet moves relativistically along the jet axis which is closely aligned with our line of sight. Relativistic protons, whose particle density $n_p$ follows a power law spectrum $\propto \gamma_p^{-q_p}$ in the range $2 \leq \gamma_p \leq \gamma_{p,\text{max}}$, are injected instantaneously into a highly magnetized environment ($B = \text{const.}$ within the emission region), and are subject to energy losses due to proton-photon interactions (meson production and Bethe-Heitler pair production), synchrotron radiation and adiabatic expansion. The mesons produced in photon-meson interactions always decay in astrophysical environments. However, they may suffer synchrotron losses before the decay, which is taken into account in this model.

If the relativistic electrons are accelerated together with the protons at the same site, their injection spectrum shows most likely the same spectral shape $\propto \gamma_e^{-q_e}$ with $q_e = q_p$. The relativistic primary $e^-$ radiate synchrotron photons which constitute the low-energy bump in the blazar SED, and serve as the target radiation field for proton-photon interactions and the pair-synchrotron cascade which subsequently develops. The SPB-model is designed for objects with a negligible external target photon component, and hence suitable for BL Lac objects. The cascade re-
distributes the photon power to lower energies where the photons eventually escape from the emission region. The cascades can be initiated by photons from $\pi^0$-decay ("$\pi^0$ cascade"), electrons from the $\pi^\pm \rightarrow e^\pm$ decay ("$\pi^\pm$ cascade"), $p$-synchrotron photons ("$p$-synchrotron cascade"), charged $\mu$, $\pi$ and $K$-synchrotron photons ("$\mu^\pm$-synchrotron cascade") and $e^\pm$ from proton-photon Bethe-Heitler pair production ("Bethe-Heitler cascade"). Because "$\pi^0$ cascades" and "$\pi^\pm$ cascades" generate rather featureless photon spectra (Mücke & Protheroe 2001, Mücke et al. 2003), proton and muon synchrotron radiation and their reprocessed radiation turn out to be mainly responsible for the high energy photon output in blazars. The contribution from the Bethe-Heitler cascades is mostly negligible. The low energy component is dominated by synchrotron radiation from the primary $e^-$, with a small contribution of synchrotron radiation from secondary electrons (produced by the $p$- and $\mu^\pm$-synchrotron cascade). A detailed description of the model itself, and its implementation as a (time-independent) Monte-Carlo code, has been given in Mücke & Protheroe (2001) and Reimer et al. (2004). This code has been used, e.g., to generate the spectral fits presented in Bottcher & Reimer (2004) for BL Lacertae in 2000 (see also Fig. 5).

### 4. MODELING RESULTS FOR BL LACERTAE IN 2000

Both the leptonic and hadronic models described in the previous sections have been applied successfully to the data obtained during the multiwavelength observing campaign on BL Lacertae in 2000 (Böttcher et al. 2003). The best time-averaged spectral fits are shown in Figs. 1 and 5. The best-fit parameters for the leptonic and hadronic model fits differ substantially in the following ways: (a) The overall jet power required in the hadronic models is $\sim 2$ orders of magnitude higher than for the leptonic models ($\sim 6 \times 10^{44}$ ergs s$^{-1}$ vs. $\lesssim 6 \times 10^{42}$ ergs s$^{-1}$); (b) the magnetic fields in hadronic jet models are a factor of $\sim 20$ higher than for leptonic models ($B \sim 30 – 40$ G vs. $\sim 2$ G), and the bulk Lorentz factor of the emission region is a factor of $\sim 2$ lower for the hadronic models ($\sim 7 – 9$ vs. $\sim 18$).

Considering the time-averaged emission of BL Lacertae in 2000, hadronic models predict a sustained level of multi-GeV – TeV emission which should be detectable with second-generation atmospheric Cherenkov telescope systems like VERITAS, HESS, or MAGIC. In contrast, our leptonic model only predicts a peak flux exceeding the anticipated nominal MAGIC sensitivity during short flares; the accumulated fluence over observing time scales of several hours might not be sufficient for a significant detection. Thus, a future VHE detection of BL Lacertae would be a strong indication for hadronic processes being at work in this object.

The detailed spectral evolution of our best-fit leptonic jet simulation is shown in Fig. 6. In order to determine the best-fit variability scenario, various generic flaring scenarios had been investigated and compared to the observed optical and X-ray spectral variability patterns (see Fig. 7). Specifically, we had investigated scenarios invoking a temporary increase in jet power, a flattening of the electron injection spectral index, an increasing high-energy cutoff $\gamma_{2}$ of the electron injection spectrum, and various combination of these. Other parameter fluctuations could be ruled out on the basis of general, analytical con-
siderations, without detailed simulations. We found
that the observed optical and X-ray spectral vari-
ability in BL Lacertae in 2000 can be reproduced
through short-term fluctuations of only the electron
injection spectral index, with all other parameters
remaining unchanged.

Remarkably, our time-dependent fits indicated that
an injection index larger than $q \sim 2.3$, even dur-
ing the peak of an individual short-term flare, is
required. If the injection of ultrarelativistic elec-
trons into the emitting volume is caused by Fermi
acceleration at relativistic shocks, detailed numeri-
cal studies have shown that with fully developed tur-
bulence in the downstream region, a unique asym-
totic index of $q \sim 2.2 - 2.3$ should be expected
e.g., Achterberg et al. 2001, Gallant et al. 1999).
However, recently Ostrowski & Bednarek (2002) have
shown that Fermi acceleration might lead to drasti-
cally steeper injection spectra if the turbulence is not
fully developed. Furthermore, depending on the ori-
entation of the magnetic field at the shock front, an
abrupt steepening of the injection spectra may result
if the shock transits from a subluminal to a super-
luminal configuration. In this context, our leptonic
fit results may indicate that such predominantly geo-
metric effects, may be the cause of the rapid vari-
ability observed in BL Lacertae.

Our spectral-variability simulation predicted coun-
ter-clockwise spectral hysteresis at X-ray ener-
gies. Such hysteresis was not predicted in the specific
SPB model fits presented in Böttcher & Reimer
2004, but could not clearly be ruled out either.
Thus, sensitive spectral-hysteresis measurements
of BL Lacertae could possibly serve as a test of
our modeling results and a secondary diagnostic to
distinguish between leptonic and hadronic models,
though, by itself, it would not be sufficient as a
model discriminant.

Ravasio et al. (2003) had previously noted the dis-
crepancy between the time-averaged optical and X-
ray spectra (Ravasio et al. 2003) which could not be
joined smoothly by an absorbed power-law spec-
trum. They had considered several possibilities to
explain this discrepancy, including additional particle
populations, extreme Klein-Nishina effects on the
electron cooling rates, and/or anomalies in the inter-
galactic absorption. Our successful modeling of the
observed time-dependent flux and hardness values at
optical and X-ray frequencies in the framework of a
leptonic model effectively removes the need for such
additional assumptions and indicates that the time-
averaging involved in compiling the detailed broad-
band spectral energy distribution may be the cause of
this apparent discrepancy.

REFERENCES

Achterberg, A., Gallant, Y. A., Kirk, J. G., & Guth-
mann, A. W., 2001, MNRAS, 328, 393
Aharonian, F. A., et al., 2002, A&A, 384, L23
Aharonian, F. A., et al., 2003, A&A, 406, L9
Arbeiter, C., Pohl, M., & Schlickeiser, R., 2002,
A&A, 386, 415
Bednarek, W., A&A, 342, 69
Blandford, R. D., & Levinson, A., 1995, ApJ, 441,
79
Blazejowski, M., et al., 2000, ApJ, 545, 107
Bloom, S. D., & Marscher, A. P., 1996, ApJ, 461,
657
Böttcher, M., Mause, h., & Schlickeiser, R., 1997,
A&A, 324, 395
Böttcher, M., & Bloom, S. D., 2000, AJ, 119, 469
Böttcher, M., & Chiang, J., 2002, ApJ, 581, 127
Böttcher, M., & Dermer, C. D., 1998, ApJ, 501, L51
Böttcher, M., et al., 2003, ApJ, 598, 847
Böttcher, M., Mukherjee, R., & Reimer, A., 2002,
ApJ, 581, 143
Böttcher, M., & Reimer, A., 2004, ApJ, submitted
Bradbury, S. M., 1997, A&A, 320, L5
Catanese, M., et al., 1998, ApJ, 501, 616
Chadwick, P. M., 1999, ApJ, 513, 161
Chiang, J., & Böttcher, M., 2002, ApJ, 564, 92
Collmar, W., et al., 2004, these proceedings
Dermer, C. D., Schlickeiser, R., & Mastichiadis,
A.,1992, A&A, 256, L27
Dermer, C. D., & Schlickeiser, R., 1993, ApJ, 416,
458
Dermer, C. D., Sturmer, S. J., & Schlickeiser, R.,
1997, ApJS, 109, 103
Fossati, G., 1998, MNRAS, 299, 433
Gaidos, J. A., et al., 1996, Nature, 383, 319
Gallant, Y. A., Achterberg, A., & Kirk, J. G., 1999,
A&AS, 138, 549
Georganopoulos, M., & Kazanas, D., 2003, ApJ, 594,
L27
Georganopoulos, M., & Marscher, A. P., 1998, ApJ,
506, L11
Ghisellini, G., & Madau, P., 1996, MNRAS, 280, 67
Ghisellini, G., et al., 1998, MNRAS, 301, 451
Hartman, R. C., et al., 1999, ApJS, 123, 79
Hartman, R. C., et al., 2001a, ApJ, 553, 683
Hartman, R. C., et al., 2001b, ApJ, 558, 583
Holder, J., et al., 2003, ApJ, 583, L9
Horan, D., et al., 2002, ApJ, 571, 753
Kataoka, J., et al., 2000, ApJ, 528, 243
Kirk, J. G., Rieger, F. M., & Mastichiadis, A., A&A,
333, 452

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Krawczynski, H., Coppi, P. S., & Aharonian, F. A., 2002, MNRAS, 336, 721
Kubo, H., et al., 1998, ApJ, 504, 693
Kusunose, M., Takahara, F., & Li, H., 2000, ApJ, 536, 299
Li, J., & Kusunose, M., 2000, ApJ, 536, 729
Madejski, G., et al., 1999, ApJ, 521, 145
Maraschi, L., Ghisellini, G., & Celotti, A., 1992, 397, L5
Marscher, A. P., & Gear, W. K., 1985, ApJ, 298, 114
Mastichiadis, A., & Kirk, J. G., 1997, A&A, 320, 19
Mücke, A., & Protheroe, R. J., 2001, Astropart. Phys., 15, 121
Mücke, A., Protheroe, R. J., Engel, R., Rachen, J. P., & Stanev, T., 2003, Astropart. Phys., 18, 593
Mukherjee, R., et al., 1999, ApJ, 527, 132
Nishiyama, T., et al., in Proc. of the 26th ICRC, 3, 370
Ostrowski, M., & Bednarz, J., 2002, A&A, 394, 1141
Petry, D., et al., 1996, A&A, 311, L13
Petry, D., et al., 2000, ApJ, 536, 742
Pian, E., 1998, ApJ, 492, L17
Punch, M., et al., 1992, Nature, 358, 477
Quinn, J., et al., ApJ, 456, L83
Ravasio, M., Tagliaferri, G., Ghisellini, G., Tavecchio, F., Böttcher, M., & Sikora, M., 2003, A&A, 408, 479
Reimer, A., Protheroe, R. J., & Donea, A.-C., 2004, A&A, in press
Sambruna, R., et al., 1997, ApJ, 474, 639
Sikora, M., & Madejski, G., 2000, ApJ, 534, 109
Sikora, M., et al., 2001, ApJ, 554, 1; Erratum: ApJ, 561, 1154 (2001)
Spada, M., MNRAS, 325, 1559
Sikora, M., Begelman, M. C., & Rees, M. J., 1994, ApJ, 421, 153
Stawarz, L., & Ostrowski, M., 2003, New Astron. Rev., 47, 6-7, 521
Takahashi, T., et al., 1996, ApJ, 470, L89
Villata, M., et al., 2002, A&A, 390, 407