Modeling Intermediate BL Lac Objects Detected by VERITAS

Markus Böttcher

Astrophysical Institute, Department of Physics and Astronomy
Ohio University, Athens, OH, 45701, USA
boettchm@ohio.edu

Received Day Month Year
Revised Day Month Year
Communicated by Managing Editor

Modeling implications of recent VERITAS discoveries of Intermediate BL Lac Objects (IBLs) are presented. Leptonic jet models for the IBLs W Comae (z = 0.102) and 3C 66A (z = 0.444) are, in principle, viable with only synchrotron and synchrotron-self-Compton (SSC) components, but more plausible parameters can be achieved including an external infrared radiation field as source for Compton upscattering to produce the observed VHE γ-ray emission. The unknown redshift of PKS 1424+210 makes a theoretical interpretation difficult. A pure SSC model seems to be sufficient to represent its SED, and modeling results favor a low redshift of z \lesssim 0.1.

Keywords: Active Galaxies; Blazars; Theory; Radiation Mechanisms; Gamma-Rays

1. Introduction

Until about 3 years ago, all blazars detected at very-high-energy (VHE: E > 100 GeV) γ-rays were High-frequency peaked BL Lac Objects (HBLs). However, the recent VHE discoveries of blazars belonging to the lower-peaked blazar types of Intermediate (IBL) and Low-frequency (LBL) peaked BL Lac objects and even the flat-spectrum radio quasar (FSRQ) 3C 279 suggest that most blazars are intrinsically emitters of VHE γ-rays.

When interpreted in terms of leptonic jet models, the classical TeV blazars (HBLs) can generally well be fit with pure synchrotron-self-Compton (SSC) models, while FSRQs and LBLs required external radiation fields for Compton scattering to produce the observed (MeV-GeV) γ-ray emission. For a recent review of blazar models, see, e.g., 5. With the detection of non-HBL VHE blazars, a critical question for their model interpretation is whether all VHE blazars are still SSC dominated, while non-VHE blazars are external-Compton (EC) dominated, or whether the new classes of VHE blazars also require EC components, as expected for FSRQs and LBLs.

Based on the recent detections of the IBLs W Comae, 3C 66A, and PKS 1424+210 by VERITAS, this paper presents a brief review of modeling results of the simultaneous spectral energy distributions (SEDs) of these new VHE
blazars.

2. The Model

For modeling the SEDs of the three IBLs detected by VERITAS, a steady-state version of the time-dependent leptonic jet model of Böttcher & Chiang\(^6\) is used. In this model, the observed electromagnetic radiation is interpreted as originating from ultrarelativistic electrons (and positrons) in a spherical emission region of co-moving radius \(R_g\), which is moving with a relativistic speed \(\beta c\), corresponding to the bulk Lorentz factor \(\Gamma\). An equilibrium distribution of relativistic electrons is established by a self-consistent balance of continuous injection, radiative cooling, and escape of electrons. The radio-through soft X-ray emission of BL Lac objects is interpreted as synchrotron emission, while the \(\gamma\)-ray emission results from a combination of SSC and EC of arbitrary external radiation fields. For a more in-depth description of this quasi-equilibrium jet model, see Acciari et al.\(^2\).

![Graphs](image)

Fig. 1. **Left panel:** Fits to the SED of W Comae during its initial VERITAS detection in March 2008. Simultaneous multiwavelength data are plotted in blue; grey data are historical. Solid line = Pure SSC fit, dotted line = SSC + EC fit. **Right panel:** Fits to the SED of W Comae during the major flare in June 2008. Heavy long-dashed = SSC; heavy solid = SSC + EC; thin curves indicate the individual components of the SSC + EC model: dashed = SSC, dot-dashed = EC, double-dot-dashed = synchrotron; dotted = external IR radiation field.

3. W Comae

The IBL W Comae was detected in VHE \(\gamma\)-rays by VERITAS during observations around a major flare on March 15, 2008\(^1\). The simultaneous SED obtained during that time is shown in the left panel of Fig. 1, along with model fits. The solid curve shows a pure SSC fit to the SED. While it seems to represent the SED reasonably well, it requires an implausibly low magnetic field of \(B = 0.007\) G, which is about a factor of 20 lower than corresponding to equipartition with the nonthermal electron distribution. Alternatively, the \(\gamma\)-ray emission can be reproduced with an external-Compton component. However, this can only be efficient if Compton scattering
out to $>100$ GeV can occur in the Thomson regime. This requires seed photons to have characteristic infrared photon energies of $h\nu_\text{i} \sim 0.1 - 1$ eV, which could plausibly represent the emission from a near-central warm dust torus. Adopting a model including an IR-EC component, as shown by the dashed curve in Fig. 1a, allows the choice of the magnetic field of $B = 0.25$ G, in exact equipartition with the nonthermal electron distribution.

W Comae was again the target of coordinated multiwavelength observations during a major $\gamma$-ray flare in June 2008. The SED and model fits are shown in the right panel of Fig. 1. The conclusions from the modeling results are consistent with the ones found during the March 2008 flare. A pure SSC model describes the overall radio - optical - UV - X-ray - VHE $\gamma$-ray SED well, but (a) is in conflict with the AGILE ($\text{GeV} \gamma$-ray) upper limit closest in time to the rest of the SED, and (b) requires a far sub-equipartition magnetic field. A satisfactory fit can be obtained with a combined SSC + IR-EC model close to equipartition, and in agreement with the AGILE upper limits.

![Figure 2](image_url)

**Fig. 2.** Fits to the SED of 3C 66A during its VERITAS detection in October 2008. Heavy dashed line = Pure SSC fit, heavy solid line = SSC + EC fit. Thin curves indicate the individual components of the SSC + EC model: dashed = SSC, dot-dashed = EC, dotted = synchrotron.
4. 3C 66A

The IBL 3C 66A was detected in VHE $\gamma$-rays by VERITAS during a $\gamma$-ray flare in October 2008 \(^4\). The SED, including simultaneous Swift, Fermi and contemporaneous Chandra data, is shown in Fig. 2, along with both an SSC and an SSC + EC model fit. The modeling conclusions are very similar to the ones found for W Comae: A pure SSC fit fails to reproduce the slope of the simultaneous Fermi (GeV $\gamma$-ray) spectrum, and would require a magnetic field a factor $\sim 8 \times 10^{-3}$ below equipartition with the relativistic electron distribution. An SSC + IR-EC model allows a good fit to the entire SED with a magnetic field close to equipartition.

![Figure 3](image-url)

**Fig. 3.** SSC model fits to the SED of PKS1424+240 in June 2009, for various assumed redshifts of the source. The inset shows a zoom-in on the VERITAS (VHE $\gamma$-ray) spectrum, illustrating the increasing discrepancy between data and model for increasing redshifts due to EBL absorption.

5. PKS 1424+240

The discovery of PKS 1424+240 marks the first VHE $\gamma$-ray blazar discovery motivated by the detection of a hard GeV $\gamma$-ray spectrum by Fermi \(^3\). The synchrotron peak of this source is observationally poorly determined, but the optical-UV and X-ray spectral slopes suggest its classification as an IBL. Unfortunately this source has so far not been intensively monitored, and hence we lack information about the characteristic minimum variability time scales as well as potential superluminal motion measurements which would yield constraints on the Doppler boosting at work in this object. However, the greatest obstacle to a reliable model interpretation is
its unknown redshift. Lower limits on the redshift, based on the non-detection of a host galaxy, have been derived to \( z > 0.06 \) by \(^{10}\) and \( z > 0.67 \) by \(^{11}\). An upper limit on the redshift can be derived by extrapolating the measured hard Fermi spectrum (\( \Gamma_{\text{LAT}} = 1.73 \pm 0.07_{\text{stat}} \pm 0.05_{\text{syst}} \)) to VHE \( \gamma \)-ray energies and attributing the steepening towards the measured VERITAS spectrum (\( \Gamma_{\text{VERITAS}} = 3.8 \pm 0.5_{\text{stat}} \pm 0.3_{\text{syst}} \)) exclusively do intergalactic \( \gamma \gamma \) absorption by the Extragalactic Background Light (EBL). This yields \( z < 0.66 \) at the 95\% confidence level.

Since the redshift of PKS 1424+240 is unknown, we have explored a range of plausible redshifts in our modeling procedure, including a low value of \( z = 0.05 \), similar to the redshifts of the closest VHE BL Lacs, up to a redshift of \( z = 0.7 \), consistent with the lower limit of \(^{11}\). Other model parameters have been chosen to be in the range typically required for modeling other VHE \( \gamma \)-ray blazars, and consistent with the observed X-ray variability time scale of \( t_{\text{var}} \sim 1 \) d. The simultaneous SED, including simultaneous Swift and Fermi-LAT data, is plotted in Fig. 3, along with the SSC model fits for the various assumed redshifts. The slope of the electron injection distribution function \( (Q_\gamma) = Q_0 \gamma^{-q} \) for \( \gamma_1 \leq \gamma \leq \gamma_2 \) is tightly constrained by the X-ray spectral slope as \( q = 5.1 \), and for all fits, the low-and high-energy cutoffs are \( \gamma_1 \sim 3.5 \times 10^4 \) and \( \gamma_2 \sim 4 \times 10^5 \). Other relevant model parameters are listed in Table 1, as a function of assumed redshift. Here, \( L_\nu \) is the kinetic power in relativistic electrons, \( L_B \) is the power in the Poynting flux carried by the magnetic field, and \( \epsilon_B \equiv L_B/L_\nu \) is the equipartition fraction. \( D = (\Gamma [1 - \beta \cos \theta_{\text{obs}}])^{-1} \) is the Doppler factor. All models have been corrected for EBL absorption using the model of Gilmore et al.\(^{9}\). Using the alternative models of Franceschini et al.\(^{8}\) or Finke et al.\(^{7}\) would have only minimal impact on the final results.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( z = 0.05 )</th>
<th>( z = 0.1 )</th>
<th>( z = 0.2 )</th>
<th>( z = 0.3 )</th>
<th>( z = 0.4 )</th>
<th>( z = 0.5 )</th>
<th>( z = 0.7 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_\nu [10^{43} \text{ erg s}^{-1}] )</td>
<td>1.60</td>
<td>4.12</td>
<td>10.7</td>
<td>18.9</td>
<td>29.2</td>
<td>47.1</td>
<td>88.8</td>
</tr>
<tr>
<td>( L_B [10^{44} \text{ erg s}^{-1}] )</td>
<td>1.66</td>
<td>5.47</td>
<td>16.9</td>
<td>31.1</td>
<td>45.9</td>
<td>49.8</td>
<td>66.2</td>
</tr>
<tr>
<td>( D )</td>
<td>15</td>
<td>18</td>
<td>25</td>
<td>30</td>
<td>35</td>
<td>45</td>
<td>60</td>
</tr>
<tr>
<td>( B ) [G]</td>
<td>0.37</td>
<td>0.31</td>
<td>0.25</td>
<td>0.24</td>
<td>0.25</td>
<td>0.38</td>
<td>0.14</td>
</tr>
<tr>
<td>( \epsilon_B )</td>
<td>1.04</td>
<td>1.33</td>
<td>1.59</td>
<td>1.65</td>
<td>1.57</td>
<td>1.06</td>
<td>0.75</td>
</tr>
<tr>
<td>( R_B ) [m]</td>
<td>1.2</td>
<td>2.2</td>
<td>3.4</td>
<td>4.0</td>
<td>4.0</td>
<td>4.5</td>
<td>5.0</td>
</tr>
</tbody>
</table>

As the fits in Fig. 3 and the parameter values in Table 1 indicate, generally, satisfactory fits can be achieved with a pure SSC model to the overall SED shape of PKS 1424+240 at any assumed redshift, with a model close to equipartition between the magnetic field and the relativistic electron distribution, although at a redshift \( z \gtrsim 0.5 \), very large Doppler factors of \( D > 50 \) would be required. However, the inset in Fig. 3 illustrates how \( \gamma \gamma \) absorption by the EBL increasingly steepens the model VHE spectrum, compared to the measured VERITAS spectrum, and makes the two incompatible for redshifts of \( z \gtrsim 0.1 \). Therefore, our modeling results seem to favor
6 M. Böttcher

a redshift of \( z \lesssim 0.1 \).

Acknowledgments

This work has been partially supported by NASA through Chandra GO grant GO8-9100X, XMM-Newton GO grant NNX08AD67G, and Fermi GO grant NNX09AT82G.

6. References

References