PREDICTIONS OF THE HIGH-ENERGY EMISSION FROM BL LACERTAE OBJECTS: THE CASE OF W COMAE

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ABSTRACT 
Spectral fitting of the radio through hard X-ray emission of BL Lac objects has previously been used to predict their level of high-energy (GeV–TeV) emission. In this paper, we point out that such spectral fitting can have very large uncertainties with respect to predictions of the very high energy (VHE) emission, in particular if no reliable, contemporaneous measurement of the GeV flux is available and the \( \nu F_\nu \) peak (flux and frequency) of the synchrotron component is not very precisely known. This is demonstrated with the example of the radio-selected BL Lac object W Comae, which is currently on the source list of the STACEE and CELESTE experiments, based on extrapolations of the EGRET flux measured from this source, and on model predictions from hadronic blazar jet models. We show that the best currently available contemporaneous optical–X-ray spectrum of W Comae, which shows clear evidence for the onset of the high-energy emission component beyond \( \sim 4 \) keV and thus provides a very accurate guideline for the level of hard X-ray synchrotron self-Compton (SSC) emission in the framework of leptonic jet models, still allows for a large range of possible parameters, resulting in drastically different greater than 40 GeV fluxes. We find that all acceptable leptonic-model fits to the optical–X-ray emission of W Comae predict a cutoff of the high-energy emission around \( \sim 100 \) GeV. We suggest that detailed measurements and analysis of the soft X-ray variability of W Comae may be used to break the degeneracy in the choice of possible fit parameters and thus allow a more reliable prediction of the VHE emission from this object. Using the available soft X-ray variability measured by BeppoSAX, we predict a greater than 40 GeV flux from W Comae of \( (0.4-1) \times 10^{-10} \) photons cm\(^{-2}\) s\(^{-1}\) with no significant emission at \( E > 100 \) GeV for a leptonic jet model. We compare our results concerning leptonic jet models with detailed predictions of the hadronic synchrotron-proton blazar model. This hadronic model predicts greater than 40 GeV fluxes very similar to those found for the leptonic models, but results in greater than 100 GeV emission that should be clearly detectable with future high-sensitivity instruments like VERITAS. Thus, we suggest this object as a promising target for VHE \( \gamma \)-ray and coordinated broadband observations to distinguish between leptonic and hadronic jet models for blazars. 

\textbf{Subject headings:} BL Lacertae objects: individual (W Comae) — galaxies: active — gamma rays: theory 

1. INTRODUCTION 
After the detection of six high-frequency peaked BL Lac objects (HBLs) with ground-based air Cerenkov telescope facilities, the field of extragalactic GeV-TeV astronomy is currently one of the most rapidly expanding research areas in astrophysics. The steadily improving flux sensitivities of the new generation of air Cerenkov telescope arrays (Konopelko 1999; Weekes et al. 2002) and their decreasing energy thresholds provides a growing potential to extend their extragalactic source list toward intermediate and even low-frequency peaked BL Lac objects (LBLs) with lower \( \nu F_\nu \) peak frequencies in their broadband spectral energy distributions (SEDs). Detection of such objects at energies \( \sim 40-100 \) GeV might provide an opportunity to probe the intrinsic high-energy cutoff of their SEDs, since at those energies, \( \gamma \gamma \) absorption due to the intergalactic infrared background is still expected to be negligible at redshifts of \( z \lesssim 0.2 \) (de Jager & Stecker 2002). 

Theoretical predictions of the high-energy emission of BL Lac objects on the basis of their emission at lower frequencies (Stecker, de Jager, & Salamon 1996; Costamante & Ghisellini 2002) are essential for careful planning of future observations by ground-based very high energy (VHE) \( \gamma \)-ray observatories. Such studies have generally been restricted to considerations of the observed broadband spectral properties of potential candidate sources and have mostly been based on nonsimultaneous spectral measurements alone. In this paper, we point out that such considerations can have very large uncertainties and ambiguities with respect to the predicted VHE emission. The importance and potential scientific return of including detailed variability
information in the modeling of HBLs has been pointed out by Coppi & Aharonian (1999), who have shown the wide variety of correlated X-ray and VHE $\gamma$-ray variability patterns that can result in time-dependent synchrotron self-Compton (SSC) models for blazars. In particular, they have pointed out that combined X-ray spectral and variability information may be sufficient to predict the level of intrinsic TeV emission in HBLs, even if no direct measurements at GeV-TeV energies are available. Here we demonstrate that similar conclusions hold for LBLs and investigate the example of the radio-selected BL Lac object W Comae (=ON 231 = 1219+285; $z = 0.102$), which is currently on the source list of the STACEE and CELESTE experiments. Its GeV-TeV source candidacy is based on the fact that W Comae has been detected by the EGRET instrument on board the Compton Gamma-Ray Observatory (CGRO) at energies above 100 MeV, exhibiting a very hard spectrum (von Montigny et al. 1995; Sreekumar et al. 1996). A power-law extrapolation of the average EGRET 0.1–10 GeV flux into the multi–GeV-TeV range yields a VHE flux well above the current detection threshold of both STACEE and CELESTE (see Fig. 3). Dingus & Bertsch (2001) also report on the detection of a 27.3 GeV photon from this source by EGRET in 1993 April. Furthermore, Mannheim (1996) has predicted a TeV flux near the detection limit of the Whipple air Cerenkov telescope at the time, based on a proton-blazar model fit to a nonsimultaneous broadband spectrum of W Comae.

The source was observed in a multiwavelength campaign in 1996 February, covering the electromagnetic spectrum from GHz radio frequencies to TeV energies (Maisonet et al. 1997). No TeV emission was detected by either Whipple or HEGRA.

While W Comae is generally observed to exhibit a typical one-sided jet morphology in VLBI images, Massaro et al. (2001) report the detection of a weak apparent counterjet component in 1999.13, if the brightest jet component with the flattest radio spectrum is identified with the core. Such a feature has not been found in any previous or later radio maps of the source. Massaro et al. (2001) demonstrate that it is implausible that this component is actually the emission from the counterjet. Alternatively, they suggest, e.g., that it could be due to a small-angle displacement of the jet direction in a general configuration in which the jet is directed at a very small average angle with respect to the line of sight.

The most detailed currently available simultaneous broadband spectrum of W Comae has been measured in 1998 May (Tagliaferri et al. 2000) and is shown in Figures 3 and 4. The X-ray spectrum has been measured by BeppoSAX and shows clear evidence for the intersection of the low-frequency (synchrotron) component and the high-frequency (Compton) component of the SED of W Comae at ~4 keV. There was clear evidence for variability on a ~10 hr timescale in the LECS count rate at photon energies of 0.1–4 keV, while no evidence for variability was found in the MECS count rate at 4–10 keV and the PDS count rate at 12–100 keV. A 3 $\sigma$ upper limit of 40% on the short-term variability amplitude in the MECS count rate could be derived in the 1998 May observations (Tagliaferri et al. 2000). The four individual spectral points in the EGRET energy range have been measured in 1998 March and are not strictly simultaneous to the BeppoSAX observations. The EGRET detection was at low significance (2.7 $\sigma$) and allowed only a rather crude source localization to within 1.5. We have calculated the spectrum of the source using four broad-energy bins, as described more fully in §2.

The remainder of this paper is organized as follows. The reanalysis of the available EGRET data is presented in §2. In §3 we describe the leptonic jet model that we use to reproduce the broadband spectrum of W Comae. The modeling results and the model-dependent predictions for VHE emission from W Comae are presented in §4. In §5 we discuss how a detailed measurement and analysis of the photon-energy dependent fast X-ray variability of W Comae and other BL Lac objects might be used to break the degeneracy of model parameters still present in the pure spectral modeling using a leptonic jet model. A comparison to the modeling results and predictions of a hadronic jet model are presented in §6. We summarize in §7.

2. GAMMA-RAY OBSERVATIONS

ON 231 is the suggested identification of the EGRET source 3EG J1222+2841, and the association of the EGRET source with this BL Lac object is based on probabilistic arguments. 3EG J1222+2841 was a weak EGRET source that was never detected at greater than 6 $\sigma$ in any individual viewing period (VPs). The locations of low-confidence EGRET sources are not well determined because of the wide point-spread function at photon energies greater than 100 MeV (Thompson et al. 1993; Mattox, Hartman, & Reimer 2001), and identification of EGRET sources with counterparts based on position alone is difficult. Analysis of EGRET data from 1991 to 1995 yielded a 7.7 $\sigma$ detection and a hard spectrum with photon index $\alpha = 1.73 \pm 0.18$ (Hartman et al. 1999), and 3EG J1222+2841 was identified with ON 231 with “high confidence.” However, this identification was based on the $E > 1$ GeV position of Lamb & Macomb (1997) rather than the $E > 100$ MeV position, as is standard practice for EGRET sources.

Mattox et al. (2001) have recently done a quantitative reevaluation of potential radio identifications for the 3EG radio sources by calculating the probability of each identification. They note that based on its $E > 100$ MeV position, 3EG J1222+2841 cannot be included in their list of high-confidence identifications. Using the $E > 1$ GeV position, Mattox et al. (2001) get the probability of identification to be 4%, which is classified as “plausible.” Future observations with GLAST will be important in determining the source position with more accuracy and securing a more confident identification. For the purpose of our analysis, we assume that W Comae is the counterpart of 3EG J1222+2841. However, the low significance of the ~2.7 $\sigma$ detection in 1998 May and its nonsimultaneity to the BeppoSAX observations prevents us from deriving any strong constraints from the EGRET flux or spectrum.

EGRET has observed 3EG J1222+2841 = W Comae several times since its launch in 1991. Table 1 lists the VPs during which the source was observed and the corresponding integral fluxes for energies greater than 100 MeV. Only photons with inclination angles less than 30° were used for the analysis. For phase 1 through cycle 4 of the EGRET observations (1991–1995), Table 1 lists data from the 3EG catalog (Hartman et al. 1999). Three additional observations were made in cycles 5, 7, and 9. We have analyzed these data using the standard EGRET data processing technique, as described in Mattox et al. (1996) and Hartman et al. (1999), and included them in the table. The light curve
for 3EG J1222+2841 is shown in Figure 1. The figure shows fluxes for all detections at a level greater than 2\(\sigma\) for detections below 2\(\sigma\), upper limits at the 95% confidence level are shown.

We have computed the background-subtracted \(\gamma\)-ray spectra of 3EG J1222+2841 for the strongest detections, as well as for 1998 March, close to the time of the BeppoSAX observations. The spectra were determined by dividing the EGRET energy band of 30 MeV to 10 GeV into four bins and estimating the number of source photons in each interval, following the standard EGRET spectral analysis technique (Nolan et al. 1993). We have fitted a single power law of the form \(F(E) = k(E/E_0)^{-\gamma}\) photons cm\(^{-2}\) s\(^{-1}\) MeV\(^{-1}\) to the data, where \(F(E)\) is the flux, \(E\) is the energy, and \(\gamma\) is the photon spectral index (see Fig. 2).

### TABLE 1

| Viewing Period | Start Date | End Date | Flux | Significance | \(\alpha\) |
|----------------|------------|----------|------|--------------|---------|
| 0020           | 1991 May 30| 1991 Jun 08| 36.4 ± 13.2 | 2.9 | ... |
| 0030           | 1991 Jun 15| 1991 Jun 28| <20.2 | 0.0 | ... |
| 0040           | 1991 Jun 28| 1991 Jul 12| 10.8 ± 3.9 | 3.5 | ... |
| 0110           | 1991 Oct 03| 1991 Oct 17| <25.0 | 0.0 | ... |
| 204+           | 1992 Dec 22| 1993 Jan 12| 23.4 ± 10.7 | 2.8 | ... |
| 2180           | 1993 Apr 20| 1993 May 05| 13.7 ± 6.9 | 2.5 | ... |
| 34220          | 1993 May 24| 1993 May 31| <35.0 | 0.2 | ... |
| 304+           | 1993 Oct 19| 1993 Oct 25| 15.4 ± 4.7 | 4.2 | ... |
| 3086           | 1993 Nov 23| 1993 Dec 01| 28.1 ± 9.4 | 4.3 | 2.02 ± 0.47 |
| 311+           | 1993 Dec 13| 1993 Dec 20| 17.4 ± 6.9 | 3.1 | ... |
| 3130           | 1993 Dec 27| 1994 Jan 03| 30.9 ± 12.7 | 3.1 | ... |
| 3220           | 1994 Apr 05| 1994 Apr 19| 12.2 ± 7.0 | 2.2 | ... |
| 3260           | 1994 May 10| 1994 May 17| 32.0 ± 13.0 | 3.6 | ... |
| 4060           | 1994 Dec 13| 1994 Dec 20| <56.4 | 0.2 | ... |
| 4180           | 1995 Apr 25| 1995 May 09| 53.6 ± 14.1 | 5.3 | 1.88 ± 0.29 |
| 5150           | 1996 Feb 20| 1996 Mar 05| 19.2 ± 7.1 | 3.3 | 2.54 ± 0.56 |
| 7155           | 1998 Mar 20| 1998 Mar 27| 38.2 ± 19.3 | 2.7 | 1.27 ± 0.58 |
| 9111           | 2000 Feb 23| 2000 Mar 01| <107.2 | 0.0 | ... |

Note.--The flux is the greater than 100 MeV flux in units of 10\(^{-8}\) photons cm\(^{-2}\) s\(^{-1}\); the spectral index \(\alpha\) is the photon index. Upper limits are at the 2\(\sigma\) level.

Fig. 1.—Lower panel: EGRET light curve of W Comae over the entire lifetime of CGRO. Upper panel: Best-fit spectral indices (photon indices) of some of the most significant EGRET detections.

3. SPECTRAL MODELING OF W COMAE USING LEPTONIC MODELS

For the purpose of spectral modeling using a generic leptonic jet model, it is assumed that a population of ultrarelativistic, nonthermal electrons and positrons is injected instantaneously into a spherical emitting volume of comoving radius \(R_b\). The injected pair population is specified through a comoving density \(n_e\), low- and high-energy cutoffs \(\gamma_1\) and \(\gamma_2\), respectively, and a spectral index \(p\), so that \(n_e(\gamma) = K\gamma^{-p}\) for \(\gamma_1 \leq \gamma \leq \gamma_2\) at the time of injection. The location of the injection site is characterized by its height \(z_i\) above the plane of a central accretion disk for which we
have assumed a bolometric luminosity of $L_D = 10^{45}$ ergs s$^{-1}$. A magnetic field $B_0$ at the point of injection is chosen in equipartition with the nonthermal pair distribution at the time of injection and decreases as $B = B_0 (z/z_i)^{-1}$. The emitting region moves with relativistic speed $v/c = \beta_T = (1 - 1/\Gamma^2)^{1/2}$ along the jet, which is directed at a small angle ($\theta_{\text{obs}} = 1'$) with respect to the line of sight. The choice of a very small observing angle implies that the observer is located within the beaming cone of relativistically beamed emission from the emitting region for all values of $\Gamma$ considered here and is consistent with the moderate superluminal motion of $\beta_{\text{app}} \lesssim 2$ and the Massaro et al. (2001) result concerning the occasional two-sidedness of the radio structure observed in W comae, as mentioned in § 1.

The Doppler boosting of emission from the comoving to the observer’s frame is determined by the Doppler factor $D = (\Gamma(1 - \beta \cos \theta_{\text{obs}}))^{-1}$.

Using the time-dependent radiation transfer code of Böttcher, Mause, & Schlickeiser (1997) and Böttcher & Bloom (2000), we follow the evolution of the electron population and the radiation spectra as the emission region moves outward along the jet. Radiation mechanisms included in our simulations are synchrotron emission, Compton upscattering of synchrotron photons (SSC scattering; Marscher & Gear 1985; Maraschi, Celotti, & Ghisellini 1992; Bloom & Marscher 1996) and Compton upscattering of external photons (external Compton [EC] scattering), including photons coming directly from the disk (Melia & Königl 1989; Dermer, Schlickeiser, & Mastichiadis 1992; Dermer & Schlickeiser 1993), as well as reprocessed photons from the broad-line region (Sikora, Begelman, & Rees 1994; Blandford & Levinson 1995; Dermer, Sturner, & Schlickeiser 1997). The broad-line region is modeled as a spherical shell between $r_{\text{BLR, in}} = 0.2$ pc and $r_{\text{BLR, out}} = 0.25$ pc, and a radial Thomson depth $\tau_{T, \text{BLR}}$, which is considered a free parameter.

The most rapid variability has been observed in soft X-rays, where approximately symmetric flare profiles on a timescale of $\sim 10$ hr have been seen (Tagliaferri et al. 2000). This constrains the size of the emission region to be $R_0 \lesssim D \times 10^{15}$ cm. For typical Doppler factors of $D \sim 10$, this motivates our choice of $R_0 = 10^{16}$ cm, which we adopt throughout this paper.

Fig. 2.—Four-point EGRET spectra during the most significant EGRET detections of W Comae. The lines show the power-law fits to those spectra.
The assumption that the magnetic field is in approximate equipartition with the emitting electron/positron population allows an independent estimate of the comoving magnetic field: a power-law population of electrons with spectral index $p$, emitting a synchrotron $\nu F_\nu$ peak flux of $\nu F_\nu^{pk} = 10^{-10} f_{-10}$ ergs cm$^{-2}$ s$^{-1}$ at a dimensionless photon energy $\nu \epsilon^{pk} = h\nu F_\nu^{pk}/(m_e c^2) = 10^{-6} - \epsilon_{-6}$, requires a magnetic field of

$$B = 9 \left( \frac{D}{10} \right)^{-1} \left( \frac{d_{27}}{f_{-10}} \right)^{2/7} \left( \frac{2/7}{1 + z} \right) \left( \frac{2/7}{c^{1/3} \epsilon_{-6}^{1/3} R_{BLR}^{1/3} (p - 2)^{3/7}} \right) G,$$

where $d_{27}$ is the luminosity distance in units of $10^{27}$ cm, $\epsilon_{-6}$ is the magnetic-field equipartition factor, and $R_{BLR}$ is $R_B$ in units of $10^{15}$ cm. For $d_{27} = 1.45$, $f_{-10} \sim 1$, $\epsilon_{-6} \sim 1$ (corresponding to equipartition), and $R_{BLR} = 10$ (corresponding to a peak frequency in the near-infrared), $R_{BLR} = 10$, and $p \sim 2.5$, we find $B_{\text{eq}} \sim 1.8$ G, which is within a factor of $\sim 2$ of the values quoted in Table 2. The above value of $B_{\text{eq}}$ implies a synchrotron cooling timescale (in the observer’s frame) of electrons emitting synchrotron radiation at an observed energy $E_{150}$ of $1 E_{\text{keV}}$ keV of

$$\tau_{150} \approx 0.12 \left( \frac{B}{1.8 \, G} \right)^{-3/2} \left( \frac{D}{10} \right)^{-1/2} E_{\text{keV}}^{-1/2} \, \text{hr},$$

which, for X-ray photon energies, is shorter than the dynamical timescale $R_B/(Dc)$, in agreement with the approximately symmetric shape of the X-ray light curves. Since the optical–$\gamma$-ray spectrum constitutes a time average over a timescale of $\tau \gtrsim 20$ hr, we expect to observe the time-averaged emission from a strongly cooled electron...
population down to synchrotron energies of
\[ E_c = 3.5 \times 10^{-2} \tau_{20}^2 \left( \frac{B}{1.8 \, \text{G}} \right)^{-3} \left( \frac{D}{10} \right)^{-1} \, \text{eV}, \]  
which is in the infrared range. In equation (3), \( \tau_{20} = \tau / (20 \, \text{hr}) \). If additional electron cooling mechanisms play a significant role (see § 5), the cooling timescale \( \tau \) will obviously be shorter than \( \tau_{20} \), further strengthening the argument for time-averaged emission observed beyond infrared frequencies.

4. SPECTRAL MODELING RESULTS AND PREDICTIONS FOR VHE EMISSION

Since the EGRET detection of W Comae during 1998 May was of rather low significance (see § 2) and not quite simultaneous to the BeppoSAX observation, and in view of the uncertainty of the source identification, we first focus on the simultaneous optical–X-ray spectrum. As the simplest possible variation of the leptonic jet model, we attempt to model this spectrum using a strongly SSC-dominated model in which we neglect any soft-photon input from the broad-line region (i.e., we set \( \tau_{T,\text{BLR}} = 0 \)). As a first guess, we fix a bulk Lorentz factor of \( \Gamma = 10 \), yielding \( D = 19.41 \). We then start out by choosing an arbitrary value of \( \gamma_1 \) and try to adjust the model parameters \( \gamma_2, p, \) and \( n_e \), so that a good fit to the optical–X-ray spectrum of W Comae is achieved. We find that this is possible for values of \( 500 \leq \gamma_1 \leq 2000 \). Curves 1–5 in Figure 3 illustrate the resulting model fits for a sequence of models with \( \gamma_1 \) in the above range. For substantially lower values of \( \gamma_1 \), our model spectra become too flat to join the optical and X-ray spectra. The model parameters for each simulation are listed in Table 2. The last column in Table 2 lists the integrated photon fluxes from those models at energies \( E > 40 \, \text{GeV} \). The table indicates that different SSC model fits to the optical–X-ray spectrum of W Comae predict levels of VHE emission which differ by a factor of more than 10.

In a second step, we investigate how much our results depend on the (rather arbitrary) choice of \( \Gamma = 10 \) adopted above. To this aim, we now fix an intermediate value of \( \gamma_1 = 1000 \) from the previous models and attempt to find model fits for different values of \( \Gamma \). Specifically, we repeat the fitting procedure for \( \Gamma = 4 \) and \( \Gamma = 15 \), corresponding to \( D = 7.78 \) and \( D = 28.05 \), respectively. Again, we do not encounter any fundamental problem in finding appropriate model parameters to provide a good fit to the optical–X-ray spectrum of W Comae. Similar to the previous series of fits, the two new model fits predict levels of VHE emission differing by about an order of magnitude. The fit results are shown as curves 6 and 7 in Figure 3.

Figure 3 illustrates another very interesting result: although the different SSC model fits predict very different levels of greater than 40 GeV emission, they all cut off around 100 GeV. Thus, no greater than 100 GeV emission is predicted by any of our model fits. This is related to the high-energy cutoff of the synchrotron component, which is very well constrained by the high-quality X-ray spectrum observed by BeppoSAX. Table 2 indicates that there is a certain degree of anticorrelation between \( \gamma_1 \) and \( \gamma_2 \). As mentioned above, the minimum allowed value for \( \gamma_1 \) is rather well defined, so that we do not have the freedom to choose very low values of \( \gamma_1 \) in order to attempt to find acceptable fits with very large values of \( \gamma_2 \) that would be able to produce substantially higher VHE cutoffs.

As pointed out by Tagliaferri et al. (2000), a pure SSC model fit to the 1998 SED of W Comae produces a \( \gamma \)-ray spectrum that is incompatible with the EGRET spectrum if the spectral index resulting from this low-significance detection is to be trusted. The fact that EGRET detections of the source during other viewing periods yielded similar spectral shapes in the 0.1–10 GeV regime (§ 2) provides some circumstantial evidence that there might indeed be a separate high-energy emission component producing a spectral bump centered at a peak energy of \( E_{\text{pk},\gamma} \approx 10 \, \text{GeV} \). In the framework of our generic SSC model, this can be plausibly related to an EC component. In Figure 4, we illustrate how the overall spectral shape of our model fit 1 (see Fig. 3 and Table 2) changes if an EC component due to soft photons reprocessed in the broad-line region is included in the model. The radio–hard X-ray emission from the different models remains virtually invariant under the inclusion of the EC component. The EGRET spectrum can be very well accommodated assuming a radial Thomson depth of our model BLR of \( \tau_{T,\text{BLR}} = 3 \times 10^{-3} \). This would raise the predicted greater than 40 GeV flux from the model by a factor of \( \approx 3 \) compared to the pure SSC model with otherwise identical parameters. The sharp cutoff of the VHE emission around \( \approx 100 \, \text{GeV} \) remains unchanged even with the inclusion of the EC component. The low-energy cutoff of the EC component is caused by the sharp cutoff in the electron injection function at \( \gamma_1 \). This cutoff is maintained in the evolving electron distribution throughout the simulation because the radiative cooling timescale for electrons of energy \( \gamma \approx \gamma_1 \) is much longer than the dynamical timescale for the parameters used here.

From this analysis, we can conclude that pure spectral modeling of the optical–X-ray emission of W Comae is insufficient to make reliable predictions about the expected level of VHE emission at greater than 40 GeV from this object. In the next section, we illustrate how the combination of spectral and X-ray variability information can be used to put significantly tighter constraints on the expected level of VHE emission—even without independent information about the \( \gamma \)-ray emission.

5. X-RAY VARIABILITY

Apart from the spectral information, the BeppoSAX X-ray observations of 1998 May revealed variability in the soft band (0.1–4 keV), dominated by a broad flare with a rise time of \( \approx 7 \, \text{hr} \) and a decay time of \( \approx 10 \, \text{hr} \) (see Tagliaferri et al. 2000, Fig. 2), corresponding to \( \approx 6 \) and \( \approx 9 \, \text{hr} \) in the cosmological rest frame of the source. In the hard band (4–10 keV), no significant variability was detected. Because of the limited photon statistics, local spectral indices or hardness ratios within the soft and hard bands could not be extracted with useful temporal resolution. However, such information might become available through observations with the new generation of X-ray telescopes, in particular XMM-Newton and Chandra. For this reason, we are now investigating generic light curves and spectral variability signatures at X-rays resulting from the different model fits to W Comae presented in the previous section.

To do so, we use a code that is based on the jet radiation transfer code of Böttcher et al. (1997) and Böttcher &
Bloom (2000) but accounts for time-dependent electron acceleration and/or injection throughout the evolution of the emitting region as it moves outward along the jet. A detailed code description as well as a parameter study for various generic model situations will be presented in Böttcher & Chiang (2002). The numerical approach is very similar to the one used by Li & Kusunose (2000), who had investigated the broadband spectral variability features in a pure SSC model for flaring blazars, but our code allows for the additional electron cooling and photon emission from EC scattering (both direct accretion-disk photons and accretion-disk emission reprocessed in the broad-line region) and takes into account $\gamma\gamma$ absorption intrinsic to the source, including the corresponding pair production.

In order to investigate a generic spectral-variability model for W Comae, we assume that the electron injection during a flare occurs at a constant rate over one dynamical timescale $t_{dyn} = R_B/c$ in the comoving frame and then proceeds at a lower rate, corresponding to the quiescent emission outside the flaring episode. Consequently, the parameters pertaining to the relativistic electron distributions quoted in Table 2 correspond to flaring injection luminosities of $L_{inj}^{fit} = 3 \times 10^{41}$ erg s$^{-1}$ (fit 1) to $L_{inj}^{fit} = 2.6 \times 10^{42}$ ergs s$^{-1}$ (fit 5). We choose a quiescent injection luminosity of $L_{inj}^{stat} = 10^{40}$ ergs s$^{-1}$.

Figure 5 illustrates the time-dependent photon spectra resulting from these simulations corresponding to spectral fits 1 (SSC model with the lowest SSC flux of the fits shown in Fig. 3), 5 (SSC model with the highest SSC flux of the fits shown in Fig. 3), and 10 (complete SSC+EC model with the largest EC contribution of the fits shown in Fig. 4). Figure 6 shows the light curves in the $R$ band and at four different X-ray energies resulting from the same time-dependent simulations. The figure illustrates that the light curves corresponding to fits 1 and 5 are qualitatively very different. The almost symmetric shape of the observed light curve is clearly not reproduced by the SSC-dominated case 5. However, no significant difference in the optical and X-ray light curves results from the inclusion of an EC component, even in the most extreme case of spectral fit 10 (with $T_{BLR} = 10^{-2}$).

Note, however, that even in this case, the bolometric luminosity (and, consequently, the electron cooling) is still dominated by the synchrotron component, which may explain the fact that it has only a negligible impact on the low-frequency light curves.

In Figure 7, we show tracks in the hardness-intensity diagrams (monenergetic flux, normalized to the peak flux, vs. energy spectral index $\alpha$), produced in the different model situations. As with the light curves shown in Figure 6, the synchrotron-dominated case 1 should be clearly distinguishable from the SSC-dominated case 5, while the inclusion of an EC component leaves the hardness-intensity tracks virtually unchanged.

In the simulations above, we have assumed the simplest possible time dependence of the electron acceleration, namely, a step function. Li & Kusunose (2000) have also touched on the issue of different intrinsic injection functions and found the effect on the light curves is only of minor importance, if the total duration of the flare injection event is on the same order of magnitude as the dynamic timescale and the total injected energy remains unchanged. From this, we may conclude that our results do not strongly depend on the detailed shape of the injection profile, at least to the degree of accuracy with which the soft X-ray variability could be measured by BeppoSAX.

In summary, our modeling results indicate that cooling of the ultrarelativistic electron and/or pair plasma in the jet is synchrotron- and/or EC-dominated. The most realistic model parameters therefore seem to be close to simulations 1 or 2, with a possible moderate contribution due to EC scattering, depending on whether the observed EGRET flux from 3EG J1222+2848 is indeed related to W Comae. Consequently, we predict a greater than 40 GeV flux from W Comae of $(0.4-1) \times 10^{-10}$ photons cm$^{-2}$ s$^{-1}$ with no significant emission at $E \geq 100$ GeV. Note, however, that our conclusions about the X-ray variability have so far only been
6. COMPARISON TO HADRONIC MODELS

An alternative to leptonic models are the so-called hadronic models proposed to explain \( \gamma \)-ray emission from blazars. 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. Here we use the hadronic synchrotron-proton blazar (SPB) model of Mücke et al. (2002) to model the spectral energy distribution of W Comae in 1998 May.

As in the leptonic model, the emission region, or "blob," in an active galactic nucleus jet moves relativistically along the jet axis, which is closely aligned with our line of sight. Relativistic (accelerated) protons, whose particle density \( n_p \) follows a power-law spectrum proportional to \( \gamma_p^{-\alpha} \) 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 suffer energy losses because of proton-photon interactions (meson production and Bethe-Heitler pair production), synchrotron radiation, and adiabatic expansion. The mesons produced in proton-photon interactions always decay in astrophysical environments; however, they may suffer synchrotron losses before the decay, which is taken into account in this model.

The relativistic primary \( e^- \) radiates synchrotron photons that manifest themselves in the blazar SED as the synchrotron hump and serve as the target radiation field for photon-photon interactions and the pair-synchrotron cascade that 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 redistributes 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 \( \pi^\pm \to e^\pm \) decay ("\( \pi^\pm \) cascade"), \( p \)-synchrotron photons ("\( p \)-synchrotron cascade"), charged \( \mu^- \), \( \pi^- \), and \( K \)-synchrotron photons ("\( K^- \)-synchrotron cascade"), and \( e^\pm \) from the proton-proton Bethe-Heitler pair production ("Bethe-Heitler cascade ").

Mücke & Protheroe (2001) and Mücke et al. (2002) have shown that the \( \pi^0 \) and \( \pi^\pm \) cascades generate rather featureless photon spectra, in contrast to \( p^- \) and \( \mu^- \)-synchrotron cascades that produce a double-humped SED as typically observed for \( \gamma \)-ray blazars. The contribution from the Bethe-Heitler cascades is mostly negligible. In general, direct proton and muon synchrotron radiation is mainly responsible for the high-energy hump in blazars, whereas the low-energy hump is dominated by synchrotron radiation from the primary \( e^- \), with a contribution of synchrotron radiation from secondary electrons (produced by the \( p^- \) and \( \mu^- \)-synchrotron cascade). A detailed description of the model itself, and its implementation as a (time-independent) Monte Carlo/numerical code, has been given in Mücke & Protheroe (2001).

For the modeling of the 1998 SED of W Comae we have fixed the effective size scale of the emission region to \( R_b = \frac{1}{4} c \tau_{\text{var}} D \), where \( \tau_{\text{var}} \approx 10 h \) is the measured soft \( \gamma \)-ray variability timescale. We consider bulk Doppler factors in the range \( D = 5 - 20 \) for the fitting procedure, which is consistent with the moderate superluminal motion detected by Massaro et al. (2001). The primary relativistic electrons emit synchrotron photons, which serve as the target photon field for photon-proton interactions and cascading. The synchrotron spectrum from these electrons shows a break at around \( 10^{13} \) Hz, where the synchrotron cooling timescale \( \tau_{\text{syn}} \approx 8 \times 10^8 (B/1 \text{ G})^{-2} \gamma^{-1} \) s equals the adiabatic loss timescale \( \tau_{\text{ad}} \approx \xi R_b/c \) for a relativistic jet with \( \xi \leq 1 \), taking into account a possible nonspherical geometry, the effects of

![Figure 7](https://example.com/figure7.png)

Fig. 7.—Tracks in the hardness-intensity plane resulting from the time-dependent simulations corresponding to spectral fits 1, 5, and 10, at three different X-ray energies. While the SSC-dominated model 5 produces drastically different tracks in the hardness-intensity plane than the synchrotron-dominated cases, there is no significant difference due to the addition of a moderate EC component (fit 10).
Fig. 8.—Various model fits to the SED of W Comae in 1998 March/May, using the hadronic SPB model. All models are corrected for absorption in the cosmic background radiation field using the background models in Aharonian (2001). The two high-frequency branches of the model curves indicate the resulting fluxes using the two extreme background models in Aharonian (2001). The target photon field for p-γ interactions is the primary electron synchrotron photon field, approximated by broken power laws with break energies $\epsilon_{b1} = 0.06$ eV, $\epsilon_{b2} = 173$ eV in the observer frame and photon spectral indices $\alpha_1 = 0.9$, $\alpha_2 = 2.45$, and $\alpha_1 = 2.6$. This target photon field is used as an input into the Monte Carlo code to predict the high-energy component. For the complete list of model parameters, see Table 3.

Fig. 9.—Emerging cascade spectra for SPB model 3: $p$ synchrotron cascade (dashed line), $\pi$ synchrotron cascade (solid line), $\text{π}^0$ cascade (dotted line), $\text{π}^-\text{ cascade}$ (dash-dotted line), and total (solid line). All model fluxes are corrected for absorption in the cosmic photon background as described in Fig. 8.

The target photon energy density in the jet frame is $\sim 10^{18}$–$10^{19}$ eV cm$^{-3}$. Because proton-synchrotron losses dominate in the high-energy region over pion production losses (see Fig. 10), the model predicts the main power output at several 100 MeV because of proton-synchrotron radiation, with a strong steepening by about 2 orders of magnitude in the GeV range, and γ-ray emission from the $\pi^0$-cascades extending up to about 100 TeV with a break at about 10 TeV at the source. Photons above $\sim 100$ GeV (in the comoving frame) will be subject to $\gamma\gamma$ absorption within the emission region and initiate electromagnetic cascades in the jet (see Fig. 12). Absorption of multi-GeV/TeV photons in the cosmic background radiation field will further alter the observed spectrum; the optical depth exceeds unity above 300–700 GeV for W Comae. The predicted photon flux above 40

In the framework of the hadronic SPB model the hard X-ray spectrum can naturally be explained by strong synchrotron emission from the relativistic protons, provided strong magnetic fields $B$ of several tens of Gauss exist in the emission region. For the modeling (models 3–5) we use $B = 30–40$ G, $\alpha_p = 1.5$, $\gamma_{p,\text{max}} = (5–10) \times 10^4$, a number density ratio of primary, relativistic electrons to protons, $e/p \approx 0.1$, and a proton energy density $u_p \approx 60–150$ ergs cm$^{-3}$, somewhat above the equipartition value, which is not surprising during activity in the source (for model 3, see Fig. 9). With Doppler factors $D = 12–15$,
The neutrino power at 10^{10} GeV is about as described in Fig. 8. Model fluxes are corrected for absorption in the cosmic photon background (dotted line) cascades (however, not dashed line cascades (however, not). The absorption in the cosmic photon background models in Aharonian 2001.

If the intrinsic target photon density increases to \sim 10^{11} - 10^{12} eV cm^{-3}, muon and pion production, and therefore also muon and pion synchrotron radiation, dominates over proton-synchrotron radiation (see Fig. 10). This might have been the case during the EGRET observations (see Fig. 8, models 1 and 2, and Fig. 11).

Because pions and muons possess a lower rest mass with respect to protons, their synchrotron emission peaks at higher photon energies than the protons’ synchrotron radiation for the same particle Lorentz factors and magnetic fields. The parameters used for the models representing the EGRET data (models 1 and 2) are \( D = 8 - 10, \quad B = 40 \) G, \( \alpha_p = 1.5 - 2, \quad \gamma_p, \max = (1 - 3) \times 10^2 \). This main power output in the high-energy regime for models 1 and 2 lies therefore at \sim 10 GeV and is somewhat higher at IR energies. For these parameters, photons beyond a few tens of GeV (in the comoving frame) will be subject to \( \gamma \gamma \) absorption and initiate electromagnetic cascades (see Fig. 12). Also, the model predicts TeV emission from the \( \pi \) cascades (however, not extending above 1 TeV), which, however, will partly be absorbed in the cosmic photon background.

Models involving meson production inevitably predict neutrino emission because of the decay of charged mesons. The SPB model for W Comae in 1998 predict a \( \nu_\mu + \bar{\nu}_\mu \) output of about \( 10^{-7} \) GeV s^{-1} cm^{-2} peak at around \( 10^{8.5} - 10^{9} \) GeV. The neutrino power at 10^{8} GeV is about \( 10^{-11} \ldots 10^{-10} \) GeV cm^{-2} s^{-1}. No neutrino flavor oscillations are assumed here.

In summary, the hadronic SPB model predicts TeV emission on a flux level near the detectability capabilities of CELESTE and STACEE for W Comae, but clearly above the sensitivity limit of future instruments like VERITAS. While leptonic models predict integral fluxes at greater than 40 GeV for W Comae on a similar level as hadronic models do, TeV emission detectable with very high sensitivity instruments is only predicted for the hadronic emission processes. This is in contrast to leptonic models and may therefore be useful as a diagnostic to distinguish between the hadronic and leptonic nature of the high-energy emission from W Comae, in addition to its possible neutrino emission.
7. SUMMARY

We have presented detailed modeling of the best currently available simultaneous broadband SED of the radio-selected BL Lac object W Comae, comparing state-of-the-art leptonic and hadronic jet models. The richest and most detailed portion of the SED consists of the BeppoSAX LECS+MECS+PDS spectrum from ~0.1 to 100 keV, measured in 1998 May (Tagliaferri et al. 2000). It showed the low-energy (synchrotron) component extending out to ~4 keV, exhibiting significant variability on timescales of ~10 hr, and the onset of the high-energy component beyond ~4 keV, with no evidence for short-term variability. The SED was supplemented by simultaneous radio and optical flux measurements, as well as a weak EGRET detection in 1998 March, i.e., about 2 months before the BeppoSAX spectrum was taken. We have done a careful reanalysis of all available EGRET pointings on W Comae and confirmed that the source exhibited an unusually hard GeV spectrum during the 1998 March observation, with a photon spectral index of $\alpha = 1.27 \pm 0.58$.

Our fits using leptonic jet models yielded the following main results:

1. Acceptable fits to the optical to hard X-ray spectrum of W Comae are possible with a rather wide range of parameters in a synchrotron self-Compton–dominated model. In agreement with earlier results of Tagliaferri et al. (2000), we find that such fits are generally inconsistent with the (not quite simultaneous) EGRET spectrum of 1998 March, as well as the average spectrum over the entire lifetime of EGRET.

2. The different SSC fits to the optical/hard X-ray spectrum of W Comae in 1998 May result in greater than 40 GeV fluxes of ~$10^{-1}$ photons cm$^{-2}$ s$^{-1}$, but virtually no emission beyond ~100 GeV.

3. Including the information contained in the X-ray variability measured by BeppoSAX, we can narrow down the range of possible leptonic model parameters to predict greater than 40 GeV fluxes of ~$10^{-1}$ photons cm$^{-2}$ s$^{-1}$.

4. In order to reproduce the 1998 March EGRET spectrum together with the 1998 May BeppoSAX spectrum, an EC component is required. Such fits result in greater than 40 GeV fluxes of ~$10^{-1}$ photons cm$^{-2}$ s$^{-1}$ and a strong cutoff at ~100 GeV, as in the case of SSC-dominated models.

Successful fits to the SED of W Comae were also possible using the hadronic synchrotron-proton blazar model, yielding the following main results:

5. A model with proton-synchrotron–dominated hard X-ray to GeV $\gamma$-ray emission is well suited to reproduce the entire radio-hard X-ray spectrum of W Comae in 1998 May. As with the SSC-dominated leptonic models, it is consistent with both the 1998 March and the average EGRET spectrum from the source.

6. The hadronic fit to the radio-hard X-ray spectrum of W Comae predicts a greater than 40 GeV flux of ~$(0.7-1.4) \times 10^{-10}$ photons cm$^{-2}$ s$^{-1}$, i.e., of the same order as the predictions of the leptonic jet models. However, in contrast to the leptonic models, the high-energy emission is expected to extend beyond 1 TeV at a flux level of $\Phi_{>1 \text{TeV}} \sim (3-18) \times 10^{-14}$ photons cm$^{-2}$ s$^{-1}$. Such a flux level is well within the reach of future high-sensitivity instruments like VERITAS.

7. SPB models consistent with the 1998 March EGRET spectrum underpredict the 1998 May BeppoSAX PDS hard X-ray spectrum. They result in greater than 40 GeV fluxes of ~$(5-13) \times 10^{-10}$ photons cm$^{-2}$ s$^{-1}$, but weaker TeV fluxes of $\Phi_{>1 \text{TeV}} \sim (0.7-9) \times 10^{-14}$ photons cm$^{-2}$ s$^{-1}$. In this case, STACEE and CELESTE may be able to get a weak detection of the source, and it would still be a promising candidate for detection by the future VERITAS array.

In conclusion, leptonic and hadronic jet model fits to W Comae make drastically different predictions with respect to the expected very high energy emission beyond ~100 GeV. A detection of W Comae at those photon energies with future, high-sensitivity air Cerenkov detector arrays would pose a serious challenge to leptonic jet models and might favor hadronic models instead.

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