EVIDENCE FOR INTERGALACTIC ABSORPTION IN THE TeV GAMMA-RAY SPECTRUM OF MARKARIAN 501

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ABSTRACT

The recent High-Energy Gamma-Ray Array (HEGRA) observations of the blazar Mrk 501 show strong curvature in the very high energy γ-ray spectrum. Applying the γ-ray opacity derived from an empirically based model of the intergalactic infrared background radiation field to these observations, we find that the intrinsic spectrum of this source is consistent with a power law: \( dN/dE \propto E^{-\alpha} \), with \( \alpha = 2.00 \pm 0.03 \) over the range 500 GeV–20 TeV. Within current synchrotron self-Compton scenarios, the fact that the TeV spectral energy distribution of Mrk 501 does not vary with luminosity, combined with the correlated, spectrally variable emission in X-rays as observed by the BeppoSAX and Rossi X-Ray Timing Explorer instruments, also independently implies that the intrinsic spectrum must be close to \( \alpha = 2 \). Thus, the observed curvature in the spectrum is most easily understood as resulting from intergalactic absorption.

Subject headings: BL Lacertae objects: individual (Markarian 501) — galaxies: active — gamma rays: theory

1. INTRODUCTION

Imaging air Čerenkov telescopes are currently able to detect γ-ray photons of TeV (10^{12} eV) energy from BL Lac objects within 1 hr of observation and to measure their spectra using a few hours of a good data (for a review, see Weekes et al. 1997). The objects of this class detected to date are, in order of increasing redshift: Mrk 421 (\( z = 0.031 \)) (Punch et al. 1992; Petry et al. 1996), Mrk 501 (\( z = 0.034 \)) (Quinn et al. 1996; Bradbury et al. 1997), 1ES 2344+514 (\( z = 0.044 \)) (Catanese et al. 1998), and PKS 2155–304 (\( z = 0.117 \)) (Chadwick et al. 1999). Measurements of the spectrum can be made over the energy range from 200 GeV to ~10 TeV using this technique. Because these photons interact with infrared radiation to form electron-positron pairs, the signal is expected to be attenuated by absorption both within the source itself and in the intergalactic medium. Thus, it is possible to use the observations to study the intergalactic infrared radiation field (IIRF), given some general, model-dependent constraints on the spectrum intrinsic to the source (Stecker, De Jager, & Salamon 1992; MacMinn & Primak 1996). Determining the IIRF, in turn, allows one to model the evolution of the galaxies that produced it.

In this Letter, we analyze recent observations of the object Mrk 501 (Konopelko et al. 1999a) that are unique both for the quality of the spectra obtained and their energy range (up to 20 TeV). These data, taken during a period in which the intensity of the source varied strongly, show a pronounced curvature in the spectrum, being significantly softer (steeper) toward higher energy. We unfold these data using the upper curve for the spectral energy distribution of the IIRF given by Malkan & Stecker (1998), with the corresponding γ-ray opacity as calculated by Stecker & De Jager (1998, hereafter SD98) and find that the intrinsic spectrum is flat, \( dN/dE \propto E^{-2} \). The implications of this result for both the absorption model and the synchrotron self-Compton emission model are discussed.

2. MEASUREMENT OF SPECTRUM OF Mrk 501

The BL Lac object Mrk 501 exhibited strong emission in TeV γ-rays from 1997 March to October (Protheroe et al. 1998). During this period, the source was continuously monitored by several ground-based imaging air Čerenkov telescopes (IACTs), including the High-Energy Gamma-Ray Array (HEGRA) stereoscopic system of four IACTs (Aharonian et al. 1997a), which observed it for a total exposure time of 110 hr (Aharonian et al. 1999). The unprecedented statistics of ~38,000 TeV photons, combined with the good energy resolution of ~20% over the entire energy range and with detailed studies of the detector performance (Konopelko et al. 1999b), allowed a determination of the spectrum in the energy range 500 GeV–24 TeV (Konopelko et al. 1999a). The Mrk 501 energy spectrum measured by the HEGRA collaboration extends well beyond 10 TeV, where uncertainties related to the saturation effect could in principle play a role. Various data consistency checks were performed in order to avoid these effects. In addition, simultaneous observations of the Crab Nebula (the standard-candle TeV source) were undertaken from 1997 September to 1998 March. Using similar data analysis, the Crab Nebula spectrum derived from the HEGRA data was found to be a pure power law with a differential spectrum index of 2.6 over the energy range 500 GeV–23 TeV (Konopelko et al. 1998). These results are consistent with previous measurements by the Cangaroo group in the energy range 7–50 TeV (Tanimori et al. 1998).

The flux of γ-rays from Mrk 501, averaged over the entire observation period, was about 3 times that of the Crab Nebula (3 crab). Averaged over each day, the γ-ray rate showed strong variations, with a maximum of 10 crab detected on 1997 June 26/27. As remarked by Aharonian et al. (1997b), the hardness ratio of the steepening Mrk 501 spectrum appears to be independent of the absolute flux. The high γ-ray detection rate provided event statistics of a few hundreds within 1 day’s observations (~3–5 hr), which suffices to evaluate the energy...
spectrum over the range 1–10 TeV. The analysis of the spectral shape on a daily basis did not reveal any substantial correlation between the γ-ray flux and the spectral behavior (Aharonian et al. 1999). This justifies the presentation of a time-averaged energy spectrum of Mrk 501 in its active state, which is shown in Figure 1 over the energy range from 500 GeV to 24 TeV. The vertical error bars in this figure correspond to statistical errors. Note that the systematic errors at energies below 1 TeV appear to be quite large, reaching ~50% at 500 GeV.

Over the entire range, the spectrum shows a gradual softening toward higher energy. The 19–24 TeV energy bin contains a signal with a significance of 3.7σ. However, the steep energy spectrum and 20% energy resolution do not permit one to exclude the interpretation that these γ-rays may have spilled over from the lower energy bins. Therefore, the energy spectrum is consistent with the hypothesis of a maximum energy for the detected γ-rays of ~18 TeV. The shape of the energy spectrum is well described by a power law with an exponential cutoff. A fit of the data over the energy region in which the systematic errors are small, i.e., from 1 to 24 TeV, gives

\[ dN/dE = AE^{-\alpha} \exp(-E/E_0) \, \text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}, \tag{1} \]

where

\[ A = 9.7 \pm 0.3 \, \text{(stat)} \pm 2.0 \, \text{(syst)} \times 10^{-11}, \]
\[ \alpha = -1.9 \pm 0.05 \, \text{(stat)} \pm 0.05 \, \text{(syst)}, \]
\[ E_0 = 5.7 \pm 1.1 \, \text{(stat)} \pm 0.6 \, \text{(syst)} \, \text{TeV}. \]

The logarithmic slope of the energy spectrum (“power-law index”) is 1.8 in the energy range 1–5 TeV and 3.7 above 5 TeV.

Independent measurements of the Mrk 501 TeV energy spectrum by the Whipple Observatory (Samuelson et al. 1998) are in very good agreement with these results. The best fit to the data presented by the Whipple group agrees precisely with a fit to the HEGRA data in the energy range 500 GeV–10 TeV. However, the HEGRA group measured the spectrum well above 10 TeV, where it exhibits a further steepening.

3. ABSORPTION ON THE DIFFUSE INTERGALACTIC INFRARED BACKGROUND

The formulae relevant to absorption calculations involving pair production are given and discussed in Stecker et al. (1992). For γ-rays in the TeV energy range interacting at redshifts \( z \ll 1 \), the pair-production cross section is maximized when the soft photon energy is in the infrared range:

\[ \lambda(E_{\gamma}) \approx \frac{E_{\gamma}}{2m_c^2} = 2.4E_{\gamma,\text{TeV}} \mu\text{m}, \tag{2} \]

where \( \lambda_c = h/(mc) \) is the Compton wavelength of the electron. For a 10 TeV γ-ray, this corresponds to a soft photon in the mid-infrared region of the spectrum, having a wavelength around 24 μm. Pair-production interactions take place with photons over a range of wavelengths around the optimal value, as determined by the energy dependence of the cross section. SD98 have computed the absorption coefficient of intergalactic space using a new, empirically based calculation of the spectral energy distribution of intergalactic low-energy photons (Malcan & Stecker 1998). Assuming that the IIRF is basically in place by a redshift \( z \sim 0.3 \), having been produced primarily at higher redshifts (Stecker & De Jager 1997; SD98; Madau 1995), SD98 limited their calculations to \( z < 0.3 \). Evolution in stellar emissivity affects the predicted IIRF and is expected to level off or decrease at redshifts greater than \( z \\sim 1.5 \) (Madau 1996). In this Letter, we assume that evolution continues up to \( z = 2 \), leading to the higher of the two IIRFs used by SD98. This is more consistent with recent data on IR galaxy evolution, dust absorption, and the lower limits from IR galaxy counts (Stecker 1999). To compute the absorption, we adopt the SD98 parametric expressions for \( \sigma(E, z) \) for \( z < 0.3 \), taking a Hubble constant of \( H_0 = 65 \, \text{km s}^{-1} \text{Mpc}^{-1} \).

The unfolded HEGRA data points are also shown in Figure 1, together with a fit to a power-law energy spectrum. We find

\[ dN/dE = (1.32 \pm 0.04) \times 10^{-10} (E/1 \text{TeV})^{-2.00 \pm 0.03} \tag{3} \]

photons cm\(^{-2}\) s\(^{-1}\) with \( \chi^2 = 18.6 \) for 15 degrees of freedom, giving a high chance probability of 0.2. In the mid-energy region 1–10 TeV, in which the measured energy spectrum is very well defined, the data points deviate from the fit by less than 15%, which equals the estimated systematic error. Note that both the statistical and the systematic uncertainties of the spectrum measurements increase toward the upper end of the energy range, where they reach 30% and 60%, respectively. Thus, the data points of the unfolded spectrum are consistent, within the statistical and systematic errors, with the simple power-law fit of differential spectrum index 2.0. Our analysis shows that fitting the unfolded spectrum using an additional exponential term results in a \( \chi^2 \) value of the same magnitude.

4. IMPLICATIONS FOR THE INTRINSIC SPECTRUM AND THE INTERGALACTIC ABSORPTION

In order to understand the implications of the absorbed and deabsorbed spectra shown in Figure 1, it is necessary to adopt a model or scenario for the production of TeV photons in the
source. Of the many suggestions in the literature, interest has recently centered on those in which a single population of relativistic electrons is responsible for both the TeV photons and for photons in the X-ray region of the spectrum, as in the synchrotron self-Compton (SSC) and external Compton models (e.g., Bloom & Marscher 1996; Inoue & Takahara 1996; Ghisellini & Madau 1996; Dermer, Sturner, & Schlickeiser 1997; Mastichiadis & Kirk 1997, hereafter MK97; Sikora et al. 1997; Georganopoulos & Marscher 1998; Ghisellini et al. 1998; Levinson 1998). These models are favored because they provide a natural way to understand the similar variability timescales of the X-ray and TeV emission.

During the period of the TeV observations, Mrk 501 was also observed in X-rays using the BeppoSAX instrument (Pian et al. 1998) and the Rossi X-Ray Timing Explorer (Lamer & Wagner 1998). The spectrum in this energy range varied strongly, with generally a very hard spectral index extending to much higher energies (∼100 keV) than during less active epochs. There was a close temporal correlation between the X-ray and TeV fluxes, further strengthening the case for the origin of X-rays and TeV emission in a common electron population.

Extensive studies of the variability properties of the SSC model have been undertaken (MK97), which show that the mechanism most likely to be responsible for the variability shown by the object Mrk 421 is a change in the maximum energy (expressed as a Lorentz factor: $\gamma_{\text{max}}$) to which electrons are accelerated. These results were also applied to Mrk 501 (Mastichiadis & Kirk 1999), where, once again, variability induced by a change in $\gamma_{\text{max}}$ appears to give a reasonable fit to the X-rays and to the TeV data then available.

For such models, the most important property revealed by the HEGRA observations discussed above is the lack of variation in the TeV spectrum, despite the fact that the correlated variations in the X-rays show strong spectral variations, which are consistent with an increase in $\gamma_{\text{max}}$. Inspection of the model light curves in the TeV range show that the softer the spectral slope becomes, the more sensitively it reacts to changes in $\gamma_{\text{max}}$. This is because intrinsic spectra softer than a photon index of $\alpha = 3$ are a direct result of the electron cutoff, whereas harder spectra (photon index $\alpha \approx 2$) can be formed by power-law electrons scattering off a range of target photon energies.

Thus, on the basis of the homogeneous SSC model, we find that intensity variations with constant spectral shape imply an intrinsic spectrum with a photon index of $\alpha \approx 2$. This provides additional evidence that the spectrum of Mrk 501, which has a slope $\alpha \approx 3.7$ above 5 TeV, must be modified by the effects of intergalactic absorption. Of the two IIRFs considered by SD98, only the higher provides sufficient absorption to account for such a strong modification. We note again that lower limits from galaxy counts in the mid-IR, as well as other observational data (Dwek et al. 1998), favor the high IIRF (Stecker 1999).

As well as constraining the intergalactic absorption, the observation of an intrinsic spectrum of $\alpha \approx 2$ at 10 TeV requires a higher Doppler factor than considered by MK97 and Mastichiadis & Kirk (1999). Using the approximate scaling laws presented in MK97, we can estimate that a Doppler boosting factor of $\delta \approx 50$ suffices to produce $\alpha \approx 2$ at 10 TeV, and we have confirmed this by running full simulations. It is interesting to note that such boosting factors, although larger than values measured in sources that display apparent superluminal motion (Vermeulen & Cohen 1994), seem to be indicated by observations of both intraday variability (Wagner & Witzel 1995) and extremely rapid variations in the TeV flux of blazars (e.g., Gaidos et al. 1996).

A completely model-independent conclusion is still elusive and will remain so until observations of comparable quality on other blazars of different redshifts are available. Nevertheless, the two independent arguments we have presented favoring an intrinsic emission spectrum close to $\alpha = 2$ indicate that the effect of absorption by the intergalactic infrared background radiation in the spectrum of Mrk 501 is strong and suggest a Doppler boosting factor for this source of $\delta \approx 50$.

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