Understanding the Spectra of TeV Blazars: 
Implications for the Cosmic Infrared 
Background

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Abstract

With the arrival of powerful, ground-based $\gamma$-ray detectors, we can now begin to seriously probe, via simultaneous X-ray/TeV observations, the origin of the $\gamma$-ray emission in the blazars Mrk 421 and 501. If the synchrotron-Compton emission model turns out to work, then we know that the same electrons are responsible for both the X-ray and the $\gamma$-ray emission of these objects. In this case, we show that we can use their observed X-ray spectra to robustly estimate their intrinsic $\gamma$-ray spectra. Among blazars, Mrk 421/501 are particularly well-suited for this task because the Compton scattering which produces their TeV $\gamma$-rays is likely to be in the Klein-Nishina limit, where the outgoing photon has an energy insensitive to the incoming photon energy. With a better handle on their intrinsic TeV spectra, we can then begin to search for evidence of absorption due to $\gamma$-ray pair production on diffuse infrared background radiation. We discuss some of the pitfalls that arise when one attempts to do this without knowing the intrinsic spectrum. Even though Mrk 421/501 are very nearby, the emission of these sources extends to sufficiently high energies ($\gtrsim 20$ TeV in Mrk 501) that we may nevertheless be able to derive interesting constraints on the infrared background. If correct, the combination of the COBE 140 $\mu$ detection and the measurement of Mrk 501’s spectrum out to beyond $\sim 20$ TeV rules out conventional galaxy evolution and star formation scenarios, implying that much of the star formation in the Universe indeed occurs at early times in highly obscured sources that have been missed until now.

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1 Introduction

The last years have seen a revolution in ground-based $\gamma$-ray detectors. We can now detect the spectra of nearby TeV blazars like Mrk 421 and 501 out to $\sim 20$ TeV, and during the strongest flares (with observed TeV fluxes up to 10 times that of the Crab), we can follow fluctuations in these spectra on timescales down to the shortest ones likely in these objects. This represents a unique opportunity. Using these detectors in combination with X-ray satellites like ASCA, SAX, and RXTE, we can now begin to simultaneously follow all significant X-ray/$\gamma$-ray variations in a blazar's emission (e.g., see the contribution by Takahashi in this proceedings). This will provide the most stringent test yet for the synchrotron-Compton (SC) blazar emission model (see, e.g., [1] and [2] for reviews of current emission models and controversies). In this paper, we will argue that such a test is crucial in helping us reach one of the “holy grails” of TeV astronomy: the detection of absorption in blazar $\gamma$-ray spectra due to $\gamma$-ray pair production on the low energy diffuse extragalactic background radiation (DEBRA). As discussed in detail by several authors in this proceedings (see the contributions of Primack, Stecker, and Biller and references therein), a strong constraint on the amount of absorption is very exciting because it constrains the density of the target infrared/optical DEBRA photons responsible for it. The DEBRA at these energies is most probably redshifted stellar and dust emission and thus contains important information on galaxy evolution and cosmology. It is hard to measure by other means, especially in the $\sim 5-50\mu$ range, because of the large Galactic and solar system foregrounds present. In §2 below, we briefly review what sort of absorption effects one should expect to see in objects like Mrk 421 and Mrk 501. We then show that it is difficult to constrain absorption at $\sim 1-10$ TeV without knowing in detail the shape of the intrinsic, unabsorbed $\gamma$-ray spectrum. (Note that since blazars are so variable, one really needs to know the shape of the instantaneous $\gamma$-ray spectrum.) In particular, even though Mrk 421/501 are nearby, their spectra may already be significantly absorbed (by a factor up to 2!) at 3 TeV. Therefore, the lack of a sharp cutoff in the spectra of both Mrk 421 [3] and Mrk 501 [4–7] up to 10 TeV does not allow us to unambiguously extract information on DEBRA, although these data probably are enough to rule out some of the more exotic DEBRA models [8]. We then note that the extension of the HEGRA measurement of the Mrk 501 spectrum to at least $\sim 20$ TeV (Konopelko, this proceedings) may be extremely important. Making rather minimal assumptions about the intrinsic $\gamma$-ray spectrum at these energies, we obtain a strong constraint on the DEBRA intensity at $\sim 10-60\mu$. All recently published DEBRA models either run into trouble with this constraint or significantly underpredict the flux detected by COBE at $140\mu$. If the
COBE detection is correct, this implies the sources responsible for the far IR DEBRA are qualitatively different from the typical ones we see today. Most of the star formation in the early Universe must occur in highly obscured, dusty environments. In §3, we show that if the SC model works during a large flare (where the emission from a single region may dominate), then we can use the observed X-ray spectrum to robustly predict the intrinsic TeV spectrum. Then, and only then, we can try to look for absorption below $\sim 10$ TeV.

2 Gamma-Ray Pair Production on Diffuse Background Radiation

To obtain the mean free path for a $\gamma$-ray of energy $E_\gamma$, one must in general convolve the DEBRA photon number distribution, $n(\epsilon)$, with the pair production cross-section. However, this cross-section is peaked, and for nearby ($z \ll 1$) HBLs and almost all plausible DEBRA shapes, over half the interactions occur on DEBRA target photons with energies $\epsilon_*=4m_e^2c^4/E_\gamma \approx 1.04(E_\gamma/1\text{TeV})^{-1}$ eV. To accuracy better than $\sim 40\%$, we can thus approximate the absorption optical depth as

$$\tau_{\gamma\gamma}(E_\gamma) \approx 0.24\left(\frac{E_\gamma}{1\text{TeV}}\right)\left(\frac{u(\epsilon_*)}{10^{-8}\text{eVcm}^{-3}}\right)\left(\frac{z_s}{0.1}\right)h_{60}^{-1}.$$  

Here $u(\epsilon_*) = \epsilon_2 n(\epsilon_*)$ is the typical energy density in a energy band centered on $\epsilon_*$, $h_{60}$ is the Hubble constant in units of $60\text{km s}^{-1}\text{Mpc}^{-1}$, and $z_s$ is the source redshift. If $I_0(E_\gamma)$ is the intrinsic source spectrum, the corresponding observed spectrum is then $I(E_\gamma) = I_0(E_\gamma) \exp(-\tau_{\gamma\gamma})$. Note that if the DEBRA spectrum near $\epsilon_*$ can be approximated by a power law, $n(\epsilon) \propto \epsilon^{-\alpha_*}$, then $\tau_{\gamma\gamma}$ goes as $E_\gamma^{\alpha_*-1}$. Connecting the COBE far IR measurements to the latest UV background estimates, one gets a crude DEBRA spectral index $\alpha \sim 2$ (e.g., see [9] for a good compilation of the latest DEBRA observations and models). To zeroth order, then, $\tau_{\gamma\gamma} \propto E_\gamma$, and the observed spectrum should be $\sim I_0(E_\gamma) \exp(-E_\gamma/E_c)$ where the cutoff energy $E_c$ is set by $\tau_{\gamma\gamma}(E_c) = 1$. Interestingly, this is exactly the type of shape seen in HEGRA observations of Mrk 501 (Konopelko, this proceedings). Does this mean we are seeing absorption? No. An intrinsic blazar $\gamma$-ray spectrum of this type is exactly what one expects (e.g., see next section) in an SC emission model.

To next order, the DEBRA is better described as the sum of two emission components: starlight from galaxies peaking at $\sim 1$ eV, and dust re-emission peaking at $\sim 100\mu$ (see Fig. 1a). The $1-10\mu$ side of the “valley” between the DEBRA emission peaks is typically a power law with $\alpha \sim 1$. At the corresponding $E_\gamma \sim 1-10$ TeV, roughly the energy range of current TeV detectors, $\tau_{\gamma\gamma}$ is thus $\sim$ constant! The shape of the spectrum is unchanged, and if we only had the $\sim 1-10$ TeV data, we again cannot infer absorption (even if it is
Fig. 1. (a-left panel) The DEBRA assumed for the absorption calculations shown in the adjoining panel. The two rightmost data points (black squares) are the COBE detections with 2σ errorbars shown. The leftmost point with errorbars (2σ) is the recent 3.5 μ result [10]. The remaining data points are various lower limits taken from the compilation of Dwek et al. [9], see their Fig. 8. Curve a shows the DEBRA model of Franceschini et al. [11]. Curve b shows the same model, but multiplied by a factor 2. Curves c and d show two modifications to the DEBRA prediction in the 10-140 μ range which are normalized respectively to match the COBE 140 μ best fit value and the 2σ lower limit. (b-right panel) The heavy (lower) solid line shows the best fit spectrum reported by HEGRA for Mrk 501 (Konopelko, these proceedings). The other curves show the intrinsic blazar spectra obtained by correcting this observed spectrum for absorption caused by the corresponding backgrounds in the left panel. The dashed vertical line at 20 TeV represents a conservative estimate for the maximum detected photon energy.

We demonstrate this explicitly in Fig. 1b by computing the intrinsic source spectrum corrected for absorption effects. (The numerical calculations shown use the exact energy dependent cross-section for γ-γ pair production.) Between ~ 1 – 10 TeV, both the corrected and uncorrected spectra are very reasonable looking SC spectra, and without more information (next section), we have no constraint. Note that recent results at ε∗ ~ 3μ [10] give a high DEBRA energy density, u(3μ) ~ 2 × 10^{-3}. Even for Mrk 501 (z_s = 0.034), τ_{γγ} ≈ 0.5 at E_γ ~ 3 TeV, i.e., absorption corrections may in fact be important (I_0/I ~ 2)!

Without detailed spectral information, the strongest DEBRA constraints may in fact come from energies E_γ ~ 10 – 30 TeV, which probe DEBRA energies on the “other” side of the valley (ε∗ ~ 10 – 60μ). Here, α > 2 and absorption should grow super-exponentially with γ-ray energy. HEGRA does not show such a rapidly falling spectrum. The implications of this for the background
models of Fig. 1a are shown in Fig. 1b. As a representative example of current DEBRA models, we took that of Franceschini et al. [11]. This model significantly underpredicts the COBE flux points, yet it is still marginally ruled out by the fact that the “unabsorbed” spectrum begins to curve up at \(\sim 18\) TeV, and at 25 TeV exceeds a power law extrapolation from lower energies by a factor 3. If the SC model applies, this is a serious problem since the shape of the intrinsic Compton \(\gamma\)-ray spectrum is generically concave down. Arbitrarily increasing the Franceschini et al. [11] DEBRA by a factor 2, we obtain a model that fits the COBE data well and appears compatible with current upper limits at other energies. However, the unabsorbed spectrum then explodes above \(\sim 10\) TeV and almost certainly is not compatible with the intrinsic \(\gamma\)-ray spectrum of Mrk 501. Most of the DEBRA models shown in the compilation of Dwek et al. [9] have similar problems. To avoid them, the predicted 10 – 40\(\mu\) DEBRA flux must be low (a few nW m\(^{-2}\)sr\(^{-1}\)). To match the COBE points, the DEBRA at longer wavelengths must then increase rapidly with wavelength. For example (see curves \(c\) and \(d\) in Fig. 1), if we assume the DEBRA spectrum shortward of 140 \(\mu\) is a power law \(n(\lambda) \propto \lambda^\alpha\), then \(\alpha\) must be \(\gtrsim 4\). Since the DEBRA is an integral (smoothed) quantity, the individual spectra of the objects that dominate the DEBRA must be at least as steep. Either the standard DEBRA/galaxy evolution scenario is correct and the COBE and/or HEGRA measurements are wrong (favored by Stecker, this proceedings), or the far IR DEBRA is produced by objects that are not typical of what we see in our local Universe. An increasingly discussed possibility (see Primack, these proceedings) is that much of the star formation in the Universe in fact occurs in heavily obscured regions, e.g., in ultraluminous IR galaxies like Arp 220 which are relatively rare today. If the COBE and TeV data are both correct, this conclusion becomes inescapable. Note that if the IR DEBRA sources are like Arp 220 (with an IR emission peak at \(\sim 60\mu\)), the 20 TeV absorption constraint tells us they must evolve very strongly with redshift (\(\gtrsim (1 + z)^3\)) and emit the bulk of their light at \(z \sim 3\).

3 Predicting the Intrinsic Gamma-Ray Spectrum of a TeV Blazar

If the SC model works for TeV blazars, we may be able to robustly predict their intrinsic \(\gamma\)-ray spectra. The key is that the Compton scattering responsible for the TeV \(\gamma\)-rays probably occurs in the Klein-Nishina limit. In this regime, the target photon comes away with essentially all the energy of the incident electron. Also, the cooling of the electrons is dominated by synchrotron radiation. In an external acceleration scenario (where electrons are injected into the source region), this means the only way to change the shape of the cooled electron distribution is to change the shape of the electron injection function, i.e., the cooled electron spectrum may be rather insensitive
to changes in the source. Since the scattering electron is effectively replaced by a photon of the same energy, this also means the observed TeV \( \gamma \)-ray spectrum is essentially the cooled GeV/TeV electron distribution (see dotted line in Fig. 2) and, hence, may be similarly insensitive to source changes. In particular, it does not depend on the target photon distribution, as shown in Fig. 2, where a completely different (non-synchrotron) target photon distribution gives the same Compton upscattered spectrum. This may explain the remarkable stability of the Mrk 501 TeV spectrum despite the large changes seen in source luminosity (and may mean that coadding spectra to improve statistics, e.g., Konopelko, this proceedings, is justified). In short, if we can “invert” the observed synchrotron X-ray spectrum to obtain the underlying electron distribution (e.g., as in Fig. 2), we have all we need to predict the shape of the upscattered TeV spectrum. Extrapolating from the spectrum observed at low energies where intergalactic absorption should not be important (e.g., 500-700 GeV), we then predict the unabsorbed flux at TeV energies. Our accuracy is limited by uncertainties in \( B \) and \( \delta \) (the region’s characteristic magnetic field and Doppler boost factor) and the presence of external IR target photons (too many low energy ones take the model out of the Klein-Nishina regime). However, bad estimates of \( B \) and \( \delta \) only cause an overall energy shift of the predicted \( \gamma \)-ray spectrum by a factor \( (\frac{\delta}{\delta_0})^{1/2} \), i.e., a fairly weak dependence. Also, the rest frame energy density of external IR photons must exceed the synchrotron photon energy density to cause significant deviations in the predicted spectrum. This is possible, but not likely since objects like Mrk 421/501 have underluminous accretion disks and do not have a \( \gamma \)-ray (Compton) luminosity that significantly exceeds the X-ray (synchrotron) luminosity.

4 Conclusions

TeV blazars like Mrk 421/501 sources provide ideal laboratories to test in detail the emission models for these objects. If we can show that a simple SC model works during at least the strongest flares, then we can use good broadband X-ray spectra of these sources to infer their intrinsic TeV spectra. Then, and only then, can we look for evidence of \( \gamma \)-ray absorption below \( \sim 10 \) TeV and attempt to constrain the corresponding \( \sim 1 - 20 \mu \) DEBRA. (Blazar modelers should also not forget that the Compton spectra they are trying to fit could be strongly attenuated!) Above \( \sim 10 \) TeV, absorption is expected to grow so rapidly with \( \gamma \)-ray energy that simply requiring the absorption-corrected spectrum to be concave down is sufficient to impose very interesting constraints on the DEBRA. If the COBE and HEGRA Mrk 501 data are correct, the DEBRA must rise very steeply \( n(\lambda) \propto \lambda^{\alpha}, \) with \( \alpha \sim 4 \) longwards of \( \sim 40 \mu \). Unless we identify closer sources at 20-30 TeV, the finite energy resolution of detectors will prevent us from obtaining much stronger constraints
Fig. 2. The solid line is the time-integrated photon spectrum from a variable SSC model chosen to give spectra similar to those seen in the April 1997 Mrk 501 flare [12,13]. (In this model, the variable parameter is total electron luminosity; electrons are always injected into the source with the same energy spectrum.) The dashed line shows the synchrotron and Compton fluxes produced by the electron distribution reconstructed from the “observed” 0.1-300 keV model X-ray spectrum. The target soft photon distribution used to compute the Compton spectrum was $n(\epsilon) \propto \epsilon^{-2}$ between $0.2 < \epsilon < 5$ eV (as measured in the source frame). The dotted line shows the electron distribution in a steady-state SSC model with the same mean parameters as the variable SSC model. The distribution is plotted in the same way as the photon distribution, i.e., as $\gamma^2 N(\gamma)$ (\gamma is the electron Lorentz factor.) Above $\sim 1$ TeV, note the excellent agreement with the Compton $\gamma$-ray spectrum. The distribution has not been rescaled.

than those presented for this wavelength region. In any single observation, absorption effects could be due both to intrinsic blazar IR/O photons as well as intergalactic ones. While these contributions can be difficult to disentangle (note, though, that internal absorption does not affect the concave down argument), Mrk 421 and 501 conveniently have the same redshift. Thus, we can require that any absorption attributed to intergalactic photons be exactly the same for all flares in both sources. These two sources alone may give us the first firm handle on DEBRA $\gamma$-ray absorption.

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