Constraining blazar distances with combined Fermi and TeV data: an empirical approach

E. Prandini1*, G. Bonnoli2, L. Maraschi3, M. Mariotti1, F. Tavecchio2

1 Dipartimento di Fisica, Padova University and INFN Sez. di Padova, via Marzolo 8, I–35131 Padova, Italy
2 INAF – Osservatorio Astronomico di Bologna, via E. Bianchi 46, I–23807 Merate, Italy
3 INAF – Osservatorio Astronomico di Bologna, via Breda 28, I–20100 Milano, Italy

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ABSTRACT

We discuss a method to constrain the distance of blazars with unknown redshift using combined observations in the GeV and TeV regimes. We assume that the VHE spectrum corrected for the absorption through the interaction with the Extragalactic Background Light can not be harder than the spectrum in the Fermi/LAT band. Starting from the observed VHE spectral data we derive the EBL-corrected spectra as a function of the redshift $z$ and fit them with power laws to the LAT data. We apply the method to all TeV blazars detected by LAT with known distance and derive an empirical law describing the relation between the upper limits and the true redshifts that can be used to estimate the distance of unknown redshift blazars. Using different EBL models leads to systematic changes in the derived upper limits. Finally, we use this relation to infer the distance of the unknown redshift blazar PKS 1424+240.

Key words: galaxies: distances and redshifts - gamma-rays: observations - radiation mechanisms: non–thermal

1 INTRODUCTION

The extragalactic TeV sky catalogue (E $>$ 100 GeV), counts nowadays 35 objects. Many of these sources have recently been detected also at GeV energies by the Fermi satellite (Abdo et al. 2009), allowing for the first time a quasi-continuous coverage of the spectral shape of extragalactic VHE emitters over more than 4 decades of energy. Except for two starburst galaxies and two radiogalaxies, all the others are blazars, radio-loud active galactic nuclei with a relativistic jet closely oriented toward the Earth, as described in Urry & Padovani (1995). The apparent luminosity of the non-thermal radiation emitted by the jet is then largely enhanced by relativistic beaming and dominates the observed high energy emission. Typically, the spectral energy distribution (SEDs) emitted from these objects, extending from radio waves to gamma-ray frequencies, is composed of two broad humps. In the case of TeV detected blazars, the first component usually peaks in the UV-X-ray band, and the second peak is located at GeV-TeV energies. The first component is identified as electron synchrotron radiation, whilst the second component is widely attributed to inverse Compton scattering of ambient photons by the same synchrotron emitting electrons. Relativistic electrons are accelerated within a region in bulk relativistic motion along the jet (e.g. Tavecchio et al. 1998).

VHE photons emitted by cosmological sources are effectively absorbed, through the pair production process, $\gamma\gamma \rightarrow e^+e^-$, by the interaction with the so-called Extragalactic Background Light (EBL) (Stecker, de Jager & Salamon 1992). EBL is composed of stellar light emitted and partially reprocessed by dust throughout the entire history of cosmic evolution. The expected EBL spectrum is composed by two bumps at near-infrared and far-infrared wavelengths (Hauser & Dwek 2001). Direct measurement of the EBL has proved to be a difficult task, primarily due to the zodiacal light that forms a bright foreground which is difficult to suppress. Due to the lack of direct EBL knowledge, many models have been elaborated in the last years (Stecker, Malkan & Scully 2006; Franceschini, Rodighiero & Vaccari 2008; Gilmore et al. 2009; Kneiske & Dole 2010). Moreover, for some blazars the derivation of the intrinsic spectrum is also difficult due to the uncertainty or lack of a redshift measurement. In particular a direct spectroscopic measure of the redshift is often difficult in BL Lac objects, which are characterized by extremely weak emission lines (equivalent width < 5 Å).

In this paper we discuss a method to derive upper limits on the redshift of a source based on the comparison between the spectral index at GeV energies as measured by LAT (unaffected by the cosmological absorption up to redshifts far beyond those of interest here) and the deabsorbed TeV spectrum. Basically, for larger distances the deabsorbed spectrum becomes harder. A solid upper limit to the redshift can be inferred deriving the redshift at which
the slope of the deabsorbed spectrum coincides with that measured by LAT. Our approach can be considered complementary to those used by Stecker & Scully (2010) and Georganopoulos, Finke & Reyes (2010) (see also Abdo et al. 2009), where the comparison of the spectral slopes at GeV and TeV energies of blazars at known distances is used to derive limits on the EBL. Starting from the derived limits, we find a simple law relating these values to real redshift, that can be used to guess the distance of unknown redshift blazars.

We assume a cosmology with $h = 0.72$, $\Omega_M = 0.3$ and $\Omega_{\Lambda} = 0.7$.

## 2 BLAZARS SPECTRAL BREAK

We consider the blazar sample containing all the extragalactic TeV emitters located at redshift larger than $z = 0.01$, detected by LAT after 5.5 months of data taking as reported in Abdo et al. (2009). The photon flux emitted by a blazar in both GeV and TeV regimes can be usually well approximated with power laws, of the form $dN/dE = f_0(E/E_0)^{-\Gamma}$, where $\Gamma$ is the power law index.

Fig. 1 represents the comparison between the power law indices, listed in Table 1, obtained by fitting the photon spectra of sixteen sources measured by Fermi/LAT in the GeV regime and the slopes in the TeV regime measured with the new generation of Fermi/LAT (blue) and Cherenkov instruments (red).

The systematic difference between the two distributions is pri-
Blazar distance indications from Fermi and TeV observations

3 RESULTS

Of the sixteen sources considered in this study, 14 blazars have well known redshift and are used to test the method, while the remaining two blazars (3C 66A and S5 0716+714) have uncertain redshift, and are considered separately. The central columns of Table 1 reports the \( z^* \) calculated following the method described in the previous section, using three different EBL models: a low limit model (Kneiske & Dole 2010), a mean (Franceschini et al. 2008) and a high level one (Stecker et al. 2006, baseline model). The absorption coefficients of the last model were obtained from a simple extrapolation of the values given for fixed redshifts in Stecker et al. (2006) (F. Stecker, private communication). The errors on \( z^* \) are estimated taking into account both errors on the TeV and LAT slopes.

Fig. 2 shows the comparison between the real redshift, x-axis, and the estimated one, y-axis, obtained with the mean EBL density model. All the \( z^* \) lie above the bisector (dashed line) meaning that their values are larger than the real redshift ones. This is expected since we are not considering the presence of the intrinsic break in the blazar spectra. This result confirms that the method can be used to set safe upper limits on blazars distance. The only exceptions are the two sources with uncertain distance, S 0716+714 and 3C 66A (open circles).

Stecker and Scully (2010) derived a linear expression for the steepening of the observed TeV slope due to EBL absorption. Since in our procedure \( z^* \) is related to this steepening, it is natural to assume that also \( z^* \) and \( z[\text{true}] \) are related by a linear function,
shift, column of Table 1 we report the values of the time calculated excluding from the fit the source for which wees-

er different between the EBL models used here, the linear behaviour 

er the optical depth evolution is 

er the EBL model (black circles), the estimated redshifts are all shifted 

er a low photon density model (blue circles) the shift is downwards. Even if the optical depth evolution is 

er a high photon density model (red line). The open points were not used in the fit calculation since their 

er a measure of the intrinsic spectral break measured by 

er the Veritas Collaboration (Acciari et al. 2010b) during 

er a measure (increasing values for decreasing EBL level) of theoptical 

er a measure of the optical depth of the EBL model used. 

We interpolate with this linear function the data with well 

known distance of Fig. 2. The linear fit (continuous line) describes 

the data even if the observations in the different energy bands were 

not simultaneous. The impact of this choice, however, is probably 

moderated by fact that we do not use the flux but only the values 

of the slopes, less variable than the flux (unless in extreme states). 

For example the spectral slope of the HBL 1ES 1218+304 recently 

observed TeV spectrum. 

We presented a method that allows the estimation of the quantity 

z*, upper limit on the redshift of a TeV emitting blazar with a GeV 

counterpart observed by Fermi/LAT, obtained by deabsorbing the 

observed TeV spectrum. 

In order to use the largest sample of spectra for this study, we 
made several assumptions: first of all we combined GeV and TeV 
data even if the observations in the different energy bands were 

not simultaneous. The impact of this choice, however, is probably 
moderated by fact that we do not use the flux but only the values 
of the slopes, less variable than the flux (unless in extreme states). 

For example the spectral slope of the HBL 1ES 1218+304 recently 
measured by the Veritas Collaboration (Acciari et al. 2010b) during 

\[ z^* = A + B z[\text{true}] \]

The meaning of the coefficients is rather transparent: basically A is a measure of the intrinsic spectral break 
of the sources, while, following Stecker & Scully (2010), B is a measure (increasing values for decreasing EBL level) of the optical 

depth of the EBL model used. 

We interpolate with this linear function the data with well 

known distance of Fig. 2. The linear fit (continuous line) describes 

very well the data, as confirmed by the reduced chi-squared value 
of the fit, \( \chi^2/\text{d.o.f.} = 9.9/12 \), and corresponding probability of 62%. The results obtained with the other two EBL models 

drawn in Fig. 3. It is evident that with a low photon density 

EBL model (black circles), the estimated redshifts are all shifted 
at higher values, while with a high photon density model (blue circles) the shift is downwards. Even if the optical depth evolution is 
different between the EBL models used here, the linear behaviour 
is evident also in the two extreme cases. The parameters are listed 
in Table 2.

Table 2. Parameters of the linear fitting curves \( z^* = A + B z[\text{true}] \) plotted in Fig. 3.

| EBL Model  | A       | B       |
|------------|---------|---------|
| Low level  | 0.062±0.017 | 1.86±0.17 |
| Mean level | 0.054±0.012 | 1.36±0.14 |
| High level | 0.040±0.009 | 0.96±0.08 |

\( \Delta z \) plot \( (z[\text{true}]-z[\text{rec}]) \) (filled histogram) and superimposed the 
two sources with uncertain redshift (S5 0716+714 and 3C 66A), not used 
for the Gaussian fit.

\[ \Delta z = z[\text{true}] - z[\text{rec}] \]

The differences between the real and the 
reconstructed redshifts, \( \Delta z \) is drawn in Figure 4 filled area. 
Despite the low statistic, the distribution is quite well described by a 
Gaussian centered in zero with a \( \sigma \) of 0.05. The separated shaded 
histogram represents the \( \Delta z \) of the uncertain redshift sources.

4 DISCUSSION AND CONCLUSIONS

We presented a method that allows the estimation of the quantity 

z*, upper limit on the redshift of a TeV emitting blazar with a GeV 

counterpart observed by Fermi/LAT, obtained by deabsorbing the 

observed TeV spectrum.

In order to use the largest sample of spectra for this study, we 
made several assumptions: first of all we combined GeV and TeV 
data even if the observations in the different energy bands were 

not simultaneous. The impact of this choice, however, is probably 
moderated by fact that we do not use the flux but only the values 
of the slopes, less variable than the flux (unless in extreme states). 

For example the spectral slope of the HBL 1ES 1218+304 recently 
measured by the Veritas Collaboration (Acciari et al. 2010b) during
a high flux level, matches within the errors the slope determined during its quiescent state.

Secondly, in this work we use TeV spectra observed with various Cherenkov experiments, characterized by different sensitivities. This difference, especially at high energies, could affect the result, leading to systematic effects in the distance limit determination. Another possible cause of systematics could be the use of all the blazar sample, independently from the nature of the source: we didn’t apply any distinction between HBL, LBL and FSRQ, characterized by a different position of the IC peak.

Despite all these approximations, the method presented in this paper applied to a sample of test sources gave satisfactory results. The \( z^* \) values obtained by correcting the spectra from the EBL absorption, are, in fact, all above the real redshift values if we use a mean background photon level. This suggest the use of this method for constraining the distance of unknown redshift sources.

We applied the \( z^* \) estimate also to two sources with uncertain distance: in both cases the limit lies below the quoted values. This result could be due to some intrinsic properties of the sources (specifically, a more moderate intrinsic spectral break between the GeV and TeV bands than that of the other sources), or to a wrong estimate of their distances. In the latter case, our method would constrain the redshift of S5 0716+714 below 0.21 ± 0.09 and that of 3C 66A below 0.34 ± 0.05. It can be pointed out that in the case of S5 0716+714, the redshift of 0.31 used in this work, recently reported by Nilsson et al. (2008), is estimated by assuming the luminosity of its host galaxy. Another estimate on the blazar distance, based on the spectrography of the three galaxies close to this source, gives the value of \( \sim 0.26 \) for its redshift, more in agreement with our derived limit.

The same procedure was applied to our sample using two extreme EBL models. The low density one gives even safer upper limits on the sources distances, while the \( z^* \) obtained with the high density model are closer to the real redshift values. Even with this model, all the estimates are above or on the bisector, confirming our assumption that the deabsorbed TeV slope cannot be harder than the GeV slope reported by Fermi/LAT.

Following previous works, we tested the possibility of a linear relation between our \( z^* \) estimates and the real distances of the sources. We found that the linear fit describes quite well our results, independently on the EBL model considered, although the slope and intercept of the fits are different in the three cases (Table 2).

The relation found suggests to use the \( z^* \) estimate not only to set an upper limit on unknown distances of blazars, but also, via the inverse-formula, to try an evaluation of this distance. In order to investigate this opportunity, we tested it on our sample of sources using the mean EBL model, paying a special attention to avoid biases in the calculation. The distribution of the difference \( \Delta z \) between the reconstructed and the real redshift is well described by a Gaussian peaked in zero with a \( \sigma \) of 0.05. Once again, the uncertain redshift sources are outside the expected interval. The value of the redshift of S5 0716+714 obtained with this method is 0.11 ± 0.05, where the error quoted is the \( \sigma \) of the Gaussian fitting the \( \Delta z \) of Fig. 4.

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