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Blazars distance indications from *Fermi* and TeV data

E. Prandini(¹)(*), G. Bonnoli(²), L. Maraschi(³), M. Mariotti(¹)
and F. Tavecchio(²)

(¹) *Dipartimento di Fisica and INFN, Sezione di Padova - via Marzolo 8*
35134, Padova, Italy
(²) *Osservatorio Astronomico di Merate - via E. Bianchi 46, 23807, Merate (Lc), Italy*
(³) *Osservatorio Astronomico di Brera - via Brera 28, 20121, Milano, Italy*

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Summary. — A new method to constrain the distance of blazars with unknown redshift using combined observations in the GeV and TeV regimes will be presented. The underlying assumption is that the Very High Energy (VHE) spectrum corrected for the absorption of TeV photons by the Extragalactic Background Light (EBL) via photon-photon interaction should still be softer than the extrapolation of the gamma-ray spectrum observed by *Fermi*-LAT. Starting from the observed spectral data at VHE, the EBL-corrected spectra are derived as a function of the redshift z and fitted with power laws. Comparing the redshift-dependent VHE slopes with the power-law fits to the LAT data an upper limit to the source redshift can be derived. The method is applied to all TeV blazars detected by LAT with known distance and an empirical law describing the relation between the upper limits and the true redshifts is derived. This law can be used to estimate the distance of unknown redshift blazars: as an example, the distance of PKS 1424+240 is inferred.

PACS `95.55.Ka` – X- and γ-ray telescopes and instrumentation.
PACS `98.54.Cm` – Active and peculiar galaxies and related systems (including BL Lacertae objects, blazars, Seyfert galaxies, Markarian galaxies, and active galactic nuclei).
PACS `98.70.Vc` – Background radiations.

1. – Introduction

The extragalactic TeV sky catalogue ($E > 100\,\text{GeV}$) counts nowadays 45 objects(¹). Many of these sources have been recently detected also at GeV energies by the *Fermi* satellite [1], allowing for the first time a quasi-continuous coverage of the spectral shape

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(*) E-mail: `prandini@pd.infn.it`
(¹) For an updated list see: `http://www.mppmu.mpg.de/~rwagner/sources/`

of extragalactic VHE emitters over more than 4 decades of energy. The large majority of extragalactic TeV emitting objects are blazars, radio-loud active galactic nuclei with a relativistic jet closely oriented toward the Earth, as described in [2]. Here, we discuss a method, recently published in [3], to derive an upper limit on the redshift of a blazar, 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 TeV spectrum corrected for the absorption. Starting from the derived limits, we find a simple law relating these values to real redshift, which can be used to guess the distance of unknown redshift blazars. We assume a cosmological scenario with $h = 0.72$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$.

2. – Results

The photon flux emitted by a blazar in both GeV and TeV regimes can be well approximated by power laws, of the form $\mathrm{d}N/\mathrm{d}E = f_0(E/E_0)^{-\Gamma}$, where Γ is the power-law index. At VHE, the photons of the spectrum interact with the extragalactic background light (EBL), via electron-positron pair creation. Quantitatively, the effect is an exponential attenuation of the flux by a factor $\tau(E,z)$, where τ is the optical depth, a function of both photon energy and source redshift. Thus, the observed differential energy spectrum from a blazar, F_{obs}, is related to the emitted one, F_{em}, according to $F_{\mathrm{obs}}(E) = e^{-\tau(E)}F_{\mathrm{em}}(E)$.

In order to estimate a safe upper limit to the source distance, we can reasonably assume that the intrinsic spectrum at TeV energies cannot be harder than that in the adjacent GeV band. Indeed, from the brightest objects studied at both GeV and TeV energies it appears that the SED is continuous, with a broad peak not requiring additional spectral components [4]. Hence, a natural assumption is to require that the slope measured in the GeV energy range is a limit value for the power-law index of the de-absorbed TeV spectrum.

For the study, we consider the blazar sample listed in table I and containing all the extragalactic TeV emitters located at redshift larger than $z = 0.01$, detected by LAT after taking 5.5 months of data [1]. In order to estimate the redshift z^* for which the TeV spectral slope equals to the GeV one, the measured spectral points of each source have been corrected for the corresponding absorption factor [7], starting from redshift $z = 0.01$, and the resulting spectrum fitted with a power law. The procedure, applied in fine steps of redshift, is iterated until the slope of the de-absorbed spectrum equals the one measured by LAT. The corresponding redshift, z^*, reported in table I, is the limit value on the source distance.

Among the 16 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 errors on z^* are estimated taking into account both errors on the TeV and LAT slopes. Figure 1 shows the comparison between the known redshift, x-axis, and z^*. All the z^* lie above the bisector (dashed line) meaning that their values are larger than those of the real redshift z[true]. This is expected since we are not considering the presence of the intrinsic break in the blazar spectra, and *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). This could be either due to some intrinsic properties of the sources or to a wrong estimate of their distances. In the latter case, our method would constrain, at the two-sigma level, the redshift of S5 0716+714 below 0.39 and that of 3C 66A below 0.44.

TABLE I. – *TeV blazars used in this study. The sources used in this study are listed in the first column, their redshift (second column), their Fermi-LAT slope (third column), the VHE slope of the observed differential energy spectrum fit (fourth column) and the value* z^* *(last column). Detailed references can be found in* [3].

Source name	z[real]	*Fermi*-LAT slope	TeV slope	z^*
Mkn 421	0.030	1.78 ± 0.03	2.3 ± 0.1	0.08 ± 0.02
Mkn 501	0.034	1.73 ± 0.06	2.3 ± 0.1	0.10 ± 0.02
1ES 2344+514	0.044	1.76 ± 0.27	2.9 ± 0.1	0.20 ± 0.06
Mkn 180	0.045	1.91 ± 0.18	3.3 ± 0.7	0.20 ± 0.12
1ES 1959+650	0.047	1.99 ± 0.09	2.6 ± 0.2	0.09 ± 0.04
BL Lacertae	0.069	2.43 ± 0.10	3.6 ± 0.5	0.23 ± 0.12
PKS 2005−489	0.071	1.91 ± 0.09	3.2 ± 0.2	0.19 ± 0.04
W Comae	0.102	2.02 ± 0.06	3.7 ± 0.2	0.23 ± 0.05
PKS 2155−304	0.116	1.87 ± 0.03	3.4 ± 0.1	0.22 ± 0.01
1ES 0806+524	0.138	2.04 ± 0.14	3.6 ± 1.0	0.23 ± 0.15
1ES 1218+304	0.182	1.63 ± 0.12	3.1 ± 0.3	0.21 ± 0.08
1ES 1011+496	0.212	1.82 ± 0.05	4.0 ± 0.5	0.49 ± 0.12
S5 0716+714	0.310(a) (b)	2.16 ± 0.04	3.4 ± 0.5	0.21 ± 0.09
PG 1553+113	0.400(c)	1.69 ± 0.04	4.1 ± 0.2	0.57 ± 0.05
3C66A	0.444(a)	1.93 ± 0.04	4.1 ± 0.4	0.34 ± 0.05
3C279	0.536	2.34 ± 0.03	4.1 ± 0.7	0.75 ± 0.72

(a) Uncertain.
(b) From [5].
(c) From [6].

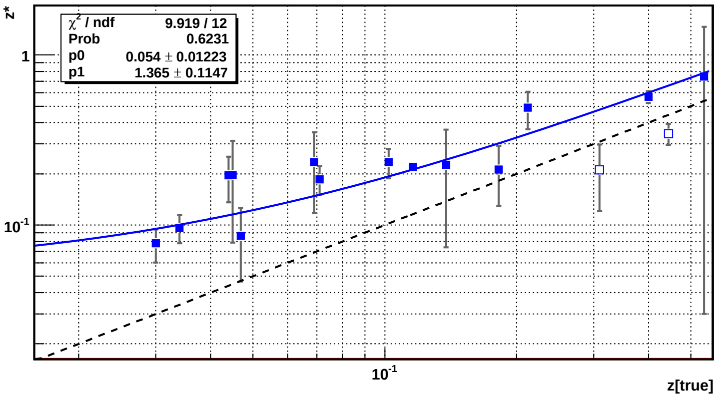

Fig. 1. – z^* *vs.* true redshift derived with the procedure described in the text. The open points are the two uncertain redshift sources, namely 3C 66A and S5 0716+714, not used in the fit calculation (continuous line). The dashed line is the bisector.

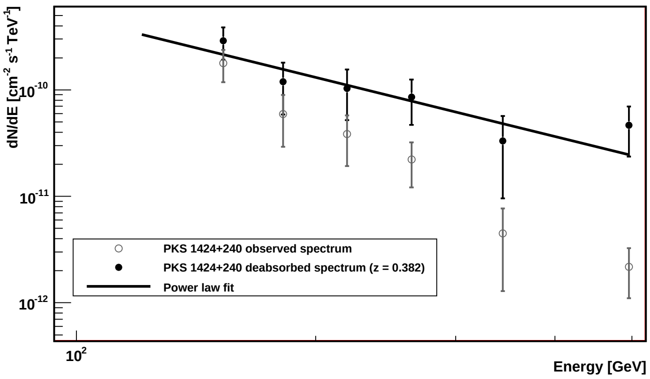

Fig. 2. – Measured (open points) and de-absorbed (filled points) spectrum of PKS 1424+240 at redshift $z = 0.382$.

In [8], a linear expression for the steepening of the observed TeV slope due to EBL absorption is derived. Since in our procedure z^* is related to this steepening, it is natural to assume that also z^* and z[true] are related by a linear function, of the form $z^* = A + Bz[\text{true}]$. The meaning of the coefficients is rather transparent: basically A is a measure of the intrinsic spectral break of the sources, while, following [8], 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. 1. The linear fit (continuous line) has a probability of 62%. Once derived this empirical relation, one can use it to *determine the redshift* of sources with uncertain distance. For S5 0716+714 the reconstructed redshift is $z[\text{rec}] = 0.11 \pm 0.05$, while that of 3C 66A is $z[\text{rec}] = 0.21 \pm 0.05$. The error quoted is estimated in [3].

3. – The redshift of PKS 1424+240

As a final example of application, we use our procedure on PKS 1424+240, a blazar of unknown redshift recently observed in the VHE regime by Veritas [9]. The slope spectrum measured by *Fermi*-LAT between 0.2 and 300 GeV is 1.85 ± 0.05. The corresponding z^* redshift at which the de-absorbed TeV spectrum slope becomes equal to it, is 0.382 ± 0.105, fig. 2, using the EBL model [7]. This result is in agreement with the value of 0.5 ± 0.1, reported in [9], calculated applying the same procedure but only simultaneous *Fermi* data. Our estimate on the most probable distance for PKS 1424+240, obtained by inverting the z^* formula, is $z[\text{rec}] = 0.24 \pm 0.05$, where, as before, the error quoted is estimated in [3].

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