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Letter to the Editor

On the distance of PG 1553+11

A lineless BL Lacertae object active in the TeV band

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ABSTRACT

Context. The redshift of PG 1553+11, a bright BL Lac object ($V \sim 14$), is still unknown. It has been recently observed in the TeV band, a fact that offers an upper limit for the redshift $z < 0.4$.
Aims. We intend to provide a lower limit for the distance of the object.
Methods. We used a χ^2 procedure to constrain the apparent magnitude of the host galaxy in archived HST images. Supposing that the host galaxy is typical of BL Lac objects (M_R −22.8), a lower limit to the distance can be obtained from the limit on the apparent magnitude of the host galaxy.
Results. Using the 3σ limit on the host galaxy magnitude, the redshift is found to be ≥0.25.
Conclusions. The redshift of PG 1553+11 is probably in the range $z = 0.3$–0.4, making this object the most distant extragalactic source so far detected in the TeV energies. We suggest that other bright BL Lac objects of unknown redshift and similar spectroscopic characteristics may be interesting targets for TeV observations.

Key words. galaxies: active – BL Lacertae objects: individual: PG 1553+11 – gamma rays: observations

1. Introduction

Although having been studied with advanced instruments, the very bright ($V \sim 14$) BL Lac object PG 1553+11 still has no line detected (e.g. Falomo & Treves 1990; Sbarufatti et al. 2006, and an example in Fig. 1). Based on the hypothesis that the active nucleus sits in a typical host galaxy (a giant elliptical of $M_R \sim -23$, see Sect. 2.2 and Sbarufatti et al. 2005), Sbarufatti et al. (2006) propose a lower limit to the redshift $z > 0.1$ derived from the upper limit of the equivalent widths of absorption lines.

PG 1553+11 has been recently detected in the TeV band using the atmospheric Cherenkov technique, both by the HESS and the MAGIC collaborations (Aharonian et al. 2006; Albert et al. 2007). Because of the opacity due to photon-photon interaction on the extragalactic background light (EBL, for a recent contribution on the subject and references, see Mazin & Raue 2007), the very detection of the source in the TeV band implies an upper limit to its distance. Its actual value depends on the hypothesis on the intrinsic TeV spectral shape, and limits of $z < 0.8$ and $z < 0.4$ have been proposed (Mazin & Goebel 2007) that assume a minimal EBL contribution. The most restrictive value corresponds to the reasonable assumption of an intrinsic spectrum without flattening and high-energy breaks.

In this letter we reanalyze the images obtained with the WFPC2 camera onboard HST in order to constrain the lower limit to the redshift (Sect. 2). Our results are then compared with those from the TeV observations, and the overall astrophysical picture is briefly discussed.

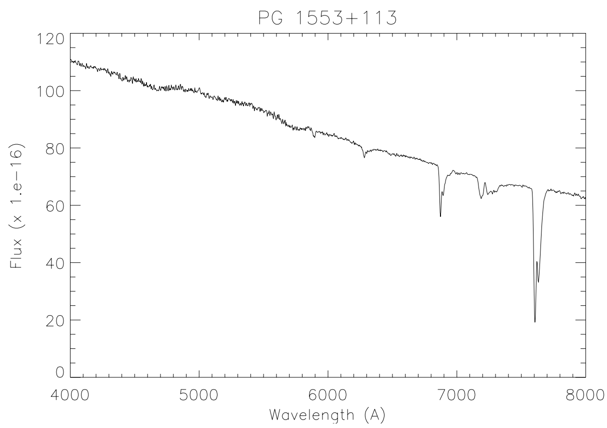

Fig. 1. The optical spectrum of the BL Lac object PG 1553+11 obtained with VLT and FORS. Apart from the telluric absorptions, the spectrum consists of a non thermal featureless emission (see for details Sbarufatti et al. 2006). Additional faint absorptions at short wavelengths are due to molecular gas in our galaxy.

⋆ Associated to INAF and INFN.

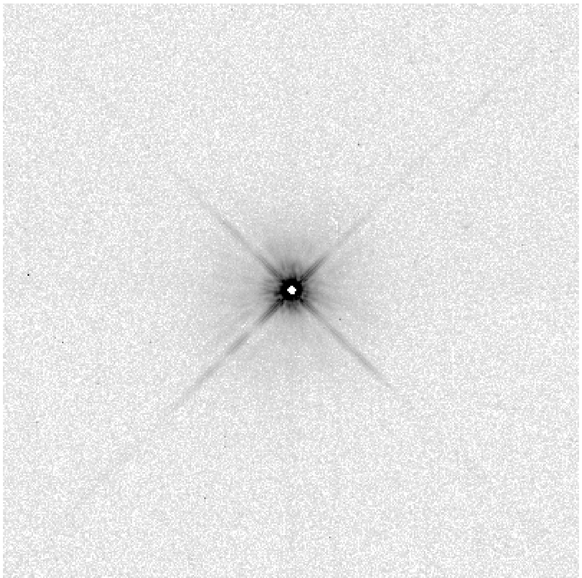

Fig. 2. The optical (*R* filter) image of the BL Lac object PG 1553+11 obtained by HST + WFPC2 (a 18.3 × 18.3 $arcsec^2$ box is shown).

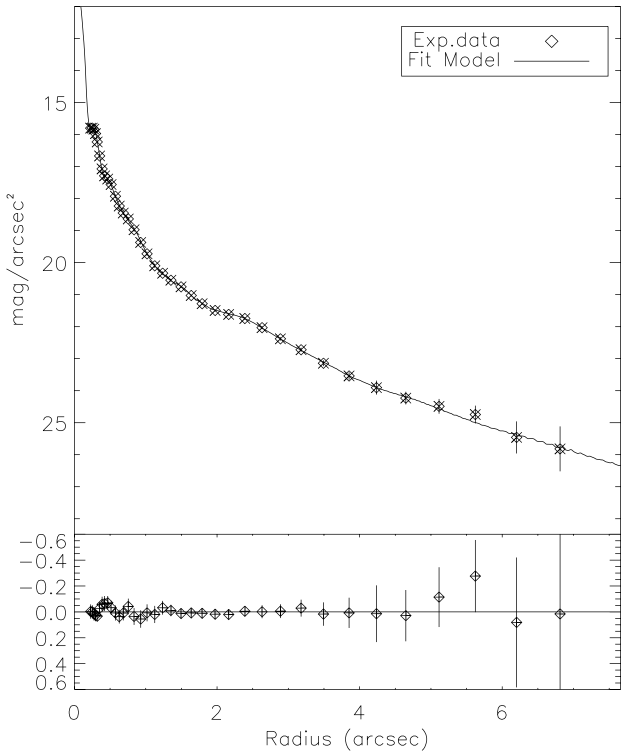

Fig. 3. The radial surface brightness profile of PG 1553+11 as derived from the HST + WFPC2 image (*F702W* filter). The observed profile (filled dotted) is compared with the scaled PSF profile.

2. The image of PG 1553+11

2.1. Analysis of the HST image

The object was imaged by the PC camera (0.046 arcsec/pixel) of HST/WFPC2, observed with the *F702* filter for 610 s, as part of a program aimed at systematically studying the host galaxies of BL Lac objects (Scarpa et al. 2000; Urry et al. 2000). The HST image, obtained by combining 3 images with different time exposures, is reported in Fig. 2. Scarpa et al. (2000) and Urry et al. (2000) did not find any evidence of a host galaxy, confirming previous indications from ground-based observations (Hutchings & Neff 1992). The object was noticed because the absence of the host galaxy was combined with a high nuclear brightness. We analyzed the combined image with AIDA (Astronomical Image Decomposition and Analysis), a software package for 2d model fitting, specifically designed to measure host galaxies of AGN (Uslenghi & Falomo 2007).

The BL Lac image was prepared for the analysis by building a mask to exclude any residual bad pixels. Because the image of the target is saturated, the central core of the object (up to 0.2 arcsec) was also masked. The local background was estimated from the signal's average level computed in a circular annulus centered on the object (8−9 arcsec).

The PSF was modeled using the PSF generated by Tiny Tim (Krist 1995) at the object's location in the core (within 1.5 arcsec). However, it is known that Tiny Tim does not properly model the external faint halo produced by the scattered light. To take this effect into account, an exponential component was added to the external part, with a smooth transition (1.5−3.5 arcsec) between the pure Tiny Tim and the mixed PSF. An archive image of a star produced with the same instrumental setup was used to constraint model parameters by fitting.

The BL Lac image was fitted with the PSF model, showing that the radial profile of the object agrees well with the PSF, and no deviation is seen at large radii. Thus, the object is not resolved (in agreement with previous analysis carried out on this image). In Fig. 3 we report the azimuthally-averaged radial profile and compare it with the profile of a scaled PSF. The overall agreement is very good, but some small deviations at radii smaller than ∼1.5 arcsec are apparent in the plot of the residuals (see lower panel of Fig. 3). These wave-shaped deviations from the pure TinyTim model are very likely due to the undersampling of the HST PSF and to the "breathing" of HST that produces a slight change in the PSF shape at the focal plane. This shows the importance of systematic effects and casts some doubt on the suitability of the χ^2 statistics.

In this framework, the χ^2 is no longer a maximum-likelihood estimator and the statistics cannot provide a way to compute the χ^2 value corresponding to an upper limit of a given significance level, but χ^2 minimization is still applicable to best-fitting. Since our aim is to evaluate a limit on the host-galaxy magnitude, we need to take the contribution of systematic errors into account.

The best fit of the data with the PSF (Fig. 3) yields χ^2 = 1.127, and the rms of the residuals is 0.06 mag. We consider this quantity as the 1σ global uncertainty of the fit. Applying this 1σ variation to the magnitude of the scaled PSF (0.06 mag brighter), we derived a fit with $\chi^2 = 1.141$. If a 3σ variation is considered, the χ^2 of the fit is 1.216.

We considered all fits to the data with $\chi^2 < 1.216$ (corresponding to the variation at the 3σ level) equivalent to the fit with a simple PSF (object unresolved). In order to evaluate the upper limit to the brightness of a possible host galaxy, we computed the χ^2 of a two-component fit of the data (PSF+host galaxy) as a function of the magnitude of the host galaxy (with effective radius 10 kpc) at given redshifts. An example in Fig. 4 is shown for $z = 0.35$. There is a sharp monotonic increase of the χ^2 for increasing galaxy luminosities. We take the magnitude corresponding to χ^2 at the 3σ limit as upper limit of the host magnitude. In the case reported in the figure, this corresponds to a maximum magnitude of the host $R = 18.07$. The procedure was repeated for redshifts in the range from 0.05 to 0.9. This produces a relation between the upper limit of the absolute host magnitude and the redshift (see Fig. 5).

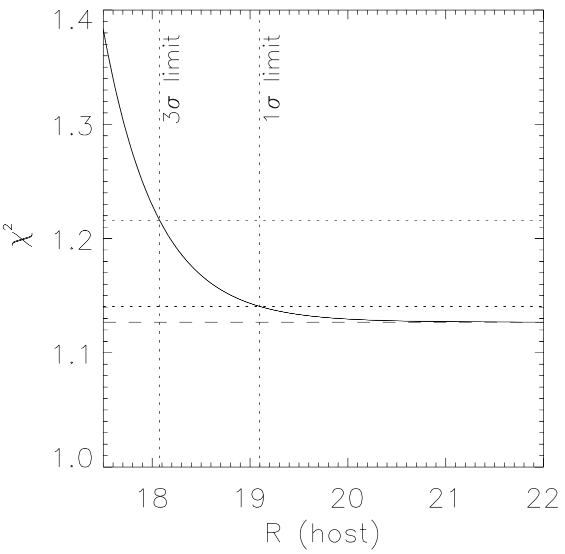

Fig. 4. χ^2 versus magnitude of the host galaxy of the BL Lac object PG 1553+11 (R = 14.4), for a host galaxy with R_e = 10 kpc at redshift 0.35.

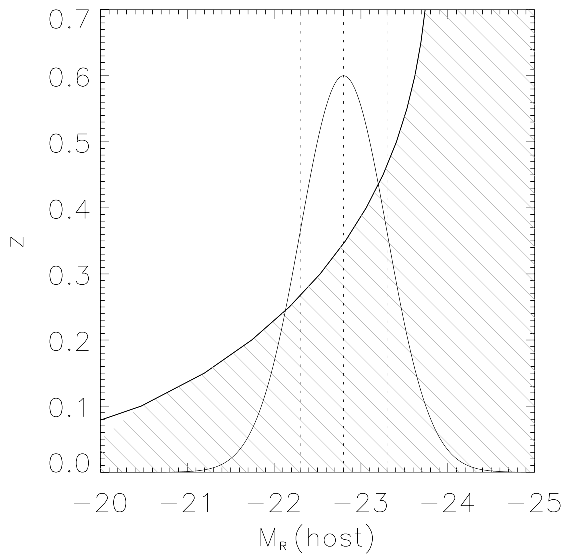

Fig. 5. Relation between the upper limit of the host galaxy (R_e = 10 kpc) magnitude and the redshift for the BL Lac object PG 1553+11. Permitted parameters are in the area above the curve. The Gaussian envelope of the BL Lac host magnitude distribution is also shown for reference (Sbarufatti et al. 2005).

The curve divides the $[M_R, z]$ plane in two regions: one with permitted values (host not detectable) above the line and one forbidden below. The same procedure has been applied assuming a host galaxy with radius 5 kpc, with very similar results.

In the transformation of apparent magnitude into absolute one, we assumed galactic extinction $A_R = 0.14$; k-corrections derived from Poggianti (1997) and a cosmology with H_0 = 70 km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

2.2. Determination of the redshift lower limit

Based on the limit of the host galaxy magnitude, it is possible to infer a lower limit to the distance of the source, because it was shown (Sbarufatti et al. 2005) that the host galaxy luminosity is encompassed in a relatively narrow range for all BL Lac objects resolved with HST. The magnitude distribution is well-fitted by a Gaussian peaked at $M_R \simeq -22.8$ with *FWHM* of 1 mag, which is reported in Fig. 5. If the host galaxy of PG 1553+11 is fairly typical, it is apparent from the figure that its redshift must be ≥0.25.

As mentioned above, the HST images of PG 1553+11 derive from a systematic study of 110 BL Lacs (Urry et al. 2000; Scarpa et al. 2000). In 14 cases, one being PG 1553+11, the redshift is unknown and no indication of a host galaxy was found. For all the objects, a limit to the magnitude of the host galaxy was obtained supposing that the dominant errors were statistical. Therefore a 3σ limit could be deduced by searching for a χ^2 variation $\Delta\chi^2 = 6.6$ where two variable parameters are considered, i.e. the apparent magnitude of the host galaxy and its radius. In the case of PG 1553+11, a limit $m_R > 21.6$ was obtained by considering a de Vaucouleurs galaxy with a 10 kpc effective radius. Correspondingly a redshift limit $z > 0.79$ was proposed by Sbarufatti et al. (2005).

Compared with our estimate (see Fig. 4), the difference in the limit magnitude of the host galaxy is ~2.5 mag, which is ascribed to the assumption that the uncertainties were dominated by statistical errors.

3. Discussion

Comparing our lower limits on the redshift with those deduced from TeV data, we are led to propose a redshift $z = 0.3-0.4$, making PG 1553+11 the most distant TeV source detected thus far. The absorption of EBL would therefore be severe (Mazin & Goebel 2007).

From the optical point of view, PG 1553+11 belongs to a restricted group of very bright objects ($R < 16$), for which neither the redshift nor the host galaxy is known. Similar cases are 0048–099, 1722+119 and 2136–428 (e.g. Sbarufatti et al. 2006). For all of them, not detecting of the host galaxy places stringent limits on the redshift. They are all obvious targets for a search in the TeV band. Their detection would be a major result and, at the same time, may yield an upper limit to the distance.

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References

Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2006, A&A, 448, L19
Albert, J., Aliu, E., Anderhub, H., et al. 2007, ApJ, 654, L119
Falomo, R., & Treves, A. 1990, PASP, 102, 1120
Hutchings, J. B., & Neff, S. G. 1992, AJ, 104, 1
Krist, J. 1995, ASPC, 77, 349
Mazin, D., & Goebel, F. 2007, ApJ, 655, L13
Mazin, D., & Raue, M. 2007, A&A, 471, 439
Poggianti B. M. 1997, AAS, 122, 399
Sbarufatti, B., Treves, A., & Falomo, R. 2005, ApJ, 635, 173
Sbarufatti, B., Treves, A., Falomo, R., et al. 2006, ApJ, 132, 1
Scarpa, R., Urry, C. M., Falomo, R., Pesce, J. E., & Treves, A. 2000, ApJ, 532, 740
Urry, C. M., Scarpa, R., O'Dowd, M., et al. 2000, ApJ, 532, 816
Uslenghi, M., & Falomo, R. 2007, AIDA: Astronomical Image Decomposition and Analysis, to appear in Proceedings of DAA – Data Analysis in Astronomy Workshop