Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008

Vol. 3 (OG part 2), pages 957–960

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07
Mérida, México

Observations of 1ES 1101−232 with H.E.S.S. and at lower frequencies: A hard spectrum blazar and constraints on the extragalactic background light

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Abstract: VHE observations of the distant (z=0.186) blazar 1ES 1101−232 with H.E.S.S. are used to constrain the extragalactic background light (EBL) in the optical to near infrared band. As the EBL traces the galaxy formation history of the universe, galaxy evolution models can be tested with the data. In order to measure the EBL absorption effect on a blazar spectrum, we assume that usual constraints on the hardness of the intrinsic blazar spectrum are not violated. We present an update of the VHE spectrum obtained with H.E.S.S. and the multifrequency data that were taken simultaneously with the H.E.S.S. measurements. The data verify that the broadband characteristics of 1ES 1101-232 are similar to those of other, more nearby blazars, and strengthen the assumptions that were used to derive the EBL upper limit.

Introduction

The detection of VHE emission from 1ES 1101−232 with the H.E.S.S. Cherenkov telescopes has attracted particular attention for two reasons: The object has been the farthest detected *VHE blazar* with confirmed redshift (z=0.186), and at the same time it has exhibited a hard spectrum, with a photon index of $\Gamma \approx 2.9$ between 0.2 and 4 TeV. Both facts taken together allowed to place a limit on the density of the extragalactic background light (EBL) in the near-infrared band: under the assumption of a normal-behaved intrinsic emission spectrum of 1ES 1101−232, the energy density of the EBL at $1.5\,\mu\mathrm{m}$ has to be at or below $\nu F_\nu = 14\,\mathrm{nWm^{-2}sr^{-1}}$ [1].

Here we present an update of the VHE spectrum and broadband data that were taken simultaneously to the H.E.S.S. data. We show that the hard γ-ray spectrum of 1ES 1101−232 is close to the borderline of what is possible to model using standard one-zone blazar emission scenarios. On the other hand, from the broadband data there is no evidence that the emission characteristics of 1ES 1101−232 are not in agreement with those of the remaining class of VHE blazars. A detailed description of the results can also be found in [2].

H.E.S.S. data and EBL limit

Fig. 1 shows the spectrum of 1ES 1101−232, derived from the total H.E.S.S. data set of the years 2004 and 2005. Compared to the analysis results used in [1], an improved energy calibration of the telescope system was applied to the data [3]. For the given total data sample, this energy scale recalibration yields a safe energy threshold of 225 GeV (compared to 165 GeV used in [1]) and a flux normalisation increase of 27% at 1 TeV. After this correction, the systematic flux uncertainty is now estimated as 20% [3]. Reconstructed spectral indices were not affected significantly by these calibration

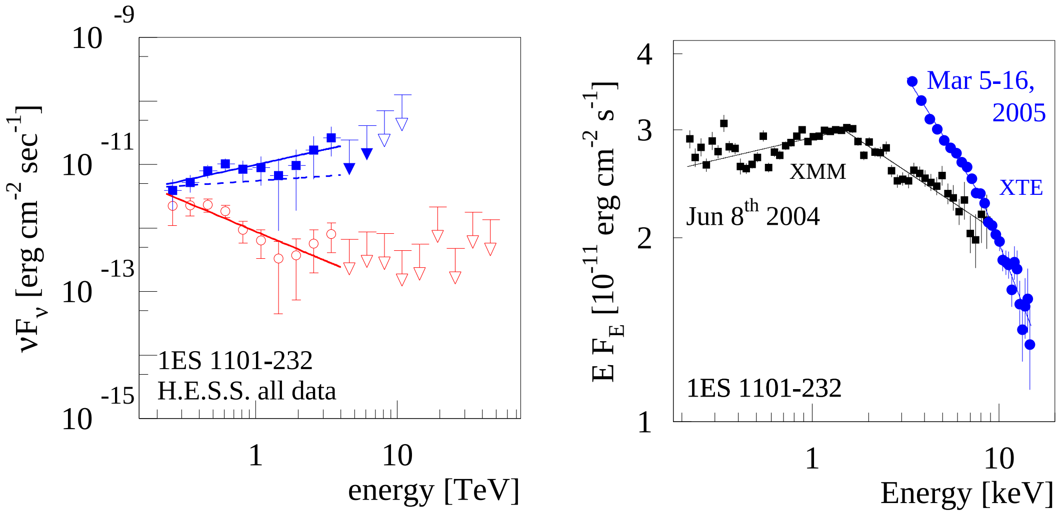

Figure 1: **Left panel:** VHE γ-ray spectrum of 1ES 1101−232, from the total H.E.S.S data set of the years 2004 and 2005, in νF_ν-representation. The red, open circles denote the reconstructed flux as measured with H.E.S.S. The spectrum after correction for *maximum* EBL absorption with $14\,\mathrm{nWm^{-2}sr^{-1}}$ at $1.5\,\mu\mathrm{m}$ is shown with blue, filled circles. Upper limits in the deabsorbed spectrum above 7 TeV are shown as open symbols only, because of strong EBL uncertainties at these high energies. The solid lines denote power-law fits between 0.2 and 4 TeV to the measured and deabsorbed spectra. The dashed line indicates the effect if the EBL level used for deabsorption would be lowered to $10\,\mathrm{nWm^{-2}sr^{-1}}$ at $1.5\,\mu\mathrm{m}$. **Right panel:** X-ray spectra from observations taken simultaneously with the H.E.S.S. June 2004 (XMM-Newton) and March 2005 (RXTE) data.

	livetime	Γ_{abs}	$\Gamma_{\mathrm{deabs,max}}$	$\Gamma_{\mathrm{deabs,min}}$
EBL shape used for deabsorption			$P0.45$	$P0.34$
present day EBL shape			$P0.55$	$P0.40$
present day $\nu F\nu(1.5\,\mu\mathrm{m})$			$14\,\mathrm{nWm^{-2}sr^{-1}}$	$10\,\mathrm{nWm^{-2}sr^{-1}}$
fit energy range		0.23–4.0 TeV	0.23–4.0 TeV	0.23–4.0 TeV
All Data	42.7 hrs	$2.94^{+0.20}_{-0.21}$	$1.51^{+0.17}_{-0.19}$	$1.85^{+0.18}_{-0.19}$
March 2005	31.6 hrs	$2.94^{+0.21}_{-0.23}$	$1.49^{+0.19}_{-0.20}$	$1.84^{+0.20}_{-0.21}$
June 2004	8.4 hrs	$3.16^{+0.48}_{-0.61}$	$1.70^{+0.47}_{-0.61}$	$2.05^{+0.47}_{-0.61}$

Table 1: Photon indices from power-law fits to the VHE spectra of 1ES 1101−232. Γ_{abs} are from fits to the measured spectra. $\Gamma_{\mathrm{deabs,max}}$ are from fits to the deabsorbed spectra using the EBL shape $P0.45$, corresponding to the *maximum* EBL level with the present day shape $P0.55$ ($\nu F_\nu(1.5\,\mu\mathrm{m}) = 14\,\mathrm{nWm^{-2}sr^{-1}}$) after scaling down by 15% to take galaxy evolution effects into account. $\Gamma_{\mathrm{deabs,min}}$ represents the result if the EBL level is lowered to $\nu F_\nu(1.5\,\mu\mathrm{m}) = 10\,\mathrm{nWm^{-2}sr^{-1}}$, at the level of the EBL lower limit from galaxy counts. Γ_{abs} and $\Gamma_{\mathrm{deabs,max}}$ correspond to the fits shown as solid lines in Fig. 1, the fit corresponding to $\Gamma_{\mathrm{deabs,min}}$ is shown as dashed line.

updates, the systematic error estimate for reconstructed photon indices is $\Delta\Gamma_{\rm sys} \sim 0.1$ [1, 3].

Lacking the intrinsic blazar spectrum, one can assume a power-law type intrinsic spectrum with $\Gamma_{\rm deabs}$ and a typical EBL model around $1.5\,\mu$m. Then EBL absorption simply leads to a softening of the VHE spectrum above $\sim\ 100\,\rm GeV$ of $\Delta\Gamma = \Gamma_{\rm abs} - \Gamma_{\rm deabs}$, where $\Gamma_{\rm abs}$ is the photon index of the measured spectrum. Using a template EBL spectrum "P" and scaling it with a factor p results in the relation $\Delta p = 0.34\Delta\Gamma$ [1].

The EBL has a *lower limit* from galaxy counts [4], with about $10\,\rm nWm^{-2}sr^{-1}$ at $1.5\,\mu$m, corresponding to $P0.40$ using the scaled EBL scheme. Already with this smallest possible deabsorption, the VHE spectrum of 1ES 1101−232 is harder than $\Gamma_{\rm deabs} = 2$ (see dashed line in Fig. 1), i.e. the intrinsic VHE power output peak of the source is above $\sim 3\,\rm TeV$ for any EBL level.

The intrinsic spectrum of VHE blazars is expected to be not harder than 1.5, i.e. $\Gamma_{\rm deabs} \geq 1.5$, taking the present observational and theoretical knowledge of VHE blazar spectra into account [1]. This translates into an *upper limit* of the EBL of $P0.55$. This *maximum* EBL has $14\,\rm nWm^{-2}sr^{-1}$ at $1.5\,\mu$m. This limit is identical (within 1%) using either the spectrum used in [1], with $\Gamma_{\rm abs} = 2.88$ between 0.16 - 3.3 TeV, or the recalibrated spectrum with $\Gamma_{\rm abs} = 2.94$ between 0.23 - 4.0 TeV. We note that the limit at $1.5\,\mu$m is quite insensitive to the choice of the EBL parametrisation, see [1], [5].

This EBL upper limit is in conflict with models such as the "fast evolution" model by [6] and the "best fit" model by [7], with an EBL density of about $\nu F_\nu(1.5\,\mu{\rm m}) \simeq 20\,\rm nWm^{-2}sr^{-1}$. Such high EBL levels would lead to an intrinsic spectrum of 1ES 1101−232 with $\Gamma_{\rm deabs} \sim 1$. Such a Γ would isolate 1ES 1101−232 in the class of VHE blazars.

Broadband data and SED

Here we present truly simultaneous SEDs of 1ES 1101−232. The data show no indication for a $\Gamma{\sim}1$ type spectrum in the synchrotron branch. 2004 H.E.S.S. observations were made in April and June (4 nights each). On June 8, 2004, XMM-Newton X-ray and optical monitor data were obtained. In March 2005, H.E.S.S., RXTE X-ray, and ROTSE 3c optical data were taken simultaneously during 11 nights. The H.E.S.S. data did not reveal variability on any time scale. Also, the XMM-Newton data showed a constant flux. The nightly averaged light curve of the RXTE data showed mild variations of 15% (min-max), optical variations were below 10%. We note that the two X-ray spectra obtained in the two different years are quite different, see right panel of Fig. 1.

We therefore constructed two simultaneous SEDs, one for March 2005 and one for June 2004, see Fig. 2. The SED was modeled using a time-independent SSC model [8], with a one-zone homogeneous, spherical emitting region and a homogeneous magnetic field which propagates towards the observer. The high-energy electron distribution was modeled with a broken power law, with particle energy index p_1 between Lorentz factors $\gamma_{\rm min}$ and $\gamma_{\rm b}$, and p_2 between $\gamma_{\rm b}$ and $\gamma_{\rm max}$. Thin lines correspond to models with $p_1 = 2$ as expected from an uncooled, shock-accelerated particle distribution. Thick lines are models with $p_1 \simeq 1.5$, for instance from particle acceleration at strong shocks in a relativistic gas.

The $p_1{=}2$ models nicely reproduce the X-ray and optical data, but fail to fit the 2005 H.E.S.S. data. The $p_1{=}1.5$ model can marginally fit the 2005 H.E.S.S. data. An improved fit could be obtained if the EBL was below $\nu F_\nu = 14\,\rm nWm^{-2}sr^{-1}$. Adopting the $p_1{\simeq}1.5$ models, one has to attribute the optical emission to a different emission zone (not modeled in Fig. 2), which is viable because of the lack of correlated variability arguments.

Conclusions

The VHE SED of 1ES 1101−232 peaks above 3 TeV. Nevertheless, a standard emission scenario can be used to essentially explain the broadband data of 1ES 1101−232, if the EBL used to deabsorb the VHE data is at or below $\nu F_\nu(1.5\,\mu{\rm m}) = 14\,\rm nWm^{-2}sr^{-1}$. H.E.S.S. observations of other distant VHE blazars (H 2356−309, 1ES 0347−121) confirm the low EBL level as deduced from the 1ES 1101−232 H.E.S.S. spectrum. The general "hardness" of the spectra of distant VHE blazars might be explained through the better VHE detectability of hard-spectrum sources.

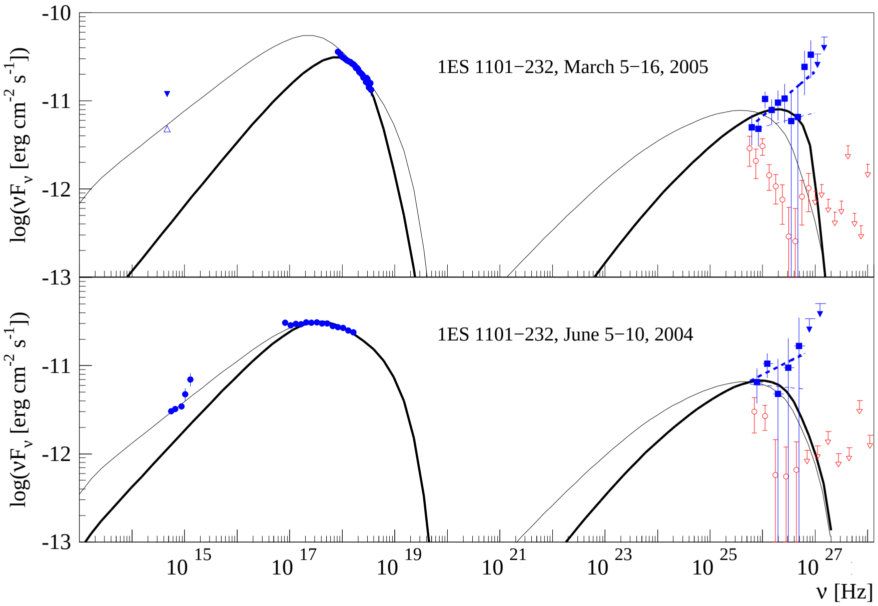

Figure 2: Spectral energy distribution of 1ES 1101−232. **Upper panel:** Data from March 5-16, 2005. In the VHE band, the measured H.E.S.S. spectrum (red, open symbols) and the deabsorbed spectrum using a maximum EBL level of $14\,\mathrm{nWm^{-2}sr^{-1}}$ at $1.5\,\mu\mathrm{m}$ are shown. The thick dashed line is a power-law fit to the deabsorbed data as plotted, while the thin dashed line indicates the effect if the EBL is lowered to the minimum level of $10\,\mathrm{nWm^{-2}sr^{-1}}$. X-ray data are from RXTE. In the optical band, an upper limit (filled triangle) and a tentative lower limit (open triangle) from ROTSE 3c data are shown. **Lower panel:** Data from June 2004. In the VHE band, H.E.S.S. data taken between June 5-10, 2004, are shown. X-ray and optical data were derived from an XMM-Newton pointing on June 8, 2004.

Acknowledgements

The support of the Namibian authorities and of the University of Namibia in facilitating the construction and operation of H.E.S.S. is gratefully acknowledged, as is the support by the German Ministry for Education and Research (BMBF), the Max Planck Society, the French Ministry for Research, the CNRS-IN2P3 and the Astroparticle Interdisciplinary Programme of the CNRS, the U.K. Particle Physics and Astronomy Research Council (PPARC), the IPNP of the Charles University, the South African Department of Science and Technology and National Research Foundation, and by the University of Namibia. We appreciate the excellent work of the technical support staff in Berlin, Durham, Hamburg, Heidelberg, Palaiseau, Paris, Saclay, and in Namibia in the construction and operation of the equipment. We thank the ROTSE collaboration for providing the ROTSE 3c optical data, and L. Ostorero for help with the optical data analysis.

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