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Observations of PKS 2155-304 in gamma-rays with H.E.S.S., and interpretation with simultaneous multiwavelength data

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The high-frequency peaked BL Lac PKS 2155-304, at a redshift z = 0.117, has been detected with high significance at energies greater than 160 GeV, using the H.E.S.S. stereoscopic array of imaging atmospheric-Cherenkov telescopes in Namibia. A strong signal is found in each of the data sets corresponding to dark periods in 2002 & 2003. Energy spectra are measured for these individual periods of data taking and are characterized by a steep power law with a 2003 time-averaged photon index of Γ = 3.34 ± 0.05 (± 0.10 syst).

In late 2003, observations of PKS 2155-304 were performed simultaneously with H.E.S.S., the PCA on board the RXTE satellite, the ROTSE optical telescope, and with the Nançay decimetric radiotelescope. Results from these data represent the first simultaneous detections over such a wide energy range, and establish that the source was in a low or quiescent state at that time. During this low state, no correlation can be established between the X-ray and the gamma-ray fluxes, or any of the other wavebands, over the small range of observed variability. A broadband spectral energy distribution (SED) is obtained from these simultaneous multiwavelength observations, and is used to place constraints on emission model parameters, taking into account the effect of Extragalactic Background Light absorption.

In contrast, preliminary results from a similar multiwavelength campaign in 2004 show a higher activity state, and suggest a correlation between the gamma-ray and the X-ray fluxes.

1. Introduction

PKS 2155-304 is a high-frequency peaked BL Lac object which was discovered in X-rays [1] and is one of the brightest X-ray sources in the sky. It is well studied over the entire electromagnetic spectrum and its maximum power is emitted between the UV and soft X-ray range. It is also the brightest BL Lac detected in the UV regime [2] and has a history of strong broad-band variability. In the gamma-ray domain, this source has been occasionally detected above 30 MeV by EGRET on board the CGRO [3], and above 300 GeV by the Mark 6 Cherenkov telescope [4], but it has not been detected by the CANGAROO experiment [5].

The confirmation by the High Energy Stereoscopic System (H.E.S.S.) of the detection of VHE gamma-rays from PKS 2155-304 [6], even when the source was in a low state, provides valuable data that can be combined with simultaneous observations at other wavelengths [7] to constrain the physical processes involved in the TeV gamma-ray emission from the central engine and jets of blazars. Measurement of the global SED, in addition to correlated flux variability, spectral variations and time lags across the broad-band observations, allow modeling of particle distributions and their radiation processes, as well as probe the acceleration mechanisms that are involved.

2. H.E.S.S. observations and results

In its first phase, the H.E.S.S. array consists of four atmospheric-Cherenkov telescopes operating in stereoscopic mode. However, much of the data shown here were taken during the construction phase of the system, with the number of telescopes ranging from one up to four. Each telescope has a tessellated 13 m-diameter (107 m^2 surface area) mirror which focuses the Cherenkov light from the showers of secondary particles created by the interaction of γ-rays in the atmosphere onto a camera in the focal plane. This camera consists of 960 photomultipliers with embedded GHz sampling electronics, providing a pixel size of 0.16° and a field of view of 5°. For the four-telescope system, the effective γ-ray *psf* is better than 0.1°, the γ-ray trigger threshold at zenith is ≈ 100 GeV and the spectral threshold is 160 GeV with an energy resolution ≃ 15%. The experiment is located in the Khomas highlands in Namibia, (23° S, 15° E, 1800 m a.s.l.). A description of the detector system is given in [8] and more details can be found in [9] and [10] for the optical system, in [11] for the camera, in [12] for the trigger and in [13] for the calibration.

Observations of PKS 2155-304 were made between July 2002 and Aug. 2004 with the various configurations shown in Table 1, in either *On-Off* mode or *Wobble* mode [6]. Only data passing run quality selection criteria and with significant observing time have been used in the analysis and entered in Table 1. The event reconstruction procedure [6] includes calibration and image cleaning steps, Hillas-type parameterization, and stereoscopic reconstruction. The cosmic-ray background is estimated either from the *Off* runs (mono), or from a ring around the source location (stereoscopic data). The significance of the excess is calculated following the Li & Ma method [14].

Table 1. H.E.S.S. data samples, Source significance and Spectral parameters

Dark Period	Nb Telesc.	Obs. time [h live]	Signif. [σ]	Average flux I_0 $\left[\times 10^{-12}\ \frac{1}{cm^2.s.Tev}\right]$	Photon Index Γ ±0.10 syst.
July 2002	1	2.5	13	15.6±2.1	2.84±0.24
Oct. 2002	1	4.3	8.2	6.36±1.75	3.10±0.46
June 2003	2$^+$	10.8	21.1	2.42±0.28	3.56±0.17
July 2003	2	22.1	22.1	1.75±0.18	3.26±0.11
Aug. 2003	2	19.6	27.7	1.84±0.18	3.36±0.09
Sept. 2003	2-3	2.1	14.7	2.40±0.41	3.42±0.15
Oct-Nov. 2003	2-3*	32.4	34.3	2.73±0.17	3.37±0.07
[June-Nov] 2003	*2-3*	*87,0*	*55,6*	*2,22±0.10*	*3.34±0.05*
July-Sept. 2004	4*	52.6	95.6	2.17±0.08	3.58±0.04

+ : Software stereo, * : Multi-wavelength monitoring campaign

PKS 2155-304 is strongly detected by H.E.S.S. in all the dark periods of observations. As an illustration, the two-dimensional γ-ray sky map for the Oct-Nov. 2003 period is shown in Fig 1. The methods used for reconstructing the energy of each event and for determining a spectrum are described in [6], and the spectra are fitted by a simple power-law of the form $dN/dE = I_0\ (E\ /\ 1\ \mathrm{TeV})^{-\Gamma}$ where I_0 is the flux at 1 TeV and Γ the photon index. The flux I_0, averaged over each dark period, is shown in Table 1. As expected for a Blazar, the emission is highly variable, but it can be seen that PKS 2155-304 is easily detected by H.E.S.S. even when it is in a relatively low state. Within the statistics and the systematics of the experiment, there is no evidence of index variation as a function of the activity level.

3. Multi-wavelength observations and results

Simultaneous H.E.S.S. VHE γ-ray, RXTE/PCA X-ray, ROTSE optical, and NRT decimetric observations of PKS 2155-304 have been performed in the framework of a ToO (Target of Opportunity) program during the dark periods from Oct. 19 to Nov. 26, 2003. Details on the equipment, data sets, and analysis can be found in [7]. The obtained light curves show clearly that the activity level of the source, despite displaying significant flux variability, was not very high during this period. The minimum fluxes seen are consistent with historically low values. For these data sets, no correlation between the emission at these various wavelengths is observed.

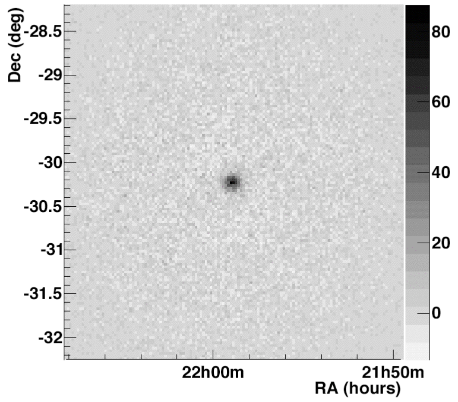
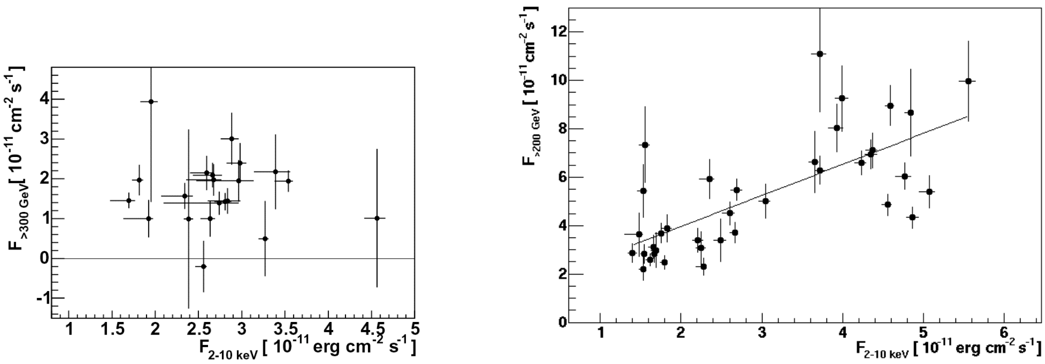


Figure 1. (Left) The two-dimensional distribution of excess events observed in the direction of PKS 2155-304 in Oct.-Nov. 2003 while the source was in a rather low state. The bins are not correlated and represent the actual distribution of observed γ-rays on the sky. The right hand scale is the number of counts per pixel.

Figure 2. (Below) Correlation plots between γ-rays measured with H.E.S.S. and X-rays measured with RXTE.
Left panel: results for the 23 RXTE data segments (spread over 2 months) that overlapped exactly with a H.E.S.S. observation during Oct.-Nov. 2003 (almost low state); a poor correlation is found.
Right panel: data for coincident measurements, in quality selected runs, during the X-ray flares of Aug. 2004 (44 data segments within 2 weeks); a close correlation is seen with a correlation factor r = 0.71±0.05.



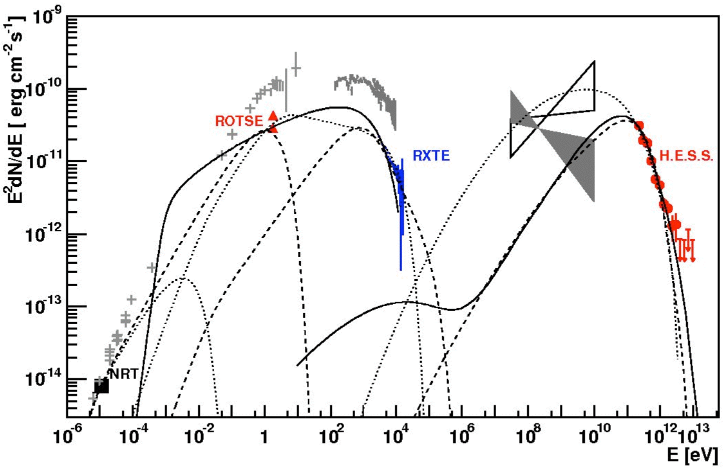


Figure 3. Spectral energy distribution of PKS 2155-304. Only simultaneous measurements are labeled. Non-contemporaneous data are in grey symbols. The H.E.S.S. spectrum is derived from Oct. and Nov. 2003 data (*filled circles*) as is the RXTE spectrum. The NRT radio point (filled square) is the average value for the observation carried out during this period. The two triangles are the highest and lowest ROTSE measurements for the Oct.-Nov. observations. Archival SAX data represent the high state observed in 1997 [15]. Archival EGRET data are from the third EGRET catalog (shaded bowtie) and from a very high γ-state reported in [3] (open bowtie). The solid line is the hadronic blazar model described in the text. The dotted and dashed lines are the same electromagnetic model with different assumptions. All the VHE emission in the blazar models are absorbed according to the Primack04 EBL model.

A new monitoring program was performed in Aug 2004 when the source was in a more active state as shown by the X-ray light curve. Preliminary results from runs passing strict quality criteria (July 14 - Sept. 10) show a clear correlation (r = 0.71±0.05) between VHE γ-rays and X-rays (Fig. 2).

4. Source modeling and propagation effect

Due to the non-negligible redshift (z = 0.117) of PKS 2155-304, the observed VHE spectra must be corrected for the absorption by the extragalactic background light (EBL). Three EBL models at wavelength ≤ 5 µm have been tested. Dubbed "Phigh", "Primack01", and "Primack04" [7], they boost the absorption-corrected 2003 VHE spectral index Γ' to 1.5, 2.3, and 2.8 respectively.
The simultaneous 2003 measurements of the SED, from radio to VHE γ-rays (Fig. 3), have been fitted with several electromagnetic (synchrotron self-Compton SSC) and hadronic (proton synchrotron SPB) models of γ-ray production [7, and references therein]. For the SSC single-zone model with Primack04 EBL, the radio emission requires a separate more extended component. With Phigh EBL, the peak of the VHE emission in this scenario is pushed above 4 TeV, thus requiring extreme parameters in the model ($B \approx 0.02$ G, and $\delta_b \approx 50$) and decreasing the agreement significantly. On the other hand, the SPB single zone model with Primack04 EBL reproduces the simultaneous data with $B \approx 40$ G, and $\delta_b \approx 20$, while the Phigh EBL can also be accommodated with these parameters if some others are changed. Thus, this hadronic model is less sensitive to the EBL models used here. We are still investigating the fluxes and spectra from the 2004 multiwavelength data sample, and further progress in the understanding of PKS 2155-304 is expected.

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