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Long-Term VHE Gamma-Ray Monitoring of PKS 2155−304 with H.E.S.S. and Multiwavelength measurements, 2002-2005

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Abstract: The high-frequency peaked BL Lac PKS 2155−304, the lighthouse of the Southern hemisphere sky at VHE gamma-ray energies, has been followed by the H.E.S.S. array of atmospheric Cherenkov telescopes since the first light of the project, first with a single telescope in 2002, then with two & three telescopes in 2003, and since 2004 with the full-sensitivity four-telescope array. In this mode, a number of multi-wavelength campaigns have been performed with observations from the Rossi X-ray Timing Explorer (RXTE), Rotse (Optical), Spitzer (IR), James Clark Maxwell Telescope (JCMT, sub-mm) and others in both quiescent and active states, based on both fixed campaigns and triggers from H.E.S.S. Here we present the results of this series of observations up to 2005 inclusive, together with the implications for source models of the spectral measurements and search for correlated variability with X-rays, Optical, and IR measurements. The exceptional flare activity of 2006 is covered in a separate paper at this conference.

Introduction

The H.E.S.S. experiment (High Energy Stereoscopic System, [1]) has been in operation since 2002, though reaching full sensitivity in 2004 with the installation of the final element in the four-telescope array. During all this time, a prime target of H.E.S.S. has been the high-frequency peaked BL Lac PKS 2155−304, which is one of the brightest blazars in the Southern sky in the very-high-energy (VHE) γ-ray domain. These observations have been coupled with multi-wavelength campaigns, both planned and resulting from Target of Opportunity (ToO) triggers by H.E.S.S. in the case of exceptional activity of this source, working with such instruments as the Rossi X-ray Timing Explorer (RXTE), the Chandra X-ray satellite, the X-ray telescope (XRT) and UV-optical telescope (UVOT) on board the SWIFT satellite, Spitzer (IR), James Clark Maxwell Telescope (JCMT, sub-mm), the Rapid Optical Transient Search Explorer (ROTSE-III), and the Nançay Radio Telescope (NRT).

The source PKS 2155−304, at a red-shift of $z = 0.116$, is an X-ray selected object of the BL Lac class, and has been the focus of studies in many wavelength ranges (see e.g. [2]) over the past 20 years. It was first seen at VHE energies by the Durham Mark 6 telescope [3], and this detection was confirmed by H.E.S.S. in the observations referred to here. The multi-wavelength observations of this source have shown broad-band variability on timescales from years to minutes, as also seen in the VHE range with H.E.S.S. This variability is presumed to be associated with a relativistic jet aligned close to the line of sight to the observer, allowing the processes in the jet to be probed by such studies.

Observations with H.E.S.S.

PKS 2155−304 has been observed by H.E.S.S. since its inception, first with a single telescope in 2002, then with two & three telescopes in 2003, and since 2004 with the full-sensitivity four-telescope array. Figure 1 shows a summary of the observations taken on this source, where in each case the average integral flux above 1 TeV is shown for each observation period, together with the significance of the detection above the threshold of the instrument in the given configuration. All data here are analysed using the H.E.S.S. standard analysis procedures, for data passing run quality selection criteria, some previously reported in [4]. The data for 2005/2006 are still undergoing analysis, and these preliminary results are shown for comparison, including the excess number of γ-rays above threshold for both standard and loose cuts. The 2006 data are not detailed on a month-by-month basis here.

The most striking conclusions which can be drawn from this series of observations is that the source is clearly variable on year-by-year and month-by-month timescales, and that it is detected in all months where a hour or more observation time was taken. It can also be seen that the activity of the source was very high in 2002, though it was observed with a low-sensitivity single-telescope configuration; this activity was greater on average than that in 2006. However, as described in [5] at this conference & published in [6], the large data-set in 2006 contains nights with exceptional activity, in one of which ~ 3 minute time-variability is seen.

Obs. Period [mth-year]	Live-time [hrs]	Avg flux @ 1 TeV [10^{-12} cm^{-2}s^{-1}TeV^{-1}]	± Error	Standard cuts: Excess (>thr.)	Standard cuts: Signif. [σ]	Loose cuts: Excess	Loose cuts: Signifi.	System status
07-02	~4	15.6	± 2.1		13			Single dish, 1-telescope
10-02	~10	6.4	± 1.8		8			
06-03	~10	2.4	± 0.3		21			Faux-stereo, 2-telescope
07-03	~50	1.8	± 0.2		22			Stereo, 2-telescope
08-03		1.8	± 0.2		28			
09-03		2.4	± 0.3		15			
10:11-03		2.7	± 0.2		34			Stereo, 3-telescope
								Stereo, 4-telescope
07:10-04	~96	2.2	± 0.1		96			↓ onwards ...
8-05	0.9	1.4	± 0.3	84	9	158	5	
9-05	1.7	1.4	± 0.2	155	13	357	10	
10-05	3.4	2.0	± 0.2	314	19	809	15	
11-05	0.4	~0		-5	-1	2	0	
2005	6.5	1.6	± 0.2	548	18	1326	18	
2006	61.1	6.9	± 0.1	32216	268	71729	264	

Figure 2: Long-term monitoring of PKS 2155−304 with H.E.S.S., showing where available for each observation period, the observation time, average flux above 1 TeV in units of $10^{12}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{TeV}^{-1}$, γ-ray excess above threshold, and significance.

Multi-wavelength campaign in 2003

On October 18th 2003, the highly-significant detections of this source with H.E.S.S. (in its 3-telescope stereo configuration) prompted the triggering of an RXTE ToO proposal, with a number of quasi-simultaneous observations being taken in conjunction with RXTE/PCA, ROTSE, and NRT. From October 19th to November 26th, 2003, This campaign provided the first wide-band simultaneous spectrum on PKS 2155−304, although the source appeared to be in a low state during these observations. The Spectral Energy Distribution measured by the instruments in this campaign is shown in Figure 2. The average spectral index measured with H.E.S.S. was $3.37 \pm 0.07_{\mathrm{stat}}$, similar to that measured at other epochs. The simultaneous data-points are fitted by several models. Due to the relatively distant red-shift of this source, the models must include absorption on the Extragalactic Background Light (EBL) in the μmetre range. Two leptonic models were fitted: single-zone Synchrotron Self-Compton (SSC) models in which the optical emission is either from the same population of electrons as the X-ray, or produced by an extra VLBI component, probably from the compact core, along with the radio. These models imply values of EBL in the low range for reasonable values of fitted magnetic field and Doppler factor. One hadronic model was tested, the Synchrotron Proton Blazar (SPB) model, which also could fit the data for a range of EBL values. Note that subsequent observations of more distant blazars with H.E.S.S., 1ES 1101−232 and H 2356−309, favour the low range of EBL values also [9].

In this campaign, no correlation was seen between the VHE γ-rays and the X-rays or the optical flux, or indeed between X-rays and optical. However, within the X-ray band a correlation was seen between the hardness ratio (defined as ratio of the flux from 4–11 keV to that from 1–4 keV) and the rate, with a correlation of $r = 0.76 \pm 0.12$ (see Figure 3), implying that the spectrum becomes harder as the source brightens in X-rays.

This campaign is reported in greater detail in [10].

Multi-wavelength campaign in 2004

In 2004, a planned monitoring programme on PKS 2155−304, proposed by H.E.S.S., was carried out from July 14th to September 11th. Ob-

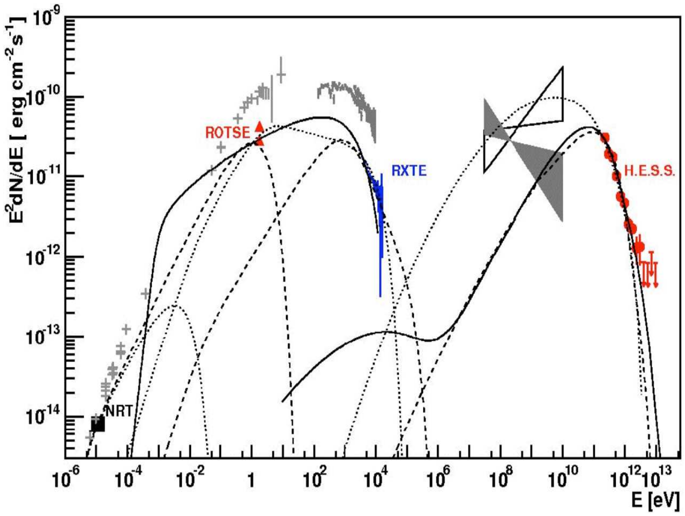

Figure 1: SED of PKS 2155−304 as measured in 2003. Only simultaneous data are labelled; non-contemporaneous data are shown in grey. The H.E.S.S. spectrum is from Oct. and Nov. 2003 data (filled circles) as is the RXTE spectrum. The NRT radio point (filled square) is the average value for the observation during this period. The two triangles are the highest and lowest ROTSE measurements for the Oct.-Nov. observations. Archival SAX data show the high state observed in 1997 [7]. Archival EGRET data are from the third EGRET catalogue (shaded bowtie) and from a very high γ-state reported in [8] (open bowtie). The solid line is the hadronic blazar model described in the text, while the dotted and dashed lines are the leptonic models

servations were performed simultaneously with RXTE/PCA, ROTSE, and NRT. The source in this case had become more active than in the previous year as seen by the X-ray data, and a preliminary analysis of the VHE data passing strict quality criteria show a strong positive correlation ($r = 0.71 \pm 0.05$) between the VHE γ-rays and the X-rays [11]. Compared to the previous campaign in 2003, then, it would appear that the correlation became apparent for the larger variability range seen in this years' data.

A number of nights of H.E.S.S. data from this campaign were affected by large-scale smokey haze; the correction of these data for loss of Cherenkov photons is covered in [12] at this conference. This should provide further data to be included for the VHE γ-ray / X-ray correlation.

Multi-wavelength campaign in 2006

The exceptional activity in 2006 previously referred to prompted the publication of an Astronomers Telegram by H.E.S.S., and the observation of the source with RXTE, CHANDRA, SWIFT, and optical telescopes. This campaign is still under analysis, but the much wider variability range shown (up to 15 Crab-level at peak) should provide ample testing-ground for multi-band correlations.

Conclusions

The observations of PKS 2155−304 with H.E.S.S. since the inception of the telescope has provided a relatively long baseline over which the activity of this brightest blazar in the Southern sky can be evaluated, and giving an estimate of its duty-cycle. In VHE γ-rays alone, the activity is seen to vary over orders of magnitude, on time-scales of years, months, days, down to minutes, and very high activity was seen both in the first year of observation, 2002, and last year, in 2006.

Several multi-wavelength campaigns have been carried out, either planned or as target of opportunity. In these campaigns, it has been seen that the X-ray spectrum became harder as the source

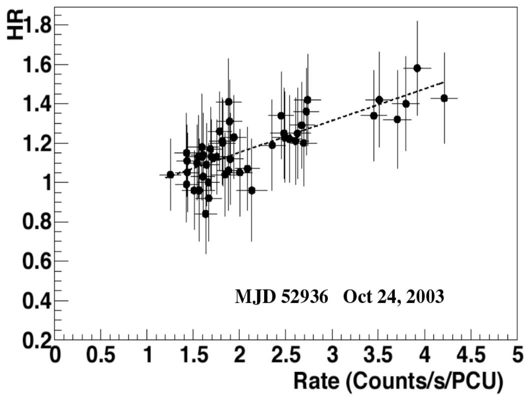

Figure 3: Correlation within the RXTE measurements taken during the H.E.S.S. multi-wavelength campaign in 2003, where a clear correlation is seen with between the X-ray activity and the hardness ratio as defined in the text, with a correlation factor $r = 0.76 \pm 0.12$.

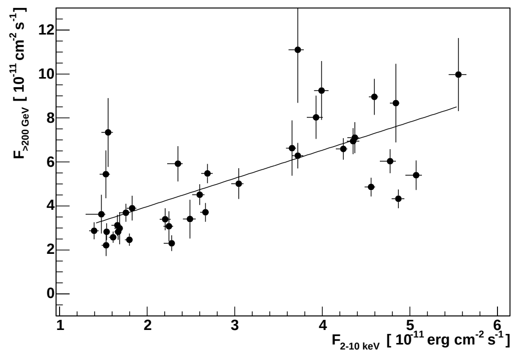

Figure 4: Correlation between H.E.S.S. and RXTE for coincident measurements, in quality selected runs during the X-ray flares of Aug. 2004 (44 data segments within 2 weeks); a close correlation is seen with a correlation factor $r = 0.71 \pm 0.05$.

increased in brightness (2003 campaign), and that inter-band (VHE γ-ray / X-ray) correlations became apparent only with a larger variability range (2004 campaign). From the 2003 campaign, a multi-waveband SED has been produced which can be fitted by either leptonic or hadronic models, in the former case favouring a low range of Extragalactic Background Light. The 2006 multi-wavelength campaign triggered by H.E.S.S. due to spectacular activity of the source is still under analysis but should yield further insights into the processes at work in this category of source.

This source, given its highly active and variable states and soft spectrum, should be a prime candidate for future GLAST/H.E.S.S. multi-wavelength campaigns.

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