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Long term lightcurve of the BL Lac object 1ES 0229+200 at TeV energies

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The high-frequency peaked BL Lac object 1ES 0229+200 (z = 0.14) was first detected in very high energy (VHE, E > 100 GeV) γ-rays by the H.E.S.S. (High Energy Stereoscopic System) collaboration in 2006 [1]. No flux variability was reported in the initial study and its spectral characteristics have been used to derive constraints on the extragalactic background light (EBL, [1]) and on the intergalactic magnetic field (IGMF, e.g. [2, 3, 4, 5]). 1ES 0229+200 has been observed with H.E.S.S. for ∼130 hours from 2004 to 2013: the full dataset analysed with a more sensitive method will be presented here. The results indicate that the source is not constant and displays flux variability on yearly and monthly timescales. The existence of flux variability affects the derivation of the constraints on the IGMF. The H.E.S.S. observations cover several simultaneous multi-frequency campaigns and the VHE variations are compared with those reported in different bands.

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1. Introduction

1ES 0229+200 is a blazar, and a member of the high frequency peaked BL Lac objects (HBL) subclass. It is hosted in an elliptical galaxy located at a redshift $z = 0.1396$. It was first discovered in X-rays by the *Einstein* IPC Slew Survey in 1992 [6]. Its synchrotron emission reaches 100 keV and possibly up to 200 keV[1]. Despite being relatively bright in optical and X-rays, it is faint in radio and γ-rays. It has been detected at VHE above 500 GeV for the first time by H.E.S.S. in 2006 [1], and only in 2011 at high energies (HE, 100 MeV < E < 100 GeV) between 1 and 300 GeV, after more than three years of *Fermi* observations [5]. Contrary to what one could expect from its blazar nature, 1ES 0229+200 shows little variability at all energies, even if it is known to have flux variations in the X-ray band of a factor of ~ 2. (e.g. [7]). Hints of variability at TeV energies were reported on yearly and monthly timescales by the VERITAS collaboration in 2014 [8], while none was detected in the source in the initial H.E.S.S. study.

1ES 0229+200 has been one of the key sources for deriving constraints on the extragalactic background light (EBL, [1]) and on the intergalactic magnetic field (IGMF, e.g. [2, 3, 4, 5]) thanks to the combination of its hard spectrum (Γ_{PL} ~2.5, [1, 8]) reaching ~ 10 TeV and its considerable distance (for a TeV source). The spectrum allows one to probe the near- and mid-infrared wavelengths of the EBL (~ 2 - 20 μm) at high optical depths ($\tau \sim 1$ - 6 for γ-ray energies between ~ 1 - 10 TeV). This is unique, since only a few other sources have been observed at these energies. For the IGMF studies, a multi-TeV hard spectrum in combination with high optical depths implies that a considerable part of the emitted TeV photons will be absorbed via pair production through their interaction with the EBL and re-emitted at (typically) GeV energies, causing a surplus of HE emission. Lower limits on the strength of the IGMF can be calculated measuring the GeV emission and making assumptions on the intrinsic spectrum. Since reprocessing involves emission from an ensemble of charged particles that are spread over an extended volume by the action of the magnetic field, time delays are of the order of the light travel time of the excess distance that the re-emitted photons must cover with respect to the line of sight to the source. Time delays are also energy dependent, since a given magnetic field will affect more strongly the trajectories of low-energy particles. This holds true as long as the Compton cooling time is of the order of the gyroradius. If it is too fast, re-emission is almost immediate and time delay negligible. If it is too slow, this and not the magnetic field determines the time delay. The observed reprocessed emission corresponds therefore to the time-averaged original VHE emission. Constrains on the IGMF hence rely on the assumption of a steady VHE flux on time scales of these delays. Is the VHE flux variable, average values can be used as long as the variability is shorter than the reprocessing time delay.

2. Observations and Analysis

2.1 H.E.S.S.

H.E.S.S. observations have been carried out almost yearly between 2004 and 2013, for a total of 354 observation runs[2]. 311 of them pass the standard quality cuts for a total livetime of ~ 133 h

[1] `http://bat.ifc.inaf.it/100m_bat_catalog/100m_bat_catalog_v0.0.htm`

[2] The term "run" refers to a single observation, with a typical exposure of 28 minutes.

Table 1: Statistics of the yearly and total H.E.S.S. observations.

Period	Dates (MJD)	Live Time (h)	ON counts	OFF counts	excess	Significance (σ)	Flux (> 580 GeV) (10^{-13} cm^{-2}s^{-1})
2004 - 2013	53259 - 56606	132.5	1839	14138	699	18.1	6.2 ± 0.5
2004	53259 - 53317	3.8	47	349	18	2.9	3.5 ± 1.9
2005	53613 - 53649	16.4	169	1518	42	3.4	2.5 ± 1.0
2006	53967 - 54088	47.1	750	4577	368	15.8	9.0 ± 0.8
2007	54322 - 54336	10.5	137	1080	47	4.4	5.6 ± 1.7
2008	54681 - 54789	12.2	149	1420	31	2.6	4.0 ± 1.6
2009	55063 - 55151	19.0	215	1825	63	4.6	5.2 ± 1.4
2011	55801 - 55909	7.4	112	918	35	3.6	1.9 ± 2.0
2013	56514 - 56606	17.8	241	2189	95	6.9	7.4 ± 1.3

Note: the normalization factor β between the ON and OFF area is 1/12 for all years with the exception of 2013 1/15.

(122 h when corrected for acceptance). The mean zenith angle is 45.2° and the mean offset from the pointing position 0.51°. The exposure was not homogeneous during these observation years, ranging from 3.8 h in 2004 to 47.1 h in 2006. Refined quality selection criteria allowed for a larger dataset for the years 2004-2006 than the one published in [9] and [1]. Part of the 2009 and 2013 data belong to multiwavelength (MWL) campaigns. The first one was organized with XMM-*Newton* and ATOM on August 21 and 23, 2009, the second one with *NuSTAR*, *Swift*-XRT, MAGIC and VERITAS on October 1, 5 and 11, 2013. Data reduction has been performed using the Model analysis[3] [10] with *Standard* cuts. For the background determination for the spectral and temporal analyses, the *Reflected Region Background* method [11] was used. The source is detected with a significance of 18.1 standard deviations (σ) for the whole dataset. The results for the total dataset and for every year of observation can be found in Tab.1, as well as in Tab.2 for the 2006 and 2009 observing periods.

Spectral analyses have been carried out on different data subsets using the forward-folding technique [12] and a simple power-law (PL) spectral shape. No spectral variability is detected on a yearly nor monthly timescale. The lightcurves are derived adjusting the normalization of a PL with index $\Gamma = 2.9$ to the γ-ray excess in every time bin. Only energies above a common threshold of 580 GeV are considered. The monthly and yearly lightcurves are shown in the top two panels of Fig. 1 and discussed in Sec. 3. All results have been cross checked with a different software and calibration chain.

2.2 High Energy

HE data have been collected by the Large Area Telescope (LAT) onboard the *Fermi* satellite starting August 4, 2008. Data up to April 27, 2015 have been analysed with the Science-Tool software package version `v9r33p0`. Only events belonging to the 'Source' class within 15° from the position of 1ES 0229+200 were selected. Moreover, cuts on zenith angle (100°),

[3]software version paris-0-8-24, DSTs Prod26

Table 2: Statistics of the 2006 and 2009 observation periods.

Period	Dates (MJD)	Live Time (h)	ON counts	OFF counts	excess	Significance (σ)	Flux (> 580 GeV) (10^{-13} cm^{-2}s^{-1})
	2006						
August	53967 - 53977	13.5	226	1581	94	7.1	8.1 ± 1.6
September	53994 - 54005	16.0	329	1813	178	11.9	12.2 ± 1.6
November	54048 - 54063	12.5	146	813	78	7.8	6.9 ± 1.4
December	54077 - 54088	5.1	49	370	18	2.9	6.8 ± 2.0
	2009						
August	55063 - 55074	9.3	72	815	4	0.5	-0.5 ± 1.5
October	55115 - 55121	5.1	73	561	26	3.4	7.0 ± 2.9
November	55145 - 55151	4.6	70	449	33	4.5	16.6 ± 3.8

Note: the normalization factor β between the ON and OFF area is 1/12 for all periods. The observing periods are defined by the lunar cycle and do not always strictly match the given month, which is given for an easier identification.

rocking angle (52°) and distance from the Sun (5°) were applied. For the binned maximum-likelihood spectral analysis, the instrument response functions `P7REP_SOURCE_V15` were used, together with the publicly available standard Isotropic and Galactic diffuse emission background models iso_source_v05.txt and `gll_iem_v05 rev1.fit`.

1ES 0229+200 is detected with a significance of 10.5 σ in the energy range 100 MeV - 500 GeV, compared to the 6.7 σ between 1 and 300 GeV in [5]. The low flux in the *Fermi*-LAT band does not permit detailed temporal studies on monthly timescales. Nonetheless, the variability index[4] for the monthly lightcurve has a value of 157 for 81 degrees of freedom, which indicates variability at the 5 σ level.

2.3 X-rays

In this work, X-ray data from *Swift*, *RXTE* and XMM-*Newton* are used[5] (Fig. 1, third and fourth panels). The 30-days bin *Swift*-BAT lightcurve between 15 and 85 keV is derived from the 15-days bin one in the 66 months Palermo BAT Catalog[6]. The 2008 and 2009 XMM-*Newton* and *Swift*-XRT, as well as the 2010 *RXTE* data are taken from [7], while the whole 2010-2011 *RXTE* lightcurve is taken from [13]. Finally, the most recent *Swift*-XRT data have been collected between the nights of October 1-2 and 10-11, 2013 during the aforementioned MWL campaign.

All the available *Swift*-XRT data collected between 2008 and 2015 (ObsIDs 00031249001-00031249050 and 00080245001-00080245006) were analysed using the HEASoft software package v. 6.16[7] with CALDB v. 20140120. All the events were cleaned and calibrated using the

[4] $TS_{var} = 2\Sigma_i[\log\mathcal{L}_i(F_i) - \log\mathcal{L}_i(F_{const})]$ where F_{const} and F_i are the average source flux and the flux of the i-th time bin. No limits on the bin significance are required.

[5] *NuSTAR* data are not taken into account here since they are subject of a dedicated paper, in preparation.

[6] `http://bat.ifc.inaf.it/bat_catalog_web/66m_bat_catalog.html`

[7] `http://heasarc.gsfc.nasa.gov/docs/software/lheasoft`

`xrtpipeline` task and the data in the 0.3-10 keV energy range with grades 0-2 for WT mode and 0-12 for PC mode were analysed. The lightcurve flux points were calculated from the spectra of single snapshots integrating between 2 and 10 keV. These were derived in the following way: the data were grouped using the `grappha` tool to have a minimum of 30 counts/bin and then fit using XSPEC v. 12.8.2 with a single power-law model and Galactic hydrogen absorption fixed to $n_H = 8.06 \times 10^{20}\,\mathrm{cm}^{-2}$ [14].

2.4 Optical

Optical monitoring of 1ES 0229+200 has been carried out with the ATOM telescope [15] between 2007 and 2012. ATOM is a 75 cm altazimuth telescope equipped with an Apogee Alta U47 camera (Apogee Alta E47+ between 2004 and 2011) and works in robotic mode. It is part of the H.E.S.S. project and is used mainly for optical monitoring of variable γ-ray sources as a constant support for MWL observations. The observations for 1ES 0229+200 have been carried out typically once every three nights during the August-December visibility window. The standard reduction, the photometry and the source calibration are done with an automatic pipeline. The photometry uses an aperture of $4''$, while two reference stars in the vicinity of the source and present on the same frame are used for the calibration. During the 2013 MWL campaign ATOM was not operational and data were collected with the 70 cm telescope of the Abastunami Observatory (Georgia), equipped with an Apogee 6E camera. Observations taken with a R Cousins filter have been analysed with the Daophot II reduction software using an aperture diameter of $10''$.

3. Results and discussion

The Model analysis is more sophisticated and sensitive than the Hillas analysis [16] used in the previous publications. Its use permits therefore to have a much higher sensitivity to small flux variations. The monthly and yearly VHE lightcurves (top two panels of Fig. 1) show an emission which is not constant, neither on a yearly, nor on a monthly timescale. A fit to a constant value yields a χ^2 of 84.3 (33.3) for 22 (7) degrees of freedom for the monthly (yearly) lightcurve. This translates in a probability of 5×10^{-9} and 2×10^{-5} respectively. The values for the fractional variability ([17], though whose errors are calculated as in [18]) are then 0.60 ± 0.15 and 0.39 ± 0.11. Variability is detected on a monthly timescale also between 0.58 to 1 TeV and above 1 TeV (probability of a constant flux of 1×10^{-4} and 2×10^{-5}, respectively).

In 2009, H.E.S.S. and VERITAS observed the source contemporaneously (though on different nights). The time range spanned by the VERITAS observations was significantly longer than the H.E.S.S. one. Taking the windows into account, the measurements of both experiments are consistent with an increasing flux that reaches its maximum just before MJD 55150 and then decreases. The comparison of the VHE and X-ray data in 2009 [7] is very interesting. The source is in very low state for both H.E.S.S. and XMM-*Newton* during the MWL campaign (MJD ~55065). This changes in the following three months, when *Swift*-XRT detects a factor ~2 flux increase [7] (also seen by *Swift*-BAT), which is mirrored by an enhancement in the emission in γ-rays of a factor 2 or 3 (Fig. 1). In all three wavebands, this state is followed by a decrease in the emission. Despite the limited sensitivity of *Swift*-BAT in the hard X-ray band, it is interesting to notice that the three periods of low VHE fluxes in 2008 and 2009 are mirrored also in this band. The R and B bands

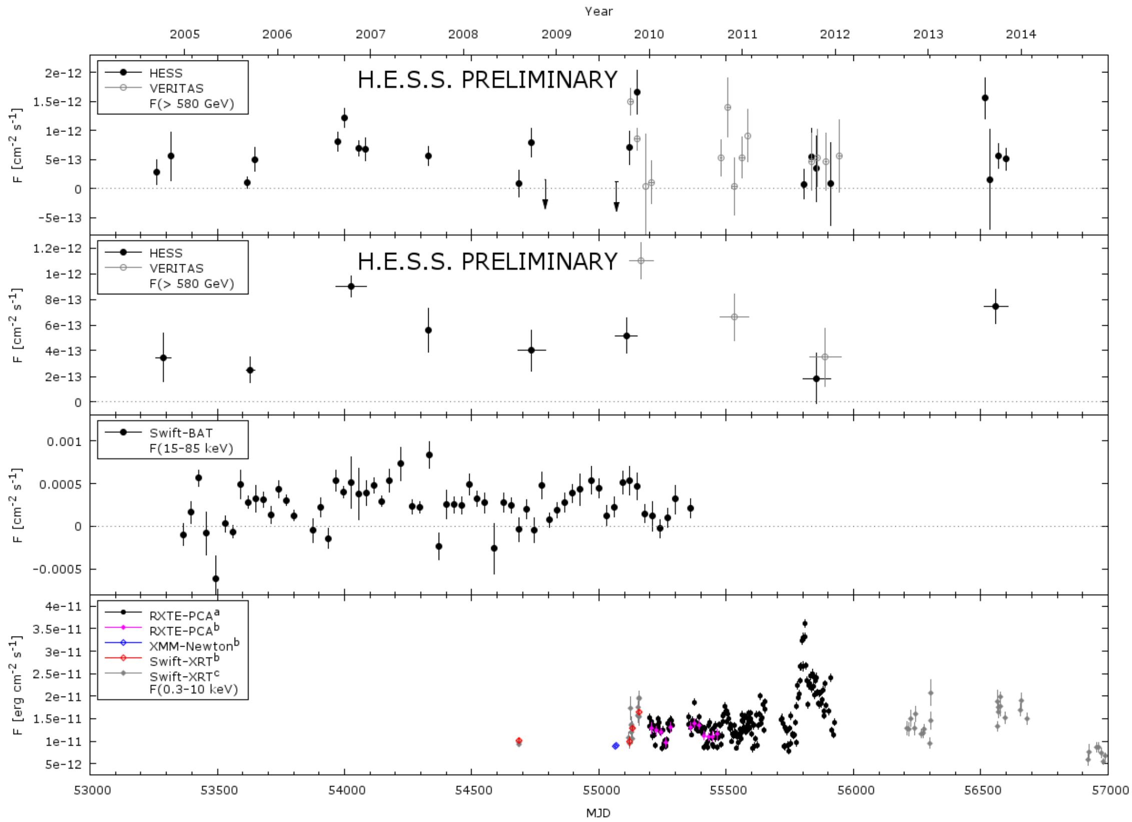

Figure 1: Lightcurves of the BL Lac object 1ES 0229+200 in different energy bands between 2004 and 2013. From *top* to *bottom*: monthly and yearly H.E.S.S. lightcurves above 580 GeV - the VERITAS values from [8] are also depicted as comparison; hard X-rays monthly lightcurve between 15 and 85 keV from *Swift*-BAT (the Palermo BAT Catalogue); soft X-ray lightcurve between 2 and 10 keV for different instruments: $^{a)}$ 2010-2012 *RXTE* dataset from [13], $^{b)}$ XMM-*Newton*, *Swift*-XRT and *RXTE* data from [7], $^{c)}$ *Swift*-XRT data analysed in this work. The source is clearly variable in all energy bands. The discrepancy between the H.E.S.S. and VERITAS points in 2009 is explained by the non identical observation windows of the two instruments (see text). Three point at MJD 53831, 55331 and 55377 have been removed for clarity from the *Swift*-BAT plot because of their large negative fluxes or error bars.

optical lightcurves, instead, are constant within the errors and do not show any variations. During the second MWL campaign in 2013 (MJD ~56570), 1ES 0229+200 seems to be relatively bright in X-rays and on its average value in TeV.

A correlation in the X-ray-VHE emission is actually expected by the SSC model, implying that the two components are generated by the same electron population. On the other hand, the big peak shown by *RXTE* in 2011 (MJD ~55800) does not have a clear correspondence in TeV. This could be explained by the very low exposure in three out of the four periods of H.E.S.S. observations, or by a period of high activity of one of the other X-ray sources present in the field of view of *RXTE* (e.g. 1RXS J023558.0+201215, 1RXS J023427.5+192247 or one of the numerous XMM sources).

A third possibility could be the presence of a second X-ray emitting zone, not related to any γ-ray emission. Finally, also Klein-Nishina suppression could play a role under certain conditions.

The confirmation of VHE variability on these timescales (already suggested in [8]) affects the determination of constrains on the IGMF. Focusing on the detected variability, if the ~600 GeV emission consists of secondary photons ("maximal" case in [4]), then a measurement of the IGMF can actually be done. Extrapolating Fig. 2 of [4] to shorter time delays, one measures the IGMF to be $B_{IGMF} \sim 3 \times 10^{-16}$ G.

The detection of monthly variability above 1 TeV, along with the indication of monthly variability in the *Fermi* energy range, together strongly challenge those proton-cascade models (and "maximal" type cascade models in general) that require the TeV emission to be constant and consisting of secondary radiation only (e.g. [19]). Future studies investigating further the energy dependendent variability will allow the contribution of the cascade emission to the flux to be probed more deeply for both hadronic and leptonic models.

4. Conclusion

The 10 years long H.E.S.S. monitoring of the blazar 1ES 0229+200 between 2004 and 2013 has been presented for the first time in a MWL context. Clear variability is detected at VHE on monthly and yearly timescales. A hint of correlation between TeV and X-ray emission comes from the contemporaneous observations with XMM-*Newton* and with *Swift* in 2009: the fluxes increase in all energy bands in similar way over four months. This supports an SSC emission model for the X-ray and VHE emission in this source. The VHE monthly flux variability affects the derivation of lower limits on the IGMF. Assuming the emission at ~600 GeV to be of secondary photons, one can actually obtain a measurement of the IGMF of $B_{IGMF} \sim 3 \times 10^{-16}$ G.

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