PROCEEDINGS OF SCIENCE

Time-resolved multiwavelength observations of the blazar VER J0521+211 from radio to gamma-ray energies

H. Prokoph[*a] **for the VERITAS Collaboration**[†]

[a] *Department of Physics and Electrical Engineering, Linnaeus University, 351 95 Växjö, Sweden*
E-mail: heike.prokoph@lnu.se

P. Da Vela[b] **and C. Schultz**[c] **for the MAGIC Collaboration**[‡]

[b] *Università di Siena and INFN Pisa, I-53100 Siena, Italy*
[c] *Università di Padova and INFN, I-35131 Padova, Italy*

VER J0521+211 (RGB J0521.8+2112) is one of the brightest and most powerful blazars detected in the TeV gamma-ray regime. It is located at a redshift of $z = 0.108$ and since its discovery in 2009, VER J0521+211 has exhibited an average TeV flux exceeding 0.1 times that of the Crab Nebula, corresponding to an isotropic luminosity of 3×10^{44} erg s^{-1}. We present data from a comprehensive multiwavelength campaign on this object extending between November 2012 and February 2014, including single-dish radio observations, optical photometry and polarimetry, UV, X-ray, GeV and TeV gamma-ray data (VERITAS, MAGIC). Significant flux variability was observed at all wavelengths, including a long-lasting high state at gamma-ray energies in Fall 2013. Nightly-resolved spectra at X-ray and TeV energies are be presented, and emission mechanisms explaining the observed flux and spectral variability are discussed.

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[*] Speaker.
[†] veritas.sao.arizona.edu
[‡] magic.mpp.mpg.de

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1. Introduction

VER J0521+211, spatially associated with the radio and X-ray source RGB J0521.8+2112, was discovered in 2009 as TeV emitter by VERITAS [1] and is now unambiguously classified as a BL Lac-type blazar [2]. As usually observed in blazars, VER J0521+211 is highly variable at all wavelengths. With an average integral flux above 200 GeV of about > 0.1 Crab[1], VER J0521+211 is among the brightest known TeV blazars. Located at a redshift of $z = 0.108$ [4], this flux corresponds to a gamma-ray luminosity of about $3 \times 10^{44}\,\mathrm{erg\,s^{-1}}$ and is thus significantly brighter than the classical northern high-synchrotron-frequency-peaked BL Lacs (HBLs) such as Mrk 421, Mrk 501 and 1ES 1959+650. VER J0521+211 itself shows a synchrotron peak in the optical regime, suggesting a classification as intermediate-frequency-peaked BL Lac (IBL). However, during the TeV high state in November 2009 [5], VER J0521+211 showed more HBL-like properties, especially given the observed spectral hardening in the X-ray regime with increased flux. The observed variability and its bright TeV flux motivated further multiwavelength observations of VER J0521+211 in order to extend the detailed time-resolved spectral modeling available for nearby HBLs [6, 7, 8] to a more luminous blazar which are reported here.

2. VERITAS

VERITAS is an array of four 12 m-diameter imaging atmospheric Cherenkov telescopes (IACTs), located in southern Arizona, USA. It is sensitive to gamma-ray energies between 85 GeV and $>$30 TeV and is capable to detect a source with 0.01 Crab flux in under $\sim$ 25 hours of observations. VERITAS observations of VER J0521+211 reported here were taken in two seasons: the 2012 season comprising data taken between 2012 Nov 11 and 2013 Feb 14; and the 2013 season (2013 Oct 15 to 2014 Feb 01). All data were taken in *wobble mode* for which the source is observed with an offset of 0.5° with respect to the center of the instrument's field of view to allow for simultaneous background measurements [9]. After quality selection, the dataset comprised 5.0 h live time in the 2012 season and 16.5 h in the 2013 season. VERITAS data analysis followed the procedure outlined in [10]. Cherenkov light from air showers initiated by gamma rays and cosmic rays triggers the readout of PMT signals, which are then calibrated and used to reconstruct an image of the shower in the focal plane. Individual telescope images are parameterized by moment analysis, and geometrical reconstruction is used to estimate the arrival direction, θ, of the primary particle with respect to the source location. The signal was extracted using a reflected region background model with an ON region of 0.17° radius centered on the position of VER J0521+211 (R.A. = $05^{\mathrm{h}}21^{\mathrm{m}}45^{\mathrm{s}}$, Decl. = $+21^\circ 12' 51.''4$, J2000). The strength of the gamma-ray signal is evaluated using Eq. 17 in [11] and was found to be $19.0\,\sigma$ in 2012 and $60.3\,\sigma$ in 2013. The average flux levels in the two seasons are $F^{`12}_{>0.2\,\mathrm{TeV}} = 2.4 \pm 0.2$ and $F^{`13}_{>0.2\,\mathrm{TeV}} = 4.2 \pm 0.1$ in units of $10^{-11}\,\mathrm{cm^{-2}\,s^{-1}}$. For comparison, the time averaged flux in [2] was 1.9 ± 0.1 in the same units (as shown in Figure 1).

3. MAGIC

MAGIC is a stereoscopic system of two 17 m-diameter IACTs, located at La Palma, Canary

[1]The gamma-ray flux of the Crab Nebula used here is $F(E > 200\,\mathrm{GeV}) = 2.1 \times 10^{-10}\mathrm{cm^{-2}s^{-1}}$ [3].

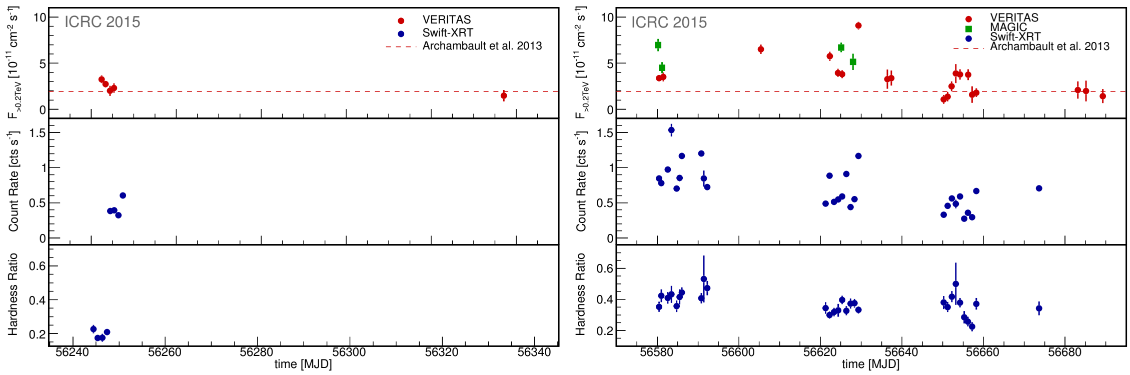

Figure 1: Evolution of the TeV flux, X-ray flux, and X-ray hardness ratio as a function of time during the 2012 (*left*) and 2013 seasons (*right*). It should be noted that the MAGIC and VERITAS observations in 2013 were not taken simultanously.

Islands. It is sensitive to gamma-ray energies above ~ 50 GeV (in normal trigger mode) and underwent a series of upgrades during summer 2011 and 2012 [12]. In stereoscopic mode, the integral sensitivity for sources with Crab Nebula-like spectra above 220 GeV is $(0.66 \pm 0.03)\%$ of Crab Nebula flux in 50 h of observations (more details about the MAGIC performance are given in [13]). MAGIC observations of VER J0521+211 were taken between 2013 Oct 15 and Dec 2 and were triggered by the high state in optical and high-energy gamma rays reported by KVA (E. Lindfors, private communication) and *Fermi*-LAT [14], respectively. Observations covering a zenith angle range from 7° to 26° were performed in *wobble mode* with an offset of 0.4°. After quality selection and dead time correction, the total effective observation time was ~ 4.5 hours. The data were analyzed using the MAGIC analysis and reconstruction software package [15], which has been adapted to stereoscopic observations [16]. The signal was extracted from an ON region of 0.11° radius centered on the position of VER J0521+211. The analysis of the overall data set yielded a strong signal of $30.5\,\sigma$ significance [11], while the significances of the signal from the individual nights are $18.6\,\sigma$, $9.7\,\sigma$, $21.9\,\sigma$ and $6.2\,\sigma$ for Oct 15, 16, Nov 29 and Dec 2, respectively. Given the significance of the signal, night-wise spectra could be obtained above the energy threshold of 65 GeV for the observations in October and November and are shown in Figure 2.

4. X-ray

The *Swift* X-ray telescope (XRT [17]) monitored VER J0521+211 in the X-ray band (0.3-10 keV) for most of the nights of the campaign. Data were processed using the most recent versions of the standard Swift tools: Swift Software version 3.9, FTOOLS version 6.12 and XSPEC version 12.7.1. Light curves are generated using `xrtgrblc` version 1.6. More details on the monitoring program and the analysis procedure can be found in [18].

5. Flux and spectral variability

The TeV fluxes measured in 2012 and 2013 are higher than those reported during the discovery of the source [2], with the average flux in 2013 being a factor of 2 brighter than that of 2009. The

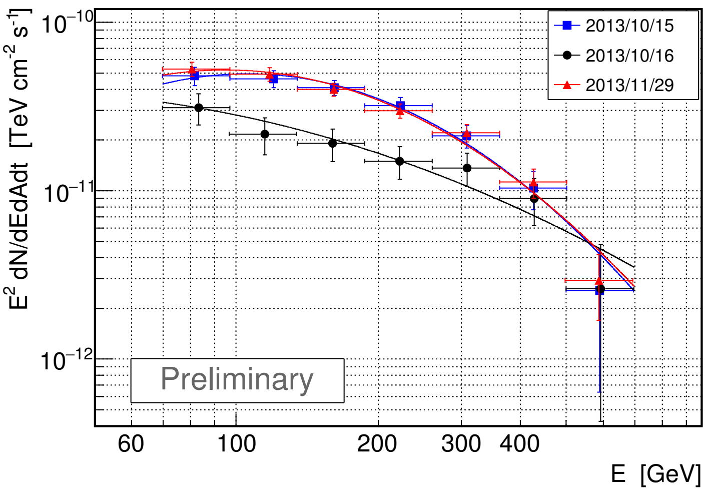

Figure 2: Spectral energy distribution of VER J0521+211 as obtained by MAGIC during three single nights in 2013.

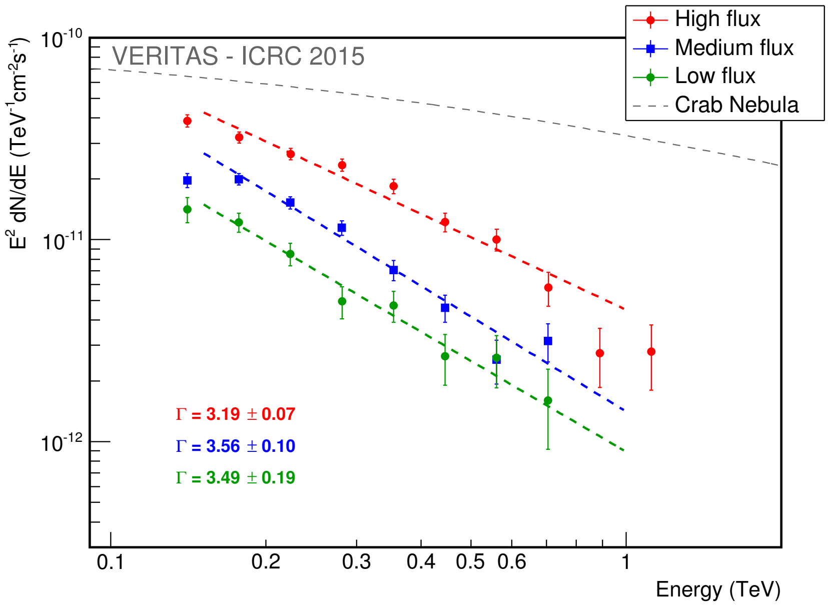

Figure 3: Comparison of the spectral energy distributions measured with VERITAS at different flux states. Spectra have been obtained by stacking observations with nightly fluxes $F_{>0.2\,\mathrm{TeV}} < 3\times10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (*low* flux), $F_{>0.2\,\mathrm{TeV}} > 4\times10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (*high* flux), and a *medium* flux bin defined between these two values.

nightly flux (Figure 1) shows significant variability down to timescales of 1 day.

To test for spectral variability, we have produced gamma-ray spectra for individual observing nights (Figure 2) and by stacking observations at different flux levels (Figure 3). At low and medium flux levels we find gamma-ray spectra largely compatible with a power-law with index $\Gamma = 3.44 \pm 0.20$ that was reported in previous observations [2]. Co-adding the spectra from the three nights with higher fluxes we measure $\Gamma = 3.10 \pm 0.07$, constituting evidence for a mild hardening of the gamma-ray spectrum when the emission is brighter. In addition, the lower threshold of the MAGIC observations (Figure 2) helps to reveal some evidence of spectral curvature, suggesting a peak of the inverse-Compton emission component at energies of ~ 100 GeV.

Similar levels of 1-day-scale flux variability can be seen in the X-ray band (Figure 1). The evolution of the hardness ratio in the X-ray band (Figure 4) suggests only small changes of the X-ray spectral shape at different flux levels. Data from the nights with simultaneous observations by VERITAS and *Swift*-XRT (Figure 5) show a clear correlation between the measured fluxes in both bands.

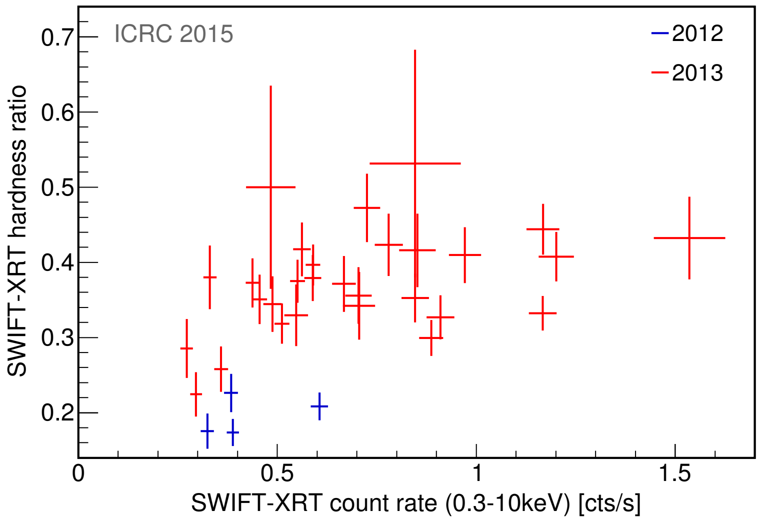

Figure 4: X-ray hardness ratio as a function of X-ray flux measured by *Swift*-XRT. The hardness ratio is defined as the rate in the 2-10 keV band divided by the rate in the 0.3-2 keV band.

6. Discussion

The data presented in these proceedings constitute the first extensive multi-wavelength campaign on VER J0521+211. Significant changes in the X-ray and TeV fluxes from the source were seen in timescales of ~ 1 day, with an amplitude of approximately a factor of 5 in both bands. Spectral variability in the TeV band is first reported here, displaying a mild hardening of the spectrum at higher flux levels. The spectral variability is however much less significant than typically found in HBLs.

The observed correlation between the fluxes in the X-ray and TeV bands suggests a connection between the synchrotron and the high-energy spectral components of the emission, as expected if the high-energy emission is dominated by synchrotron self-Compton. However, a contribution

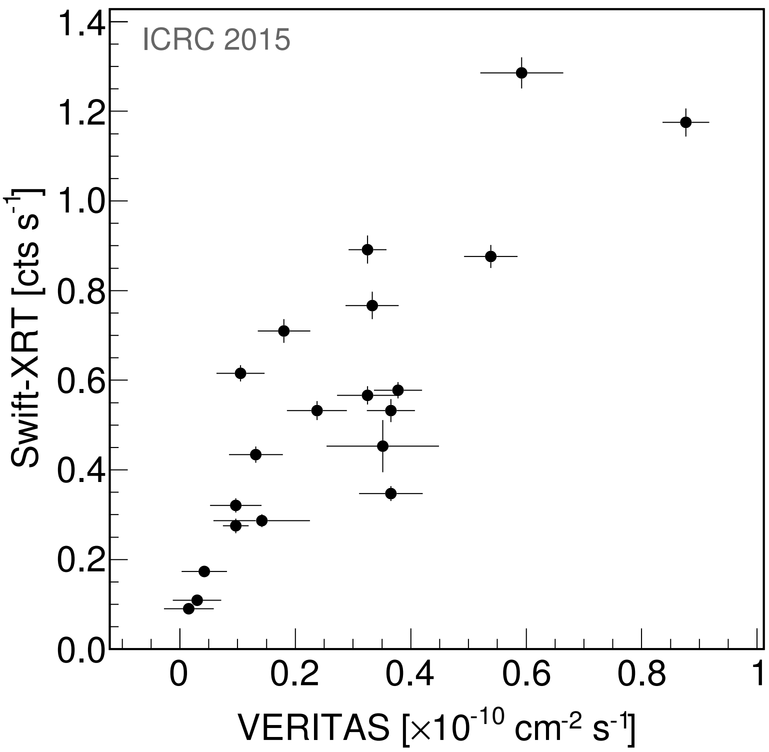

Figure 5: X-ray flux as a function of the TeV flux for nights with simultaneous observations in both bands.

from inverse-Compton emission from electrons and positrons interacting with other radiation fields external to the jet cannot be excluded.

Compared to similar studies conducted on TeV HBLs (Mrk 421, Mrk 501, 1ES 1959+650), the level of spectral variability in the TeV regime is small given the high-significance of the detections and the TeV flux changing by a factor of ~ 5. This small level of spectral variability and a softer spectral index seem characteristic of IBLs, where electrons and positrons with energies beyond the TeV scale will be less dominant than in HBLs given the higher rate of inverse-Compton cooling.

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