Multiwavelength Observations of the high-frequency-peaked BL Lac Object RGB J0710+591

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Summary: We report the results of multiwavelength observations in the optical, X-ray, high-energy (HE; MeV-GeV), and very-high-energy (VHE; E > 100 GeV) bands of the high-frequency-peaked BL Lac object RGB J0710+591.

Abstract: The high-frequency-peaked BL Lac object RGB J0710+591 was discovered at very-high energies (E > 100 GeV) by **VERITAS**[1]. This object was observed for 22.1 hours (dead time corrected) by VERITAS from December 2008 through March 2009. Contemporaneous optical and X-ray data were obtained from the Michigan-Dartmouth-MIT (**MDM**) observatory, the Swift Ultra-Violet and Optical Telescope (**UVOT**), and the Swift X-ray Telescope (**XRT**). These data were analyzed together with gamma-ray data from the *Fermi* Large Area Telescope (**LAT**) covering the same period. At a redshift of z = 0.125 and with a measured spectral index of $\Gamma = 2.59 \pm 0.26_{stat} \pm 0.20_{sys}$ in the VHE band, RGB J0710+591 is one of the hardest VHE blazars known to date. The spectral energy distribution (SED) was modeled using an equilibrium synchrotron self-Compton (SSC) model[2]. The hard X-ray spectrum required a very steep electron injection spectrum and the fit required a low magnetic field, well below equipartition. Adding an external-Compton (EC) component did not result in a better fit and did not bring the magnetic field closer to equipartition.

1. RGB J0710+591:

RGB J0710+591 is a BL Lac object located at a redshift z = 0.125[3]. BL Lac objects are characterized by non-thermal emission and a SED containing two broad peaks. The peak at low energies is interpreted as synchrotron radiation, while the peak at higher energies can be leptonic or hadronic in origin[4]. The low-energy peak is located at > 10^{18} Hz[5], identifying this object as a high-frequency-peaked BL Lac (HBL). RGB J0710+591 was not detected in the HE band by the EGRET detector on board the Compton Gamma-Ray Observatory, nor by the Whipple 10-m imaging atmospheric Cherenkov telescope (IACT) in the VHE band[6]. The HEGRA IACT system reported a 99% confidence level upper limit above 1.08 TeV of 0.91 x 10^{-12} cm^{-2} s^{-1} corresponding to 6% of the Crab Nebula flux[7]. The hardness of the X-ray spectrum and the moderate redshift made this object a good candidate for the current generation of significantly more sensitive TeV instruments.

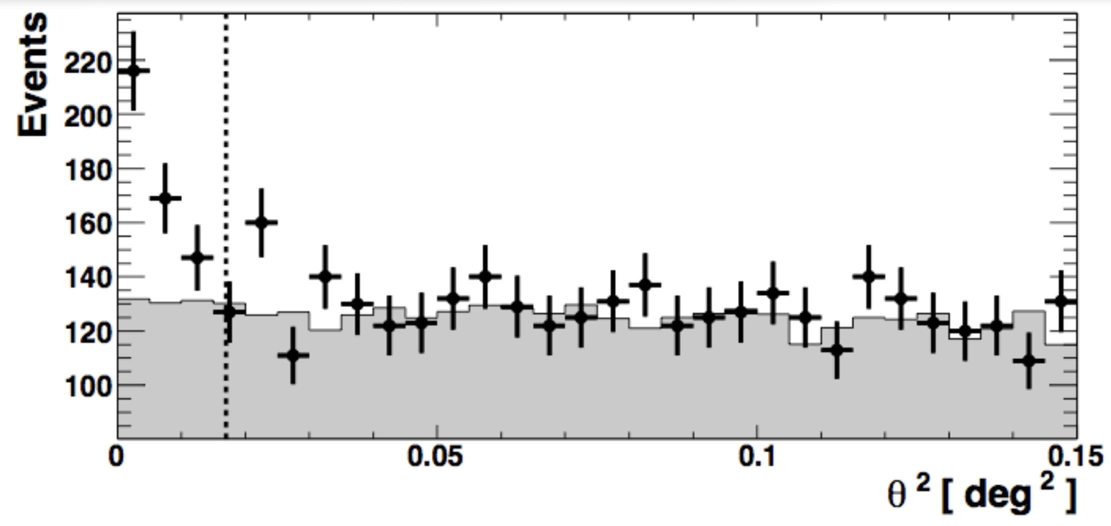

Fig. 1: Distribution of the squared angular distance (θ²) between the event directions and the nominal position of RGB J0710+591 for on-source VHE events (points) and normalized off-source events (shaded region). The dashed line represents the cut applied to the VERITAS data.

2. VERITAS Observations:

The VERITAS observatory consists of an array of four 12-m IACTs located in southern Arizona at the Fred Lawrence Whipple Observatory[8,9].VERITAS has an energy resolution of ~15% between 100 GeV and 30 TeV, an angular resolution of ~0.1° per event, and a field of view of 3.5°. A source with a spectrum similar to that of the Crab, but with a flux level only 5% of the Crab's, can be detected by VERITAS in ~2.5 hours.

VERITAS observed RGB J0710+591 from December 2008 through March 2009 for **22.1 hours** (live time). The data were calibrated using the standard procedures[10] and the reflected region model was used to calculate the background[11]. A total of 576 on-source events are observed from the direction of RGB J0710+591 and 3890 in the background regions (see Fig. 1). After normalizing the number of background events (α = 0.115), a point-like excess of 129 events is detected, corresponding to a statistical significance of **5.5 σ**. The excess is located at $07^h10^m26.4^s \pm 2.4^s_{stat}$, $59°09'00'' \pm 36''_{stat}$ (systematic error on the pointing is 90″), consistent with the VLA 5 GHz coordinates for this object[12] (see Fig. 2). The photon spectrum is well described (χ^2/NDF = 1.3/3) by a power law. The integral flux above 300 GeV is 3.87 ± 0.77 x 10^{-12} γ cm^{-2} s^{-1} (2.8% of the Crab Nebula flux above 300 GeV). The spectral index is $\Gamma = 2.59 \pm 0.26_{stat} \pm 0.20_{sys}$.

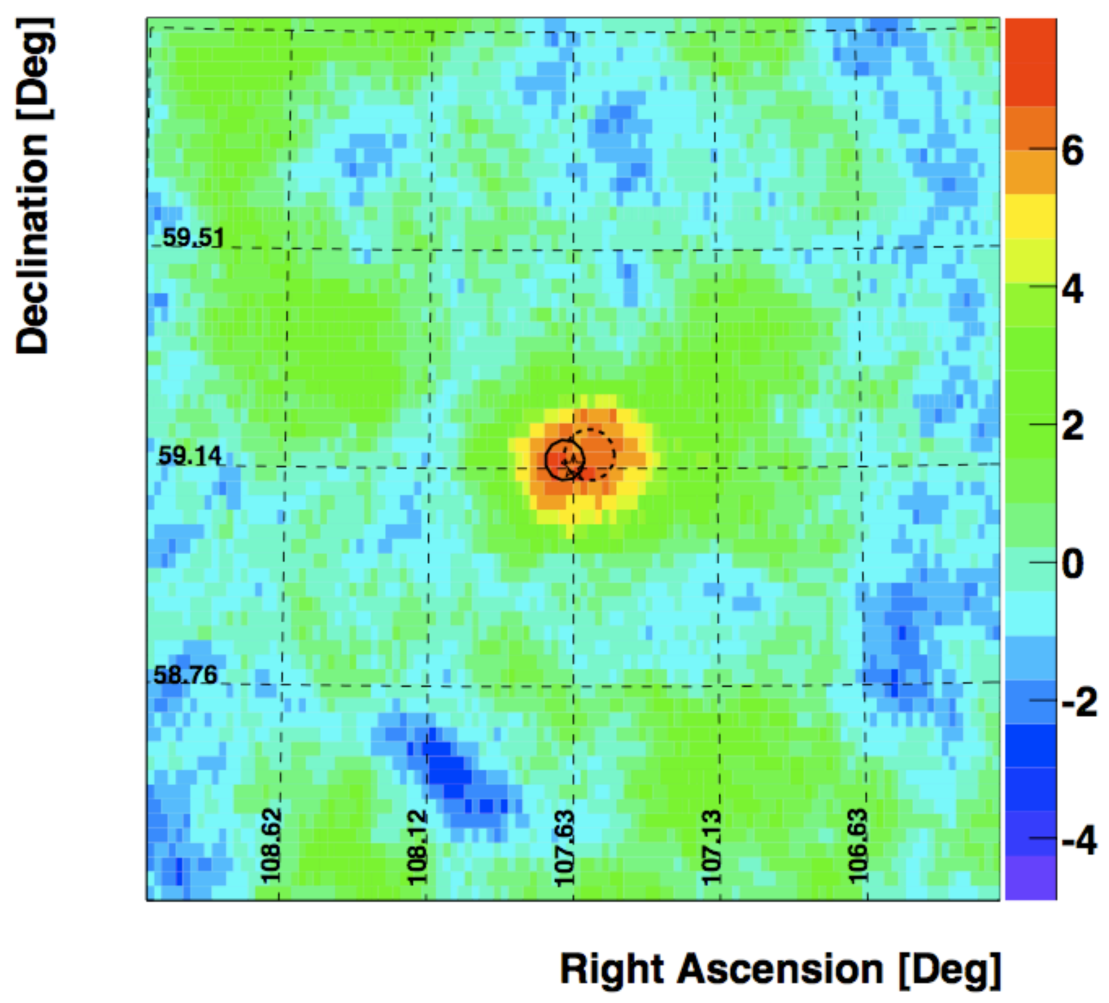

Fig. 2: Smoothed VHE significance map of RGB J0710+591. The VLA location of the blazar is shown as a star. The solid circle is the best fit plus statistical and systematic errors to the VHE excess, while the dashed circle is the best fit plus 95% error radius to the *Fermi* HE emission. Both locations are consistent with each other and with the VLA position of RGB J0710+591.

3. *Fermi* Observations:

The *Fermi* LAT data for this analysis were taken from a region of 10° radius centered on RGB J0710+591 from 4 August 2008 to 4 August 2009. These data were analyzed using the standard *Fermi* analysis software (ScienceTools v9r15p3; IRF P6_V3_DIFFUSE) available from HEASARC. The contribution from discrete sources, a diffuse galactic background, and an isotropic background[13] were modeled in the analysis. Events were analyzed using an unbinned maximum likelihood method[14,15]. A point source is detected with a significance of more than **8 σ**. The best-fit position ($07^h10^m37^s$, 59°09′32″) has a 95% error radius of 2.7′ and is consistent with the VLA coordinates of RGB J0710+591 (see Fig. 2). No evidence for variability was found for the source flux and spectral index during the course of these observations. The photon spectrum is well fit by a power law where F_0 is $1.43 \pm 0.35_{stat} \pm 0.10_{sys}$ x 10^{-14} cm^{-2} s^{-2} MeV^{-1}, E_0 is 8775 MeV, and Γ is $1.46 \pm 0.17_{stat} \pm 0.05_{sys}$. The most energetic photon in the *Fermi* data is at 75 GeV.

4. Swift Observations:

Seven Swift XRT and UVOT observations[16] were performed between February 20 and March 2, 2009. The Swift XRT data were analyzed with HEAsoft 6.5. The XRT data were fit with an absorbed power law model with the Hydrogen column density fixed at 4.4 x 10^{20} cm^{-2}, resulting in a combined spectrum with a spectral index of 1.86 ± 0.01, placing the synchrotron peak above 10 keV. The Swift UVOT data were analyzed using the uvotsource tool and are presented in 6 bands (UVW1, UVM2, UVW2, U, B, V).

5. MDM Observations:

Observations were performed from February 19 through 24, 2009 with the MDM Observatory 1.3 m telescope[17] in the R and B bands. The data were analyzed using the Image Reduction and Analysis Facility (IRAF)[18,19]. The host galaxy of RGB J0710+591 makes a significant contribution to the optical fluxes measured by MDM and was subtracted using previously calculated fluxes[20]. No substantial optical variability is seen over the course of the 5-day observing run.

6. *SED* and Conclusions:

The SED of RGB J0710+591 is shown in Fig. 3. The data are fit with the equilibrium SSC version of the model of Böttcher & Chiang[22] which takes into account intergalactic absorption using the EBL model of Franceschini et al[22]. Many of the model parameters are unconstrained from the observations.

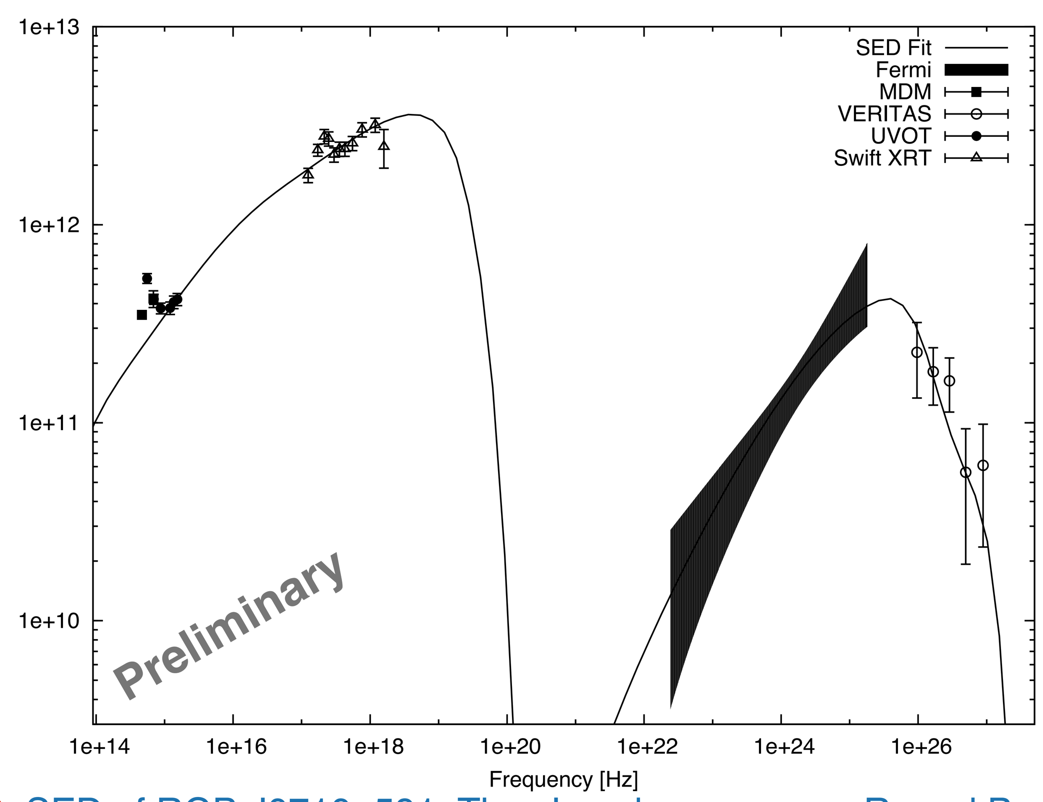

Fig. 3: SED of RGB J0710+591. The closed squares are R- and B-band data from the MDM, the closed circles are from the Swift UVOT, open triangles are from the Swift XRT, the shaded area is the *Fermi* LAT measurement, and the open circles are the measured VERITAS data points. The model is the equilibrium SSC version from Chiang & Böttcher[22] which takes into account intergalactic absorption using the EBL model of Franceschini et al[22]. The higher flux seen in the U/B and V bands is due to errors associated with the host galaxy subtraction and are thus not used in the SED fit.

Regardless of the choice of the bulk Lorentz factor and observing angle, the self-consistent cooling break always appears far below the X-ray regime. In order to get the observed hard X-ray spectrum a very hard injection index (q = 1.5) has to be assumed. This poses challenges to standard (1st-order) Fermi acceleration models, and might indicate second-order Fermi acceleration or other modes of acceleration. The fit also requires a rather low magnetic field (B ≈ 10s mG) far below equipartition. Adding an EC component does not improve the fit or bring the magnetic field closer to equipartition.

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