A Deep Observation of the Cassiopeia A Supernova Remnant with VERITAS

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Abstract

Supernova remnants (SNRs) have long been considered the leading candidate sites for the acceleration of cosmic rays within the Galaxy through the process of diffusive shock acceleration. The connection between SNRs and cosmic rays is supported by the detection of high energy (HE; 100 MeV to 100 GeV) and very high energy (VHE; 100 GeV to 100 TeV) gamma rays from young and middle-aged SNRs. However, the interpretation of the gamma-ray observations is not unique. This is due to the fact that gamma rays can be produced by electrons through non-thermal Bremsstrahlung and inverse Compton scattering, and by protons through proton-proton collisions and subsequent neutral pion decay. To disentangle and quantify the contributions of electrons and protons to the gamma-ray flux, it is necessary to measure precisely the spectra and morphology of SNRs over a broad range of gamma-ray energies. Cassiopeia A (Cas A) is one such young SNR (~350 years) which is bright in radio and X-rays. It has been detected as a bright point source in HE gamma rays by *Fermi*-LAT and in VHE gamma rays by HEGRA, MAGIC and VERITAS. Cas A has now been observed with VERITAS for more than 60 hours, tripling the published exposure. The observations were taken between 2007 to 2013 over a wide range of zenith angles. In particular, half of the total data was taken at large zenith angle to boost the effective area above a few TeV.

Data selection and analysis

Cassiopeia A data were taken using all four telescopes under dark and clear sky conditions. The table below summarizes the 6-year data set.

Data Set	Date	N_{tels}	θ_Z range (deg)	$Average\theta_Z$ (deg)	Wobble (deg)	Live Time (Hours)	Mean trigger rate (Hz)
I	09/07 - 11/07	4	27-40	34	0.5	18	250
II	12/11 - 12/11	4	33-43	38	0.5	2	350
III	09/12 - 12/13	4	24-39	30	0.5	19	400
IV	09/12 - 12/13	4	40-64	56	0.5	25	300

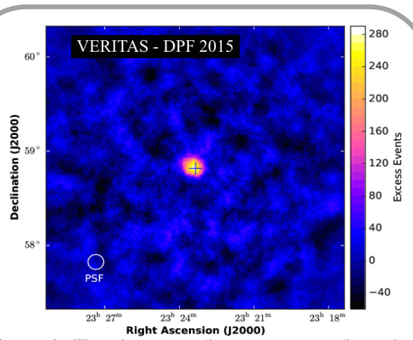


Figure 1. The sky map of excess counts from the region of Cas A for Data Set III, generated using the reflected-region background model [5] and smoothed with a circular window of radius 0.09 degrees, yielding a statistical significance of 11 σ. The white circle indicates the size of the VERITAS point spread function. The blue cross on the sky map shows the centroid ($23^h23^m20.4^s \pm 0^\circ.006_{stat} \pm 0^\circ.014_{sys}$ $+58.817 \pm 0^\circ.006_{stat} \pm 0^\circ.014_{sys}$) of the gamma-ray source, determined by fitting a 2-D Gaussian function to the uncorrelated excess map. Errors are dominated by the systematics even for this reduced data set.

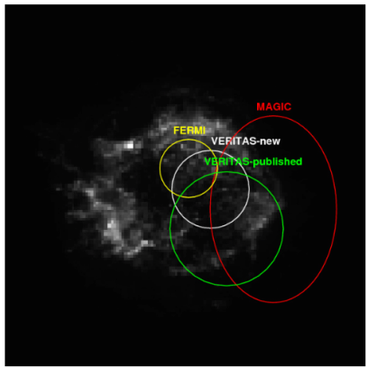
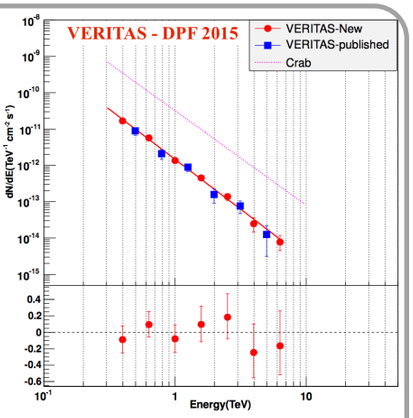


Figure 2. Comparison of centroid positions from *Fermi*-LAT (yellow, [6]), previous VERITAS (green, [4]) and MAGIC (red, [3]) with the new VERITAS result (white) overlaid on a *Chandra* map [7]. The results are consistent with the center of the remnant and with the *Fermi*-LAT and MAGIC centroids.

Figure 3. New spectral points in comparison with the previously published VERITAS results [4]. A power-law fit is shown by the red line. Cas A is at 3% of the Crab flux. Additional spectral points have been added at low and high energy, and the error on the index reduced by ~60%.



Spectral Analysis

The spectral points are fitted with a power-law (Figure 3) in the energy range from 300 GeV to 7 TeV, giving a χ^2 of 2.22 for 5 degrees of freedom, resulting in a good fit probability of 81% for the whole data set. The differential energy spectrum for the whole data set, yielding a normalization of $1.45 \pm 0.11_{stat} \pm 0.44_{sys}$ at 1 TeV and a spectral index of $-2.75 \pm 0.10_{stat} \pm 0.20_{sys}$, is in agreement with previous results by HEGRA [2], MAGIC [3] and VERITAS [4]. An updated *Fermi*-LAT analysis using 85 months of Pass-8 data processed with fermi-tools-v10p0r5 and IRFs P8R2_SOURCE_V6 in the 1-500 GeV range is also shown in Figure 4. Fitting the broad-band spectrum above 2 GeV, a broken power law model is favored at the >4.9 sigma level over a single power law. Systematic uncertainties in the TeV and GeV bands reduce the significance to >3.5 sigma.

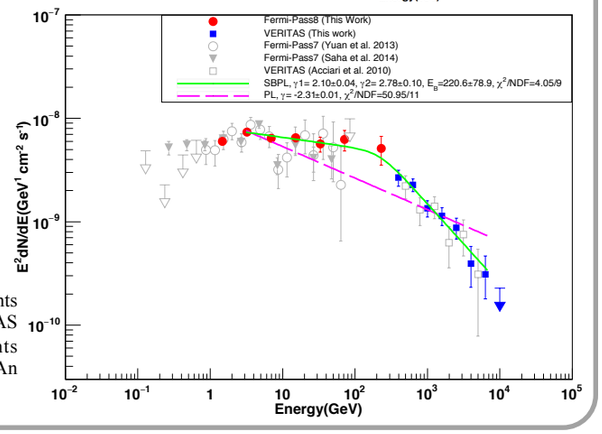


Figure 4. Combined spectral points for Cas A: *Fermi*-LAT and VERITAS current results. VERITAS points shown are for the entire data set. An upper limit is set at the 10 TeV bin.

Summary and Conclusions

Cas A has been observed by VERITAS for ~ 65 hours over a period of 6 years. One third of the total data has already been published [4]. The new data extend the spectrum to both lower and higher energy, reducing the statistical errors on the spectral index by ~60%, which will place strong constraints on leptonic and hadronic models of gamma-ray production. For the centroid of the gamma-ray emission, we are now limited by the systematics in the pointing of our telescopes (50 arcseconds).

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