The TeV Morphology of the Interacting Supernova Remnant IC 443

Brian Humensky[1] for the VERITAS collaboration[2]

[1]Columbia University, humensky@nevis.columbia.edu

[2]http://veritas.sao.arizona.edu

Abstract

IC443 is a Galactic supernova remnant (SNR) in which there is clear evidence for the interaction of a dense molecular cloud with the supernova blast wave. This interaction makes the region an excellent laboratory in which to study the connection between particle acceleration and gamma ray emission in SNRs. Previous observations in the GeV to TeV band with MAGIC and VERITAS showed gamma-ray emission coincident with an extended region of interaction between the shock wave and the molecular cloud. At lower energies (MeV to GeV), Fermi-LAT observations have revealed the signature of hadronic emission with its characteristic "pion bump". Furthermore, observations in other wavelengths such as radio, infrared, optical and X-rays indicate that the environment around the remnant is complex, with a range of different densities. In this new study, with the help of additional data, VERITAS observations have been used to resolve the TeV morphology of IC443 at the few arc-minute scale. We will present results on the gamma-ray morphology and discuss possible sources of the emission, including the shell of the remnant and other gaseous structures in the vicinity.

Introduction

IC 443 is a middle-aged shell-type supernova remnant (SNR), expanding into an inhomogeneous environment. As seen in radio and optical wavelengths, IC 443 appears to be expanding asymmetrically, with a smaller hemisphere expanding into relatively dense media to the northeast, and a larger hemisphere breaking out into a less dense environment to the southwest [1]. At a distance of 1.5 kpc [2], the SNR's diameter of 0.75° corresponds to 20 pc. IC 443 is a strong gamma–ray source, in both the GeV [3,4] and TeV [5,6] energy ranges. Detection of OH maser emission [7,8] and molecular lines [9] from the direction of IC443 showsthat it is interacting with the molecular clouds. This interaction makes IC 443 an excellent laboratory in which to study the the physics of Galactic cosmic ray acceleration, diffusion, and escape. Hadronic cosmic rays interacting with the dense matter provided by the molecular clouds produce pions, which decay rapidly into γ-rays. Most recently, *Fermi*-LAT data [10], from MeV to GeV energy, shows a clear signature of acceleration of hadronic cosmic rays through the detection of a "pion bump" feature in the gamma-ray energy spectrum. In this new study, we performed a deep observation of IC 443 with VERITAS and have been able to resolve the γ-ray emission from the IC 443 in the TeV band.

VERITAS Observatory

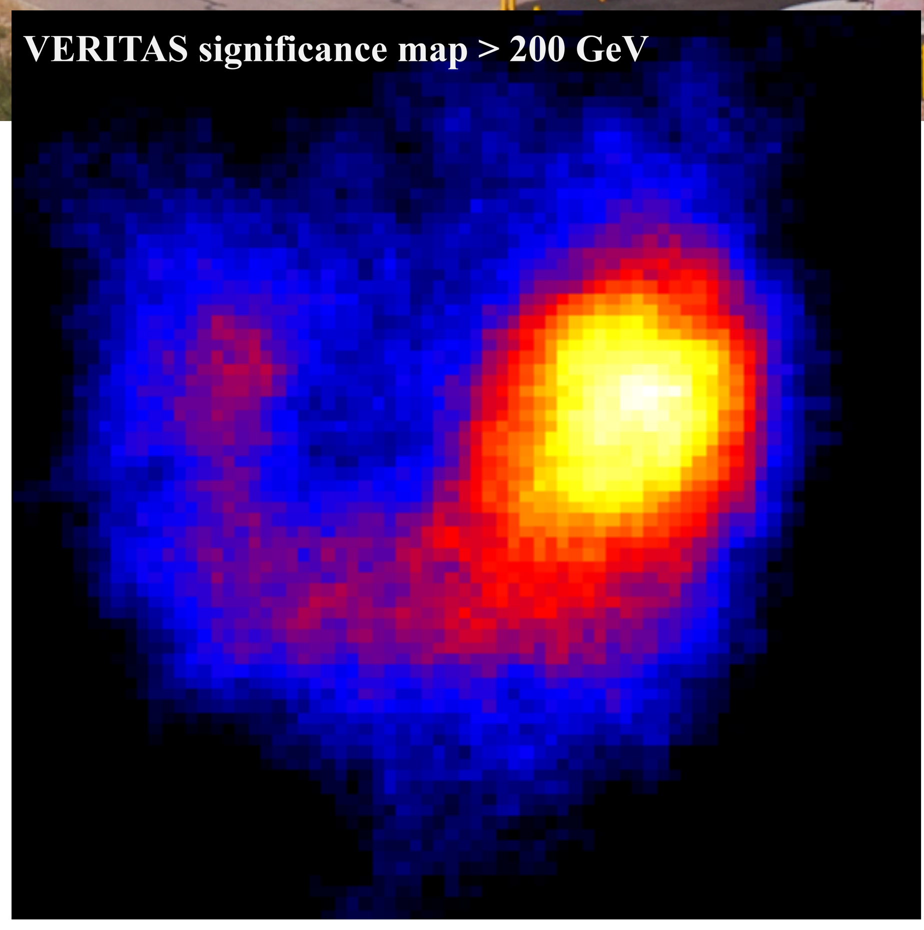
VERITAS (Very Energetic Radiation Imaging telescope Array System) is a ground-based γ-ray observatory located at the Whipple Observatory in southern Arizona, USA. It consists of an array of four telescopes, each with a 12-m diameter optical reflector. In the focal plane of each telescope, a camera made up of 499 Photomultiplier tubes (PMTs) is placed to record the image of the γ-ray shower. Some of the main performance parameters of the telescope array are shown in the table below [11]:

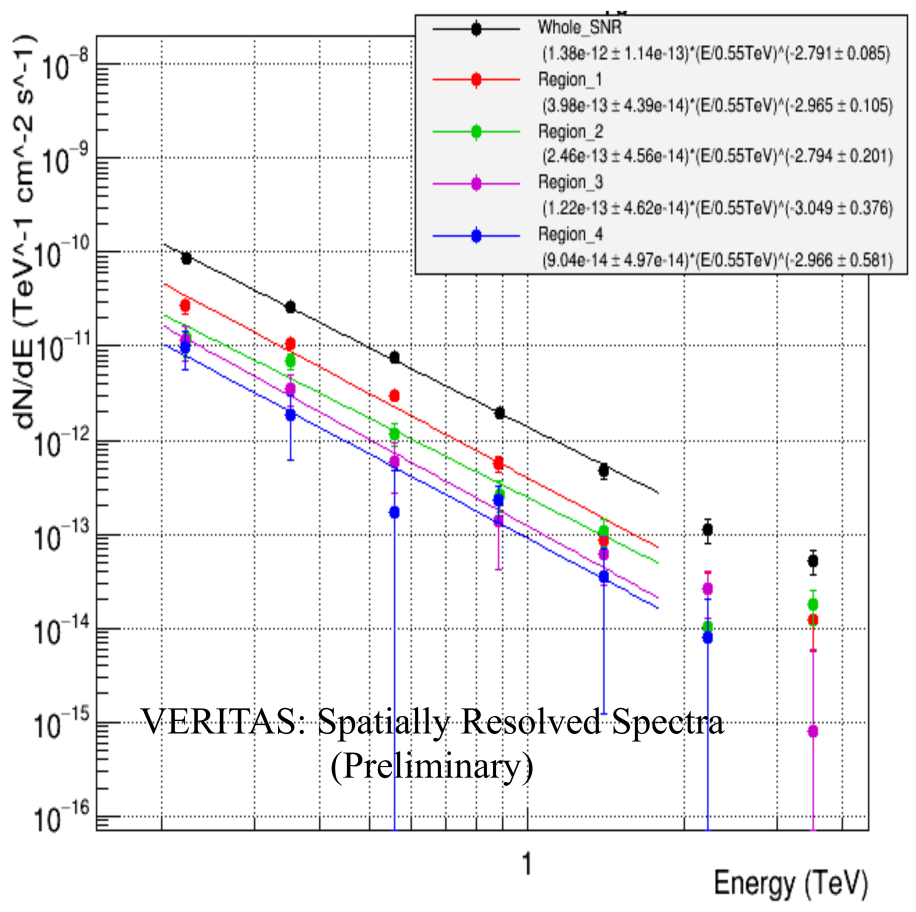
Energy range	85 GeV – 30 TeV
Energy resolution	15-25 %
Sensitivity	1% Crab in 25h
Angular resolution	$R_{68\%}$ < 0.10° above 1 TeV

Data and Analysis

VERITAS observations of IC 443 span a period of 8 years, starting in February 2007 and concluding in January 2015. In total, 177 hours of observations were taken, yielding 155 hours after quality selection and correction for dead time. These data include 52.5 hours taken in the first epoch, prior to the relocation of telescope T1, 42.4 hours in the second epoch with the new location of telescope T1, and finally 81.9 hours in the third epoch with the upgrades in the camera trigger system and PMTs. This data set provides an increase by a factor of 4.5 over the exposure used in [6] for sky maps, and by a factor of 9 for the spectral studies compared to [6]. For the analysis of the data, the standard VERITAS procedure is adopted [12]. We use "moderate" cuts which require that at least three images pass the image quality cuts, giving an energy threshold of ~240 GeV. The excess map is constructed using an integration radius of 0.10° (optimized for the point source), while the spectra are extracted from four regions using integration radii of 0.13°, as well as from the entire SNR using a integration radius of 0.35°.

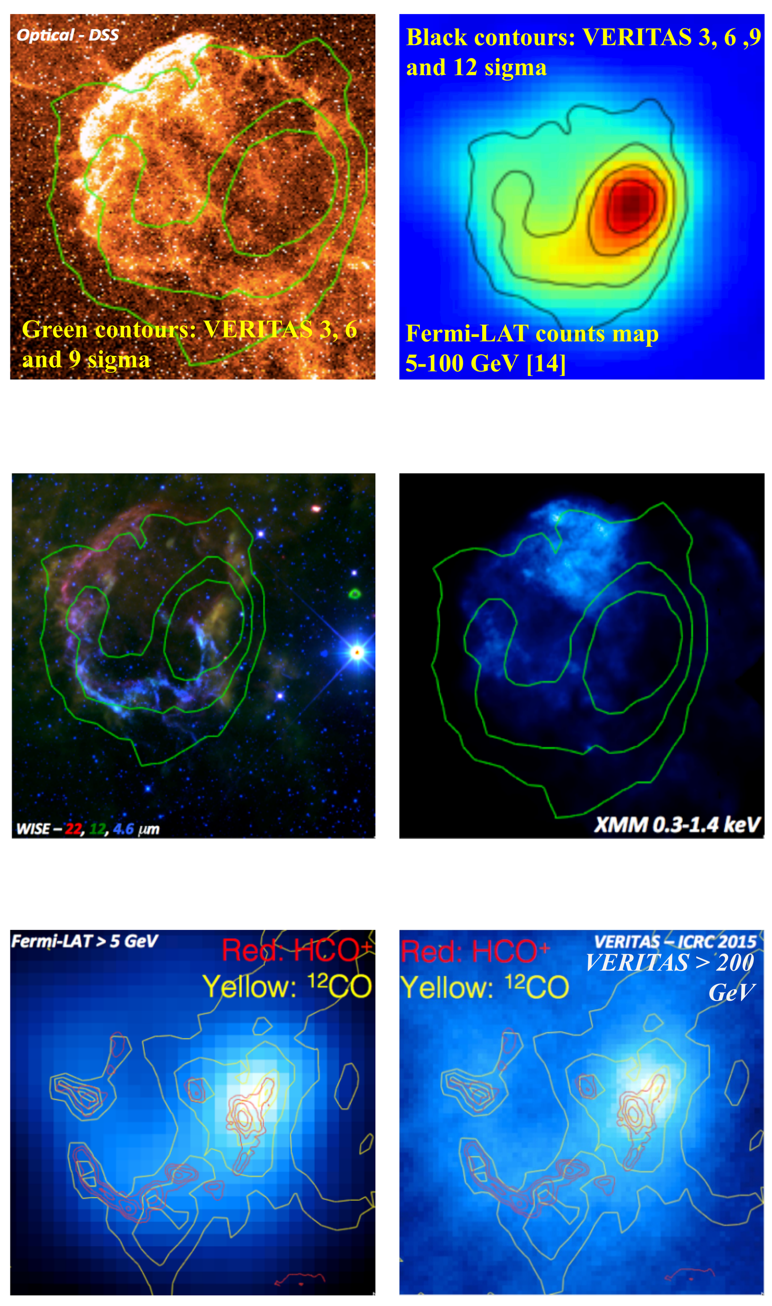
VERITAS significance map > 200 GeV





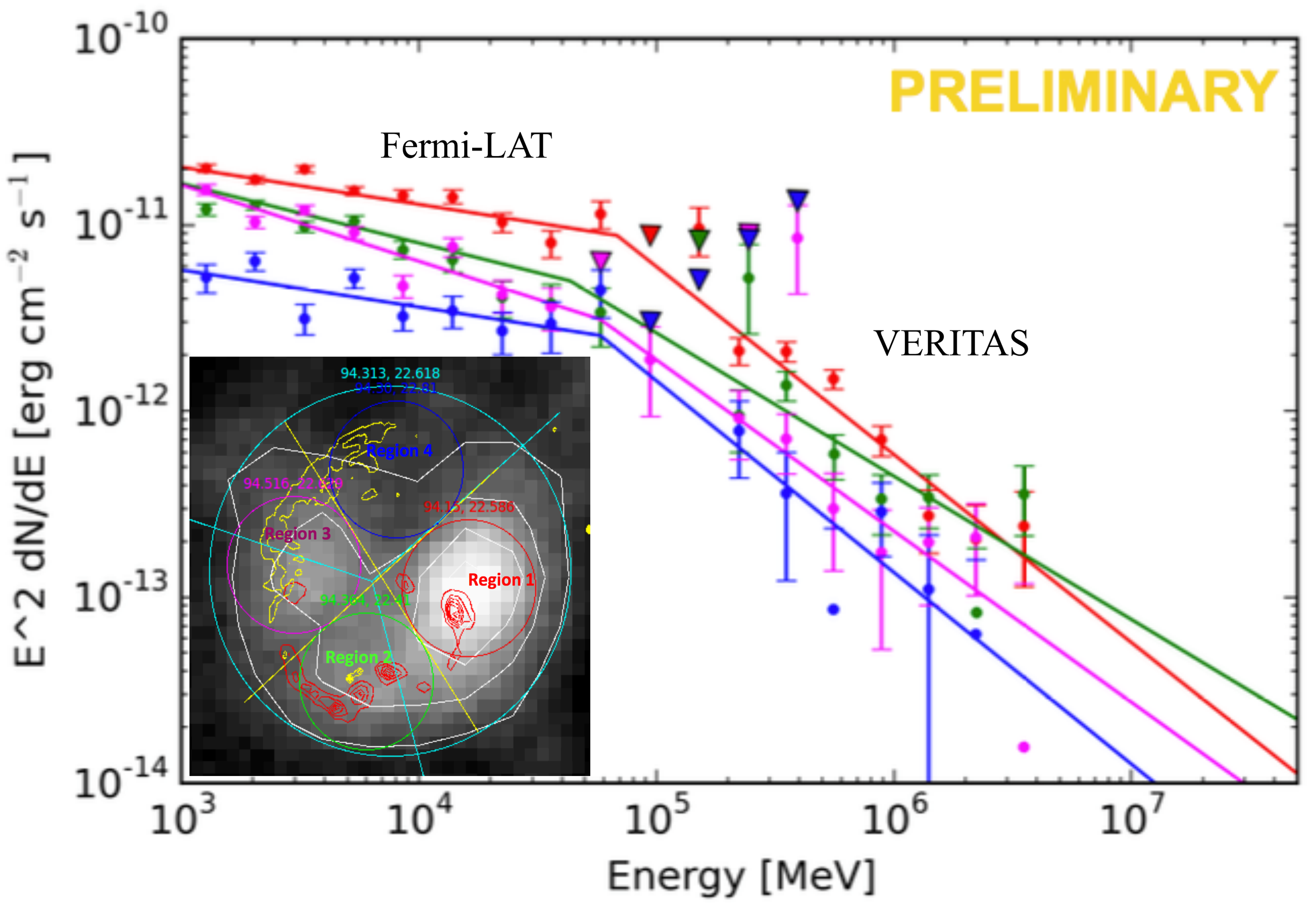
VERITAS: Spatially Resolved Spectra (Preliminary)

Multi-wavelength Comparisons



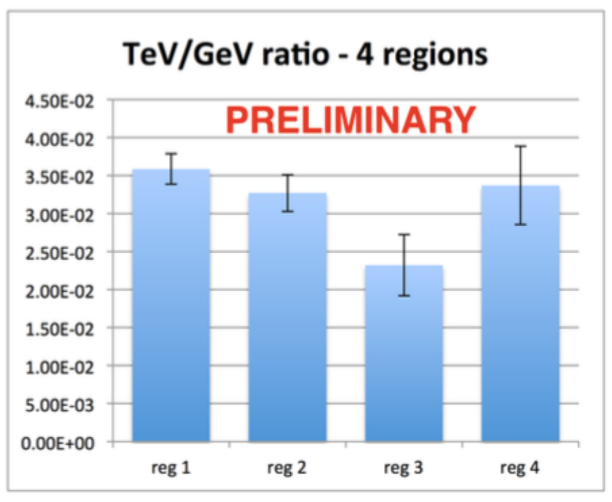
Results

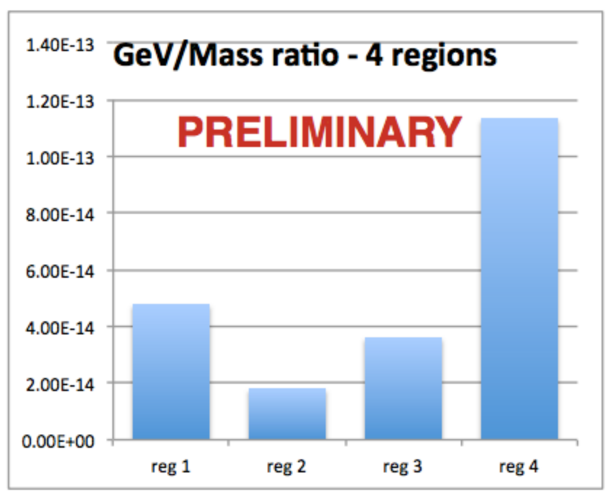
- Significant TeV emission is observed from the entire northeast lobe, but remains brightest in the SNR/MC interaction region.
- Energy spectra are extracted from the VERITAS data for four circular regions (0.13° radius) and the entire SNR (0.35° radius), as indicated below, and shown along with Fermi-LAT spectra extracted for each (approximate) quadrant [14].
- The broad-band γ-ray spectra for all regions are well described as broken power laws with $\Gamma_1 \sim 2.3$, $\Gamma_2 \sim 2.9$, and a break energy $E_b \sim 60$ GeV [14].
  - Uncertainties in the absolute flux calibration between Fermi-LAT and VERITAS are not considered here.
  - **No clear difference in spectral shape for distinct emission regions (e. g. dense clound in region 1 vs. fast atomic shock in region 4).**



Comparing Regions: GeV vs TeV Fluxes vs Gas Mass

- TeV/GeV integral flux ratios are consistent within statistical errors between all four regions, despite ~10x change in brightness [14].
  - ✓ E^2 dN/dE (erg cm^{-2} s^{-1}) flux ratios in the 1-200 GeV (LAT) and 0.2-6.0 TeV (VERITAS) energy ranges.





- Ratio of flux to gas mass shows significant differences between the dense molecular (1,2,3) and diffuse atomic (4) regions [14].

Multiwavelength Comparisons

- Optical: TeV emission fills northeastern lobe but is brightest along the lane of extinction across the middle of the SNR that is due to the foreground, interacting giant molecular cloud (seen in ^{12}CO maps).
- The GeV emission shows remarkably good spatial correlation with the TeV emission, arguing for a single population of cosmic rays responsible for both.
- The IR traces out the shocked gas in the southern molecular ridge and interacting atomic regions along the northeast, and is well tracked by the TeV emission.
- Soft, thermal X-rays anticorrelate with the TeV emission.
- Tracers of the ambient gas (eg, ^{12}CO) and shocked gas (eg, HCO+) are tracked well by the TeV emission.

Conclusions:

- The 5-100 GeV emission from *Fermi*-LAT correlates very well with the E>200 GeV emission from VERITAS, and the morphology of GeV-TeV emission agrees better with the shocked gas distribution than the total gas distribution.
- Resolved GeV and TeV emission from the entire shell allows the exploration of particle acceleration and diffusion under multiple environmental conditions in a single object. These include shock interactions with clouds of different masses, types, and, likely, locations relative to the shock front, as well as emission from regions with no clouds.
- Broad-band γ-ray spectrum from 100 MeV to 2-3 TeV for each of four distinct regions is possible for the first time in a single interacting SNR.
- Strong differences in environment but no clear differences in spectral shape!
- Order of magnitude variation in intensity but TeV/GeV integral flux ratios consistent within errors.

Acknowledgments

This research is supported by grants from the U.S. Department of Energy Office of Science, the U.S. National Science Foundation and the Smithsonian Institution, and by NSERC in Canada. We acknowledge the excellent work of the technical support staff at the Fred Lawrence Whipple Observatory and at the collaborating institutions in the construction and operation of the instrument. The VERITAS Collaboration is grateful to Trevor Weekes for his seminal contributions and leadership in the field of VHE gamma-ray astrophysics, which made this study possible.

References

[1] Braun & Strom 1986, A&A 164:19.
[2] Fesen 1984, ApJ 281:658.
[3] Abdo et al. 2010, ApJ 712:459.
[4] Tavani et al. 2010, ApJ 710:L151.
[5] Albert et al. 2007, ApJ 664:L87.
[6] Acciari et al. 2009, ApJ 698:L133.
[7] Claussen et al 1997, ApJ 489:143.
[8] Hewitt et al. 2006, ApJ 652:1288.
[9] Seta et al. 1998, ApJ 505:286.
[10] Ackermann et al. 2013, Science 339:807.
[11] Park 2015, arXiv 1508.07070.
[12] Acciari et al. 2008, ApJ 679:1427.
[13] Humensky 2015, arXiv 1512.01911.
[14] Hewitt et al. 2015, 6th Fermi Symposium.