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VERITAS VHE gamma-ray observations of SNR G106.3+2.7 region

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Recent results from the ground-based air shower gamma-ray observatories have revealed gamma-ray emission with energies in excess of 100 TeV from several sources in the Galaxy. Among these, the emission from the SNR G106.3+2.7 region is particularly interesting because the counterpart of the emission is still unclear, and the region is very bright in gamma rays compared to the radio and X-ray bands. Observations with imaging atmospheric Cherenkov telescopes (IACTs) provide unique information about the spatial and energy distributions of the gamma-ray emission from these sources as IACTs have better angular resolution and better sensitivity from ~100 GeV up to ~10 TeV compared to the air shower gamma-ray observatories. Indeed, the discovery of very-high-energy gamma-ray emission (E>100 GeV) in the region by VERITAS has shown a clear extension of the emission that is offset from the nearby pulsar, PSR J2229+6114. Recent MAGIC measurements presented the detection of two separate gamma-ray sources in the region. The counterparts of these sources remain unclear. In this contribution, we present the status of VERITAS observations of the region and discuss the origin of emission based on the recent multiwavelength/multi-messenger observations of the region.

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1. Introduction

The cosmic-ray spectrum measured at Earth covers a wide energy range from a few GeV up to 10^{21} eV with a few distinctive spectral index changes. The lowest spectral index change is observed at an energy of 3 PeV (3×10^{15} eV), which is referred as the "knee." A widely accepted hypothesis explains this feature as originating from the the limited maximum energy obtained by particles from Galactic astrophysical objects. Supernova remnants (SNRs) have been suggested and accepted as the best accelerator candidates to explain the Galactic cosmic-ray flux. In this scenario, we expect to detect gamma rays with energies up to several hundred TeV from SNRs as the interactions of cosmic rays create gamma rays. Over the last several decades, dozens of SNRs have been detected in the GeV–TeV energy range by both space-based and ground-based gamma-ray experiments. While the flux measurements around hundreds of MeV revealed evidence of the hadronic interactions for some SNRs, we have not found any SNRs with clear evidence of accelerating hadronic particles up to the knee energy range.

The SNR G106.3+2.7 region has an oblong-shaped SNR discovered by the Galactic plane survey in the radio band [1]. In the radio band, the object is composed of a radio-bright head to the northeast and a diffuse and dimmer extended tail to the southwest. A pulsar, PSR J2229+6114, is located at the northern edge of the remnant's head, and the pulsation has been detected from radio up to the GeV energy range [2, 3]. A boomerang-shaped radio pulsar wind nebular (PWN) and compact X-ray PWN are associated with PSR J2229+6114 [4].

Gamma-ray emission from the region of SNR G106.3+2.7 was first reported by Milagro as "source candidate C4" at a median energy of ~20 TeV [5]. Follow-up observations by VERITAS detected an extended emission region in the 1–10 TeV energy range with 33.4 hours of observation [6]. The centroid of the emission measured by VERITAS is ~0.4° away from PSR J2229+6114. A coincidence between the VERITAS emission region and a molecular cloud, combined with a hard spectral index up to a few tens of TeV, made this target an interesting case to study Galactic accelerators that can accelerate hadronic particles up to the PeV energy range. GeV gamma-ray measurements with the *Fermi*-LAT show that the hard-index spectrum extends down to a few GeV [7]. Recent measurements by the ground-based air shower array experiments, including HAWC [8], Tibet [9], and LHAASO [10, 11], extended the gamma-ray measurements up to a few hundred TeV. The combined spectral energy distribution is shown in Figure 1.

The origin of gamma-ray emission is unclear. If the gamma-ray emission is from leptonic processes, such as inverse Compton scattering, the emission may be a relic pulsar wind nebulae of PSR J2229+6114 or electrons accelerated by SNR G106.3+2.7. If the gamma-ray emission is from hadronic processes, this would indicate the acceleration of high-energy cosmic rays in the SNR. The spatial distribution of the gamma-ray emission and energy-dependent morphology studies will provide additional information to study the origin of the emission. The observations with imaging Atmospheric Cherenkov Telescopes (IACTs) provide the best measurements for this because of its good angular resolution. Recently, MAGIC provided such studies based on 121.7 hours of data, showing two potential emission regions within SNR G106.3+2.7 [12]. While statistically consistent, the northern region nearby the pulsar showed a slightly softer spectral index. Emission from both regions can be explained with leptonic and hadronic models. Still, the studies noted that explaining the emission in the southern region with the pure leptonic model is more challenging.

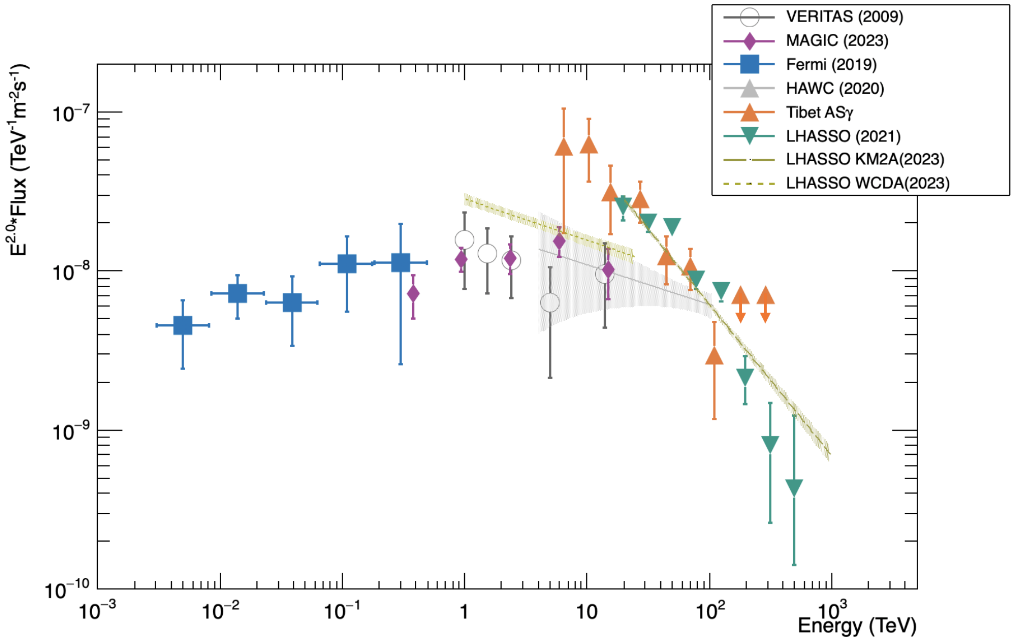

Figure 1: Gamma-ray SED measured in the vicininty of SNR G106.3+2.7. The integration area of the gamma-ray emission differ from experiment to experiment. *Fermi*-LAT observation estimated flux based on the disk-shaped morphology with a radius of 0.25°. The discovery paper of VERITAS and MAGIC results shown here used the integration radius of 0.32°. HAWC and Tibet estimated the flux with a point-source assumption as their measurements didn't detect significant extension of the source.

In this paper, we report on gamma-ray studies of the SNR G106.3+2.7 region with deep observations with VERITAS.

2. VERITAS Observations

VERITAS is an array of four atmospheric Cherenkov telescopes located at the Fred Lawrence Whipple Observatory (FLWO) in southern Arizona (31 40N, 110 57W, 1.3km a.s.l.) [13]. The telescope is designed to study astrophysical sources of gamma-ray emission in the 100 GeV to >30 TeV range by detecting the Cherenkov light generated by air showers, cascades resulting from the interactions of the gamma rays in the atmosphere. Each of the four telescopes covers a field of view of 3.5° with a 499-pixel photo-multiplier tube (PMT) camera at the focal plane, collecting light from a 12 meter diameter reflector consisting of segmented mirrors. In its current configuration, the array has the sensitivity to detect a point source with a flux of 1% of the Crab Nebula flux within 25 hours, and has an angular resolution better than 0.1° at 1 TeV.

VERITAS has observed the SNR G106.3+2.7 region from 2006. The initial observations were pointed toward PSR J2229+6114, which later changed to around the center of SNR G106.3+2.7, where the initial gamma-ray emission was detected. From 2008 up to 2022, VERITAS has accumulated over 150 hours of exposure in this region. Over 86 hours were taken after the camera update occurred in 2012, which updated the camera to high quantum efficiency PMTs [14]. Figure 2 shows the skymap of VERITAS with data accumulated after the camera update. The analysis used the

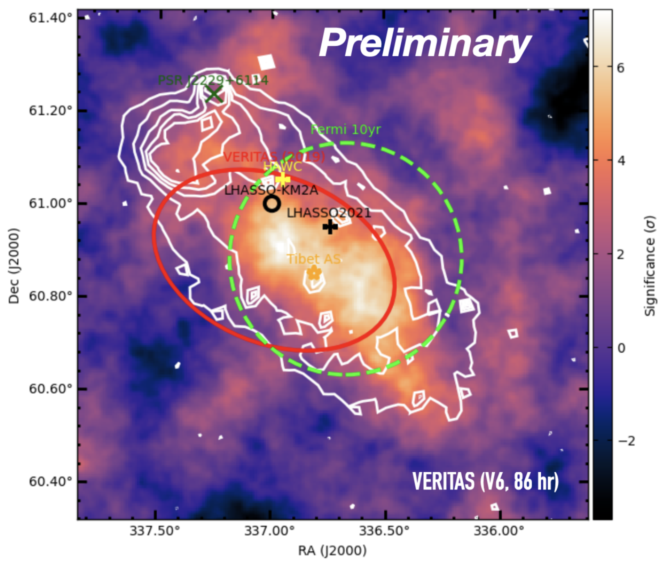

Figure 2: VERITAS skymap with partial data. White contours show the observed radio flux in the region. The centroid of gamma-ray measured by various experiments are indicated with a green-dashed circle (*Fermi*-LAT), a red circle (VERITAS), a yellow cross (HAWC), a yellow star (Tibet), a black circle and black cross (LHAASO).

shower-image template maximum likelihood γ-ray reconstruction method [15] to achieve a better angular resolution.

3. Discussions

VERITAS's point source search did not detect gamma-ray emission from the compact PWN of PSR J2229+6114, known as the Boomerang PWN, located on the northern edge of radio emission. A compact PWN was detected in the X-ray around PSR J2229+6114, which is slightly offset from the peak of radio emission. Recent NuSTAR X-ray observations and modelling studies combined with VERITAS observations showed that a distance of 8 kpc to the PWN provides the most plausible solution to explain the multiwavelength data from radio up to gamma-ray emission [16].

The remaining radio emission can be divided into the 'head' and the 'tail' regions. The head region is closer to the Boomerang PWN, where the radio emission is stronger, and the tail region covers the southern region of the SNR, where the radio emission is weak and diffused. MAGIC reported separate gamma-ray emission from both the head and tail regions in their energy-dependent morphology studies. In their study, lower-energy gamma-ray emission (E<1.1 TeV) is stronger at the head region, while higher-energy gamma-ray emission (E>6 TeV) is stronger at the tail region. As shown in Figure 2, VERITAS observation revealed diffused emission in the entire SNR. Further energy-dependent morphology studies are necessary to test whether the emission of the head region is distinctively different from the emission from the tail region. The flux in the entire SNR was estimated with an integration radius of 0.5 degrees, which resulted in a hard index spectrum with a spectral index of $1.8 \pm 0.1_{\mathrm{stat}}$. The estimated flux is consistent with the previous VERITAS results and fluxes measured by other air shower array instruments within statistical and systematic errors.

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References

[1] Joncas, G., & Higgs, L. A. , 1990, A&AS, 82, 113

[2] Halpern, J. P. et al., 2001, ApJ, 552, 2

[3] Abdo, A. A. et al., 2009, ApJ, 706, 2

[4] Halpern, J. P. et al., 2001, ApJ, 547, 1

[5] Abdo, A. A. et al., 2007, ApJ, 664, 2

[6] Acciari, V. A. et al., 2009, ApJL, 703, 1

[7] Xin, Y. et al., 2019, ApJ, 885, 2

[8] Albert, Al. et al., 2020, ApJL, 896, 2

[9] The Tibet ASγ Collaboration, 2021, NatAs, 5

[10] Cao, Z. et al., 2021, Nat, 594, 7861,

[11] Cao, Z. et al., 2023, arXiv:2305.17030

[12] MAGIC Collaboration, 2023, A&A, 671

[13] Weekes, T. C. et al., 2002, APh, 17, 2

[14] Kieda, D. B. et al., 2012, 33rd ICRC

[15] Christiansen J. et al., 2017, 35th ICRC

[16] I. Pope et al., 2023, ApJ submitted

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A. Acharyya[1], C. B. Adams[2], A. Archer[3], P. Bangale[4], J. T. Bartkoske[5], P. Batista[6], W. Benbow[7], J. L. Christiansen[8], A. J. Chromey[7], A. Duerr[5], M. Errando[9], Q. Feng[7], G. M. Foote[4], L. Fortson[10], A. Furniss[11], W. Hanlon[7], O. Hervet[12], C. E. Hinrichs[7,13], J. Hoang[12], J. Holder[4], Z. Hughes[9], T. B. Humensky[14,15], W. Jin[1], M. N. Johnson[12], M. Kertzman[3], M. Kherlakian[6], D. Kieda[5], T. K. Kleiner[6], N. Korzoun[4], S. Kumar[14], M. J. Lang[16], M. Lundy[17], G. Maier[6], C. E McGrath[18], M. J. Millard[19], C. L. Mooney[4], P. Moriarty[16], R. Mukherjee[20], S. O'Brien[17,21], R. A. Ong[22], N. Park[23], C. Poggemann[8], M. Pohl[24,6], E. Pueschel[6], J. Quinn[18], P. L. Rabinowitz[9], K. Ragan[17], P. T. Reynolds[25], D. Ribeiro[10], E. Roache[7], J. L. Ryan[22], I. Sadeh[6], A. C. Sadun[26], L. Saha[7], M. Santander[1], G. H. Sembroski[27], R. Shang[20], M. Splettstoesser[12], A. K. Talluri[10], J. V. Tucci[28], V. V. Vassiliev[22], A. Weinstein[29], D. A. Williams[12], S. L. Wong[17], J. Woo[30]

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