PROCEEDINGS OF SCIENCE

VERITAS Observations of M 82 and Other Selected Starburst Galaxies

Lab Saha[a,*] **for the VERITAS collaboration**

[a] *Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA 02138,USA*

E-mail: lab.saha@cfa.harvard.edu

Starburst galaxies are thought to form when two galaxies interact and sometimes merge. These unique objects have high star-formation rates and hence high supernova rates, as well as large reservoirs of very dense gas. Assuming galactic cosmic rays originate in supernovae, starburst galaxies should contain copious quantities of cosmic rays that produce diffuse very-high-energy (VHE; E>100 GeV) gamma-ray emission via their interaction with the gaseous material. VERITAS, an array of 12-m atmospheric-Cherenkov telescopes in Arizona, USA, was used to detect VHE emission from the starburst galaxy M 82 during deep observations in 2008-09. However, the initial VERITAS detection was weak and much deeper observations were needed to draw strong conclusions regarding the underlying emission and transport processes. Accordingly, VERITAS was used to perform an extensive observation campaign on M 82 and approximately 335 hours of data were taken. Several other starburst galaxies were also observed in the past few years. A brief summary of the results from these starburst-galaxy observations is presented here.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

https://pos.sissa.it/

PoS(ICRC2023)746

It is widely believed that the Galactic cosmic rays are dominantly accelerated by the winds and supernovae of massive stars. However, definitive evidence of this origin remains elusive nearly a century after their discovery [1].

Starburst galaxies have exceptionally high rates of star formation, and accordingly, they should have a high cosmic-ray density. The cosmic rays produced in the formation, life and death of their massive stars will produce γ-ray emission via their interaction with the interstellar medium (dense gas and radiation). The measurement of γ-ray emission enables a measurement of the cosmic-ray density in the galaxy. Given the detection of several starburst galaxies at GeV-TeV energies in the past $\sim$14 years by both ground-based and space-based telescopes [3–7], these objects are emerging as a prominent class of γ-ray emitters whose observations impact cosmic-ray physics.

M 82 is a bright galaxy located in the direction of the Ursa Major constellation at a distance of approximately 12 million light-years from Earth. It is an excellent laboratory for understanding the physics of star formation, with a supernova rate of 0.1 to 0.3 per year and a high gas number density of 150/cm^3. M 82 was long viewed as a promising source of γ-rays, given its likely high density of cosmic rays and its very high ambient matter density.

In 2009, the VERITAS collaboration reported the first detection of γ-rays from M 82 [5]. The initial VERITAS detection of >700 GeV emission was weak (4.8σ post trials) despite a lengthy exposure (137 h). Due to the low flux, much deeper observations were needed to draw strong conclusions regarding the underlying emission and transport processes. A long-term observation program on M 82, coupled with significant improvements to the VERITAS analysis methods, enables significant improvements to the observed photon spectrum (more points, greater energy range), and improves the uncertainties of the parameters of the power-law fit to the data (original: $\Gamma = 2.5 \pm 0.6$).

Very-High-Energy (VHE, $E > 100$ GeV) gamma-ray observations of M 82 are performed using the VERITAS telescopes. VERITAS consists of four 12-m diameters Imaging Atmospheric Cherenkov Telescopes (IACTs) located at Fred Lawrence Whipple Observatory in southern Arizona (31°40′30″ N, 110°57′07″ W, 1268 m above the sea level) in the United States of America. The energy threshold of the VERITAS stereoscopic system is about 100 GeV. It is able to detect a weak source (~0.6% of the Crab Nebula flux) at 5σ significance in 50 hours of observations at small ($< 30°$) zenith angles [8].

The initial VERITAS detection of M 82 was weak (4.8σ, post trials) in a lengthy exposure (~137 h). To have a strong understanding of the underlying physical processes of M 82, much deeper observations were required. Accordingly, M 82 was observed between 2007 and 2022, for a total of about 335 hours, at zenith angles between 38° and 50°, resulting in an average energy threshold for this analysis of ~450 GeV. To estimate the background simultaneously with the source data, the observations are performed using wobble-mode [9], with the source offset 0°.5 off-axis from the centre of the camera in four cardinal directions. After quality cuts, which account for hardware problems and poor weather conditions, and considering only four-telescope data, $\sim$254 hours of high-quality, dead-time corrected data are selected for further analysis. The analysis of the VERITAS data is performed using the updated version of standard VERITAS Analysis and Reconstruction Software [VEGAS; 14]. To maximize the science return from the data set, a new analysis method developed by VERITAS collaboration is used. It is aimed at improving VERITAS sensitivity and lowering the energy threshold. This method, ITM, i.e., Image Template Method

[13] results in increased sensitivity compared to standard analysis via a combination of improved angular resolution and increased background rejection.

An excess of 135 gamma-like events (~0.53/h) above the estimated background of 372 events is observed from the direction of M 82. This excess corresponds to a statistical significance of 6.5 σ, or a chance probability of 7.7×10^{-7}, confirming the observed VHE emission from M 82. The observed VHE photon spectrum is best fit using a power-law function with a photon index $\Gamma = 2.3 \pm 0.3_{stat} \pm 0.2_{sys}$ with no evidence of a spectral cut-off at energies below 5 TeV. The measured gamma-ray flux is $(3.2 \pm 0.6_{stat} \pm 0.6_{sys}) \times 10^{-13}\ cm^{-2}\ s^{-1}$ above the energy threshold of about 450 GeV. This corresponds to ~0.4% of the Crab Nebula flux above the same threshold. Further details on the M 82 analysis along with spectral modelling will be discussed in a future refereed journal publication.

Based upon Fermi-LAT results [11], three similar targets (IC 342, NGC 2146 and NGC 3424) were observed with the hopes of detecting VHE emission. After significant observation (~20-30 hours each), their VHE detection prospects are poor. We will evaluate if further observations are merited, or if new starburst-galaxy discovery targets should be selected.

Acknowledgement

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, by NSERC in Canada, and by the Helmholtz Association in Germany. This research used resources provided by the Open Science Grid, which is supported by the National Science Foundation and the U.S. Department of Energy's Office of Science, and resources of the National Energy Research Scientific Computing Center (NERSC), a U.S. Department of Energy Office of Science User Facility operated under Contract No. DE-AC02-05CH11231. 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

References

[1] Butt, Y. 2009, Nature, 460, 701, 10.1038/nature08127

[2] Blom, J. J., Paglione, T. A. D., & Carramiñana, A. 1999, ApJ, 516, 744, 10.1086/307155

[3] Götting, N. 2006, Ph. D. Thesis

[4] Nagai, T. 2005, PhD thesis, University of Utah

[5] VERITAS Collaboration, Acciari, V. A., Aliu, E., et al. 2009, Nature, 462, 770, 10.1038/nature08557

[6] Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, ApJS, 183, 46. http://stacks.iop.org/0067-0049/183/i=1/a=46

[7] Acero, F., Aharonian, F., Akhperjanian, A. G., et al. 2009, Science, 326, 1080, 10.1126/science.1178826

PoS(ICRC2023)746

[8] Park, N., & VERITAS Collaboration. 2015, in International Cosmic Ray Conference, Vol. 34, 34th International Cosmic Ray Conference (ICRC2015), 771, 10.22323/1.236.0771

[9] Fomin, V. P., Stepanian, A. A., Lamb, R. C., et al. 1994, Astroparticle Physics, 2, 137, 10.1016/0927-6505(94)90036-1

[10] Adebahr, B., Krause, M., Klein, U., et al. 2013, A&A, 555, A23, 10.1051/0004-6361/201220226

[11] Ajello, M., Di Mauro, M., Paliya, V. S., & Garrappa, S. 2020, ApJ, 894, 88, 10.3847/1538-4357/ab86a6

[12] Brightman, M., Walton, D. J., Xu, Y., et al. 2020, ApJ, 889, 71, 10.3847/1538-4357/ab629a

[13] Christiansen, J. 2018, VERITAS Memos

[14] Cogan, P. 2008, in International Cosmic Ray Conference, Vol. 3, International Cosmic Ray Conference, 1385–1388. 0709.4233

[15] Condon, J. J. 1992, Annual Review of Astronomy and Astrophysics, 30, 575, 10.1146/annurev.aa.30.090192.003043

PoS(ICRC2023)746

Full Author List: VERITAS Collaboration

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[11,12], 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], L. Saha[7], M. Santander[1], G. H. Sembroski[26], R. Shang[20], M. Splettstoesser[12], A. K. Talluri[10], J. V. Tucci[27], V. V. Vassiliev[22], A. Weinstein[28], D. A. Williams[12], S. L. Wong[17], and J. Woo[29]

[1]Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA
[2]Physics Department, Columbia University, New York, NY 10027, USA
[3]Department of Physics and Astronomy, DePauw University, Greencastle, IN 46135-0037, USA
[4]Department of Physics and Astronomy and the Bartol Research Institute, University of Delaware, Newark, DE 19716, USA
[5]Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA
[6]DESY, Platanenallee 6, 15738 Zeuthen, Germany
[7]Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA 02138, USA
[8]Physics Department, California Polytechnic State University, San Luis Obispo, CA 94307, USA
[9]Department of Physics, Washington University, St. Louis, MO 63130, USA
[10]School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA
[11]Department of Physics, California State University - East Bay, Hayward, CA 94542, USA
[12]Santa Cruz Institute for Particle Physics and Department of Physics, University of California, Santa Cruz, CA 95064, USA
[13]Department of Physics and Astronomy, Dartmouth College, 6127 Wilder Laboratory, Hanover, NH 03755 USA
[14]Department of Physics, University of Maryland, College Park, MD, USA
[15]NASA GSFC, Greenbelt, MD 20771, USA
[16]School of Natural Sciences, University of Galway, University Road, Galway, H91 TK33, Ireland
[17]Physics Department, McGill University, Montreal, QC H3A 2T8, Canada
[18]School of Physics, University College Dublin, Belfield, Dublin 4, Ireland
[19]Department of Physics and Astronomy, University of Iowa, Van Allen Hall, Iowa City, IA 52242, USA
[20]Department of Physics and Astronomy, Barnard College, Columbia University, NY 10027, USA
[21] Arthur B. McDonald Canadian Astroparticle Physics Research Institute, 64 Bader Lane, Queen's University, Kingston, ON Canada, K7L 3N6
[22]Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA
[23]Department of Physics, Engineering Physics and Astronomy, Queen's University, Kingston, ON K7L 3N6, Canada
[24]Institute of Physics and Astronomy, University of Potsdam, 14476 Potsdam-Golm, Germany
[25]Department of Physical Sciences, Munster Technological University, Bishopstown, Cork, T12 P928, Ireland
[26]Department of Physics and Astronomy, Purdue University, West Lafayette, IN 47907, USA
[27]Department of Physics, Indiana University-Purdue University Indianapolis, Indianapolis, IN 46202, USA
[28]Department of Physics and Astronomy, Iowa State University, Ames, IA 50011, USA
[29]Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA

PoS(ICRC2023)746