VERITAS Observations of M 82 and Other Selected Starburst Galaxies

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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.
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 ~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/cm³. 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: Γ = 2.5 ± 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, ~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
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 $\sigma$, or a chance probability of $7.7 \times 10^{-7}$, 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 $\Gamma = 2.3 \pm 0.3_{\text{stat}} \pm 0.2_{\text{sys}}$ with no evidence of a spectral cut-off at energies below 5 TeV. The measured gamma-ray flux is $(3.2 \pm 0.6_{\text{stat}} \pm 0.6_{\text{sys}}) \times 10^{-13} \text{cm}^{-2} \text{s}^{-1}$ 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.

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References

Gamma-rays from Starburst galaxies

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