Very-High-Energy Gamma-Ray Observations of M 31 with VERITAS

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Abstract

M 31 (the Andromeda galaxy) is the closest large spiral galaxy to the Milky Way and thus one of the prime targets for the study of diffuse γ rays. In this work observations of high- and very-high-energy γ rays with the Fermi-LAT and VERITAS are reported, along with a theoretical prediction of the diffuse γ-ray flux from the interaction of cosmic rays with the interstellar medium on the order of 0.05 - 3.5% of the Crab Nebula flux and spread around an the annular star-forming region ~ 10 kpc from the galaxy core, a separation that is resolvable with VERITAS. A preliminary VERITAS point source analysis of 14.6 hours of data shows no bright point sources (~3% Crab upper limit > 130 GeV). An extended source analysis is ongoing.

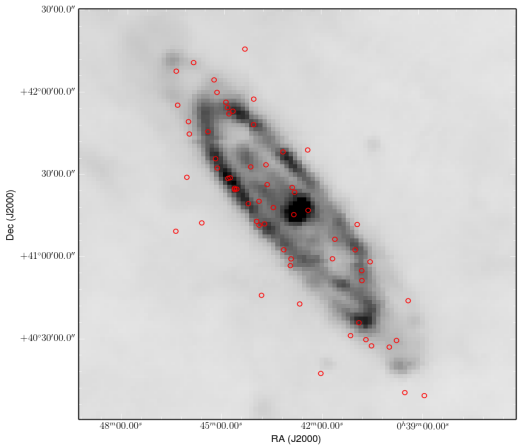

Fig. 1: IRIS 100 μm image [5], showing the ISM rich ring at ~10 kpc, overplotted with supernova remnants (red) from the M31DEEPXMM [6]. The diffuse emission is expected to be localised away from the bright central region in the ISM and SNR rich ring.

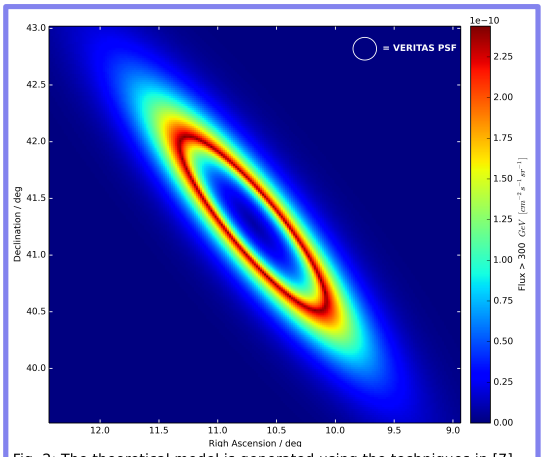

Fig. 2: The theoretical model is generated using the techniques in [7] and [8] and uses the radial column density profile from [9]. This shows that the diffuse emission is localised away from the bright core but spread out over a large region, several times the PSF of VERITAS. The total flux is 7.7 x 10^{-14} ph cm^{-2} s^{-1} and should be considered a lower limit since it does not include other contributors to the diffuse emission or discrete point sources.

Table 1: Predictions of the VHE flux from M 31. The scaled predictions for M 82 and NGC 253 are calculated by taking the measured VHE fluxes [10, 11]and correcting for the relative distances, SFRs and total mass of ISM hydrogen in the galaxies (values from [2]).

Prediction	Threshold / GeV	Predicted Flux / % Crab
Extrapolated Fermi-LAT Result	300	0.3 ± 0.2
Theoretical Model	300	0.05
M 82 Scaled	700	3.5
NGC 253 Scaled	250	0.37

Introduction

M 31 is the closest spiral galaxy to the Milky Way (MW, d = 780 kpc [1]) with apparent dimensions of 190' x 60'. Due to its proximity and size, it has been very well studied and is the ideal candidate to study the origins of diffuse γ-ray emission across an entire galaxy. It has been detected by the Fermi-LAT in high-energy (HE, 0.1 - 100 GeV) γ rays [2] with a > 100 MeV photon flux of (1.06 ± 0.25) x 10^{-8} ph cm^{-2} s^{-1} and a spectral index of Γ = 2.31 ± 0.08, it has yet to be detected at very-high-energy (VHE, > 100 GeV) energies. The HEGRA Collaboration has published an upper limit (> 500 GeV) of 3% of the Crab flux for point sources within the central region [3].

It is believed that diffuse γ-ray emission is caused by the interaction of cosmic rays (CR) with the interstellar medium (ISM) and thus scales with the star formation rate (SFR) and hydrogen gas density. M 31 has an annular ring structure ~ 10 kpc from its centre where the majority of the ISM, star formation and supernova remnants (SNRs) are located. The higher resolution of the VERITAS observations over the existing Fermi-LAT HE γ-ray observations will allow comparison with existing knowledge of M 31 and models of diffuse γ ray production.

With a significant Dark Matter (DM) content that extends beyond the star forming ring, M 31 also provides an interesting candidate for DM studies (see [4] for more details).

VERITAS Observations

VERITAS is an imaging atmospheric Cherenkov telescope array, consisting of four 12 m telescopes designed to detect VHE γ-rays. It has a point-spread-function of 0°.1, a field-of-view (FOV) of ~3°.5, a threshold energy (E_{thresh}) of 120 GeV and an effective area of 10^5 m^2. Observing M 31 with VERITAS has several challenges due to its large spatial extent (a significant fraction of the FOV) and the optical brightness which raises the trigger (and thus energy) threshold of the affected parts of the camera, creating a "hole" in the image (see Fig. 3). VERITAS has conducted 13.4 hours of targeted observations and has 14.6 hours of additional data covering M 31.

To reduce the impact of the optical brightness, a variation of the standard image cleaning technique has been employed, replacing the pixel specific thresholds with a uniform threshold across the entire camera. This has reduced both the size and the depth of the hole (Fig. 3), at the cost of a slight reduction in the absolute sensitivity (6% loss on the Crab, E_{thresh} = 130 GeV). To date, this technique has only been applied the M 31 targeted observations with no bright point sources detected, giving a 3% Crab upper limit above 130 GeV. The extended source analysis is ongoing. Using this cleaning it will take ~100 hours to detect a 0.5% Crab point source.

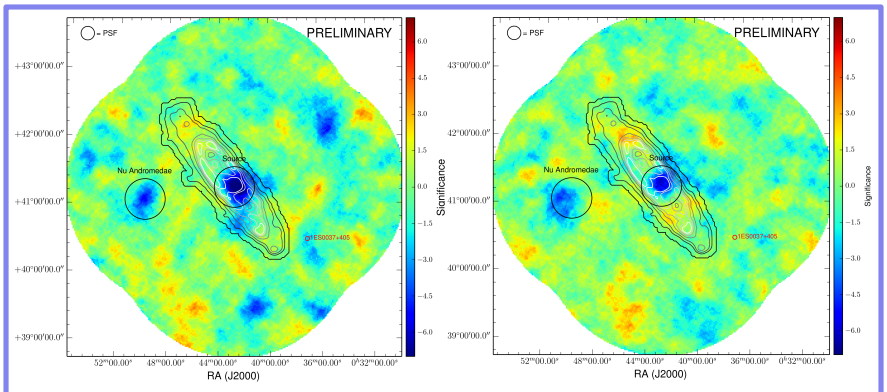

Fig. 3: Skymaps of the VERITAS analysis of M 31 showing the significance for a point source analysis overlaid with the IRIS 100 μm contours. The left map is the standard analysis, the right map shows the impact of the improved cleaning showing a reduction in the impact of the optical brightness of M 31 and ν-Andromeda.

Diffuse Gamma-Ray Emission

The major source of diffuse γ rays is expected to be the interaction of CRs with the ISM thus the measured flux is expected to scale by the SFR rates (SFR_{M31} / SFR_{MW} ~ 0.35 [2]), mass of hydrogen in the ISM and the relative distances squared. Predictions for the diffuse γ-ray flux (see Table 1) for M 31 as a point source have been generated by extrapolating the Fermi-LAT spectrum, from a theoretical model (Fig. 2) and by scaling the flux from the starburst galaxies M 82 and NGC 253. These predictions vary by ~2 orders of magnitude reflecting the uncertainties in some of the input parameters and the different mechanisms included.

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Conclusions

M 31 presents an excellent opportunity to study diffuse γ-ray emission which is predicted to be primarily from the gas-rich, SNR-rich star-forming region ~ 10 kpc from the galaxy core.

Observations with VERITAS are challenging due to M 31's spatial extent and optical brightness. Fixing the image cleaning thresholds across the camera has reduced the impact of the optical brightness. With this cleaning, detecting a 0.5% Crab point source will take ~100 hours of data.

No bright point sources have been detected with 14 hours of targeted observations (~ 3% Crab UL > 130 GeV) with predictions of the total flux ranging from 0.05 to 3.5% of the Crab flux.

Further work on image cleaning and analysis of the rest of the dataset, including an extended source analysis is ongoing.

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