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DETECTING γ-RAYS FROM THE ANCORA SUPERNOVA REMNANT

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RESUMEN

Recientemente, se descubrió un nuevo remanente de supernova (SNR), G288.8–6.3, en longitudes de onda de radio como una cáscara débil con el Australian Square Kilometer Array Pathfinder (ASKAP) en el estudio del Mapa Evolutivo del Universo (EMU). Esto provocó una investigación detallada de los rayos γ de la región que nos gustaría describir aquí. Para esta tarea, se analizaron quince años de datos del *Fermi*–Large Area Telescope (LAT) entre 400 MeV y 1 TeV. Detectamos emisiones de rayos γ espacialmente extendidas que se superponen con el SNR de radio con una significancia de detección de hasta $8.8\,\sigma$. El modelo preferido era un modelo espacial de disco combinado con un modelo espectral de ley potencial, produciendo un flujo de energía de $(4.80 \pm 0.91) \times 10^{-6}\,\mathrm{MeV\,cm^{-2}\,s^{-1}}$, con el espectro que se extiende hasta 5 GeV. Dadas las estimaciones de densidad, edad y distancia del gas, es más probable que la emisión sea de origen leptónico.

ABSTRACT

Recently, a new supernova remnant (SNR), G288.8–6.3, was discovered at radio wavelengths as a faint shell with the Australian Square Kilometre Array Pathfinder (ASKAP) in the Evolutionary Map of the Universe (EMU) survey. This prompted a detailed investigation of γ-rays from the region that we would like to describe here. For this task, fifteen years of *Fermi*–Large Area Telescope (LAT) data were analysed between 400 MeV and 1 TeV. We detected spatially extended γ-ray emission overlapping with the radio SNR with a detection significance of up to $8.8\,\sigma$. The favoured model was a disk spatial model combined with a power-law spectral model, yielding an energy flux of $(4.80 \pm 0.91) \times 10^{-6}\,\mathrm{MeV\,cm^{-2}\,s^{-1}}$, with the spectrum extending up to 5 GeV. Given the estimates for the gas density, age and distance, the emission is more likely to be of leptonic origin.

Key Words: cosmic rays — ISM: gamma-rays — ISM: radio continuum — ISM: supernova remnants — ISM: individual objects: G288.8–6.3 (SNR)

1. INTRODUCTION

Since the discovery of cosmic rays (CRs) by Victor Hess there has been speculation on their origin. The current consensus is that cosmic protons with energies up to 3×10^{15} eV originate from within our Galaxy (Aloisio et al. 2012). Supernova Remnants (SNRs) were first suggested as CR sources by Baade and Zwicky. Currently, around three hundred SNRs have been detected (Green 2019) at radio wavelengths, with around 10% also being detected in γ-rays (Acero et al. 2016).

In the last few years, supernova remnants at high Galactic latitudes have received some attention, with the detection of a few previously unknown sources at γ-ray energies (e.g. Ackermann et al. 2018, Araya 2013).

We detected extended γ-ray emission from the G288.8–6.3 region, spatially coincident with a low-surface-brightness shell-like SNR first discovered by Filipovic et al. (2023) using *Australian Square Kilometre Array Pathfinder (ASKAP)* data. The authors reported an estimated distance of ~ 1.3 kpc, with a distance of about 140 pc above the Galactic plane, and, based on the surface brightness, an age of > 13 kyr.

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TABLE 1

BEST-FIT PARAMETERS OF THE RADIAL DISK MODEL WITH THE POWER-LAW SPECTRAL MODEL FOR ANCORA SNR

Parameter	Unit	Value
Position		
R.A. / Dec	deg / deg	157.488 / −65.214
GLON / GLAT	deg / deg	288.8 / −6.3
Spatial model		*RadialDisk*
Spectral model		*PowerLaw*
TS	—	77.14
N^{o} of predicted photons	—	1331
Photon flux	ph cm^{-2} s^{-1}	$(3.14 \pm 0.41) \times 10^{-9}$
Energy flux	MeV cm^{-2} s^{-1}	$(4.80 \pm 0.91) \times 10^{-6}$
> 1 GeV (to 316 GeV)	MeV cm^{-2} s^{-1}	$(3.29 \pm 0.78) \times 10^{-6}$
Spectral parameters		
N_0	MeV−1 cm^{-2} s^{-1}	$(1.23 \pm 0.16) \times 10^{-12}$
Γ	—	2.32 ± 0.11
E_0	MeV	1000*
Spatial parameters		
Extension	deg	0.92 ± 0.06
TS_{ext}†	—	52.56

*Parameter fixed

†Test statistic for the extension hypothesis against the null hypothesis of a point-like source.

2. DATA ANALYSIS

The analysis was conducted using fifteen years of *Fermi*−Large Area Telescope (LAT) Pass 8 data (Aug 2008 – July 2023), and the `P8R3_SOURCE` class (Atwood et al. 2013) was applied. Data were selected within a radius of 12° in the region of interest (ROI) around the centre of the detected radio SNR at Galactic position GLON/GLAT = 288.8°/−6.3° in an energy range of 400 MeV − 1 TeV. We also made cuts on the PSF (point-spread function) class (`evtype = 56`), discarding low-quality (`PSF0`) class events.

The analysis was executed using the Python package *Fermipy* (v1.1.6, Wood et al. 2017) and *Fermitools* software (v2.2.0[11]) by employing the standard procedure of the binned maximum-likelihood analysis technique. The fourth Fermi catalogue (Abdollahi et al. 2020), 4FGL-DR3 (Abdollahi et al. 2022), with source modelling up to 3° outside the ROI, was used.

The models used to fit the source extension were a radial disk model, and a radial, symmetric two-dimensional (2D) Gaussian, and smoothed radio template, as well as using a power-law and a log-parabola spectral model.

3. RESULTS

Different spatial and spectral models were tested for in the course of the study, and their their relative log-likelihood values were compared, as well as the value of the Akaike information criterion (AIC; Akaike 1974)[12] We modelled the region with and without taking into account the 4FGL-DR3 catalogue source 4FGL J1028.7-6431c (abbreviated as J1028), which was positioned about 0.7*circ* from the centre of the remnant, which has not been confirmed to be associated with any known source.

The best-fit models, taking into account the AIC criterion, were a radial disk spatial model combined with a power-law spectral model, both with and without modelling J1028. In this work we show the results where the excess for J1028 is not separately modelled. Some excess remains around the position of J1028 – it is thus not entirely clear if this excess is associated with Ancora SNR or part of an unrelated source overlapping in this region. The best-fit parameters can be found in Table 1. The significance map of the region is shown in Fig 1 (left) in a field-of-view of approximately $4.0° \times 4.5°$, and the extracted spectral energy distribution (SED) from the source (marked with a white circle) is shown in Fig. 1 (right). More details of the modelling and results can be found in C.B.S. et al. (2024).

Overall, the γ-ray emission seems to be more extended than the radio signal, and there is no clear shell-like morphology seen in γ-rays. The SED extends up to 5 GeV and the fit power-law spectrum shows an energy flux of $(4.8 \pm 0.91) \times 10^{-6}$ MeV cm^{-1} s^{-1} with a spectral index of $\Gamma = 2.32 \pm 0.11$, with a total source significance of $\sim 8.8\,\sigma$.

Multiwavelength modelling using both radio and γ-ray flux points to investigate a leptonic inverse Compton scenario and a hadronic pion decay scenario was performed using *Naima* modelling (Zabalza 2015) assuming a power-law distribution of electrons with an exponential cutoff, and a power-law distribution of protons in the hadronic case. The results show that the energy in electrons are about 0.25% (assuming an explosion energy of 10^{51} erg) – typical values for such a source – and a spectral index of $s = 2$, matching canonical expectations. Due to the low gas density expected from observations by Filipovic et al. (2023), around 30% of the explosion energy would have to go into hadrons to explain the emission, making this scenario less likely than the leptonic one.

[11] `https://github.com/fermi-lat/Fermitools-conda`.

[12] AIC is a qualitative measure indicating which of a number of different models is preferred over the others, taking into account the difference in free parameters.

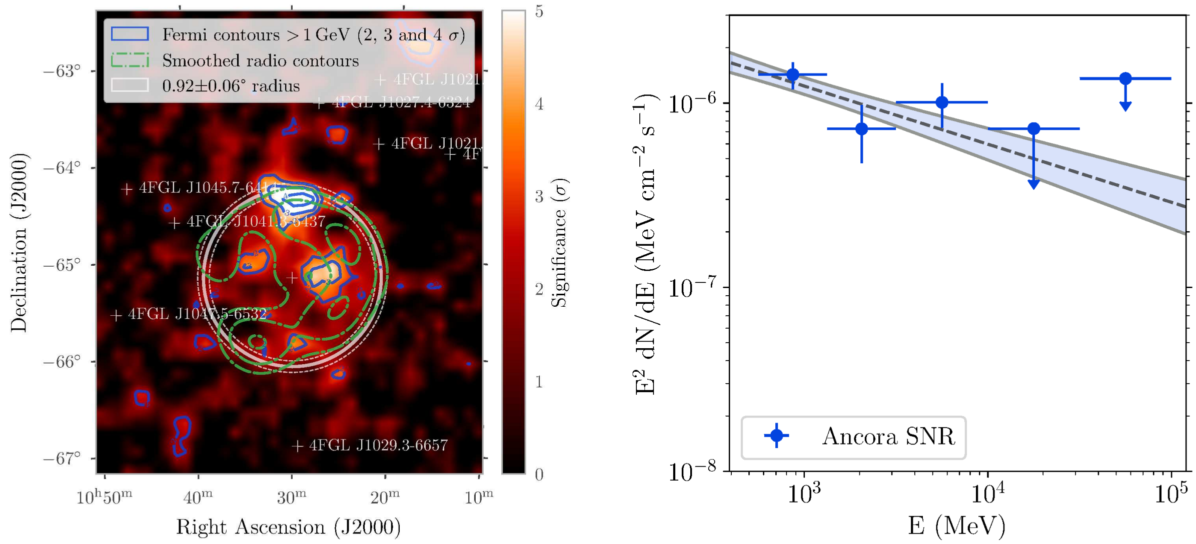

Fig. 1. Significance map of the G288.8–6.3 region, as seen with *Fermi*-LAT, after fitting with a radial disk and power-law model in the energy range of 400 MeV $-$ 1 TeV. The white circle with radius 0.92$\circ$ shows the radius of the disk obtained from the extension fitting. The violet contours highlight areas with signal above 1 GeV. The green contours overlaid show the smoothed radio contours from Filipovic et al. (2023).

4. DISCUSSION AND CONCLUSION

When comparing with other SNRs located at high latitudes detected at very high energies, it seems that Ancora SNR lies between values found for other sources, both in terms of flux, as well as considering the spectral index. The location of SNRs far from the Galactic plane and thus the potentially much lower gas densities increases the likelihood of the emission being of leptonic origin.

The authors also looked at possible interaction with molecular clouds along the line of sight by inspecting thermal dust emission maps from the *Planck* mission (Planck Collaboration 2016). While a gradient towards the Galactic plane can be observed and there is significant dust emission in the G288.8–6.3 region, the lack of correlation disfavours a sizeable hadronic contribution. Based on the gas map, leptonic emisson would seem to be the more likely scenario.

With Ancora, we have detected the only seventh off-plane supernova remnant emitting at γ-ray wavelenghts, with its spectrum extending up to 5 GeV, and morphological hotspots coinciding well with the radio shell. Further observations with upcoming Imaging Atmospheric Cherenkov Telescopes (IACTs), such as the Cherenkov Telescope Array (CTA) could give more insight into the existence of a cut-off in the spectrum and possibly deeper morphological studies at very high energies.

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