Star-forming regions as potential contributors to Galactic cosmic rays: the case of NGC 3603

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Prominent representatives of SNR at energies above 100 GeV.

Most of them show shell-like morphology supporting that SNR shocks as effective particle accelerators.

The detection of just VHE gamma rays does not prove the dominant role of SNRs in the production of galactic CRs.

Differential spectrum of historical (left panel) and other (right panel) TeV emitting SNRs.

Spectral cutoff

Aharonian et al., Nature Astronomy, 3, 2019
Another important issue with Supernova remnants

❖ The main problem is the difficulty of **disentangling** the hadronic and leptonic contributions.

❖ Both **pion decay** process and **inverse Compton process** with 2.7K CMB photons or non-thermal Bremsstrahlung process are equally effective.

With ‘pros’ and ‘cons’ for both the process gamma-radiation detected from all SNRs is under intense debate.
A new class of potential accelerator

Over the last decade, the space- and ground-based telescopes have revealed many classes of galactic gamma-ray source populations.

An alternative to SNRs:

Massive Stars clusters/Star-forming regions!!

1980: First proposed as Potential CR accelerator. However no direct evidence.

Potential site of acceleration: The vicinity of the stars or superbubbles, a multi-parsec structure caused by collective activity of massive stars.

The multiple shocks can raise the maximum energy of CR protons out to 1 PeV.
A Cocoon of Freshly Accelerated Cosmic Rays Detected by Fermi in the Cygnus Superbubble.

A 50-parsec-wide cocoon of freshly accelerated cosmic rays that flood the cavities carved by the stellar winds.

Cygnus Cocoon: 1st evidence of CR acceleration in SFR

Extended emission

1-100 GeV image

A supernova remnant
A TeV diffuse emission

Science, 334, 2011
Westerlund 1: A young massive stellar cluster

Extended VHE Gamma-ray radiation from the vicinity of Westerlund 1

A&A 537, A114 (2012)
The case of the NGC 3603

- The rich star forming region NGC 3603

- This stellar "jewel box" is one of the most massive young star clusters in the Milky Way Galaxy

- NGC 3603 is a prominent star-forming region in the Carina spiral arm of the Milky Way, about 20,000 light-years away.

- This image shows a young star cluster surrounded by a vast region of dust and gas. The image reveals stages in the life cycle of stars. The nebula was first discovered by Sir John Herschel in 1834.
Search for gamma rays from NGC 3603

Fermi-LAT observations

❖ An unidentified gamma-ray source in the 3FHL catalog (>10 GeV): **3FHL J1115-6117**.

❖ **3FHL J1115-6118** was positionally coincident with **NGC 3603**

❖ This source was also present in the 4th Fermi-LAT Catalog: **4FGL J1115.1-6118**

Making an association with NGC 3603 requires detailed morphological and spectral analysis.
Morphology of 4FGL J1115.1-6118

Why morphological analysis?

To check the extension: Radially symmetric Gaussian model

Best-fit location and extension of 4FGL J1115.1-6118

RA = 168.78 +/- 0.01, DEC=-61.29 +/- 0.02 (in deg)
Extension: 0.08 +/- 0.02 (in deg)
TS_ext = 7.7

❖ The source is not extended
❖ No diffuse emission

Spectral analysis of 4FGL J1115.1-6118

Energy range: **300 MeV to 1 TeV**

Spectral fit with power-law spectral shape.

The SED may suggest that the emission has two components, one below **10 GeV** and the other above **10 GeV**.

To understand the significance of the spectral curvature, we fit the data with different spectral shapes:
- Power-law
- Exponential cutoff power-law
- Log parabola
- Sum of two Log parabola models

![Graph showing spectral fit results]
**Leptonic model:**
- Bremsstrahlung and Inverse Compton.
- Ambient matter density: \( 35/\text{cm}^3 \)
- Bremsstrahlung can explain SED below 10 GeV whereas IC can explain SED above 10 GeV.
- Estimated synchrotron contribution. Not significant.

**Hadronic model:**
- The observed SED can be explained with the hadronic model
- Ambient matter density: \( 35/\text{cm}^3 \)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Leptonic</th>
<th>Hadronic</th>
</tr>
</thead>
<tbody>
<tr>
<td>spectral index ((\alpha))</td>
<td>2.5</td>
<td>2.3</td>
</tr>
<tr>
<td>Low energy cutoff, (E_{\text{min}}) (GeV)</td>
<td>(10^{-3})</td>
<td>1.0</td>
</tr>
<tr>
<td>High energy cutoff, (E_{\text{cutoff}}) (GeV)</td>
<td>(1.0 \times 10^2)</td>
<td>(5.0 \times 10^3)</td>
</tr>
<tr>
<td>Ambient proton density, (n_0) (cm(^{-3}))</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Total energy (10(^{48}) ergs)</td>
<td>4.6</td>
<td>5.5</td>
</tr>
</tbody>
</table>

- Given the large uncertainties in the SED at high energies the parameters of the models are not well constrained.

\[ \text{Saha et al, ApJ, 897, 2020} \]
Is it associated with a star-forming region?

- All other associations with the known classes of astrophysical objects are very less likely.

- The gamma-ray luminosity of the source is only 0.2% of the total mechanical power of the winds from the SFR (8.5 x 10^{31} W)

- Energetically the hypothesis that the source is powered by the SFR is also acceptable.

We can speculate that the observed emission is associated with the SFR.
Are these SFRs likely to be PeVatrons?

No signature of spectral cut-off yet!!

Double-bump structure: Is it real?
Conclusions

1. Our detailed analysis show that the observed gamma-ray emission from the 4FGL J1115.1−6118 source is not significantly extended.

2. The observed X-ray emission is expected to be associated with the point source 4FGL J1115.1−6118 and Galactic in origin.

3. The observed SED can be explained with both a leptonic and a hadronic model for an ambient matter density of 35 cm$^3$.

1. No firm evidence of association with any other classes of known gamma-ray emitters is found.
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2. The observed X-ray emission is expected to be associated with the point source 4FGL J1115.1−6118 and Galactic in origin.

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4. No firm evidence of association with any other classes of known gamma-ray emitters is found.

It becomes a potential candidate for studying SFRs to understand the origin of cosmic rays using the next generation of gamma-ray telescopes.
Thank you
Backup Slides
NGC 3603: X-ray association

**Chandra data**

- Energy range: 0.5 - 7.0 keV
- ObsId: 12329 (October 2010, 150 ks long exposure)
- About 300 sources are detected. 38 of them are with net counts more than 70 counts.

Extragalactic association is less likely
A HII region is well-known characteristics of an SFR.
Which emission mechanisms are active?

Leptonic or hadronic?

An estimate of the ambient matter density is very essential

- HII regions is positionally coincident with the source region
- CO molecular clouds are also present in this region

HII and CO molecular clouds are tracers.