PROCEEDINGS OF SCIENCE

Gamma-ray observations of nearby HII regions

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We present the analysis of the Fermi-LAT data in the region of the Vela Molecular Cloud Ridge (VMR). The latter is a dense region of gas located at approximately 1 kpc from us and it is the closest region that hosts intermediate-mass- and massive-star formation. Associations of massive stars have been proven to be powerful particle accelerators and are consequently expected to be bright gamma-ray sources. However, the gamma-ray emission associated with these sources has often a controversial origin, due to the superposition of multiple sources. Massive stars can be traced by observations of their surrounding HII regions. The latter are regions of gas which is ionized due to the strong radiation fields of the stars themselves. HII regions are identified by infrared observations and several of them have been recognized within the VMR. For the first time, we detected high-energy emission spatially coincident with a few of these HII regions, which leaves no doubt about the identification of gamma-ray emission with massive star associations.

7th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy (Gamma2022)
4-8 July 2022
Barcelona, Spain

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PoS(Gamma2022)039

1. Introduction

Gamma-ray astronomy is the main tool used to identify sources of cosmic rays (CRs) both in our Galaxy and beyond. The detection of a broad number of supernova remnants (SNRs) and pulsar wind nebulae (PWNe) at GeV and TeV energies, confirmed the idea that these objects are efficient particle accelerators. Most Galactic sources of gamma-rays, however, remain still unidentified [1, 2]. The need for a new class of sources raised in the last years mainly driven by the necessity to explain the origin of the PeV particles observed at Earth, but it is also necessary to understand the origin of the unidentified sources that populate the high- and very-high energy catalogs. Clusters of massive stars have been suggested to be potential particle accelerators [3, 4] and recently associations like the Cygnus OB2 and Westerlund 1 have been detected in gamma-rays up to very high energies [5, 6]. These exceptionally massive star clusters (SCs), hosting tens of early type stars, are the primary PeVatron candidates at the moment. The acceleration is powered by the collective winds of massive stars, which can reach a mechanical luminosity of $O(10^{38})$ erg s^{-1} for a single SC characterized by a mass-loss rate of $O(10^{-4})$ M$_\odot$ yr^{-1} and a wind velocity $O(10^3)$ km s^{-1}. If even a small fraction of this energy is used to accelerate particles, the collective contribution of SCs in the Galaxy can represent a significant contribution to Galactic CRs sea. Meanwhile, SCs are expected to be gamma-ray emitters. Gamma-ray observations of these type of objects can be key for understanding their acceleration power. Nevertheless, detection of high energy photons from SCs is limited to a very few objects which are often in complicated regions where many astrophysical sources overlap. Massive stars are born, evolve and die in clusters, so it is very common to find a superposition of massive SCs with SNRs, pulsars and PWNe. This makes difficult to separate the emission of the stellar association with that of other sources. The only way to avoid this inconvenient contamination is to target young SCs, younger than the typical age of massive stars ($\sim$ 10 Myr for $\lesssim$ 20 M$_\odot$ [4]) so that no explosion happened in the system yet. Very young massive SCs are usually still embedded in their gas cocoon, and are therefore opaque in optical light. Nevertheless the UV radiation of such stars ionizes the surrounding gas and heat the dust, that re-emit recombination lines (in optical and radio) and thermal infrared emission, respectively. These emission regions are known as HII regions, and are the primary tracers of young stellar objects. A deep survey of Galactic HII regions has been obtained with the Wide-field Infrared Survey Explorer (WISE), which detected more than 8000 objects [7].

For this study we considered the Vela Molecular cloud ridge (VMR). The latter is a nearby region (1–2 kpc) of dense gas which hosts several massive SCs recognized by their surrounding HII regions both in optical [8] and in infrared [7]. The list of HII regions embedded in the region is reported in Table 1. We investigate the gamma-ray counterpart of these regions to look for evidence of CR acceleration produced in these objects.

2. Gamma-ray observations

We targeted a wide region of interest (ROI) $l \in [257°, 274°]$, $b \in [-8.5°, 8.5°]$ that embeds the Vela molecular cloud complex. We used Fermi-LAT PASS8 data accumulated between August 8th 2009 (`MET 239557417`) and December 14th 2021 (`MET 632287927`). For the data reduction we used standard cuts: source type events (`evclass=128`) with the most stringent background

RCW Name	WISE name	4FGL source	LAT position (l, b) [°]	WISE size [°]	LAT size [°]	TS
RCW 27	G259.771+00.541	J0838.4-3952	$259.88^{\pm0.13}$, $0.7^{\pm0.1}$	0.933	$1.11^{+0.13}_{-0.10}$	155.4
RCW 32	G261.515+00.984	J0844.9-4117	$261.51^{\pm0.06}$, $0.95^{\pm0.08}$	0.440	$0.25^{+0.06}_{-0.05}$	211.8
RCW 34	G264.343+01.45	–	–	0.108	–	–
RCW 35	G264.681+00.272	J0853.1-4407	$264.76^{\pm0.08}$, $-0.01^{\pm0.12}$	0.155	–	87.9
RCW 36	G265.151+01.454	J0859.3-4342	$265.07^{\pm0.05}$, $1.40^{\pm0.04}$	0.224	$0.21^{+0.07}_{-0.06}$	556.1
RCW 37	–	J0900.2-4608	$264.52^{\pm0.02}$, $-3.58^{\pm0.03}$	–	–	47.4
RCW 38	G267.935-01.075	J0859.2-4729	$267.89^{\pm0.03}$,$-1.03^{\pm0.03}$	0.155	$0.24^{+0.07}_{-0.05}$	564.5
RCW 40	G269.174-01.436	–	$268.57^{\pm0.06}$, $-0.73^{\pm0.04}$	0.115	–	20
RCW 41	G270.310+00.851	J0917.9-4755	$270.04^{\pm0.13}$, $0.63^{\pm0.11}$	0.248	$0.30^{+0.15}_{-0.09}$	98.18

Table 1: Gamma-ray and infrared properties of the HII regions identified in the Rodgers-Campbell-Whiteoak (RCW) catalog in the region of the VMR. We report the infrared and gamma-ray morphology as well as the test statistic value for the gamma-ray detection.

rejection (`DATA_QUAL==1 && LAT_CONFIG==1`) , reconstructed in the front and in the back of the detector (`evtype=3`) and with maximum zenith angle 90°. The starting model included all the sources from the 4FGL source catalog along with the standard galactic (`gll_iem_v07`) and extra-galactic (`iso_P8R3_SOURCE_V3_v1`) diffuse backgrounds. We excluded from the model all the unidentified sources (listed in Table 1) in the proximity of a known HII region in the ROI and we re-modeled their morphology. Then, we extracted their spectral energy distribution (SED). For the morphological analysis we considered only events of energy higher than 1 GeV, in order to have a better angular resolution. We then extracted the spectrum in the energy range 500 MeV – 1 TeV. Notice that except for RCW34 and RCW40, all the HII regions in the ROI coincide with the location of at least 1 4FGL source. This is an indication of significant emission in these regions. We fitted the gamma-ray extension and see that in all cases, where we had convergence, it is comparable with the extension of the infrared emission. The results of the morphological fit are reported in Table 1 together with the source significance expressed as test statistic value ($TS = \sigma^2$). Among the tested regions, only RCW34 don't show any hint of gamma-ray emission. Conversely RCW40 shows a hint of emission even if there is no recognized sources at its location. Its significance is anyway little below the threshold for detection ($\sigma \gtrsim 4$). All the 4FGL sources coinciding with the ionized regions are unidentified, except for 4FGL J0838.4-3952, which is categorized as a pulsar and therefore we excluded its corresponding HII region, RCW27, from our sample. In the case of RCW35, RCW37 and RCW40 the radius determination did not converge, we think that the sources are too faint or too small to be resolved by Fermi-LAT and are treated as point-like sources. We extracted the SED for the sources which can unambiguously be identified with the HII regions, given both the lack of other possible sources and the firmly fitted morphology. Their name is highlighted in bold in Table 1 and their spectra are shown in Fig. 1.

3. Discussion and conclusions

We observe gamma-ray emission coincident with the position of a handful of HII regions in the near star forming complex of the VMR. All these emitting regions are associated with stars, although little information on the stellar content is available. The two most bright gamma-ray

PoS(Gamma2022)039

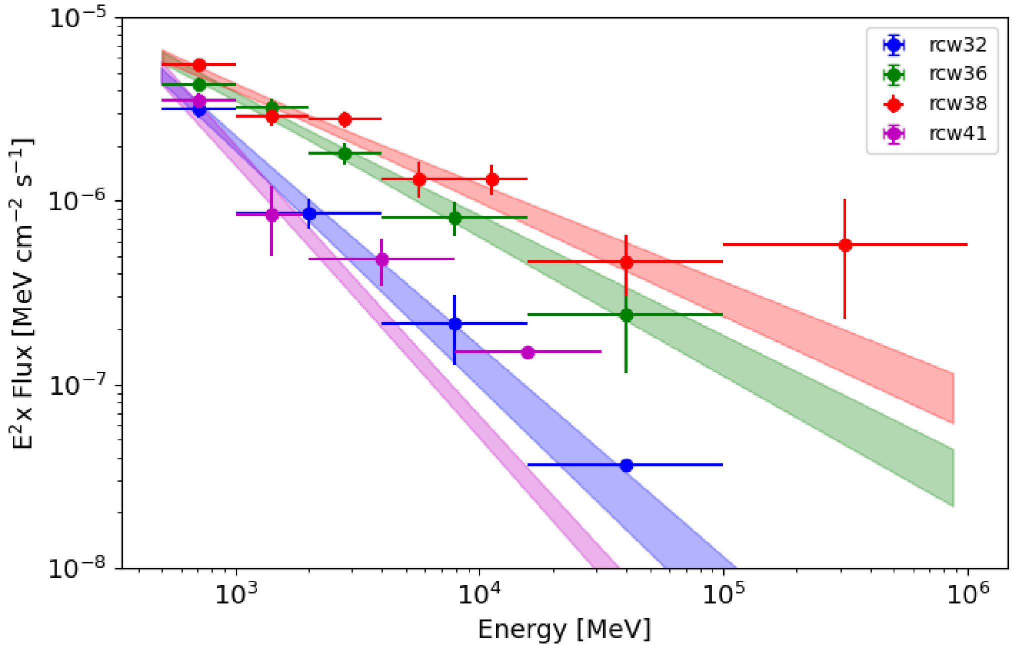

Figure 1: The spectral energy distribution of the analyzed sources and their relative best-fit models. The area represents the 1-sigma uncertainty of the model.

sources of our sample RCW38, and RCW36, both host a SC with an age of $O(1)$ Myr, containing ~30 and ~ 4 early type (O/B) stars, respectively [9, 10]. The gamma-ray luminosity derived from these observations is of the order of 10^{33} erg s^{-1} and therefore can be easily supported by a typical wind luminosity of 10^{36-38} erg s^{-1}. The extension of the gamma-ray emitting region is comparable with the extension of the HII region, suggesting a relation between the two emission. This is of the order of a few parsecs: an angular extension of 0.3° at 1 kpc corresponds to a physical size of 5 pc. In order to explain the gamma-ray observations, the particles need to be confined in the region for the timescale of a given radiation mechanism. The typical timescale for proton-proton interactions is:

$$\tau_{pp} = 1.7 \times 10^{12} \left(\frac{n}{1000 \text{ cm}^{-3}} \right)^{-1} \text{ s} \quad (1)$$

assuming a dense, $n \sim 1000$ cm^{-3}, medium. This is the average density for the VMR. For the same target density, the timescale for bremsstrahlung is comparable to τ_{pp}, while inverse Compton is much slower at GeV energies. The residence time in a region of radius R, assuming a certain pivot diffusion coefficient, D_0, is estimated as:

$$\tau_{esc} = \frac{R^2}{6D(E)} = 4 \times 10^9 \left(\frac{R}{10 \text{ pc}} \right)^2 \left(\frac{D_0}{4 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}} \right)^{-1} \left(\frac{E}{3 \text{ GeV}} \right)^{-2+\nu} \text{ s}, \quad (2)$$

where ν is the index of the turbulence spectrum with $\nu = 5/3$ in the case of a Kolmogorov turbulence or $\nu = 3/2$ for the Kraichnan turbulence [11]. Comparing this to the timescale of gamma-ray radiation processes, it results that the diffusion coefficient should be suppressed by 2 or 3 orders of magnitude in order to explain the observations.

In summary, we analyzed Fermi-LAT data in the region of the VMR and found significant gamma radiation extending to a few tens of GeV, in correspondence of several HII regions. The connection between the observed gamma-rays and the embedded clusters is supported by morphological and energetic considerations. More detailed studies are ongoing to understand the efficiency of acceleration processes in these objects and their contribution to the Galactic population of CRs and will be presented in a dedicated publication.

Acknowledgements G. P. and S. G. acknowledge the support of the Agence Nationale de la Recherche (grant ANR-21-CE31-0028). S. C. acknowledges support from the Polish Science Centre (grant DEC-2017/27/B/ST9/02272).

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