Testing spatial uniformity of the CR spectrum in the local ISM with γ-ray observations

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ABSTRACT
Gamma-ray observations of nearby radio-line-emitting gas structures in the interstellar medium allow us to probe the spectrum of cosmic rays (CRs). In this paper, we analysed Fermi Large Area Telescope (LAT) γ-ray observations of three such structures located near each other to check if their CR spectra are compatible with that of the CR background or might provide evidence for a population of “fresh” CRs. We found that the shape of the γ-ray spectrum in the Aquarius HI shell is consistent with the previously published stacked γ-ray spectrum of the Gould Belt molecular clouds. We also found that assumptions on the diffuse Galactic γ-ray background affect the spectral shapes of CRs derived in the R Coronae Australis and ρ Ophiuchi molecular clouds in which spectral deviations had previously been suggested. These two facts provide evidence to support the hypothesis of uniformity of the shapes of cosmic ray spectra in the local Galaxy environment.

Key words: gamma-rays: ISM – cosmic rays – ISM: general

1 INTRODUCTION
Every supernova (SN) explosion releases \( \sim 10^{51} \) ergs of kinetic energy in the interstellar medium (ISM). Stellar material is ejected at supersonic speeds, generating a shock wave into the ISM. The ejecta sweep up the surrounding gas and pile up a dense shell. The SN remnant (SNR) can expand over tens of parsec before the ejecta speed becomes subsonic. As the ejecta expands, the shocked gas cools and eventually recombines forming a neutral hydrogen (HI) shell (for a review, see Reynolds 2017). Multiple nearby SN explosions result in an ensemble of shock waves which inflate a superbubble surrounded by a massive HI super-shell (e.g., McCray & Kafatos 1987). SNRs are recognised as the sources of Galactic cosmic rays (CRs) with energies below \( \sim 100 \) TeV (for a review, see Berezinskii et al. 1990). It is commonly accepted that CRs gain energy through diffusive Fermi acceleration at fronts of strong SNR shocks (e.g., Krymskii 1971). The diffusive shock acceleration produces hard spectra of CRs, \( N(E) \propto E^{-2.9} \). After being accelerated, CRs escape from SNR shocks and travel through the ISM. CRs are confined in the Galaxy for \( \sim 10^7 \) yr at GeV energies and during this time the CRs accelerated by individual sources mix and contribute to the CR background. The diffusive propagation of CRs in the Galaxy makes the CR spectrum softer due to energy dependent escape rate. The resulting CR spectrum directly measured near the Earth is \( N(E) \propto E^{-2.8} \) at energies from 20 GeV to 200 GeV (Adriani et al. 2011; Aguilar et al. 2015).

CRs undergo hadronic interactions with the interstellar gas and produce neutral pions, which decay into γ rays. The ISM is mainly composed of hydrogen in atomic or molecular form (for a review, see Ferrière 2001). The tracers of these forms of hydrogen, the HI 21-cm line (Dickey & Lockman 1990; Kalberla et al. 2003) and the CO 2.6-mm line, respectively, revealed various structures in the ISM, including HI shells and supershells (e.g., Heiles 1979; Hu 1981; Ehlerová & Palouš 2013) and molecular clouds (MCs; for a review, see Heyer & Dame 2015). SNs are expected to occur near the molecular material in which their massive progenitor stars were born. Exploding in the vicinity of MCs, SNs make HI shells and MCs nearby objects, while CRs escaping from SNRs can interact with the MC gas producing γ rays (e.g., Montmerle 1979; Uchiyama et al. 2008; Aharonian et al. 2008).

If one SN occurs within 100 pc distance every Myr (that is the average SN rate in the Galactic disk, e.g., Diehl et al. 2007), the injection of CRs into the ISM can leave an imprint on the CR spectra local to the injection site (e.g., Kachelriess et al. 2015). It was proposed by Neronov et al. (2017) that discreteness of CR injection by SN events in space and time can result in the variations of the slope of the CR spectrum in the energy range of 10 GeV to 1 TeV across the local ISM. In this scenario, the CR spectrum has

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a low-energy break and the slope of the CR spectrum below the break energy is determined by the balance of the CR steady-state injection and energy-dependent propagation, whereas the variation of the spectrum above the break energy is attributed to the gradual transition from the steady-state continuous injection to the regime of discrete source injection. To test this scenario, they analysed γ-ray observations accumulated by Fermi Large Area Telescope (LAT) of high-latitude MCs belonging to the Gould Belt and reported that the slope of CR spectrum above 18^+7_−5 GeV is variable across the 1 kpc scale region, but stated that the statistics of Fermi-LAT data is only marginally sufficient to establish the two regimes of CR injection. Other studies of the CR hadron spectrum within 1 kpc used Fermi-LAT observations of a mid-latitude region in the third Galactic quadrant (Abdo et al. 2009) and of the nearby MBM 53, 54, and 55 MCs and the far-infrared loop-like structure in Perseus located within 100-150 pc of the Sun (Mizuno et al. 2010). The latter CR spectrum is seemingly harder than that from other Fermi-LAT studies (Abdo et al. 2009; Casandjian 2013).

The ejecta from a local SN explosion occurred at the distance ~100 pc has apparently reached the Earth some 2 Myr ago (Knie et al. 2003; Wallner et al. 2010). The same SN might also lead to variation in the CR spectra of the Gould Belt MCs located within ~200 kpc. The three nearest MCs amongst the high-latitude Gould Belt MCs include ρ Ophiuchi (Oph), R Corona Australis (R CrA) and Taurus located at distances of 165 pc, 150 pc, and 140 pc, respectively. The γ-ray spectrum of the ρ Oph MC is the hardest amongst the high latitude Gould Belt MCs, while the γ-ray spectrum of the R CrA MC differs from the spectra of the other MCs from the sample of Neronov et al. (2017). We compared mutual distances between the MCs from that sample and found that R CrA and ρ Oph MCs are separated by only 100 pc. This mutual distance is the smallest in the sample with the exception of the two MCs, Orion A and Orion B, in the Orion complex located 500 pc away. Given the peculiar CR spectral shapes in the ρ Oph and R CrA MCs and their short mutual distance as well as the possible CR spectral hardness of the nearby MBM 53-55 MC and the Perseus loop, it makes sense to perform a detailed analysis of the spectra of the ρ Oph and R CrA MCs and of the CR spectrum of another structure located in their vicinity in order to search for a signature of discrete source CR injection. The Aquarius (Aqr) shell identified using the HI 21-cm line observation by Hi (1981) and using far-infrared emission by Könyves et al. (2002) is located at a distance of 170 pc (Hi 1981). If we adopt this distance then the Aqr shell is at distances of 110 pc and 190 pc from the R CrA and ρ Oph MCs, respectively, and can provide us with an alternative probe of the CR spectrum in their neighbourhood.

In this paper, we analyse Fermi-LAT observations of the Aqr HI shell and the R CrA and ρ Oph MCs to test uniformity of the CR spectrum in the local Galaxy. In Section 2, we discuss the Fermi-LAT observations that we used and their analysis. We describe our models for the γ-ray emission of these nearby ISM structures in Section 3 and we discuss our results in Section 4. We discuss prospects of indirect measurements of the CR spectra in ISM gas accumulations located at short mutual distances in Section 4 and finally present our conclusions in Section 5.

2 FERMI-LAT OBSERVATIONS AND ANALYSIS

Gamma-ray observations of radio-line-emitting ISM structures allow us to indirectly measure CR spectra at different locations in our Galaxy (e.g., Abdo et al. 2009; Casanova et al. 2010; Ackermann et al. 2012a; Yang et al. 2010), since (i) the Galaxy is transparent for γ-rays, (ii) γ-ray production cross-section is independent of the chemical or thermodynamic state of the ISM gas, and (iii) γ-ray spectra are determined by their parent CR spectra.

The Fermi-LAT is a pair-conversion wide field-of-view imaging telescope onboard the Fermi satellite launched in June 2008. Fermi-LAT covers the γ-ray energy range from ~20 MeV to several hundreds of GeV (Atwood et al. 2009). To take advantage of its large field-of-view, the main observing mode of Fermi is the sky-survey mode, which applies that the exposure is almost uniform over the sky after two Fermi orbits (or about 3 hours). It makes possible our investigation because the ρ Oph and R CrA MCs and the Aqr shell are projected onto different regions of the sky despite their close mutual distances. The Fermi-LAT has an angular resolution per single event of 3^ designated by the previous-generation EGRET instrument. Wide energy coverage and large photon statistics provided by Fermi-LAT are crucial for studying the spectra of faint, extended γ-ray sources, including those of the Aqr shell and the R CrA MC.

We downloaded the Fermi-LAT Pass 8 data from the Fermi Science Support Center. We selected Pass 8 CLEAN class data (evclass = 256) spanning 9 years (MET 239557417-521539208) with energies between 200 MeV and 200 GeV. The low-energy bound is selected to reduce the possible contamination of the spectral modelling by an electron bremsstrahlung component that is expected to appear at lower energies (Neronov et al. 2012). The CLEAN class has a lower particle background rate above 3 GeV than that of the parent SOURCE class and is better suited for studying the shape of spectra above a few GeV. We chose two regions of interest (ROI) with a radius of 22^ designated by the Ayr shell and the R CrA MC, respectively, and one ROI with a radius of 15^ that encloses the Ayr shell and the R CrA MC. The choice of the radius of the ROI depends on a projected distance from each of these ISM structures to the Galactic plane. For the data analysis, we used the FERMI SCIENCE TOOLS v10r0p5 package and PSR2_CLEAN_V6 instrument response functions. To avoid contamination from the γ-ray-bright Earth’s limb we removed all events with zenith angle > 90^.

We applied the recommended time selection quality cuts (DATA QUAL:=1 & LAT CONFIG:=1), ensuring that the LAT

1 the R CrA MC does not lie inside the Gould Belt

2 https://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi

3 https://fermi.gsfc.nasa.gov/ssc/data/analysis/software/
instrument was in normal science data-taking mode. We binned the data in 30 logarithmically spaced bins in energy. We used the spatial binning with a pixel size of 0.15. To model γ-ray emission in the analysis regions, we included γ-ray sources from the LAT 4 year point source (3FGL) catalogue (Acero et al. 2016). To compute the spectral parameters of γ-ray sources, we performed a binned likelihood analysis by using the pyLikelihood package4 which is part of the FERMI SCIENCE TOOLS.

3 MODEL PREPARATION

Most of the celestial γ rays detected by Fermi-LAT are created from the interactions of CRs with the ISM. Analyses of faint, extended γ-ray sources require models of the Galactic diffuse and isotropic emission. The standard Galactic interstellar emission model (IEM) is recommended by the Fermi-LAT collaboration and is based on a linear combination of maps for interstellar gas column density and for the inverse-Compton emission produced in the Galaxy and also includes large-scale γ-ray emitting structures, such as Loop I and the Fermi bubbles. To account for dark neutral gas in our Galaxy, which is not derived from the HI and CO data (Grenier et al. 2005), a template related to the total dust column density is included in the standard IEM. The IEM we used is described by the gll_iem_v06.fits template, released with Pass 8 data (Acero et al. 2016). The IEM template comprises a set of all-sky maps representing the expected foreground emission at given energies. The corresponding isotropic component is described by the iso_P8R2_CLEAN_V06w06.txt template.

Two classes of extended γ-ray sources are possible:
(a) Extended sources emitting γ rays via mechanisms not correlated with the HI density: For modelling of such sources one needs to include the template corresponding to expected emission into the source model. This technique was used for detection of the giant outer lobes of Centaurus A (Abdo et al. 2010b) and of extended γ-ray emission from Fornax A (Ackermann et al. 2010b), and also for searches for new potential extended γ-ray sources, such as galaxy clusters (e.g., Han et al. 2012), cosmological shock waves (e.g., Prokhorov 2014) or pair haloes (e.g., Barbiellini et al. 2014).
(b) Extended sources with γ-ray emission correlated with the HI density: In this case, the standard IEM should carefully be refined and such extended γ-ray sources should be extracted from the IEM template for modelling. This class includes Galactic objects, such as Gould Belt MCs and HI gas shells (e.g., Yang et al. 2014; Mizuno et al. 2016), and extragalactic objects, such as the gaseous disc of the Andromeda galaxy (Abdo et al. 2010a). To refine the standard IEM model for objects of this class, one needs to redo a decomposition of γ-ray emission into the linear combination of templates for various components of the Galactic diffuse emission (Ackermann et al. 2012b) or to adopt a background model from other regions using the standard IEM. The former method was applied by Mizuno et al. (2016) using the dust properties derived from the Planck data to the analysis of Fermi-LAT data. Since the Planck data were not available for the development of the current, standard IEM, the former method in this case is advantageous over the latter method. In this paper, we used the latter method following Neronov et al. (2017) for ease of comparison with their results and elaborated further on implementation of this method for more detailed background modelling in its framework.

3.1 Aquarius HI shell

The Aqr shell is a Galactic HI structure clearly visible as a large ring-shaped intensity enhancement in the standard IEM model template. To illustrate that the HI shell in Aqr is identified with an extended γ-ray source, we show the neutral atomic hydrogen column density map in units of cm⁻² obtained with the survey, HI4PI (Ben Bekhti et al. 2016), and downloaded from the website, https://skyview.gsfc.nasa.gov/ on the right-hand side panel of Fig. 1 and show the Fermi-LAT 0.5-200 GeV⁶ count map smoothed by a Gaussian kernel of σ = 0.2° on the right-hand side panel. Both the panels map a square of side 20° and are centered on (l, b)=(42°, -33°). The white dashed circles in Fig. 1 have a radius of 5.5° and encompass the Aqr shell. This shell is clearly visible on both panels. Using the data of the Leiden/Argentine/Bonn survey (Kalberla et al. 2005) downloaded from the website⁷, we checked and found that the contribution of the Aqr shell to the total HI column density within the central circle of 5.5° radius is dominant (∼50%) within the velocity range from 0 to +10 km s⁻¹ in the local standard of rest (LSR) frame. Looking for substructures within other velocity ranges, we found that there is another substructure projected onto the Aqr shell and centered on (l, b)=(45°, -36°) within the velocity range from -10 to 0 km s⁻¹ in the LSR frame. We downloaded the CO line emission map⁸ produced from the Planck data and found an CO line emission counterpart of this substructure. Using the Planck Catalog of Galactic cold clumps (Ade et al. 2016), we found that the source of PGCC C45.16-36.19 is at this location. The distance to this cold clump is of 295 pc as taken from Ade et al. (2016). Taking the contribution from this source into the γ-ray signal from the Aqr shell, it is possible to set a conservative upper limit on the distance between the extended γ-ray source towards the Aqr shell and the R CrA or ρ Oph MCs. These limits are less than 200 pc and 280 pc, respectively.

6 the lower bound of 0.5 GeV is selected in order to sharpen the γ-ray count map in Figure, since the PSF is superior at these energies
7 https://lambda.gsfc.nasa.gov/product/foreground/fg-LAB_HI_Survey_get.cfm
8 http://pla.esac.esa.int/pla/aio/product-action?MAP_ID=CGM_ComMap_CU-commander_0256_R2_00.fits

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foreground region centered on \((l, b) = (31^\circ, -33^\circ)\). A similar procedure was used by Neronov et al. (2017) in their analysis of the MCs. We found that this procedure is reasonable at high Galactic latitudes and if the source is not projected onto the Fermi bubbles. To avoid the presence of pixels with negative values in the shell template, the replacement is applied only for the pixels with initial values higher than the constant value derived from the neighbourhood foreground region. To produce the template for the Aqr shell, we subtracted the refined IEM template from the standard IEM template. The model also includes 3FGL sources which were extracted the refined IEM template from the standard IEM template. The model also includes 3FGL sources which were incorporated using the make3FGLxml.py script.

The three brightest 3FGL \(\gamma\)-ray point sources which belong to a circular region of \(5.5^\circ\) radius surrounding the Aqr shell are 3FGL J2103.7-1113, 3FGL J2051.3-0828, and 3FGL J2110.3-1013. Their fluxes above 1 GeV are \(1.1 \times 10^{-9}\), \(6.6 \times 10^{-10}\), and \(3.9 \times 10^{-10}\) ph cm\(^{-2}\) s\(^{-1}\) (taken from the 3FGL catalogue). The 2nd and 3rd of these 3FGL sources are identified with the pulsar PSR J2051-082, and the FSRQ blazar PKS 2107-105, respectively, while the 1st source is unidentified. We checked the quality flag for this unidentified \(\gamma\)-ray source in the 3FGL catalogue and found no caution regarding the reality of this source or the magnitude of its measured properties. The brightest source in the entire ROI, 3FGL J2025.6-0736, is located at a distance of \(10^\circ\) from the ROI’s centre and has a flux of \(7.0 \times 10^{-9}\) ph cm\(^{-2}\) s\(^{-1}\) at \(E > 1\) GeV. We evaluated the normalisations of the refined IEM component and of the isotropic component in the ROI using the data. We took the spectral shapes of the \(\gamma\)-ray point sources from the 3FGL catalogue and derived the normalisations of the nine brightest sources in the ROI and of the 3FGL sources overlaid on the Aqr shell template using the data. To study the spectrum of the Aqr shell, we binned the Aqr shell’s model into bins in energy. The flux normalisation was left free in each of the energy bins for the Aqr shell component.

### 3.2 R CrA molecular cloud

The R CrA MC is one of the high-latitude MCs. It is located at significantly lower Galactic latitudes than those of the Aqr shell and therefore its analysis requires more detailed background modelling. This MC is enclosed in the square region of side \(6^\circ\) and with the centre at the Galactic coordinate of \((l, b) = (0.56^\circ, -19.63^\circ)\). To model a background at these Galactic latitudes, one needs to take the diffuse Galactic emission gradient with latitude into account and to produce a background template varying with Galactic latitude. The region enclosing the R CrA MC is projected onto the southern Fermi bubble and near the boundary of the cocoon, i.e. the region of enhanced \(\gamma\)-ray emission in the south-east side of the bubble. The \(\gamma\)-ray spectrum of the Fermi bubbles is hard with index of \(-2\) (Su et al. 2010) and is significantly harder than the \(\gamma\)-ray spectrum of the MC at energies above a few GeV. Thus, the region selected for background extraction should have the contribution of \(\gamma\) rays from the Fermi bubbles similar to that is expected in the region of the R CrA MC. The infrared loop centered at \((l, b) = (7^\circ, -20^\circ)\) with a radius of \(\sim 5 - 6^\circ\) (Könyves et al. 2007) is associated with the R CrA MC, but its \(\gamma\)-ray emission whether is much fainter than that of the R CrA MC or is projected onto the bright part of the southern Fermi bubble’s cocoon. Therefore, we derived the \(\gamma\)-ray spectrum for the R CrA MC, but not for the associated infrared loop.

To confidently model the background emission associated with the southern Fermi bubble, we took two different regions, A and B, centered at the same Galactic latitude. The region B centered at \((l, b) = (353.93^\circ, -19.63^\circ)\) is shifted compared with the region A centered at \((l, b) = (6.94^\circ, -19.63^\circ)\) along the axis of Galactic longitude. Both the regions have a square box shape with a size of \(6^\circ\). The region A is the same as that was used by Neronov et al. (2017) for background extraction and is located in the cocoon of the Fermi bubble, whereas the region B is located outside of the cocoon. Therefore, the contributions of \(\gamma\) rays from the southern Fermi bubble to these extraction regions are different. We illustrated it by showing the regions of A and

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9 the make3FGLxml.py script automatically adds 10 degrees to the ROI to account for sources that lie outside the data region.
B in Figure 2 as well as the Galactic γ-ray model count map centered at energy of 9 GeV. The γ-ray enhancement caused by the cocoon is clearly visible in the region A.

To take the diffuse Galactic γ-ray emission gradient into account, we used the background maps for the regions of A and B adopted from the standard IEM mapcube template. We scanned these maps along the Galactic longitude to compute the average value in each latitude band of 0.125° in width. We used these longitude-averaged values to refine the background IEM model in the square region enclosing the R CrA MC by replacing in each energy band the IEM emission with the computed average values. To produce the R CrA MC template, we subtracted the refined diffuse emission templates from the standard IEM template. We labelled the model including the diffuse and R CrA MC templates derived using the background extraction region, A, as Model A, and the model based on the background extraction region, B, as Model B. To study the spectrum of the R CrA MC, we used the R CrA MC template models binned in energy. To model point γ-ray sources in the analysis region, we adopted their spectral shapes from the 3FGL catalogue and left the normalisations of ten bright point γ-ray sources, the refined IEM component, and the isotropic component to vary freely. Two point γ-ray sources are overlaid on the R CrA MC template, including 3FGL J1913.5-3631 associated with a γ-ray blazar, PMN J1913-3630, and 3FGL J1902.3-3702c, which has no clear association. The “c” suffix in the latter 3FGL source shows that this 3FGL source is on top of an interstellar gas clump or that small-scale defect is in the standard IEM model of diffuse emission, while its significance in the 3FGL catalogue, 4.7σ, is less than specified minimum for a free source of 5.0σ. We also set the normalisations free for these two sources.

3.3 ρ Ophiuchi molecular cloud
The ρ Oph MC lies in the Gould Belt of the closest molecular complexes. The γ-ray flux from the ρ Oph MC exceeds the fluxes from the Aqr HI shell and the R CrA MC by factor of ∼ 8 and ∼ 5, respectively. The ρ Oph MC is located at lower Galactic latitudes of b ≈ 16° and is projected onto the northern Fermi bubble. Therefore, one needs to take both the diffuse Galactic γ-ray emission gradient and the hard spectral contribution from the Fermi bubble into account. Yang et al. (2014) explains the observed spectral hardness of the ρ Oph MC by the fact that point γ-ray sources contribute to the total γ-ray signal and therefore one needs to consider how to incorporate the point sources in the model in order to alleviate this problem. Below we list the improvements over the previous work based on the background extraction method.

1) We selected the ρ Oph MC region with a size of 6° × 5.5° centered on (l, b)=(353.3°, 16.2°). This selection is based on the Planck maps at frequencies of 28.5 and 44.1 GHz dominated by dense molecular gas (Ade et al. 2011). The selected region has a smaller surface area than that of 10° × 10° which was previously analysed by means of the extraction region method. Since the contribution of γ rays from the Fermi bubble is expected to scale with surface area, this contribution is expected to decrease by a factor of 3 in our analysis.

2) We used the first 4 years of Fermi-LAT data to perform an analysis of the ρ Oph MC. Taking into account that its γ-ray emission is much stronger than those of the other two structures discussed above, it is reasonable to select the data set described by the LAT 4 year point source catalogue (Acero et al. 2015) and also by the diffuse Galactic γ-ray emission template (Acero et al. 2016). It allows us to adopt the normalisation of the sources from the catalogue.

3) To model the diffuse Galactic γ-ray gradient, we used the background extraction region 2 shown as in Fig. 3. The region 2 is shifted by 30° compared with the region 1, enclosing the ρ Oph MC, along the axis of Galactic longitude. We scanned the region 2 along the Galactic longitude to compute the average value in each latitude band. We used the longitude-averaged values to refine the background IEM model by replacing in each energy band the IEM emission in
the $6^\circ \times 5.5^\circ$ rectangular region with the computed average values. We used the refined background model, in turn, to produce the $\rho$ Oph MC template. We called this background extraction model Model O1.

4) To account for $\gamma$ rays produced in the Fermi bubble which contaminate the $\gamma$-ray signal from the $\rho$ Oph MC, we introduced two other high-latitude background extraction regions, namely the regions 3 and 4 (see Fig. 3). We subtracted the $\gamma$-ray signal of the region 3 from that of the region 4 to compute the average contribution of the northern Fermi bubble to $\gamma$-ray emission. We added the northern Fermi bubble’s contribution to the refined background IEM model obtained from the region 2 to further refine the background model. We also produced the $\rho$ Oph MC template on the basis of this background model. The contribution from the northern Fermi bubble to this $\rho$ Oph MC template is therefore minimised. We called this background extraction model Model O2.

4 RESULTS

In this Section, we present the results of our spectral analyses of the Aqr shell, the R CrA MC, and the $\rho$ Oph MC based on the models described above.

To compute the statistical significance of the presence of an extended $\gamma$-ray source at the location of each of these ISM structures, we used the Test Statistic (TS) defined as

$$\text{TS} = 2 \ln \left( \frac{L_{\text{max},0}}{L_{\text{max},1}} \right),$$

where $L_{\text{max},0}$ is the maximum likelihood value for a model without an additional source (the ‘null hypothesis’) and $L_{\text{max},1}$ is the maximum likelihood value for a model with the additional source at a specified location. We chose the energy bins centered at 240 MeV, 450 MeV, 890 MeV, 1.55 GeV, 2.85 GeV, and 6.5 GeV to yield confident detections in all bins.

We used the naima package (Zabalza 2013) to search for suitable estimators characterising the shapes of CR spectra below or above the energy break using the derived $\gamma$-ray fluxes. Naima is an open source Python package which implements radiative models for computing the non-thermal emission of relativistic particle distributions, including hadronic $\gamma$-ray emission. Given that observed $\gamma$ rays were produced in $p$-$p$ interactions followed by neutral pion decay (Kafexhiu et al. 2011), we fixed the differential energy spectrum of protons at the energy break of 18 GeV, the power-law CR spectral index below the break at the value of 2.33, and allowed the power-law index above the energy break to vary in the range of (2.5, 5.0). We found that the weighted mean ratio of the fluxes computed with naima to the stacked MC’s modelled fluxes over the first three energy bins, $R_{1-3}$, only slightly (within 10%) changes with the high-energy power-law index value, while the ratio of the flux computed with naima to the stacked MC’s flux in the 6th energy bin (which is centered at 6.5 GeV) varies with high-energy power-law index by a factor of 5.

Therefore, we introduced these two estimators allowing us to characterise the low-energy and high-energy parts of CR spectra, respectively. Note that if two sources have identical proton energy spectra above the break then the values of both the low- and high-energy estimators are the same. The absolute values of estimators are proportional to the ratio of $\gamma$-ray fluxes of two sources. If two sources have different proton energy spectra above the energy break, the values of low- and high-energy estimators are different.

4.1 Aquarius HI shell

Using the introduced spectral-spatial model, we performed a binned likelihood analysis to compute the differential fluxes of the Aqr shell. We introduced a higher energy bin centered at 16.4 GeV in addition to the six energy bins. We found that the emission from the Aqr shell is detected in the first six bins with TS of 158, 245, 244, 158, 68, and 31. The square root of the TS is approximately equal to the detection significance for a given source. Thus, the $\gamma$-ray emission from the Aqr shell is detected with high confidence of $> 10 \sigma$ in each of the first four energy bins and with $5.5 \sigma$ confidence in the 6th energy bin. We found that the normalisation of the differential flux in each bin is consistent with that is expected from the model described by the Aqr shell template if the same scale factor is applied for all these energy bins. Taking this consistency into account, we fixed the flux scale factor in each energy bin to the identical value, computed the flux scale factor value by means of a likelihood method, and found that the Aqr shell is detected in $\gamma$ rays at TS=1187, i.e. with confidence of $34 \sigma$.

We computed the spectral energy distribution (SED) for the Aqr shell. The normalisation in each energy bin for the Aqr shell component was treated as a free parameter and was obtained as the result of a likelihood analysis. The computed SED is shown in Fig. 4 along with the model derived from the stacked analysis of the Gould Belt MCs. To compute the upper limit on the differential flux in the 7th energy bin, we used the upper limits python module. The computed SED agrees well with the model obtained from the stacked analysis and adopted from Neronov et al. (2017).

We also checked if the spectral slope at high energies at which most of $\gamma$-ray emission from the Aqr shell is produced by CR protons with energies above 18 GeV is compatible with that obtained from the stacked analysis of Gould Belt MCs. Since a typical energy of CR protons producing $\gamma$ rays above the minimal observed energy $E_{\gamma,\text{min}}$ is $E_{\pi,\gamma} \gtrsim 10E_{\gamma,\text{min}}$, to perform this check we used the single power-law spectrum to model the Aqr shell’s $\gamma$-ray emission above 4 GeV. The best-fitting photon power-law index at high energies found in our analysis is 2.96 $\pm$ 0.16 and is compatible with that of 2.98 $\pm$ 0.07 obtained from the stacked analysis of the Gould Belt MCs.

To quantify the difference between the spectrum of CRs producing the $\gamma$-ray signal from the Aqr shell described above and that derived from $\gamma$-ray observations of the R CrA MC by Neronov et al. (2017), we computed both the weighted mean ratios, $R_{1-3}$, for the Aqr shell fluxes to the stacked MC’s modelled fluxes, $R_{\text{Aqr}/\text{Stack},1-3}$; and for the Aqr shell fluxes to the R CrA MC modelled fluxes, $R_{\text{Aqr}/\text{RCrA},1-3}$. The computed ratios are $R_{\text{Aqr}/\text{Stack},1-3} = (7.98 \pm 0.34) \times 10^{-3}$ and $R_{\text{Aqr}/\text{RCrA},1-3} = 0.639 \pm 0.027$, respectively. These magnitudes also reflect the fact that the $\gamma$-ray flux of the Aqr shell is lower than that of the R CrA.

\[10\] In this case, 87% of $\gamma$ rays with energies above 4 GeV are produced by CR protons with energies above the break as computed with the naima python package.
MC, while the stacked analysis of the Gould Belt MCs provides us with significantly higher statistics. We compared the $R_{\text{Aqr}/\text{Stack, }1-3}$ ratio with the ratios of the Aqr shell fluxes to the stacked MC's modelled fluxes, $(8.50 \pm 1.14) \times 10^{-3}$ and $(8.99 \pm 1.77) \times 10^{-3}$, obtained from the higher energy bins centered at 2.85 GeV and 6.5 GeV, respectively. On the basis of the estimators, we found that the CR spectrum producing $\gamma$ rays from the Aqr shell is compatible within errorbars with the spectrum of CR populations responsible for most of $\gamma$ rays from the Gould Belt MCs. We also compared the $R_{\text{Aqr}/\text{RCrA, }1-3}$ ratio with the ratios of the Aqr shell to the modelled R CrA MC fluxes, $0.74 \pm 0.10$ and $1.01 \pm 0.20$, obtained from the higher energy bins centered at 2.85 GeV and 6.5 GeV, respectively. We found that the former value is compatible with that obtained at lower energies, whereas the latter computed ratio exceeds that obtained at lower energies with about 2σ confidence.

We concluded that no variation in the spectrum of CRs above energy of 18 GeV compared with the stacked spectrum of the MCs was derived from the analysis of the Aqr shell. Since the Aqr shell is located near the $\rho$ Oph and R CrA MCs and is projected onto the region of a low background, it provides us with a probe of the CR spectrum in the region containing these three objects which is less affected by background uncertainties.

### 4.2 R CrA molecular cloud

As mentioned above, the previously derived CR spectrum of the R CrA MC deviates from the stacked MC’s spectrum and this fact was interpreted as marginal evidence for a departure of the CR spectrum local to this MC from the CR background spectrum. Two possible problems in derivation of the CR spectrum of this MC are that (a) its $\gamma$-ray flux is faint in comparison with the Gould Belt MCs’ fluxes and that (b) its position is projected onto the southern Fermi bubble. Both these problems can be alleviated by using a more advanced background model (for details on background models, see Sect. 3.2). We consider two models of background $\gamma$-ray emission: models A and B. Both these models take the gradient of the diffuse Galactic $\gamma$-ray emission into account, but contain different contributions from the southern Fermi bubble to the R CrA MC $\gamma$-ray signal.

We performed a binned likelihood analysis to obtain statistical significances and differential fluxes of the R CrA MC for the model A. The evaluated TS values are 507, 1027, 862, 462, 248, and 91 in the six energy bins. We found that the shape of the derived $\gamma$-ray SED is compatible with that of the $\gamma$-ray SED previously obtained from the stacked analysis of the high latitude Gould Belt MCs. It suggests that faintness of the R CrA MC in $\gamma$ rays was an obstacle in derivation of its spectrum and supports that production of $\gamma$-ray emission from the R CrA MC involves hadrons from the CR background. The derived SED is shown in Fig. 5.

We also checked and found that the unassociated source of 3FGL J1902.3-3702c which is on top of the R CrA MC is detected with only $4.2\sigma$ in the analysis based on the model A (and with $5.5\sigma$ in the analysis based on the model B) and only slightly affects the results of the spectral analysis. Compatibility of the results obtained from the Fermi-LAT observations of the Aqr shell and the R CrA MC (derived in the framework of the model A for the R CrA MC) shows that the hypothesis of uniformity of the CR spectral shapes does not contradict these results.

#### 4.2.1 A uniform CR spectrum in the local ISM as a tool for foreground $\gamma$-ray subtraction

The Galaxy is transparent to $\gamma$ rays with the exception of rare events of solar occultations of several $\gamma$-ray sources (Barbiellini et al. 2014). At high Galactic latitudes, $\gamma$ rays produced in the local ISM involving the hadronic interactions of CRs are the most dominant foreground component. In an investigation which requires disentanglement of a signal of astrophysical origin from a foreground diffuse $\gamma$-ray

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**Figure 4.** The SED of the Aquarius shell as compared with the spectral model describing the stacked spectrum of the Gould Belt MCs. The latter model is scaled down by a factor of 120.

**Figure 5.** The SED of the R CrA MC derived for the background model A as compared with the spectral model describing the stacked spectrum of the Gould Belt MCs. The latter model is scaled down by a factor of 80.
emitting structure (e.g., for a search for γ-ray emission from the Virgo cluster which is projected onto the Galactic cir-
rus, see Prokhorov & de Jong 2014; Bianchi et al. 2017), one
would be aided greatly if the CR spectrum was spatially uni-
mous, see Prokhorov & de Jong 2014; Bianchi et al. 2017), one
would be aided greatly if the CR spectrum was spatially uni-

We showed the γ-ray spectrum of the R CrA MC as
derived from the model A in Fig. 6. This spectrum strongly
deviates from the stacked MC’s modelled spectrum and is
harder than that obtained by means of the model A. The
hardness of the spectrum of the R CrA MC obtained from
the model B is most likely explained by the significant con-
tribution of γ rays from the southern Fermi bubble to the
R CrA template produced for the model B. It also demonstra-
estrates systematic uncertainties caused by the selection of
a background extraction region for the R CrA MC an-
alysis. Despite these complexities in the analysis, the fact that
the γ-ray spectrum derived from the model A is compatible
with that of the stacked MC’s modelled spectrum likely im-
plies both that (a) the CR spectrum of the R CrA MC is
dominated by the CR background and that (b) the southern
Fermi bubble’s cocoon contributes to the total signal from
the square region of side 6° enclosing this MC. As note by
Neronov et al. (2017), the exclusion of the R CrA MC from
their sample significantly reduces the amount of evidence for
a spatial variation of the CR spectra in the local ISM.
Since we showed that the derived spectrum of the R CrA
MC depends on assumptions about a γ-ray background, the
exclusion of this MC from their sample increases reliability
of the conclusion.

4.3 ρ Ophiuchi MC
We used two models of background γ-ray emission, models
O1 and O2, to compute the SED of the ρ Oph MC using a
binned likelihood analysis. Both the models O1 and O2
take the gradient of the diffuse Galactic γ-ray emission into
account. However the latter model (i.e. O2) also minimises
the contribution from the northern Fermi bubble to the γ-
ray signal from the ρ Oph MC. In addition to the low energy
bins, we introduced the high energy bins centered at ener-
gies of 5.7, 10.4, and 19.3 GeV instead of the single bin
centered at 6.5 GeV. We treated the normalisation in each
energy bin for the ρ Oph MC component as a free parame-
ter. We showed the computed SED in Fig. 7 for the models
O1 and O2. We also showed the curves taken from the previ-
ous stacking analysis of the MCs and rescaled them for ease
of comparison. The SED computed for the model O1 seems
to be harder at high energies than that which computed for
the model O2. To quantify the spectral hardness, we used
the estimators introduced above.

We computed the weighted mean ratios, $R_{\rho Oph/Stack,1-3}$, for the
ρ Oph MC fluxes to the stacked MC’s modelled fluxes, $R_{\rho Oph/Stac-
k1-3}$, in the models O1 and O2. The computed ratios are $R_{\rho OphMO1/Stack,1-3} = 0.68 \pm 0.001$ and
$R_{\rho OphMO2/Stack,1-3} = 0.064 \pm 0.001$, respectively. We found
that the $R_{\rho OphMO1/Stack,1-3}$ ratio obtained from the model
O1 is in tension with the ratios of $R_{\rho OphMO1/Stack,7} = 0.088 \pm 0.010$ and
$R_{\rho OphMO1/Stack,8} = 0.120 \pm 0.019$ obtained from
the higher energy bins centered at 10.4 and 19.2 GeV in the
framework of the same model. The tension increases to
2.7σ statistical level in the energy bin centered at 19.2 GeV.
The advanced model, O2, reduces the deviation from the
stacked MC’s spectrum and the $R_{\rho OphMO2/Stack,1-3}$ is com-
patible with the ratios of $R_{\rho OphMO2/Stack,7} = 0.071 \pm 0.010$
and $R_{\rho OphMO2/Stack,8} = 0.098 \pm 0.018$ obtained from
the higher energy bins on the 2 σ statistical level.

We concluded that the model O2 which minimises the
contribution from the northern Fermi bubble to the ρ Oph
MC γ-ray signal allows us to describe observations of the
ρ Oph MC collected by Fermi-LAT during the first 4 years
of the mission in the framework of the standard CR back-
ground scenario for γ-ray production. It is worth to note
that only the ρ Oph and R CrA MCs from the sample of
MCs from Neronov et al. (2017) both are projected onto the Fermi bubbles and show spectral deviations compared with the stacked spectrum of the MCs, while the other MCs from that sample are projected away from the Fermi bubbles and do not show any spectral deviations. We suggest that the most probable explanation of the spectral deviations related to the ρ Oph and R CrA MCs is a difficulty in background modelling. Given that the Aqr shell is located near the ρ Oph and R CrA MCs and is projected away the Fermi bubbles, the compatibility of the γ-ray spectrum of the Aqr shell and the stacked spectrum of the Gould Belt MCs provides evidence to support the hypothesis of uniformity of the shapes of CR spectra in the local Galaxy environment.

5 DISCUSSION AND OUTLOOK

If one SN event injects \( E_{\text{inj}} \sim 10^{50} \) erg in CRs, it might produce a significant increase in the overall CR flux above 18 GeV in the ISM gas structure located at \( R = 150 \) pc from the SN site. To show this, let us assume that the intensity of cosmic rays to be the one measured near the Earth, \( J(E) = 1.8 \times (E/\text{GeV})^{-2.7} \) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) GeV\(^{-1}\) (Gaisser 1990) and calculate the integral of the intensity above \( E_{\text{brk}} = 18 \) GeV. One finds that the CR energy density above \( E_{\text{brk}} \), \( \epsilon = (4\pi/\epsilon) \times \int_{E_{\text{brk}}}^{\infty} J(E) dE \), is \( \epsilon = 2.3 \times 10^{-13} \) erg cm\(^{-3}\). One SN event is sufficient to fill the volume of a sphere of radius, \( R = (3E_{\text{inj}}/(4\pi\epsilon))^{1/3} \), which is about 150 pc, with CR protons of energy density similar to the locally measured one. These CR spectral distortions can be possibly detectable in γ rays with Fermi-LAT. This calculated distance determines the radius of influence of one SN event. It is expected that the ISM structures at a mutual distance of less than the radius of influence have a similar imprint on their high-energy CR spectra left by one SN event. Therefore, indirect CR measurements by means of γ-ray observations in such ISM structures, including those we analysed in the paper, are of interest to search for a signature of discrete source CR injection.

In the case of anisotropic propagation of CR protons, the radius of influence can depend on the direction because CRs spread faster along the Galactic magnetic field lines. Owing to this effect, the CR spectra in the nearby ISM gas structures could potentially be different from each other. Thus, the direction of magnetic field lines in the space between three nearby ISM structures would be measured if their CR spectra were different. This is because any three non-collinear points in space determine a unique plane. A normal vector to the plane determines the direction perpendicular to a line between any two of given three points.

Radio band and γ-ray observations of nearby ISM gas structures are a unique tool to look for the effect of discreteness of CR injection events in space and time. Accumulation of γ rays and mapping of local ISM structures with radio observations will open the possibility for a further analysis including disentanglement of the contributions from the interacting HI shell and MC in each of these analysed structures as well as in other local regions of the Galaxy and possibly a determination of the direction of a magnetic field in the region of three ISM structures localised within the radius of influence.

6 CONCLUSIONS

The p-p collisions between CR hadrons and the ISM gas followed by neutral pion decay result in production of γ rays measured with telescopes, e.g. Fermi-LAT. The ISM gas structures containing atomic and/or molecular hydrogen provide a target for such collisions. The spatial distribution of atoms or molecules of hydrogen is available from observations of HI 21-cm or CO 2.6-mm lines with radio telescopes, respectively. Measurements of γ-ray spectral shapes produced in the ISM gas accumulations can make a study of injection sites of CR protons possible.

The first 3 years of Fermi-LAT γ-ray observations of high latitude Gould Belt MCs led to the conclusion that the spectra of individual MCs are consistent with each other (Neronov et al. 2012), while 8 years of Fermi-LAT observations of the same MCs led to the indication of variations in the slope of the CR spectrum above about 18 GeV (Neronov et al. 2017). A transition from the steady-state continuous injection to the regime of discrete source injection was proposed as an explanation for the slope variation in CR spectra of these MCs. They found that the softest and hardest spectral slopes at high energies are in the R CrA MC and in the ρ Oph MC, respectively. Comparing the mutual distances between the MCs from their sample, we found that the distance between the R CrA and ρ Oph MCs is one of the shortest (after that between the Orion A and Orion B clouds) and is only 100 pc. Given the close mutual distance of these two clouds with distinct CR spectra, we searched for another ISM structure located in the vicinity of these clouds to test similarity of CR spectra in this region. We found that the HI shell in Aquarius separated from the R CrA cloud by 110 pc provides us with an alternative probe of the CR spectrum in the region surrounding the R CrA and ρ Oph MCs and the Aqr shell. We derived the SED of γ-ray emission from the Aquarius shell and tested the shape of the CR proton spectrum. The tests showed that the CR slope obtained in the Aqr shell is compatible with that obtained from the stacked spectrum of Gould Belt MCs. We also re-analysed the γ-ray emission from the R CrA and ρ Oph MCs. We found that a more detailed background model including both the Galactic γ-ray emission gradient and the γ-ray emission from the Fermi bubbles allow us to reconcile the derived γ-ray spectrum of these two nearby MCs with that obtained from the stacked analysis of MCs. Taking into account that only these two MCs from the sample taken from Neronov et al. (2017) are projected onto the Fermi bubbles, the most probable explanation of the previously claimed spectral deviations in these two MCs is a difficulty in background modelling. All this provides evidence to support the hypothesis of uniformity of the CR spectral shapes in the local Galaxy environment.

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