Supernova Origin of Cosmic Rays from a γ-Ray Signal in the Constellation III Region of the Large Magellanic Cloud

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Cosmic rays could be produced via shock acceleration powered by supernovae. The supernova hypothesis implies that each supernova injects, on average, some 10^{50} erg in cosmic rays, while the shock acceleration model predicts a power law cosmic ray spectrum with the slope close to 2. Verification of these predictions requires measurement of the spectrum and power of cosmic ray injection from supernova population(s). Here, we obtain such measurements based on γ-ray observation of the Constellation III region of the Large Magellanic Cloud. We show that γ-ray emission from this young star formation region originates from cosmic rays injected by approximately two thousand supernovae, rather than by a massive star wind powered by a superbubble predating supernova activity. Cosmic ray injection power is found to be $(1.1^{+0.5}_{-0.2}) \times 10^{50}$ erg/supernova (for the estimated interstellar medium density 0.3 cm^{-3}). The spectrum is a power law with slope $2.09^{+0.06}_{-0.07}$. This agrees with the model of particle acceleration at supernova shocks and provides a direct proof of the supernova origin of cosmic rays.

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The bulk of the flux of cosmic rays reaching Earth is believed to be generated by a shock acceleration process [1–3] operating in supernova powered sources [4–6] and/or superbubbles of star formation [7]. However, direct verification of either the supernova or the superbubble scenario is difficult because information on sources is erased during propagation of cosmic rays through the interstellar medium toward Earth [8].

It is also difficult to derive the spectrum and power of cosmic ray injection from the γ-ray signal of astronomical sources like supernova remnants because of uncertainties of individual source parameters (e.g., distance, density of the ambient interstellar medium and/or of the preexisting stellar wind bubble structure) and distortion of the spectrum by the effect of escape from the source [9,10]. Enhanced γ-ray emission from interactions of hadronic cosmic rays is often observed at locations of molecular clouds located near or interacting with supernova remnants. In this case, the γ-ray flux depends on the uncertain density of the cloud and on the uncertain details of propagation of cosmic rays toward the cloud. Another source of uncertainty is in the separation between the γ rays produced in interactions of high-energy protons via production and decays of pions from and those produced by electrons through the inverse Compton and/or bremsstrahlung.

Cosmic rays injected into an interstellar medium retain their injection spectrum as long as they form a finite size expanding cocoon around the source. Observations of γ-ray flux from cosmic ray interactions with an interstellar medium inside such a cocoon potentially provide a possibility of calorimetric measurement of the spectrum and power of cosmic ray injection from the source [11,12].

However, interpretation of γ-ray data on such cosmic ray cocoons in the Milky Way (like that in the Cygnus region [13]), is complicated because the γ-ray signal is superimposed onto background diffuse γ-ray emission from the Milky Way disk [14]. Projection effects also superimpose a stellar population of different ages and at different distances [15] so that it is difficult to separate the γ-ray flux component generated by youngest cosmic ray sources from that of the older ones. For example, in the particular case of the Cygnus cosmic ray cocoon, the cosmic rays might originate either from a young Cyg OB2 association, which has not yet produced supernovae, or by one or many supernovae (like, e.g., γ Cygni), depending on the (uncertain) distance to the supernova(e).

Clear discrimination between the cosmic ray injection by acceleration processes operating in stellar-wind powered superbubbles and by supernovae would be possible if young star forming regions would be observed as an isolated source on the sky, not superimposed onto other potential sources. Measurement of the spectra of γ-ray emission from such isolated regions might even provide a timing of the moment of the onset of cosmic ray injection with several Myr precision. This is possible because the spectrum of cosmic rays residing in the region is modified by propagation effects only after some time delay, estimated as the time needed for cosmic rays to diffuse out of the production region.

The projection problem is removed and young star forming regions could be observed as isolated sources in the Large Magellanic Cloud (LMC), which is the nearest galaxy with on-going star formation and with the disk observed almost face-on [16,17]. Contrary to the Milky Way, absence of projection effects allows us to better control the details of the star formation history at the sites of on-going star formation in the LMC [18,19].

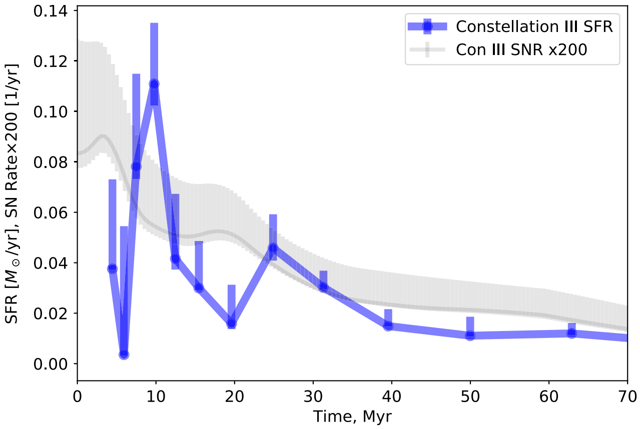

FIG. 1. History of the SFR of the CON III region from Ref. [18]. Grey shaded band shows the supernova rate time evolution derived from the SFR. Band width indicates the uncertainty of the supernova rate estimate.

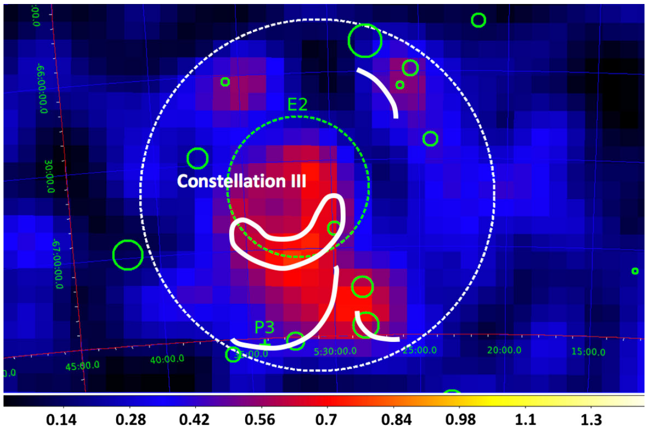

FIG. 2. LAT count map of LMC in the energy band $E > 10$ GeV smoothed with 0.3 degree Gaussian. Small green circles show positions of known supernova remnants [24]. White dashed circle of radius 1° outlines the extent of the CON III region. White arclike curves show positions of CON III star forming complexes from Ref. [18]. Green dashed circle shows "$E2$" source [17].

In what follows, we use γ-ray data of the Fermi Large Area Telescope (LAT) [20] to obtain a calorimetric measurement of the spectrum and overall energy injected in cosmic rays by a population of supernovae which have exploded during the last several million years in one of the young star forming regions in the LMC, the Constellation III (CON III) region. We show that this measurement provides a full test of the supernova scenario of the origin of cosmic rays first proposed in 1934 by Baade and Zwicky [4].

CON III is one of the youngest star forming regions in LMC. Its star formation rate (SFR) history [18,19] is shown in Fig. 1. References [18,19] have derived SFR based on analysis of color-magnitude diagrams of stellar complexes in the CON III region. The peak of the SFR which occurred $\mathcal{T}_{\rm SFR} \simeq 10$ Myr ago leads to an increase of supernova rate with a time delay 5–10 Myr [21,22] at $\mathcal{T}_{\rm SN} \simeq 5$ Myr. Figure 1 shows this increase by the grey curve calculated using the method of Ref. [22], via convolution of the SFR history with a kernel function describing evolution of supernova rate following an instantaneous star burst. The CON III region is spatially coincident with the hard spectrum "$E2$" γ-ray source reported in Ref. [17]. The γ-ray emission is naturally explained by interactions of cosmic rays with the interstellar medium. Hardness of the source spectrum indicates that the cosmic rays are still contained in a finite size cocoon, like that in the Cygnus region [11–13].

Identification of the γ-ray source with CON III allows us to refine the analysis and draw important conclusions from the γ-ray measurements. For our analysis we have used the data of the Fermi/LAT telescope collected between August 4, 2008 and June 1, 2017. The data were processed in the standard way using FERMI SCIENCE TOOLS version v10r0p5 [23]. γ-ray events belonging to the SOURCE class were selected.

Figure 2 shows the γ-ray count map in the energy range $E > 10$ GeV. The white circle of the radius 1° centered at RA = 82.7°, DEC = −66.7° shows the extent of the CON III region for which the star formation history was derived in Refs. [18,19]. The γ-ray emission does not exhibit an excess at the positions of known supernova remnants listed in Ref. [24]. Stellar complexes in CON III include several arclike structures [18] also shown in Fig. 2. The morphology of the diffuse γ-ray emission does not repeat that of the stellar arcs. It extends around the arcs. A consistent interpretation of such morphology is in its origin from interactions of cosmic rays spreading into the interstellar medium.

The source spectrum shown in Fig. 3 was calculated using the unbinned likelihood analysis. The sky model fitted to the data included a set of point sources from the four-year Fermi LAT catalog [25] as well as point and

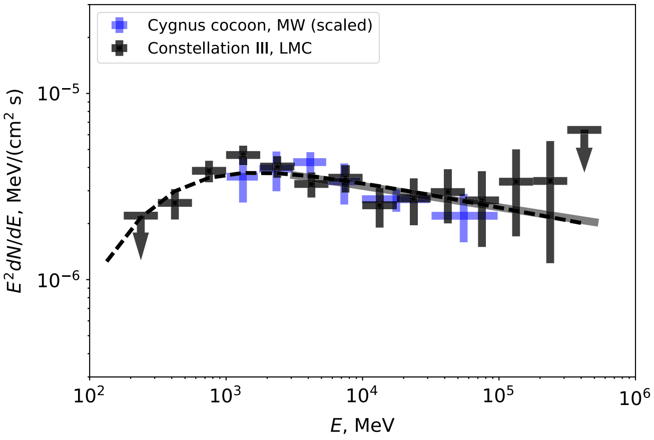

FIG. 3. γ-ray spectrum of the CON III region (black data points). Blue semitransparent data points show rescaled spectrum of Cygnus cocoon [13]. Grey solid line shows the best fit power law spectrum. Dashed curve shows the best fit pion decay spectrum.

extended sources in the LMC found in Ref. [17], except for the LMC disk and the source $E2$ which is situated at the position of CON III. For these two sources, we have chosen the spatial model which is adapted to the analysis of Refs. [18,19]. This model takes into account that the LMC disk is observed almost face-on [26]. A kiloparsec-wide region of the disk occupied by CON III presumably extends over the entire disk thickness. This suggests spatial models of the two extended sources, large scale LMC disk and CON III region arranged like a puzzle game. The CON III region circle fits into a matching hole in the larger disk of the LMC. The CON III disk has a 1° radius and is centered at $\mathrm{RA} = 82.7°$, $\mathrm{DEC} = -66.7°$, the center of the CON III region defined in Ref. [18]. The LMC disk has a 4° radius and is centered at the position of the Fermi LMC disk source extending over the size of the HI disk of the LMC [27]. In the absence of *a priori* knowledge of the surface brightness distribution of the two extended sources, we have chosen a simple flat radial brightness profile for both the CON III and the LMC disks.

A point source $P3$ reported in Ref. [17] is situated at the border of the CON III region (see Fig. 2) within one of the stellar arcs. It is not clear whether this soft spectrum point source is a part of the diffuse emission or if it is, indeed, an isolated bright source (e.g., a pulsar wind nebula). We include this source as a point source in the likelihood analysis.

The shape of the spectrum of the CON III source agrees with the previous measurement of the $E2$ source spectrum [17], but the measurement extends to higher energies due to a longer exposure and larger signal collection region. In the energy range above 2 GeV, the spectrum is well fit by a power law $dN/dE = A(E/1\ \mathrm{GeV})^{-\Gamma}$ with the slope $\Gamma = 2.11 \pm 0.12$ and normalization $A = 4.1^{+2.3}_{-1.1} \times 10^{-12}\ (\mathrm{MeV\,cm^2\,s})^{-1}$. The χ^2 of the fit is 2.4 for 7 degrees of freedom. The underlying model is that of γ-ray emission from neutral pion decays produced by interactions of cosmic ray distribution which is a power law in momentum p: $dN_{\mathrm{CR}}/dp \propto p^{-\Gamma_{\mathrm{CR}}}$. Using the parametrization of pion decay spectrum from proton-proton interaction cross sections from Ref. [28], one finds $\Gamma_p = 2.09^{+0.06}_{-0.07}$ from the γ-ray data fit in the energy range $200\ \mathrm{MeV} < E < 400\ \mathrm{GeV}$. The χ^2 of the fit is 10.5 for 11 degrees of freedom.

The spectrum of CON III is consistent with that of the Cygnus region cosmic ray cocoon in the Milky Way [13] also shown in Fig. 3. Hardness of the Cygnus cocoon spectrum has been interpreted as possibly being due to the presence of "fresh" cosmic rays injected from Cygnus OB2 association [13] which is still too young to produce supernovae. This implies that cosmic ray production could start before the onset of supernova activity in star forming regions. However, the superposition of the star forming complexes of different ages in the Cygnus region [15] precludes the possibility of firm association of cosmic ray population with parent stellar population.

The projection problem is absent in the case of the CON III region. Cosmic rays residing in the region are produced following the most recent star formation episode which occurred 10–15 Myr ago. Timing of the moment of the onset of cosmic ray production could be established from the spectral properties of the cosmic ray population. The spectrum of cosmic rays softens with time due to the energy-dependent diffusion of particles away from their production sites. Measurements in the Milky Way galaxy suggest that the diffusion coefficient scales with energy as $D(E) \simeq 3 \times 10^{28} (E/10\ \mathrm{GeV})^{\delta}$ [6] with $\delta \simeq 0.33$ [29] so that the cosmic ray spectrum softens from the injection spectrum $dN/dE \propto E^{-\Gamma_0}$ to $dN/dE \propto E^{-(\Gamma_0+\delta)}$ on the time scale $t \sim R^2/D(E) \simeq 10(R/1\ \mathrm{kpc})^2 (E/10\ \mathrm{GeV})^{-\delta}$ Myr of escape from the production region of the size R (about 1 kpc in the CON III region, see Fig. 2).

If the mechanical energy of massive star winds would provide a sizeable power for cosmic ray production in the CON III region, injection of cosmic rays would have started 10–15 Myr ago and the spectrum of cosmic rays would be softened to $dN/dE \propto E^{-(\Gamma_0+\delta)}$ by now. Its slope would match the average slope of the cosmic ray spectrum of the Milky Way disk and of the LMC, $\bar{\Gamma} \simeq 2.4, \ldots, 2.5$ [30–32]. To the contrary, the supernova rate in the CON III region has reached a peak at the present epoch, see Fig. 1. Cosmic rays injected by supernovae still retain their injection spectrum. The slope of the cosmic ray spectrum in the region, $\Gamma_{\mathrm{CR}} \simeq 2.1$ agrees with the $\bar{\Gamma} - \delta = 2.1, \ldots, 2.2$ injection spectrum slope inferred from the average Milky Way and LMC spectrum modeling [30–32]. We conclude that the CON III data do not agree with the model of injection of cosmic rays before the onset of supernova activity and agree with the model of supernova origin of the cosmic rays.

The supernova rate in the region is at the level of $\mathcal{R}_{\mathrm{SN}} \simeq 1/(2000\ \mathrm{yr})$ since $\mathcal{T}_{\mathrm{SN}} \sim 5$ Myr (Fig. 1). The cosmic ray energy $\mathcal{E}_{\mathrm{CR}}$ injected by each supernova is gradually transferred to γ rays on the time scale of proton-proton interactions energy loss $t_{pp} = (c\kappa\sigma_{pp}n)^{-1} \simeq 3 \times 10^8 [n/0.3\ \mathrm{cm^{-3}}]^{-1}$ yr, where $\sigma_{pp} \simeq 3 \times 10^{-26}\ \mathrm{cm}^2$, $\kappa \simeq 0.4$ are the cross section and inelasticity of the proton-nuclei collisions [11], c is the speed of light and n is the density of the interstellar medium. An estimate $n \simeq 0.3(H/500\ \mathrm{pc})^{-1}\ \mathrm{cm^{-3}}$ could be derived from the measured column density atomic hydrogen $N_H \simeq 10^{21}\ \mathrm{cm^{-2}}$ at the position of CON III [27], assuming the thickness of the LMC disk to be $H \sim 500$ pc [26]. The pion decay γ-ray luminosity produced by such energy release is $L_\gamma \simeq \mathcal{E}_{\mathrm{CR}}/(3t_{pp})$ where the factor $1/3$ takes into account the fact that only one third energy is deposited into neutral pions which decay into γ rays. Cumulative flux of pion decay emission generated by cosmic rays ejected from some $\mathcal{T}_{\mathrm{SN}}\mathcal{R}_{\mathrm{SN}} \simeq (2.2^{+1.0}_{-0.2}) \times 10^3$ supernovae accumulated in the CON III region from the latest star formation episode is then $\mathcal{F}_\gamma = \mathcal{T}_{\rm SN}\mathcal{R}_{\rm SN}L_\gamma/(4\pi d_{\rm LMC}^2)$, where $d_{\rm LMC} \simeq 50$ kpc is the distance to the LMC [26]. The energy output per supernova is

$$\mathcal{E}_{\rm SN} = \frac{12\pi d_{\rm LMC}^2 \mathcal{F}_\gamma}{\mathcal{T}_{\rm SN}\mathcal{R}_{\rm SN} c\kappa\sigma_{pp} n}. \quad (1)$$

Integrating the γ-ray flux over the energy range of Fermi/LAT data, one finds $\mathcal{F}_\gamma = 3.5 \pm 0.4 \times 10^{-11}$ erg/(cm^2 s) which results in the estimate

$$\mathcal{E}_{\rm SN} \simeq (1.1^{+0.5}_{-0.2}) \times 10^{50} \left(\frac{n}{0.3\ {\rm cm}^{-3}}\right)^{-1} {\rm erg}, \quad (2)$$

where only uncertainties of the supernova statistics and of the γ-ray flux measurement are taken into account.

The γ-ray spectrum has a “bump” in the GeV range characteristic to the neutral pion decay [9,10]. This shows that γ-ray emission is dominated by the pion decay component, and that electron contribution to the γ-ray emission is small. This is consistent with the overall pattern of diffuse γ-ray emission from the Milky Way disk where electrons contribute 10%–20% of the diffuse GeV γ-ray flux [14] and of LMC outside the 30 Dor region [33].

A limitation of the analysis presented above is that it is based on observations of signals from a single star forming region. For each single source measurement and model uncertainties (e.g., of the star formation history and of the model of diffusion of cosmic rays through the interstellar medium) might conspire in the estimate of the overall cosmic ray injection power and, in conclusion, about the dominance of the supernova contribution to the cosmic ray flux. It is important to observe other similar sources (isolated young star forming regions with controlled star formation history) to scrutinize the result.

Another limitation is that it refers to cosmic rays with energies up to TeV, while the Galactic cosmic ray spectrum presumably extends up to the PeV range. It is possible that the dominant source population changes with the increase of cosmic ray energy. Extension of the analysis reported above into the 1–100 TeV range (which will be possible with cherenkov telescope array) is important in this respect.

To summarize, timing of the moments of the onset of supernova activity and of cosmic ray production in the CON III region has enabled identification of supernovae (rather than a massive star wind driven superbubble) origin of cosmic rays. Calorimetric measurement of the cosmic ray content based on the γ-ray signal combined with a measurement of the size of supernova population in CON III has resulted in an estimate of $\sim 10^{50}$ (erg/supernova) cosmic ray injection energy, as expected in the supernova scenario of cosmic ray origin. γ-ray data also provide a measurement of the cosmic ray injection spectrum which is a power law with the slope $\Gamma_{\rm CR} \simeq 2.1$, as expected in the shock acceleration model. These two measurements are consistent with the basic predictions of the 80-year-old conjecture of supernova origin of cosmic rays [4,5] and of the shock acceleration model for cosmic ray production [1–3] in particular regions of the LMC galaxy.

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