Geminga SNR: Possible Candidate of the Local Cosmic-Ray Factory

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Abstract

The precise measurements of energy spectra and anisotropy could help us uncover the local cosmic-ray accelerators. Our recent works have shown that spectral hardening above 200 GeV in the energy spectra and transition of large-scale anisotropy at ∼100 TeV are of local source origin. Less than 100 TeV, both spectral hardening and anisotropy explicitly indicate the dominant contribution from nearby sources. In this work, we further investigate the parameter space of sources allowed by the observational energy spectra and anisotropy amplitude. To obtain the best-fit source parameters, a numerical package to compute the parameter posterior distributions based on Bayesian inference, which is applied to perform an elaborate scan of parameter space. We find that by combining the energy spectra and anisotropy data, the permissible range of location and age of the local source is considerably reduced. When comparing with the current local supernova remnant (SNR) catalog, only Geminga SNR could be the proper candidate of the local cosmic-ray source.

Unified Astronomy Thesaurus concepts: Galactic cosmic rays (567)

1. Introduction

As far back as the 1930s, supernova remnants (SNRs) have been proposed as the sources of Galactic cosmic rays (CRs) (Osterbrock 1996). However, due to the diffusive character of CR propagation in the Galaxy, it is hard to locate their acceleration sites by tracing back the arrival directions of CRs, with the possible exception of ultra-high energy CRs. What has been achieved in identifying CR sources up to now are mostly indirect, namely, through the multiwavelength observations of electromagnetic emission from SNRs, see Cardillo et al. (2014), Funk (2015), Dubner & Giacani (2015), and Hewitt & Lemoine-Goumard (2015). On the other hand, Mertsch (2011) and Bernard et al. (2012) have shown that CRs from the nearby young sources, within 1–2 kpc from the solar system, could give rise to large fluctuations of observed energy spectrum. As a result, the unexpected observational features probably relate to these local sources. Meanwhile, within this short distance, the CR sources are finite and discrete; thus, they are more easily found by multiwavelength observations. Therefore, it is promising to directly unveil the local CR accelerators by relating the observational features of CRs to the local source.

In fact, the single source model, in which one or a few nearby young sources make a non-negligible contribution to the spectrum, was initially put forward for the purpose of the sharpness of the knee region at ∼3–4 PeV in the all-particle spectrum (Erlykin & Wolfendale 1997). Later, with increasingly advanced instruments being put into use, the measurement accuracy has been promoted greatly and more novel features in the energy spectrum are uncovered. The single source model and its extension—the local source model, are widely used to interpret various observational phenomena. Usually, the propagation of CRs from the nearby source is time dependent, and the propagated spectrum resembles a bump-like structure, which is deemed as an excess of CR flux. Thus, the local pulsar or SNR could be the naturally origin of the positron excess above 10 GeV (Abdo et al. 2009; Adriani et al. 2009; Accardo et al. 2014; Aguilar et al. 2014) and spectral hardening of nuclei above 200 GeV (Panov et al. 2007, 2009; Adriani et al. 2011; Yoon et al. 2011; Aguilar et al. 2015b, 2015a; Adriani et al. 2019) and ensuing softening at ∼20 TeV (Atkin et al. 2017; Yoon et al. 2017; An et al. 2019). Meanwhile, it could also account for the break in all-electron spectrum at teraelectronvolt energies (Aharonian et al. 2009; Borla Tridon 2011; Staszak & VERITAS Collaboration 2015; DAMPE Collaboration et al. 2017). Furthermore, in the traditional propagation model, the predicted anisotropy amplitude from background SNRs far exceeds the measurements, which is only about 10−4−10−3 (Blasi & Amato 2012). The local source could effectively lower the amplitude, if it lies close to the direction of anti-Galactic center (Ahlers 2016; Liu et al. 2017).

In recent works, we established a coherent picture to explain both observed spectral features and anisotropy (Liu et al. 2019; Qiao et al. 2019). We find that the amplitude transition and phase flipping in the dipole anisotropy map have a common origin with the spectral hardening of nuclei above 200 GeV and ensuing falloff at ∼20 TeV. At less than 100 TeV, the anisotropy and spectral features are dominated by the local source. The position of the local source is close to the direction of the anti-Galactic center and far from the Galactic disk. We find that the Geminga SNR at its pulsar’s birthplace could be a prime candidate.

In fact, Geminga pulsar has long been considered as a local positron source, since the discovery of the increasing positron fraction above 10 GeV. Recently, the High-Altitude Water Cherenkov (HAWC) Observatory experiment measured the
extended teraelectronvolt gamma-ray emission of Geminga and PSR B0656+14 pulsars (Abeysekara et al. 2017). The inferred diffusion coefficient nearby the γ-ray emission region is far less than the standard value derived by fitting the B/C ratio. It suggested the positron excess may have an exotic origin. However, Fang et al. (2018) and Tang & Piran (2019) argued that even the inference in view of the HAWC surface brightness profile is correct, the positron excess could still be accounted for by the Geminga pulsar, as long as a two-zone diffusion model is introduced.

In this work, we aim at the parameter space of cosmic-ray sources permitted by the observed energy spectra and anisotropy. To perform an elaborate scan of the parameter space of sources, the multinest package, based on Bayesian inference, is applied. By fitting the energy spectra and anisotropy amplitude, the permissible space of the location and the age of the local source is greatly reduced. Our study further demonstrates that the Geminga SNR could be the best candidate of a local cosmic-ray source.

The remainder of the paper is organized as follows: in Section 2, the propagation model and Bayesian inference are briefly introduced. Section 3 presents the calculated results and Section 4 presents our conclusions.

2. Model Description

2.1. Propagation Model

The spatial-dependent propagation (SDP) model has received a lot of attention in recent years. It was first introduced as a two halo model (THM) (Tomassetti 2012) to explain the spectral hardening of both proton and He above 200 GeV (Adriani et al. 2011). Afterward, it is further applied to secondary and heavier components (Tomassetti 2015; Feng et al. 2016; Guo et al. 2016; Liu et al. 2018; Tian et al. 2020; Yuan et al. 2020), diffuse gamma-ray distribution (Guo & Yuan 2018) and large-scale anisotropy (Liu et al. 2019; Qiao et al. 2019). For a comprehensive introduction, one can refer to Guo et al. (2016) and Liu et al. (2018).

In the SDP model, the whole diffusive halo is divided into two parts. The Galactic disk and its surrounding area are called the inner halo (IH) region, in which the diffusion coefficient is spatial dependent and relevant to the radial distribution of background CR sources. The extensive diffusive region outside the IH is referred to as the outer halo (OH) region, where the diffusion is regarded as only rigidity dependent. The size of the IH is represented by its half thickness ξzIH, whereas the OH region’s is (1 − ξz)z. The diffusion coefficient Dxx in the diffusive halo is thus parameterized as

\[ D_{xx}(r, z) = D_0 F(r, z) \left( \frac{R}{R_0} \right)^{3/2} \xi_0 F(r, z), \]

(1)

where

\[ F(r, z) = \begin{cases} 
  g(r, z) + [1 - g(r, z)] \left( \frac{z}{\xi_0} \right)^n, & |z| \leq \xi_0 \\
  1, & |z| > \xi_0 
\end{cases} \]

(2)

with \( g(r, z) = N_m/[1 + f(r, z)] \). \( f(r, z) \) is the source density distribution, which is approximated as axisymmetric, i.e.,

\[ f(r, z) = \left( \frac{r}{r_0} \right)^{\alpha} \exp \left[ -\frac{\beta(r - r_0)}{r_0} \right] \left( \frac{-|z|}{z_s} \right)^\gamma \]

with \( r_0 \equiv 8.5 \) kpc and \( z_s \equiv 0.1 \) kpc. The parameters \( \alpha \) and \( \beta \) are taken as 1.09 and 3.87, respectively, in this work (Green 2015). The propagation of CRs from the local point source is time dependent. As for the instantaneous injection, the spatial distribution is

\[ \psi(R, r, t) = Q(R) r^{-\nu} \exp \left( -\frac{R}{R_c} \right) \]

(3)

The energy spectra at sources are assumed to have a power law of rigidity plus an exponential cutoff,

\[ q(R) \propto R^{-\nu} \exp \left( -\frac{R}{R_c} \right) \]

In this work, the diffusion-reacceleration (DR) propagation model is adopted. The numerical package DRAGON (Evoli et al. 2008) is used to solve the diffusion equation to obtain the CR distribution. Less than tens of gigaelectronvolts, the CR
fluxes are impacted by solar wind. The force-field approximation is applied to describe the solar modulation effect (Gleeson & Axford 1968; Perko 1987).

2.2. Bayesian Parameter Inference

The Bayesian analysis method has now been widely used in astrophysics, cosmology, as well as particle physics to infer the parameter. In this work, to quantitatively evaluate the probability density distribution (PDF) of the model parameters permitted by the observed CR spectra and anisotropy amplitude, the Bayesian inference approach is applied. Here, we give a brief introduction to the Bayesian inference of parameters. For a more comprehensive review, one can refer to Trotta (2008), Putze et al. (2009), Trotta et al. (2011), and Feng et al. (2016).

Bayesian inference is essentially to make use of prior PDF for the parameters of interest and the likelihood function supplied by the data to evaluate the posterior PDFs. Given the

Figure 2. Two-dimensional correlation distributions of injection parameters as well as the local source’s age and distance.
Parameter set $\Theta$ and the observational data $D$, the Bayes theorem reads as

$$P(\Theta|D) = \frac{P(D|\Theta)P(\Theta)}{P(D)}.$$  

(4)

$P(\Theta|D)$ is the posterior PDF of the parameters, while $P(\Theta)$ is the prior PDF of parameters before the observations are considered. $P(D|\Theta) = L(\Theta)$ is called the likelihood function, a function of $\Theta$ given the data set $D$. The likelihood function is defined as

$$L(\Theta) = \exp\left(-\frac{1}{2}\chi^2(\Theta)\right)$$

(5)

with $\chi^2(\Theta)$ built from the data and model, i.e.,

$$\chi^2(\Theta) = \sum_{i=1}^{n_{\text{data}}} \left(\frac{y_i^{\text{exp}} - y_i^{\text{th}}(\Theta)}{\sigma_i}\right)^2,$$

(6)

in which $y_i^{\text{exp}}$ and $\sigma_i$ are the measured value and standard deviation in experiment, and $y_i^{\text{th}}$ is the theoretical expectation under the certain parameter set $\Theta$. The denominator in Equation (4), referred to as the Bayesian evidence, is obtained by computing the average of the likelihood under the prior, i.e.,

$$P(D) = \int P(D|\Theta)P(\Theta)d\Theta.$$  

(7)

In the parameter estimation, the inferences are obtained by taking samples from the posterior using Markov chain Monte Carlo (MCMC) sampling methods, where at equilibrium the chain contains a set of samples from the parameter space distributed according to the posterior. With the posterior samples, the marginal posterior PDFs and other estimations could be available straightforward.

In this work, we adopt the public MultiNest package (Feroz & Hobson 2008; Feroz et al. 2009, 2019), which implements the nested sampling algorithm (Skilling 2004). Compared with the traditional MCMC methods, the nested sampling could navigate the parameter space with complex, multimodal posterior distribution until a well-defined termination point with high efficiency.

3. Results

The propagation and injection parameters are evaluated independently and the former can be determined by fitting the B/C and $^{10}\text{Be}/^{9}\text{Be}$ ratios. As for the SDP model, the unknown propagation parameters are $D_0$, $\delta_0$, $N_m$, $\xi$, $n$, $y_A$ and $z_A$, respectively. Figure 1 shows the comparison of the B/C and $^{10}\text{Be}/^{9}\text{Be}$ ratios between the SDP predictions and the data. The
values of corresponding propagation parameters are listed in Table 1. The red lines is the B/C ratio computed only from background sources, and the black line is the one with additional carbon contribution from the local source. As can be seen, the carbon flux from the local source lowers the total B/C ratio above ∼10 GeV. Within the uncertainty of the measurements, the computed B/C ratio is still consistent with the latest Alpha Magnetic Spectrometer Experiment (AMS-02) measurement. The B/C ratio is fitted in order to obtain the propagation parameters. Therefore, here we do not consider the production of borons in the local source, so that B/C ratio in the bg+local scenario is steeper than that of pure bg when local carbons are taken into account. Due to lack of the precise observation, the measurements of 10Be/Be have large errors, and our fitting could also account for the current data.

When the propagation parameters are fixed, we further study injection parameters as well as the local source’s age and distance. The MultiNest package is applied to perform the Bayesian inference of the corresponding parameters to obtain their posterior distributions and correlations between them allowed by the observations (Delahaye et al. 2010). The background and local source parameter set is

\[ \Theta = \{ A^p, \gamma^p, A^{He}, \gamma^{He}, q_0^p, q_0^{He}, \alpha^p, \alpha^{He}, R_c, r, t, gl, gb \} \]

\[ A^{p/He}, \gamma^{p/He} \] are the normalization background proton/He flux at 100 GeV and power index of background proton/He flux, and \[ q_0^{p/He}, \alpha^{p/He} \] are the injection power of the local source for proton/He nuclei, which is set at the rigidity of 1 GeV and the power index. \[ R_c \] is the cutoff rigidity of the local CRs. \[ r, t, gl, gb \] denote the local source’s distance, age, longitude, and latitude in the Galactic coordinate system. The data include proton and He spectra, and the dipole anisotropy amplitude. Subject to the large systematic uncertainties of the ground-based experiments and inconsistencies in measurements, we just consider the dipole anisotropy data of ASγ (Amenomori et al. 2017) and Astropysical Radiation with Ground-based Observatory at YangBaJing (ARGO-YBJ) (Bartoli et al. 2015, 2018) experiments for the fitting.

The two-dimensional correlation distributions of the parameters are illustrated in the triangular plot in Figure 2. We also show the marginalized posterior PDFs in the diagonal regions. The dark, intermediate, and light blue lines correspond to the 1σ, 2σ, and 3σ contours, respectively. The posterior distributions of each parameter are listed in Table 2. For the background parameters, \( A^p \) and \( \gamma^p \) (or \( A^{He}, \gamma^{He} \)) are distinctly anticorrelated. This can be understood since the injection spectrum is softer, the calculated flux at normalization energy 100 GeV is lower and a larger normalization flux is needed in order to fit the spectrum. So do \( q_0^p \) and \( \alpha^p \) (or \( q_0^{He} \) and \( \alpha^{He} \)) of the local source.

Meanwhile, as can be noticed that the age and distance of the local source has strong positive correlation. For a distant local source, its age is necessary to be old due to the longer propagation distance. Otherwise, the CRs have not propagated to the solar system so far if the source is too young. Correspondingly, its injection power has to be enhanced when its distance is far away. Therefore, \( q_0^p \) and \( q_0^{He} \) are positively correlated with the source’s distance \( r \).

We also found that explaining the proton and He spectra, the injection power index of the local source is slightly harder to explain than the background. For example, the power index of local protons \( \alpha \) is between −2.2 and −2.0, whereas it is between −2.40 and −2.37 for the background. So does He. This has been noticed in our previous works Liu et al. (2019). When the source is young, the shock is very strong, in which standard diffusive shock acceleration predicts the power index is close to −2. As the sources become older, the shock becomes weaker and the accelerated spectra of CRs becomes steeper. The background CRs are the sum of the contribution of both young and old sources in the Galaxy so that the injection spectra of the background is expected to be steeper than the local one. Furthermore, to fit both energy spectra and
Table 3: Characteristics of Nearby Pulsars

| No. | J2000 Name | Dist (kpc) | Age (kyr) | gl (deg) | gb (deg) |
|-----|-------------|------------|-----------|----------|----------|
| 1   | J0633+746   | 0.16       | 342.0     | 195.134  | 4.266    |
| 2   | J1932+11059 | 0.36       | 3100.0    | 47.382   | −3.885   |
| 3   | J1908+0734  | 0.58       | 4080.0    | 41.585   | −0.270   |
| 4   | J1741-2054  | 0.25       | 387.0     | 6.422    | 4.907    |
| 5   | J0953+0755  | 0.26       | 17500.0   | 228.908  | 43.697   |
| 6   | J2043+2740  | 1.13       | 1200.0    | 70.612   | −9.151   |
| 7   | J1057-5226  | 0.72       | 535.0     | 285.984  | 6.649    |
| 8   | J0659+1414  | 0.29       | 111.0     | 201.108  | 8.258    |
| 9   | J0835-4510  | 0.29       | 11.3      | 263.552  | −2.787   |
| 10  | J1740+1000  | 1.24       | 114.0     | 34.011   | 20.268   |
| 11  | J0742-2822  | 1.89       | 157.0     | 243.773  |          |
| 12  | J1549-2828  | 1.54       | 324.0     | 330.495  | 4.305    |

Table 4: Characteristics of Nearby SNRs

| No. | Dist (kpc) | D_{tot} (kpc) | Age (kyr) | A_{tot} (kyr) | gl (deg) | gb (deg) |
|-----|------------|--------------|-----------|---------------|----------|----------|
| 1   | 2.000      | ±0.100       | 11.75     | ±0.85         | 18.95    | −1.1     |
| 2   | 0.900      | ±0.100       | 26.00     | ±1.00         | 65.30    | 5.7      |
| 3   | 1.000      | ±0.400       | 16.75     | ±3.25         | 65.70    | 1.2      |
| 4   | 2.000      | ±0.100       | 20.00     | ±1.00         | 69.00    | 2.7      |
| 5   | 0.540      | ±1.00        | 10.00     | ±1.00         | 74.00    | −8.5     |
| 6   | 1.500      | ±1.00        | 7.00      | ±1.00         | 78.20    | 2.1      |
| 7   | 2.300      | ±1.00        | 20.10     | ±6.60         | 82.20    | 5.3      |
| 8   | 1.700      | ±0.500       | 5.60      | ±0.28         | 89.00    | 4.7      |
| 9   | 1.500      | ±0.200       | 50.00     | ±20.00        | 93.70    | −0.2     |
| 10  | 0.700      | ±0.000       | 7.70      | ±0.10         | 114.30   | 0.3      |
| 11  | 1.600      | ±0.000       | 20.00     | ±5.00         | 116.50   | 1.1      |
| 12  | 1.600      | ±0.000       | 20.00     | ±5.00         | 116.90   | 0.2      |
| 13  | 1.400      | ±0.300       | 10.00     | ±5.00         | 119.50   | 10.2     |
| 14  | 1.000      | ±0.100       | 25.00     | ±5.00         | 127.10   | 0.5      |
| 15  | 0.800      | ±0.500       | 10.00     | ±1.00         | 156.20   | 5.7      |
| 16  | 0.800      | ±0.400       | 5.50      | ±1.50         | 160.90   | 2.6      |
| 17  | 1.200      | ±0.400       | 600.00    | ±10.00        | 180.00   | −1.7     |
| 18  | 2.000      | ±0.500       | 7.50      | ±0.00         | 184.60   | −5.8     |
| 19  | 1.500      | ±1.00        | 30.00     | ±4.00         | 189.10   | 3.0      |
| 20  | 0.280      | ±0.030       | 86.00     | ±1.00         | 203.00   | 12.0     |
| 21  | 1.630      | ±0.250       | 29.00     | ±1.00         | 205.50   | 0.5      |
| 22  | 0.295      | ±0.075       | 11.20     | ±0.10         | 263.90   | −3.3     |
| 23  | 0.750      | ±0.010       | 3.50      | ±0.80         | 166.20   | −1.2     |
| 24  | 0.200      | ±0.140       | 1200.00   | ±0.00         | 276.50   | 19.0     |
| 25  | 1.700      | ±0.800       | 50.00     | ±10.00        | 315.10   | 2.7      |
| 26  | 1.200      | ±0.300       | 50.00     | ±10.00        | 330.495  | 15.0     |

Figure 5. 2D contour of the age and distance of the local source. The violet star represents the best-fit values of Galactic longitude and latitude, and the solid lines are 1σ, 2σ, and 3σ contours, respectively.

Anisotropy amplitude, the constraint of the local source’s cutoff rigidity is very tight, which is between 20 and 28 TeV. It seems to have no significant correlation with other parameters, and even does not change with the local source’s age and distance.

Figure 3 shows the calculated proton and He spectra with best-fit parameters. Figure 4 illustrates the corresponding amplitude and phase of anisotropy. As can be seen, the transition from local-source dominated to background dominated in the amplitude map is a little over 100 TeV. This is due to the large measurement uncertainties of ARGO-2018 at that energy, so the transition does not exactly match the AS γ contours and thus excluded. Only the Geminga pulsar/SNR and J1741-2054 are in the direction of the Galactic Center. And the Geminga SNR is very close to the best-fit value. Therefore, we think Geminga SNR is likewise the probable candidate of the local source.

4. Conclusion

We have built a unified scenario based on an SDP+local source to explain the observations of both the energy spectra and anisotropy of CR nuclei below petaelectronvolt energies. We find that at less than ~100 TeV, not only does the local...
source contribute to the spectral hardening at $\sim 200$ GeV and subsequent softening at 20 TeV in the energy spectra, but it also dominates the galactic CR streaming and determines the low energy anisotropy pattern. From the phase of the dipole anisotropy, we infer that the SNR associated with Geminga may be an important candidate source.

In this work, we further investigate the injection parameters and the local source’s position and age in detail with the aid of the Bayesian inference tool, MULTINEST. We find that the age and distance of the local source are positively correlated. For a distant local source, its age has to be older. Otherwise, the CRs could not propagate to the solar system currently if the source is too young. And the corresponding injection power is

\[ P = \frac{\sigma}{r_0^2} \]

Figure 6. 2D contour of galactic longitude and latitude. The violet star represents the best-fit values of galactic longitude and latitude, and the solid lines are $1\sigma$, $2\sigma$, and $3\sigma$ contours, respectively.

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MULTINEST (Feroz & Hobson 2008; Feroz et al. 2009) available at https://github.com/farhanferoz/MultiNest.

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