Excesses of Cosmic Ray Spectra from A Single Nearby Source (Postprint)

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Abstract

Growing evidence reveals universal hardening on various cosmic ray spectra, e.g. proton, positron, as well as antiproton fraction. Such universality may indicate they have a common origin. In this paper, we argue that these widespread excesses can be accounted for by a nearby supernova remnant surrounded by a giant molecular cloud. Secondary cosmic rays (p, e+) are produced through the collisions between the primary cosmic ray nuclei from this supernova remnant and the molecular gas. Different from the background, which is produced by the ensemble of large amount of sources in the Milky Way, the local injected spectrum can be harder. The time-dependent transport of particles would make the propagated spectrum even harder. Under this scenario, the anomalies of both primary (p, e−) and secondary (e+, ¯p/p) cosmic rays can be properly interpreted. We further show that the TeV to sub-PeV anisotropy of proton is consistent with the observations if the local source is relatively young and lying at the anti-Galactic center direction.

Full Text

Preamble

Excesses in Cosmic Ray Spectra from a Single Nearby Source

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Growing evidence reveals universal hardening across various cosmic ray spectra, including protons, positrons, and the antiproton-to-proton fraction. Such universality may indicate a common origin. In this paper, we argue that these widespread excesses can be accounted for by a nearby supernova remnant surrounded by a giant molecular cloud. Secondary cosmic rays (p̄, e) are produced through collisions between primary cosmic ray nuclei from this supernova remnant and the molecular gas. Unlike the background component, which originates from the ensemble of numerous sources throughout the Milky Way, the locally injected spectrum can be harder. Time-dependent transport of particles would make the propagated spectrum even harder. Under this scenario, the anomalies of both primary (p, e) and secondary (e , p̄/p) cosmic rays can be properly interpreted. We further show that the TeV to sub-PeV anisotropy of protons is consistent with observations if the local source is relatively young and located in the anti-Galactic center direction.

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Introduction

It is worth considering the physical implications of a flat antiproton-to-proton fraction [58-63].

It is widely accepted that cosmic rays (CRs) below the knee region originate from Galactic supernova remnants (SNRs). Based on both primordial diffusive shock acceleration [1, 2] and steady-state transport [3, 4] processes, Galactic CRs are expected to fall off as a featureless power law across a wide energy range from tens of GeV to PeV.

However, this simple picture has been challenged by new observations in recent years. Anomalies in CR electrons and positrons have been observed by numerous experiments, including HEAT [5, 6], AMS-01 [7], ATIC [8], PPB-BETS [9], PAMELA [10], Fermi-LAT [11], and most recently AMS-02 [12, 13]. The overabundance of positrons requires additional primary sources, involving either astrophysical objects such as pulsars [14-19] and hadronic interactions in SNRs [20-22], or more exotic origins like dark matter self-annihilation or decay [23-28]. For an extensive review of relevant models, see [29-33] and references therein.

Observations of protons, helium, and heavier nuclei also show remarkable hardening at energies above a few hundred GeV/nucleon [34-39]. The hadronic hardening may be ascribed to source properties [40-46], transport effects [47-52], or production mechanisms [53, 54]. Most recently, the AMS-02 collaboration released measurements of the antiproton-to-proton ratio, which shows a flat behavior up to 400 GeV [55]. This is not expected from the conventional production and propagation pattern of antiprotons [56, 57]. Although sizable error bars at high energies prevent this conclusion from being overwhelmingly certain, it is worth considering the physical implications of a flat p̄/p fraction [58-63].

In this paper, we aim to relate all these anomalies within a unified framework. We propose that a local, fresh SNR surrounded by a giant molecular cloud (MC) can explain all the aforementioned phenomena. In this scenario, both primary nuclei and electrons are accelerated by the shock wave in the local SNR, while the excess positrons and antiprotons are produced through hadronic interactions between the primary nuclei and molecular gas. Compared to the background component from the ensemble of numerous Galactic SNRs, the injection spectra of this local SNR are harder. A similar picture has been suggested by [21, 64], which focused only on secondaries—namely positrons and antiprotons. Here we extend the model to study its influence on primary CRs. Moreover, we evaluate the consequence on the Boron-to-Carbon (B/C) ratio in a realistic way, with reasonable assumptions about the source nuclear abundances. This is especially important because preliminary data published by the AMS-02 collaboration do not show significant deviation from the predictions of the standard propagation model [56]. This, in turn, can impose strong constraints on models that generate abundant secondary particles [65]. Thirdly, we deduce both background and local SNR parameters coherently without a priori assumptions about the background parameters, rendering our treatment more self-consistent.

The remainder of this paper is organized as follows: In Section II, we briefly review the production and propagation of CRs in our model. Results and discussion are presented in Section III. Finally, we present our conclusions in Section IV.

II. Cosmic Ray Transport Model

A. Background Supernova Remnants

After being injected into interstellar space, CRs diffuse within the Galactic magnetic halo by scattering off magnetic waves and MHD turbulence. The magnetic halo is usually approximated as a cylinder with radial boundary equal to the Galactic radius R = 20 kpc. Its half-thickness L, which characterizes the vertical extent of the interstellar magnetic field, is constrained by CR data. Both CR sources and the interstellar medium (ISM) are chiefly distributed in the Galactic disk, whose average width is roughly 200 pc—much smaller than the halo thickness. The transport process of CRs in the magnetic halo is described by the diffusion equation [3, 4]:

All SNRs other than the nearby one are labeled as background sources. For simplicity, the spatial distribution of background SNRs is assumed to be axisymmetric:

f(r, z) = (cid:18) r (cid:19) (cid:20) (r − r) (cid:21) zs (cid:21) (cid:20) , (4)

with r = 8.5 kpc being the distance from the solar system to the Galactic center. The parameters and are adjusted to be compatible with Fermi-LAT gamma-ray data [67].

The injection spectrum of both primary CR nuclei and electrons is parameterized as a broken power law:

Q(r, p) + · (Dxx − Vc) + ˙p − (· Vc) p2Dpp p2 (cid:21) p (cid:20)

Here (r, p, t) = dn/dp is the CR density per total particle momentum p at position r. At the halo boundary, a free escape condition is applied by default:

 (R, z, p) = (r, ±L, p) = 0. The diffusion coefficient Dxx is assumed to be isotropic on large scales and grows with particle rigidity R = pc/Ze:

Rbr (cid:19) Rbr (cid:19) (cid:18) (cid:18) R   Rbr R > Rbr

qi = qi

Some other species, such as Li, Be, B, e , p̄, and radioactive elements, are hardly synthesized during stellar nucleosynthesis. They are produced through fragmentation of parent nuclei during transport. For the production of Li, Be, and B, the so-called straight-ahead approximation is widely used, in which the kinetic energy per nucleon is conserved during the spallation process. The production rate is thus:

Dxx = D0 R0 (cid:19) (cid:18) (nH i+H→j + nHe i+He→j)v i , Xi=C,N,O

where   is the particle velocity in units of the speed of light c. Both D0 and   are treated as free parameters.

Apart from diffusion, CR particles may also experience galactic convection Vc, diffusive reacceleration Dpp, fragmentation f, radioactive decay r, energy loss ˙p, etc. In this work, we adopt the diffusive-reacceleration (DR) scenario [66]. Diffusive reacceleration originates from the random motion of magnetic fields in the ISM, which produces second-order Fermi acceleration during transport. It is usually described as diffusion in momentum space, with diffusion coefficient Dpp related to the spatial diffusion coefficient Dxx and Alfvén velocity vA by:

DppDxx = 4p2v2 3 (4 − 2)(4 −)

In this work, Galactic SNRs are separated into two classes: the local fresh SNR and all others as background sources. For background SNRs, it is reasonable to assume that the spatial distribution of CRs from them reaches steady state. However, for the local single SNR, time-dependent transport of CRs after injection is required. In the following subsections, we discuss these two components separately.

where nH/He is the number density of hydrogen/helium in the ISM and i+H/He→j is the total cross section for the corresponding hadronic interaction.

Unlike the secondary CR nuclei mentioned above, secondary e and p̄ have energy distributions. Therefore, the source term for both e and p̄ is the convolution of the energy spectra of primary nuclei Φi(E) and the relevant differential cross section d i+H/He→j/dEj:

Xi=p,He Z (cid:26) d i+H→j (pi, pj) d i+He→j(pi, pj) (cid:27) i(pi) ,

Furthermore, antiprotons may undergo non-annihilating inelastic scattering with ISM protons during propagation, in which antiprotons lose a significant amount of their kinetic energy. This is also known as tertiary production. The numerical package GALPROP¹ is used to solve the transport equation (1) to obtain the background CRs. The transport parameters are fine-tuned to fit the data together with the contribution from the local source.

[1] http://galprop.stanford.edu/

B. Nearby Young Supernova Remnant

We assume a local (< kpc) supernova explosion occurred in a giant MC about 10 -10 years ago. Charged particles were continually accelerated near the shock front as the supernova ejecta expanded. The accelerated spectrum is represented by a power law plus an exponential cutoff:

Qj = qj(R/R0)− exp[−E/Ecut].

The normalization qj for each element depends on the local chemical environment. In this work, we suppose that the element abundances in the MC are identical to the Galactic average.

Besides, CR nuclei generated by the local SNR also collide with the surrounding molecular gas and produce prolific daughter particles such as B, e±, p̄, and so forth. The yields of B and e±, p̄ inside the MC are respectively:

(nH i+H→j + nHe i+He→j)vQi(E)tcol (8)

Xi=C,N,O

Xi=p,He dEi v (cid:26) d i+H→j +n He d i+He→j dEj (cid:27) Qi(Ei)tcol ,

where nH/He is the number density of hydrogen/helium in the MC. In this work, we assume it is 1000 times greater than the mean ISM value. tcol is the collision duration, and Qi(E) is the accelerated spectrum of primary nuclei inside the local SNR.

When the radius of the shock front becomes comparable to or larger than the size of the MC, the entire MC is eventually fragmented by the expanding ejecta. All CRs then break out of the MC and diffuse into interstellar space. The time-dependent distribution of CR nuclei from a point source can be obtained using Green’ s function technique. Since the local SNR only makes significant contributions above tens of GeV, a simplified transport equation suffices here, with other terms such as reacceleration and energy loss neglected. The transport equation for nuclei becomes:

− (Dxx j) = Qj(E) (r−r) (t−t)−2h (z)Γj j ,

Here the transport equation is rewritten in terms of   = dn/dE, where E is the energy per nucleon. 2h (z)Γj is the fragmentation term, and Γj sp = (nH j+H+nHe j+He)v denotes the spallation rate of CR nuclei j. Meanwhile, since the interstellar medium is chiefly concentrated in the Galactic disk, which is much thinner than the halo boundary, the thin-disk approximation is applied. The corresponding analytical solution can be found in [42].

As for energetic electrons and positrons, the energy loss term due to synchrotron radiation in the interstellar magnetic field and inverse Compton scattering off CMB photons is far more important than fragmentation. Thus the transport equation for electrons and positrons becomes:

$$- \mathrm{Dxx}\ \ \mathrm{j} + (\ \dot{\mathrm{E}}\ \mathrm{j}) = \mathrm{Qj(E)}\ (\mathrm{r} - \mathrm{r}\ )\ (\mathrm{t} - \mathrm{t}\ )\ .$$

The energy loss rate $\dot{E}$ is approximately written as $\dot{E} = -bE^2$ in the Thomson limit. Here we use the analytical solution available in [68].

III. Results

In this paper, we apply our model to simultaneously fit the spectra of $\bar{p}$/p, p and e , as well as B/C and e . The local SNR is assumed to be located 0.1 kpc away from our solar system.

In our propagation model, the essential transport parameters are D , , vA, and L. The source parameters of the background CRs are Ap^1, p^1, e for protons, and Ae for electrons. We also allow for fluctuation of the positron background, denoted by a multiplier ce [66]. For the local SNR, the proton and electron parameters are respectively qp , p, , e. Additionally, we have a parameter specifying the collision duration of CRs within the MC, tcol. For heavier nuclei such as C, N, and O, they share the same power-law injection index as protons. To fit the low-energy data, we must account for solar modulation, represented by the modulation potential [3]. The parameters for transport, background sources, and the local SNR are summarized in separate Tables I, II, and III.

A. Energy Spectra

Figure 1 [Figure 1: see original paper] illustrates our fits assuming a relatively young local SNR with an age of 10 years. In the figure, the fluxes/ratios from the background (green dash), local primary protons and electrons (blue dash-dot), local secondary electrons and positrons (brown dash-dot), and total (black solid) are shown. Both background and total fluxes/ratios have been solar-modulated to account for low-energy spectra. The modulation potentials for p($\bar{p}$), e±, and B/C are respectively = 660, 1300, and 330 MeV.

For the B/C ratio, both background and total models fit the AMS-02 data well. In this energy range, the contribution from the local SNR is negligible, so the differences between them are tiny. The required transport parameters are D = 5.9 × 10^2 cm^2 s ^{1}, = 0.343, vA = 30 km s ^{1}, and L = 4.85 kpc, which are similar to other fits [66]. However, above 600 GeV, the local component begins to dominate, causing the total B/C ratio to harden. This characteristic can be verified by future observations. A similar effect occurs in the $\bar{p}$/p ratio. From 10 GeV, the total $\bar{p}$/p ratio gradually deviates from the prediction of the conventional model and flattens up to 10^3 GeV, which agrees well with AMS-02 data.

Since both positrons and antiprotons are mainly generated by CR protons, the spectra of protons, $\bar{p}/p$, and e collectively constrain the background and local proton components. We find that to fit all these spectra simultaneously, the power-law index of local protons $= 1.837$ must be harder than the background $= 2.49$. The high-energy cutoff Ecut of local protons is adjusted to 1.4×10 GeV to fit high-energy positron data. To produce enough positrons at high energies, the collision duration is 3.5×10^2 years when the density of the local MC is $n = 1000$ cm ^{3}.

For electron spectra, the local component has two origins: shock-accelerated primary electrons within the local SNR and products of collisions between CR nuclei and molecular gas. The normalization and injected power-law index of local primary electrons are respectively qe $= 10$ GeV ^{1} and $= 2$. Therefore, the electron-to-proton ratio in the local SNR is smaller than Kep $= 0.01$, and the injected spectrum is also harder than the background electron $= 2.83$.

Figure 2 [Figure 2: see original paper] shows similar results but hypothesizing an older local SNR (DR-B) with a fitted age of 3×10 years. Both fitted transport and background parameters are close to those of DR-A, but the injected power of the local SNR must be boosted to $q = 95 \times 10$ GeV ^{1}, nearly seven times higher than in DR-A. The total energy spectra of B/C and $\bar{p}/p$ resemble those of model DR-A. Compared to Figure 1, the main differences appear in the electron and positron spectra, where the total flux plunges dramatically at lower energies, around hundreds of GeV. Due to the earlier release time of local CRs and energy loss during propagation, only lower-energy electrons are observed today. This can be validated by the DAMPE experiment [69].

B. Anisotropy

As demonstrated above, both local SNR models with different ages can explain the current data. To distinguish between the two cases, we further compute their accompanying anisotropies for protons and electrons. The dipole anisotropy is defined as:

Owing to the spatial distribution of Galactic SNRs, there is inevitably a radial gradient of CR density directed toward the Galactic edge. Therefore, in the scenario of steady-state propagation, the anisotropy grows with the diffusion coefficient, i.e., rises with energy. However, this is incompatible with current observations of protons [70], which do not show obvious energy dependence between 1 TeV and 100 TeV. One interpretation is that a fresh nearby SNR (or more) located in the anti-Galactic center direction could offset the background streaming.

In Figure 3 [Figure 3: see original paper], we show the proton anisotropies for DR-A (left) and DR-B (right). The blue dash-dot line is evaluated from the background alone, while the black solid line includes the local SNR. Apparently, the nearby source in the anti-Galactic center direction can effectively reduce the anisotropy, but the magnitude of the reduction depends on the local SNR’ s age.

For the younger SNR, the total anisotropy can well conform with measurements from 1 TeV to tens of TeV. However, above 100 TeV, due to the high-energy cutoff of the local proton flux, the anisotropy returns to the steady-state case.

Due to the relatively nearby origin, source discreteness is more important for electron anisotropy. However, current measurements only provide upper bounds [71, 72]. We compute the anisotropies under both local source models, as shown in Figure 4 [Figure 4: see original paper]. The blue dash-dot and black solid lines represent anisotropies from the background (assuming continuous source distribution and steady-state propagation) and the total including the local SNR, respectively. Compared to DR-A, the local streaming in DR-B is comparable to the background, and the anisotropy at hundreds of GeV is tremendously suppressed. Nevertheless, both anisotropies remain far below current constraints from 1-year Fermi-LAT [71] and AMS-02 [72] data.

IV. Conclusion

Currently, excesses appear prevalent in both primary and secondary Galactic CRs according to recent observations. In this work, we address this universal anomaly from a unified perspective. Specifically, we envision that a nearby supernova explosion occurred within a giant molecular cloud. Primary CRs were accelerated by the shock wave, and secondaries (e±, $\bar{p}$, and B) were massively produced through interactions between primary CRs and molecular gas. All of them were released into interstellar space once the molecular cloud was fragmented.

To fit the spectra of protons, the $\bar{p}/p$ ratio, and positrons, the power-law index of the local source must be harder than the average of background SNRs. For the B/C ratio, the low-energy spectrum is unaffected by the local source. However, beyond 1 TeV, the total B/C ratio lies well above the background. This differs from the $\bar{p}/p$ ratio spectrum, whose transition occurs at lower energies. This stems from differences in production cross sections between boron and antiprotons. Future measurements extending to higher energies can verify this notable feature.

For the local SNR, we hypothesize two different ages, both of which can reproduce all spectra well. The main difference appears in the high-energy cutoff of the electron and positron spectra. For the younger SNR, the cutoff occurs above 1 TeV, while for the older SNR, the spectrum falls off well before 1 TeV, around hundreds of GeV. The ongoing DAMPE experiment [69] could provide more precise measurements in this energy range.

For the local source model, one validation method is to compare its high-energy CR anisotropy with observations. Under steady-state assumptions, anisotropy is proportional to the diffusion coefficient, which conflicts with accumulated data. If a local SNR is located in the anti-Galactic center direction, its CR flux could effectively counteract the streaming from the Galactic center. We compute anisotropies under our local SNR models and find that when the local SNR is younger, the total proton anisotropy agrees well with observations from 1 TeV to tens of TeV. For electrons, the local streaming cancels the background streaming in the DR-B model, and the anisotropy is greatly suppressed at hundreds of GeV. The anisotropies from both models are far below current upper limits from AMS-02 and Fermi-LAT.

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