Signatures of a Two Million Year Old Supernova in the Spectra of Cosmic Ray Protons, Antiprotons, and Positrons

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The locally observed cosmic ray spectrum has several puzzling features, such as the excess of positrons and antiprotons above ~20 GeV and the discrepancy in the slopes of the spectra of cosmic ray protons and heavier nuclei in the TeV-PeV energy range. We show that these features are consistently explained by a nearby source which was active approximately two million years ago and has injected $(2–3) \times 10^{50}$ erg in cosmic rays. The transient nature of the source and its overall energy budget point to the supernova origin of this local cosmic ray source. The age of the supernova suggests that the local cosmic ray injection was produced by the same supernova that has deposited ^{60}Fe isotopes in the deep ocean crust.

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Introduction.—Cosmic rays (CRs) with energies at least up to 10^{15} eV are thought to be a by-product of the final stages of stellar evolution [1–3]. The two main possibilities for the acceleration sites of CRs are individual supernovae (gamma-ray bursts, supernova remnants, and pulsar wind nebulae) [1,2] and superbubbles [3] hosting large numbers of supernovae (SN) and their progenitors, high-mass stars.

The direct identification of CR sources which would allow the discrimination between these two possibilities is difficult because the turbulent Galactic magnetic field (GMF) randomizes the CR trajectories and leads to an almost isotropic CR intensity. Moreover, locally detected CRs are accumulated from a large number of sources which were active over the time scale $\tau_{esc} \sim 10–30 \times 10^6$ on which CRs (of the energy $E \sim 10$ GeV) escape from the Galaxy. The superposition of the signals from a large number of sources erases possible signatures of individual sources.

The local CR flux might still have some "memory" of the individual sources composing it because of the discrete and stochastic nature of the sources (be it SN or superbubbles). The subset of near and recent CR sources could produce small features in the CR spectrum or could create anisotropies [4–7]. The identification of such features could potentially provide a possibility for the identification of the CR sources and for the measurement of their characteristics.

In what follows we show that the known differences in the slopes between CR protons and nuclei [8–10], puzzling features in the spectra of positrons [11–14] and antiprotons [15,16] could be self-consistently explained by a single nearby, recent CR source. We are able to deduce the characteristics of the source from the details of the spectra of these CR flux components. In particular, the hard spectra of antiprotons and positrons above ~20 GeV and the soft spectrum of CR protons (compared to the spectra of heavy nuclei) can be explained by a source which has injected $\sim 10^{50}$ erg in CRs in a transient event which occurred $\sim 2 \times 10^6$ years ago. The source is located at a distance of (several) hundred parsecs along the local GMF direction. The transient nature of the event, its overall energy budget, and the spectral characteristics of the injected CRs are consistent with a single SN and inconsistent with a superbubble as source.

Contribution of a local source to the proton spectrum.—Cosmic rays injected by a single source T years ago fill a region of the size $d_{\parallel,\perp} \sim (D_{\parallel,\perp} T)^{1/2}$ in the interstellar medium (ISM). Here, $D_\parallel$ and $D_\perp$ are the energy dependent components of the diffusion tensor parallel and perpendicular to the local GMF direction [17–19]. If the total injected energy $\mathcal{E}_{tot}$ is high enough, the source could produce a significant increase in the overall CR flux detectable by observers situated inside the region filled with CRs. In the particular case of locally detected TeV CRs, the source contribution to the flux, $F \propto \mathcal{E}_{tot}/(d_\parallel d_\perp^2) \propto \mathcal{E}_{tot}/T^{3/2}$ could be comparable to the locally observed CR flux if $\mathcal{E}_{tot}/T^3 \sim 10^{50}\ \mathrm{erg}/(10^6\ \mathrm{yr})^{3/2} \sim 10^{52}\ \mathrm{erg}/(10 \times 10^6\ \mathrm{yr})^{3/2}$. Thus, both a SN which occurred a million years ago and has injected $\sim 10^{50}$ erg in CRs and a superbubble which has injected $\sim 10^{52}$ erg over the last 10×10^6 yr can produce distortions in the local CR spectrum.

Cosmic rays spread faster along the direction of the GMF, $D_\parallel \gg D_\perp$. The transient enhancement of the CR flux caused by a local source could be particularly strong if the source and the observer lie close to the same magnetic field line. We model such a flux enhancement numerically using the code developed and tested in Ref. [19]. The code follows the trajectories of individual CR particles through the GMF model of Jansson-Farrar [20], starting from the moment of instantaneous injection in a single point by a transient CR source. The turbulent part of the field is chosen to follow isotropic Kolmogorov turbulence with the maximal length of the fluctuations $L_{max} = 25$ pc and the strength normalized to reproduce the observed B/C ratio, as discussed in Refs. [21,22]. The calculation of the trajectories of individual CRs in the GMF allows us to include a detailed model for the regular and the turbulent component of the GMF. We record the path length of CRs spent in a 50 pc sphere around Earth, which can be converted to the local CR flux at a given time interval.

We are interested in the case of a relatively young, $T \lesssim$ a few million years, and nearby source, $d_{source} \sim$ a few $\times$ 100 pc, and CR energies in the range 100 GeV–100 TeV. The spread of the CRs of such energy on a million year time scale is strongly anisotropic. A strong enhancement of the CR flux occurs if the source and the observer are connected by a magnetic field line. In this case, the contribution of a single source can dominate the observed total CR intensity at Earth.

Figure 1 shows an example of such a situation calculated for a source at the distance 300 pc which has injected CRs with spectrum $dN/dE \propto E^{-\gamma_{p,\mathrm{inj}}}$, $\gamma_{p,\mathrm{inj}} = 2.2$, and total injection energy $\mathcal{E}_{tot} = 2.5 \times 10^{50}$ erg. The source is placed at a GMF line passing within 50 pc from the Solar System. For $E > 10$ TeV, we calculate the CR trajectories up to 30×10^6 yr, i.e., sufficiently long to observe the exponential cutoff in the flux due to CR escape. At any given energy, we find that the observed flux F at Earth as a function of time rises, then drops as a power law $F(t) = F_{max}(t_0/t)^{\alpha(E)}$ up to the (energy-dependent) escape time and finally is exponentially suppressed as $F(t) = F_{max}(t_0/t)^{\alpha(E)} \exp(-t/\tau_{esc})$. In the energy range 1–10 TeV, we are only able to calculate trajectories up to 3×10^5 yr. We extrapolate them to later times using the power law with the slope $\alpha(E)$ derived from direct simulations in the energy range 10 TeV–1 PeV. Note that the fluctuations visible—especially at large times—are due to the relatively small number of CR trajectories used.

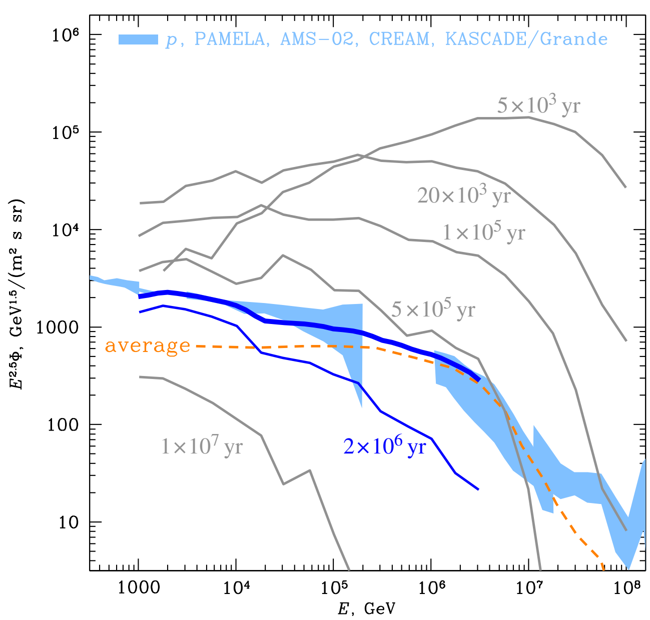

FIG. 1 (color online). Proton flux of the local source at different times. The average Galactic proton flux is shown as a thin orange line, the measured spectra of protons (light blue) from PAMELA [23], CREAM [8], KASCADE and KASCADE-Grande [10] as a band including experimental uncertainties. The sum of the average flux and the two million year old source is shown by the thick blue line.

From Fig. 1 one can see that CRs with energies above 100 TeV already reach the Earth five thousand years after the injection. If the source is able to accelerate CRs to energies above 10 PeV, their flux is already suppressed after five thousand years because of the fast escape from the Galactic disk. The escape induced flux suppression progresses towards lower energies with the increase of the source age. Below the high-energy cutoff, the slope of the spectrum softens and reaches the observed value $\tilde{\gamma}_p \sim 2.7$–$2.8$ after two million years.

The observed slopes of the spectra of the heavy nuclei component of the CR flux, $\gamma_N \simeq 2.5$, are systematically harder than the slope of the proton spectrum in the TeV-PeV range [8,9]. This harder slope of the nuclear component of the CR flux consistently explains the shapes of the knees in the spectra of individual groups of nuclei within the escape model [21,22]. The same slope of the average spectrum of 0.1–10 TeV protons/nuclei in the Galaxy is deduced from a combination of gamma-ray and IceCube neutrino data [24–26].

Assuming that the average Galactic CR proton flux at Earth also has the slope $\gamma_p \simeq 2.5$ and that it dominates the observed CR flux in the knee energy range $E \sim 1$–10 PeV (shown as “average” in Fig. 1; see Ref. [21]), one finds that the local source and the average Galactic contributions to the overall CR proton fluxes are comparable in the energy range 3–30 TeV. The uncertainty of the average flux is given by the uncertainty of measurements around the knee; cf. with the width of the blue band at PeV. The contribution of the local source with its softer spectrum explains the discrepancy between the slopes of the proton and heavy nuclei components of the TeV-PeV CR spectrum. In general, the local source also gives a contribution to the spectra of heavier nuclei. If the elemental abundance of the local source CRs is identical to the overall measured CR abundance, the contribution of the source to the heavy nuclei spectra in the $E > 1$ TeV range is subdominant because of the higher normalization of the average Galactic component of the heavy nuclei fluxes.

Positron excess from the local CR proton source.—Our suggestion that the softer slope of the TeV-PeV proton CR spectrum is caused by a local source can be tested via the identification of complementary signatures in the spectra of secondary particles—positrons and antiprotons—produced in CR interactions in the ISM.

The spectrum of CR positrons is known to have an “excess” above 30 GeV. This excess refers to a deviation from reference models (as, e.g., those of Ref. [27]) which assume that positrons are solely secondary particles produced during the propagation of a time independent CR proton and nuclei flux through the ISM. The presence of this excess is usually considered as an indication for the existence of a source of positrons in the local Galaxy. Source candidates under discussion are nearby pulsars [28], young ($\sim 10^4$ yr) supernova remnants [29], and dark matter annihilations or decays [30].

A characteristic feature of secondary production in hadronic interactions is that the slope of the energy spectrum of secondaries is very close to the one of the parent protons since scaling violations are small, except close to mass thresholds. Thus, the presence of a local source of CR protons should reveal itself through an associated component in the CR positron spectrum. The average energy fraction transferred to positrons produced in a CR interaction is $\langle z_{e^+} \rangle \simeq 3\%$ for $\gamma = 2.2$, so that positrons with energies in the 30–300 GeV range are produced by protons with energies $\gtrsim$1–10 TeV. The flux of this local positron component is a function of time. It grows as the fraction of protons interacting with the ISM increases, but it keeps approximately the shape of the parent proton distribution. Our calculation of the CR trajectories emitted from the local source presented in the previous section allows us to determine the average grammage X traversed by the CRs since the moment of injection. For energies $E \lesssim 10^{14}$ eV, the grammage is nearly energy independent, $X \simeq 0.3\ \mathrm{g/cm^2}$, for a source of the age $T = 2 \times 10^6$ yr.

The produced positrons diffuse and spread over larger and larger distances, thereby softening their energy spectrum. The process of diffusion and the resulting softening of the spectral slope is identical for positrons and protons if the age of the local source is small enough that energy losses of the positrons can be neglected. Thus, not only the injection but also the propagated spectra of protons and positrons from the local source have nearly identical slopes at any moment of time. In particular, this implies that, at present, $\gamma_{e^+} \simeq \tilde{\gamma}_p \simeq 2.7$–$2.8$.

Figure 2 shows the measured positron spectrum in the 30–300 GeV energy range [11–14] together with our calculation of the positron flux from the local source [31]. For the calculation of the hadronic production cross sections, we have been employing QGSJET-II-04 [32] in the modified version presented in Ref. [33]. Since we have fixed both the contribution of the local source to the proton flux and the grammage in Sec. 1, the normalisation of the shown positron flux is a prediction. Both the normalization and the slope $\gamma_{e^+} \simeq \tilde{\gamma}_p$ agree well with the experimental data.

An additional suppression of the positron flux may occur due to synchrotron and inverse Compton energy losses. The synchrotron and inverse Compton cooling rate is $t_{s,\mathrm{IC}}^{-1} = 0.5[U/(0.5\ \mathrm{eV/cm^2})][E_{e^+}/(300\ \mathrm{GeV})](10^6\ \mathrm{yr})^{-1}$, where U is the combined energy density of radiation and the magnetic field, $U = 0.5[B/(4\ \mu\mathrm{G})]^2\ \mathrm{eV/cm^3}$. The synchrotron and inverse Compton cooling softens the positron spectrum. Contrary to the primary CRs, which are injected instantaneously from a point source, positrons are continuously produced at a constant rate. This leads to the formation of a cooling break from γ_{e^+} to $\gamma_{e^+} + 1$ in the positron spectrum. The break energy decreases with time, as shown schematically in Fig. 2. The nonobservation of such a softening limits the age of the local source to $T \lesssim$ four million years.

Note that the association of the observed positron excess with a local source also implies a lower limit on the source age, $T \gtrsim$ two million years. Otherwise, if the source would be much more recent, CRs would not have enough time to produce the observed excess positron flux.

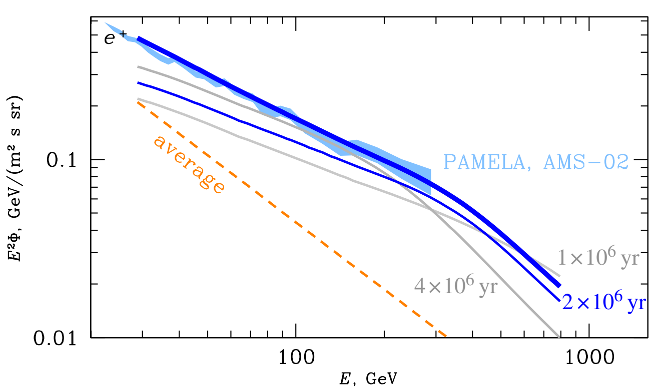

FIG. 2 (color online). Spectum of positrons from the local source for the age two million years old (thin blue curve), one million years old (light grey), and four million years old (darker grey) compared to the measured spectra of the positrons [11–14]. The dashed orange line shows an estimate of the average Galactic positron flux [34].

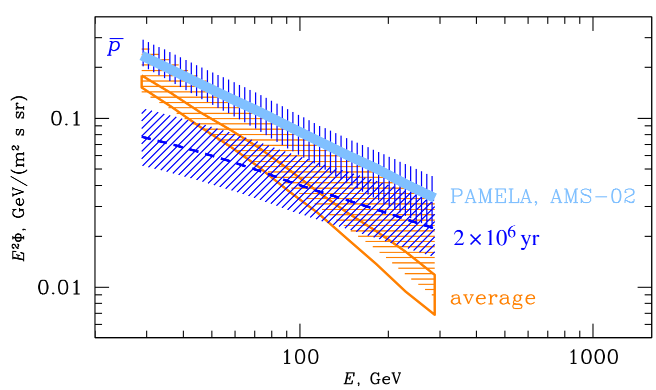

FIG. 3 (color online). Spectrum of antiprotons from the local source (the dashed blue line) compared to the measurements from Refs. [15,16] (the thick light blue line). The orange box shows an estimate of the average Galactic antiproton flux from Ref. [34]; the horizontally orange hatched range shows an alternative calculation from Ref. [35]. The blue hatched ranges show the uncertainty of the model calculation (inclined hatching) and for the sum of the local source and average antiproton fluxes (the vertical hatching).

Overall, the hypothesis of the local source contribution to the CR proton spectrum passes the positron self-consistency check and provides an explanation for the observed excess in the positron spectrum.

Antiproton flux from the local CR source.—Interactions of CR protons with the ISM also produce antiprotons. The relative size of the antiproton and positron fluxes is in the regime of negligible positron energy losses completely determined by a ratio of the corresponding Z factors, or approximately by the ratio of the spectrally averaged energy fraction $\langle z_i \rangle$ transferred to antiprotons and positrons [33]. We again use the modified version of QGSJET-II-04 [33] for the calculation of the spectrum of secondary antiprotons, keeping all parameters fixed to the ones used for positrons. The resulting spectrum of secondary antiprotons from the local source is shown in Fig. 3 by the blue line. The light blue shaded range shows the $\pm 50\%$ uncertainty band attributed to the uncertainty of the antiproton production cross section in this energy range [33,36,37].

From this figure one can see that the flux of the local source antiprotons constitutes a significant fraction of the overall CR antiproton flux. The local source contribution to the antiproton to proton ratio is at the level of $\sim 10^{-4}$, which is comparable to the measured ratio [15,16]. Note that the very preliminary AMS-02 antiproton measurements reported in Ref. [16] are consistent with the published PAMELA results [15] up to 180 GeV. The apparent independence of the $\bar{p}/p$ ratio with energy is at tension with the naive expectation that, in the steady state model of secondary antiproton production by CR interactions in the ISM, the antiproton spectrum should be softer than the proton spectrum, so that the ratio should have a decreasing trend with the increase of energy [35]. The presence of the single source contribution to the antiproton flux removes this tension. The energy dependence of the $\bar{p}/p$ ratio for the single source and for the average Galactic CR flux is different. Antiprotons originating from the source are injected by the parent protons which have spent the same time in the ISM, independently of their energy. For this component, the $\bar{p}/p$ ratio is rather slowly rising for energies well above the antiproton production threshold. The resulting independence of the $\bar{p}/p$ ratio with energy is therefore a falsifiable prediction of our model. Overall, the presence of the local source component in the antiproton flux is consistent—and possibly even favored by—the $\bar{p}/p$ ratio data.

Supernova nature of the local CR source.—The combination of the positron, antiproton, and proton signatures of a local CR source provides a possibility for constraining its parameters. The source should have the age of $T \sim$ two to four million years. An older source would be inconsistent with the absence of radiative cooling in the positron spectrum. A younger source would fail to produce a sufficient amount of antimatter. A younger source would also provide a harder feature in the proton spectrum in the TeV range, while for an older source the source contribution would be too soft to be noticeable in the TeV band.

The overall energy injected in CRs should be at the level of $\mathcal{E}_{\rm tot} \sim 10^{50}$ erg, for a wide range of source distances. The energy density of high-energy particles inside a region in the ISM filled with CRs injected by the source is nearly uniform. The region spans a ~ 100 pc wide tube of kiloparsec-scale length the along the local GMF direction. The only condition for the detectability of the CR flux from the local source is that the Solar System is situated inside this region.

The source has to be transient, in the sense that it could not remain active all through the last million years. Otherwise, the source would strongly contribute to the CR flux from more recent injection times. For example, the contribution from the last 0.1×10^6 yr period would have the spectrum shown by the orange curve in Fig. 1 multiplied by $0.1 \times 10^6\ {\rm yr}/1 \times 10^6\ {\rm yr} = 0.1$. This contribution would be comparable to the two million year old contribution. However, the energy spectrum of this younger contribution is harder, with the slope $\gamma \simeq 2.5$. The presence of such a contribution would erase the effect of softening and the spectrum of the TeV-PeV protons would have the same slope as the spectrum of the heavy nuclei.

The transient nature of the source and the overall injected energy rule out the possibility that the local source is a superbubble blown by massive star formation. The typical lifetime of superbubbles is in the 10^7–10^8 yr range determined by the lifetime of massive stars. A young superbubble formed a million years ago would still be active today.

The only plausible model of the transient local CR source is that of a SN. The average rate of SN explosions in the Milky Way disk volume $V_{\rm disk} \simeq 100$–$300\ {\rm kpc}^3$ is $\mathcal{R}_{\rm SN} \simeq (1\text{–}3) \times 10^{-2}\ {\rm yr}^{-1}$, or one SN per $(0.3\text{–}3) \times 10^4$ yr per kpc^3. This means that one could reasonably expect that about one SN has exploded within the last one million years within a 100 pc wide, kiloparsec long filament directed along the GMF line going through the Solar System.

Discussion.—Our analysis has shown that several features in the CR spectrum which appear puzzling within the standard Galactic CR injection or propagation models find a natural explanation by the presence of a local CR source. In particular, we have shown that two to four million year old source which injected $\sim 10^{50}$ erg in CRs with energies up to at least 30 TeV can consistently explain the difference in the slopes of the proton and heavy nuclei spectra in the TeV-PeV energy range, give an additional contribution to the antiproton spectrum in agreement with recent AMS-02 data, and predict the correct amplitude and slope for the positron spectrum in the 30–300 GeV energy range. The local source also gives rise to an excess anisotropy of the CR spectrum in the 1–100 TeV energy range, which for the first time explains the anisotropy data in this energy range [38]. Note that the combination of the anisotropy and the positron data constrain the source age and disfavor suggestions of younger sources in denser environments, as in Ref. [39].

The scenario of a two to four million year old local source contributing to the 1–100 TeV CR spectrum could be tested with future AMS-02 and ISS-CREAM measurements of heavy nuclei CR fluxes. Such measurements could detect the imprint of the local source on the primary-to-secondary CR nuclei ratios. In particular, the energy independent grammage ($\simeq 0.3\ \mathrm{g/cm^2}$) traversed by carbon nuclei should result in the presence of an energy-independent component of the B/C ratio in the 1–100 TeV energy band. The two million year time scale is also comparable to the decay time of ^{10}Be nuclei. This may leave an imprint in the $^{10}\mathrm{Be}/^{9}\mathrm{Be}$ ratio in the same energy range.

The presence of a nearby SN explosion was previously noticed in a completely different type of data on abundance of isotopes on Earth [40–43]. These data suggest that an episode of deposition of ^{60}Fe isotopes in the million years old deep ocean crust was produced by the passage of an expanding shell of a two million year old supernova remnant through the Solar System. The consistency of the SN age and distance estimate from the deep ocean sediment data with those found from CR data suggests it is one and the same supernova which is responsible for the CR injection and the isotope deposition on Earth.

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