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 ~ 2 Myr ago and has injected \((1 - 2) \times 10^{50}\) 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.

Introduction. Cosmic rays (CR) with energies at least up to \(10^{15}\) eV are thought to be a by-product of the final stages of stellar evolution [1, 2]. 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 number 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) randomises 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 time scale \(\tau_{\text{esc}} \sim 10 - 30\) Myr 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 SNe or superbubbles). The subset of near and recent CR sources could produce small features in the CR spectrum or create anisotropies [4]. 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 [6, 8], puzzling features in the spectra of positrons [12] and antiprotons [13, 14] 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 cosmic ray protons (compared to the spectra of heavy nuclei) can be explained by a source which has injected \(~ 10^{50}\) erg in CRs in a transient event which occurred 1–2 million 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 [15–17]. If the total injected energy \(\mathcal{E}_{\text{tot}}\) is high enough, the source could produce a significant increase in the overall CR flux detectable by observers situated inside the region filled with CR. In the particular case of locally detected TeV CRs, the source contribution to the flux, \(F \propto \mathcal{E}_{\text{tot}}/(d_{\parallel, \perp} T) \propto \mathcal{E}_{\text{tot}}/T^{3/2}\) could be comparable to the locally observed CR flux if \(\mathcal{E}_{\text{tot}}/T^{3} \sim 10^{50}\) erg/(1 Myr\(^{3/2}\)) \sim 10^{52}\) erg/(10 Myr\(^{3/2}\)). Thus, both a SN which occurred a million years ago and has injected \(~ 10^{50}\) erg in CRs and a superbubble which has injected \(~ 10^{52}\) erg over the last 10 Myr 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. [17]. The code follows the trajectories of individual CR particles through the GMF model of Jenson-Farrar [18], 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 \(L_c = 25\) pc and the strength normalised to reproduce the observed B/C ratio, as discussed in [19, 20]. The calculation of the trajectories of individual CRs in the GMF allows us to avoid the limitations of the diffusion approximation. We record the path length of CRs spent in a 50 pc sphere around the Earth, which can be converted to the local CR flux at given time interval.
We are interested in the case of a relatively young, $T \lesssim \text{few} \text{ Myr}$, and nearby source, $d_{\text{source}} \sim \text{few} \times 100 \text{ pc}$, and CRs energies in the range $100 \text{ GeV} - 100 \text{ TeV}$. The spread of the CRs of such energy on Myr time scale is strongly anisotropic. Strong enhancements of the CR flux occur 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 the Earth.

Figure 1 shows an example of such situation calculated for a source at the distance $300 \text{ pc}$ which has injected CRs with spectrum $dN/dE \propto E^{-\gamma_{p, \text{inj}}}$, $\gamma_{p, \text{inj}} = 2.2$, and total injection energy $E_{\text{tot}} = 1.5 \times 10^{50} \text{ erg}$. The source is placed at a GMF line passing within $50 \text{ pc}$ from the Solar system. For $E > 10 \text{ TeV}$, we calculate the CR trajectories up to $30 \text{ Myr}$, 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 function of time rises, then drops as a power-law $F(t) = F_{\text{max}}(t_0/t)^{\alpha(E)}$ up to the (energy-dependent) escape time and finally is exponentially suppressed as $F(t) = F_{\text{max}}(t_0/t)^{\alpha(E)} \exp(-t/\tau_{\text{esc}})$. In the energy range $1-10 \text{ TeV}$, we are only able to calculate trajectories up to $300 \text{ kyr}$. We extrapolate them to later times using the power-law with the slope $\alpha(E)$ derived from direct simulations in the energy range $10 \text{ TeV} - 1 \text{ PeV}$. Note that the fluctuations visible especially at large times are due to the relatively small number of CR trajectories used.

From Fig. 1 one can see that CRs with energies above $100 \text{ TeV}$ reach the Earth already $5 \text{ kyr}$ after the injection. If the source is able to accelerate CRs to energies above $10 \text{ PeV}$, their flux is suppressed already after $5 \text{ kyr}$, 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 cut-off, the slope of the spectrum softens and reaches the observed value $\gamma_p \sim 2.7 - 2.8$ after $2 \text{ Myr}$.

The observed slopes of the spectra of the heavy nuclei component of the CR flux, $\gamma_p \simeq 2.5$, are systematically harder than the slope of the proton spectrum in the TeV–PeV range $[6, 7]$, see Fig. 1 for an example of the CNO group spectrum. 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 developed in Refs. [19, 20]. The same slope of the average spectrum of $0.1-10 \text{ TeV}$ protons/nuclei in the Galaxy is deduced from a combination of gamma-ray and IceCube neutrino data [21, 22].

Assuming that the average Galactic CR proton flux at the Earth also has the slope $\gamma_p \simeq 2.5$ and that it dominates the observed CR flux in the knee energy range $E \sim 1-10 \text{ PeV}$, one finds that the local source and the average Galactic contributions to the overall CR proton fluxes are comparable in the energy range $3-30 \text{ TeV}$. The presence of the local source contribution with a 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 gives also 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 $E > 1 \text{ TeV}$ range is sub-dominant, because of the higher normalisation of the average Galactic component of the heavy nuclei fluxes, see Fig. 1 for the example of the CNO group spectrum.

**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 $30 \text{ GeV}$. This excess refers to a deviation from reference models (as e.g. those of Ref. [23]) which assume that positrons are solely secondary particles produced during the propagation of 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 [24], young ($\sim 10^4 \text{ yr}$) supernova remnants [25] and dark matter annihilations or decays [26].

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...
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 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 \cite{28}. The synchrotron and inverse Compton energy losses. The synchrotron and inverse Compton cooling rate is $t_{\text{IC}}^{-1} = 0.5[U/E_{\text{IC}}/(300 \text{ GeV})] \text{Myr}^{-1}$, where $U$ is the combined energy density of radiation and the magnetic field, $U = 0.5[B/(4 \mu \text{G})]^2 eV/cm^3$. The synchrotron and inverse Compton cooling softens the slope of the positron spectrum from $\gamma_{e^+}$ to $\gamma_{e^+} + 1$. The non-observation of such a softening limits the age of the local source to $T \lesssim 2 \text{ Myr}$.

Note that the association of the observed positron excess with a local source also implies a lower limit on the source age, $T \gtrsim 2 \text{ Myr}$. Otherwise, if the source would be much more recent, CRs would not have enough time to produce the observed excess positron flux.

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

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{pamela AMS-02.png}
\caption{Spectra of positrons (black thin line) and antiprotons (dashed line) from the local source, compared to the measured spectra of positrons \cite{12} and antiprotons \cite{13,14}. Shading shows the uncertainty of the model calculation of the $\bar{p}$ flux.}
\end{figure}

The produced positrons diffuse and spread over larger and larger distances, softening thereby 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 positrons and antiprotons 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 \cite{9,12} together with our calculation of the positron flux from the local source. For the calculation of the hadronic production cross sections, we have been employing QGSJET-II-04 \cite{27} in the modified version presented in \cite{28}. 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 normalisation 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 $t_{\text{IC}}^{-1} = 0.5[U/E_{\text{IC}}/(300 \text{ GeV})] \text{Myr}^{-1}$, where $U$ is the combined energy density of radiation and the magnetic field, $U = 0.5[B/(4 \mu \text{G})]^2 eV/cm^3$. The synchrotron and inverse Compton cooling softens the slope of the positron spectrum from $\gamma_{e^+}$ to $\gamma_{e^+} + 1$. The non-observation of such a softening limits the age of the local source to $T \lesssim 2 \text{ Myr}$.

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**Supernova nature of the local CR source.** The combination of the positron, antiproton and proton signatures of a local CR source provides a possibility to constrain its parameters. The source should have the age of $T \approx 2$ Myr. An older source would be inconsistent with the absence of radiative cooling in the positron spectrum. A younger source would fail to produce sufficient amount of antimatter. A younger source would 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 $E_{\text{tot}} \sim 10^{50}$ 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 $\sim 100$ pc wide tube of kpc-scale length 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 Myr period would have the spectrum shown by the orange curve in Fig. 3 multiplied by 0.1 Myr/1 Myr = 0.1. This contribution would be comparable to the 2 Myr old contribution. However, the energy spectrum of this younger contribution is harder, with the slope $\gamma \approx 2.5$. The presence of such a contribution would erase the effect of softening and the spectrum of TeV–PeV protons would have the same slope as the spectrum of 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 the 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 be still 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 $V_{\text{disk}} \approx 100$–$300$ kpc$^3$ is $R_{SN} \approx (1$–$3) \times 10^{-2} \text{yr}^{-1}$, or one SN per $(0.3$–$3) \times 10^4 \text{yr per kpc}^3$. This means that one could reasonably expect that at least one SN has exploded within the last million years within a 100 pc wide, kpc 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/propagation models find a natural explanation by the presence of a local CR source. In particular, we have shown that a $\sim 2$ Myr 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 presence of a nearby SN explosion was previously noticed in a completely different type of data on abundance of isotopes on Earth [22, 23]. 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 2 Myr 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 cosmic ray injection and the isotope deposition on the Earth.

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