PHYSICAL REVIEW D **92,** 063001 (2015)

Origin of the spectral upturn in the cosmic-ray C/Fe and O/Fe ratios

Nicola Tomassetti*

LPSC, Université Grenoble-Alpes, CNRS/IN2P3, F-38026 Grenoble, France

(Received 19 June 2015; published 2 September 2015; corrected 28 October 2015)

The observed spectrum of Galactic cosmic rays has several exciting features such as the rise in the positron fraction above ~10 GeV of energy and the spectral hardening of protons and helium at ≳300 GeV/nucleon of energy. The ATIC-2 experiment has recently reported an unexpected spectral upturn in the elemental ratios involving iron, such as the C/Fe or O/Fe ratios, at energy ≳50 GeV per nucleon. It is recognized that the observed positron excess can be explained by pion production processes during diffusive shock acceleration of cosmic-ray hadrons in nearby sources. Recently, it was suggested that a scenario with nearby source dominating the GeV-TeV spectrum may be connected with the change of slope observed in protons and nuclei, which would be interpreted as a flux transition between the local component and the large-scale distribution of Galactic sources. Here I show that, under a two-component scenario with nearby source, the shape of the spectral transition is expected to be slightly different for heavy nuclei, such as iron, because their propagation range is spatially limited by inelastic collisions with the interstellar matter. This enables a prediction for the primary/primary ratios between light and heavy nuclei. From this effect, a spectral upturn is predicted in the C/Fe and O/Fe ratios in good accordance with the ATIC-2 data.

DOI: 10.1103/PhysRevD.92.063001 PACS numbers: 98.70.Sa, 25.40.Sc, 96.50.sb

I. INTRODUCTION

The observed cosmic-ray (CR) spectrum has several unexplained features such as the 10–200 GeV rise of the positron fraction $e^+/(e^- + e^+)$ [1,2] and the spectral hardening of proton and helium above ~300 GeV/nucleon of energy [3–5], that are now being investigated with high precision by the AMS experiment [6,7]. Recently, a puzzling spectral upturn has been reported by the ATIC-2 experiment for nuclear ratios involving iron, such as the C/Fe or O/Fe ratios at ~50 GeV/nucleon of energy [8,9]. In the traditional descriptions, *primary* CRs such as electrons, protons, He, C-N-O, or Fe nuclei are injected in the interstellar medium (ISM) by a continuous distribution of Galactic sources, after being accelerated to power-law spectra $\sim E^{-\nu}$, with $\nu \approx 2$–2.4, up to PeV energies. Their spectrum is steepened by diffusive propagation in the Galactic halo (typical half-size $L \sim 3$–10 kpc) with diffusion coefficient $K \propto E^{\delta}$, where $\delta \sim 0.3$–0.7. Interactions of CRs with this gas of the Galactic disk (half-size $h \sim 100$ pc) give rise to *secondary* particles such as e^+ or Li-Be-B nuclei that are expected to be E^{δ} times steeper than primary CRs. The several models based on this picture agree in predicting smooth power-law spectra for primary nuclei, almost energy-independent primary/primary ratios, and a positron fraction decreasing steadily as $\sim E^{-\delta}$ [10]. The recently observed features in CR leptons, protons, and heavier nuclei are clearly at odds with these predictions. The observed positron excess requires an additional leptonic component that may come from nearby exotic sources, such as dark-matter particles annihilation, or known sources, such as pulsars or *old* supernova remnants (SNRs) [2]. In the *old* SNR scenario, the excess is produced by interactions of CR protons undergoing acceleration in proximity of the shock waves [11]. The $e^{\pm}$ production and subsequent reacceleration gives rise to a SNR component which is *harder* than that of primary protons or electrons, $E^{-\nu}$, and may explain the AMS data [12]. Other secondary species, such as Li-Be-B nuclei or antiprotons, are also expected to be produced in a similar way. Assuming that the observed CR flux is entirely provided by this type of sources, this mechanism predicts a *rise* of the B/C ratio at ~100 GeV per nucleon [13]. However, the measured B/C ratio does not show such a feature [14].

In Tomassetti and Donato [15], we have shown that the *old* SNR scenario is incomplete in order to account for the observations of CR hadronic spectra at TeV–PeV energies because these energies can be only attained with a magnetic field amplification mechanism which, in turn, is not compatible with secondary production at the shock [2,16]. Besides, the spectral hardening of CR proton and helium suggests that different types of sources may contribute to their flux [17]. In our two-component scenario, the total CR flux is described by a *nearby* source component ϕ^L in the ~ GeV–TeV region, arising from an *old* SNR, and by a *Galactic ensemble* SNR component ϕ^G, arising from younger sources with amplified magnetic fields, in the ~TeV–PeV region. A key consideration is that, due to Compton and synchrotron losses, the $e^{\pm}$ propagation length is limited within a typical distance $\lambda^{\rm rad} \sim \sqrt{\tau^{\rm rad} K} \propto E^{(\delta-1)/2}$ with cooling time $\tau^{\rm rad} \sim 300 \times E^{-1}$ Myr GeV^{-1}. A nearby source (within a few 100 pc) seems, therefore, necessary to explain the GeV-TeV $e^{\pm}$ flux [18]. In contrast, CR protons and light nuclei do

*nicola.tomassetti@lpsc.in2p3.fr

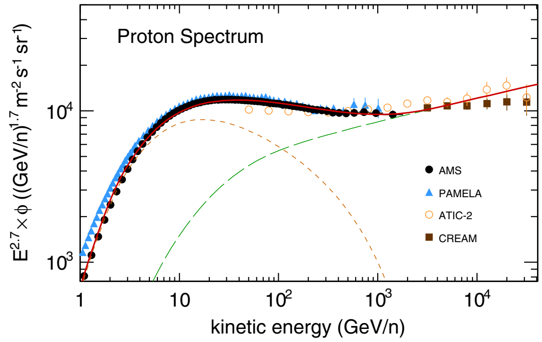

FIG. 1 (color online). Energy spectrum of CR protons multiplied by $E^{2.7}$. The solid lines indicate the model calculations. The contribution arising from the nearby SNR (short-dashed lines) and from the Galactic SNR ensemble (long-dashed lines) are shown. The data are from AMS [6], PAMELA [3], ATIC-2 [20], and CREAM [4].

not experience radiative losses, so that their local flux may arise from the contribution of a larger population of Galactic sources [19]. As shown, such a scenario may account both for the rise in the positron fraction and for the decreasing of the B/C ratio. The new AMS proton data, shown in Fig. 1, are also well consistent with a smooth flux transition as described by the model.

In this paper I show that, under such a scenario with nearby source, the shape of the spectral transition between the two components has a characteristic signature in the spectrum of heavy nuclei which is due to a combination of propagation and spallation effects. In fact, the propagation range of heavy nuclei like iron is spatially limited by inelastic collisions with the ISM nuclei, which may prevent CRs injected from distant sources to reach the Solar System. To study this effect, I make use of an effective calculation scheme, based on the propagation scale length, that enables a prediction for the ratios between light and heavy primary nuclei such as C/Fe and O/Fe. For these ratios, a remarkable spectral upturn is predicted at ~50 GeV of energy.

II. CALCULATIONS

In conventional calculations based on the diffusion approximation, as long as all sources have the same spectral properties, the model predictions for the spectra of CR nuclei at Earth are known to be only barely sensitive to the exact distribution of Galactic sources [21]. But in the case of distinct classes of sources characterized by different properties, it becomes important to account for the SNR spatial distribution [19]. This is indeed the case for the propagation of heavy nuclei in our two-component scenario, where the total observed flux arise from the superposition of two classes of SNRs, S^L and S^G, that inject CRs in the ISM with different spectral shape. In particular, the Galactic ensemble component, S^G, reflects the contribution of a large-scale SNR population that extend to several kpc of distance. Thus, the fraction of these SNRs effectively contributing to the local observed flux depends on the propagation properties of the considered element. To first approximation, the typical propagation scale distance of CR nuclei, $\lambda^{sp} \equiv \sqrt{K\tau^{sp}}$, can be estimated by using a spallation time-scale $\tau^{sp} \cong \frac{L}{h\Gamma^{sp}}$. Here, to effectively account that CRs interact only where they cross the disk, the matter density is considered as *diluted* in the propagation region by the h/L ratio [22]. In contrast to leptons, the function λ^{sp} for CR nuclei *increases* with energy and *decreases* with the mass. Roughly, the interaction cross sections increase with the projectile mass as $\sigma^{sp} \propto M^{0.7}$ [23], giving $\lambda^{sp}(E) \propto M^{-0.35}E^{\delta/2}$. This trend illustrates that, for the CR spectrum detected at Earth, heavier nuclei must come from sources located in nearer regions. Clearly, this reduces the fraction of Galactic sources that effectively contribute observed flux at Earth. In order to estimate this fraction for the relevant CR species, one has to model a realistic distribution for the Galactic SNRs as function of the distance to the Earth. For this purpose, I follow closely the effective approach of Ahlers *et al.* [24], where the spatial distribution of SNRs is determined by a toy Monte Carlo generation of randomly distributed sources drawn from a probability density function. The input function assumes a four-armed Galactic structure, which has been confirmed by a recent analysis [25]. The calculation provides the SNR distribution function in terms of Earth centered coordinates and integrated over the polar

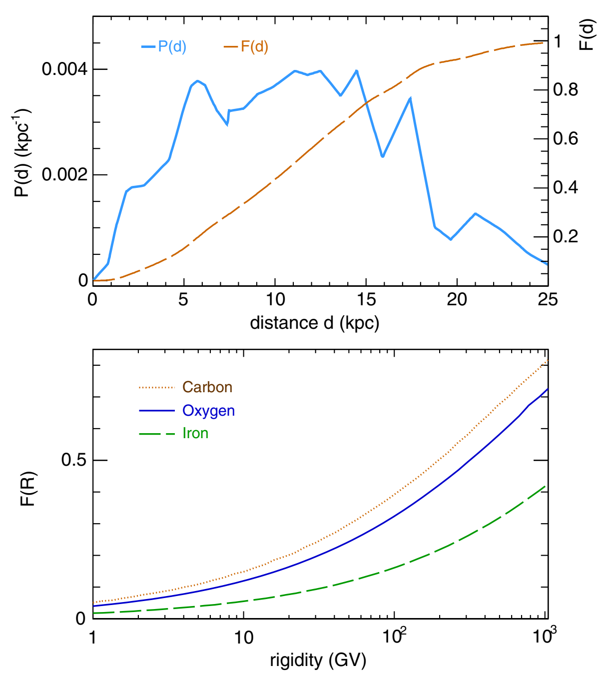

FIG. 2 (color online). Top: Distribution function (solid line) and cumulative function (dashed line) of Galactic SNRs as function of the distance d from the solar system. Bottom: Fraction of Galactic SNRs contributing to the CR flux of C (dotted line), O (solid line), and Fe (dashed line).

coordinate. The normalized probability density of SNRs, $P(d)$, is shown in Fig. 2 (top) as a function of the distance d from the Earth. As seen, the contribution is probabilistically suppressed within ~1.5 kpc due to the interarm position of the Solar System, but this does not prevent the factual occurrence of one (or few) anomalous SNR events in the Solar neighborhood that would manifest itself as a distinctive component of the local CR spectrum. In the figure, it is also shown the cumulative fraction of SNRs falling within a certain distance d, $F(d) = \int_0^d P(l)dl$. From this information, the fraction of Galactic SNRs contributing to the CR flux detected for a j-type element is estimated as $F(\lambda_j^{\rm sp})$, where $\lambda_j^{\rm sp}$ can be expressed as function of energy or rigidity.

The model setup follows closely our earlier work [15,26]. I briefly outline the key parameters. For the local SNR component, the magnetic field is $B = 1\ \mu$G and the upstream fluid speed is $u_1 = 5 \times 10^7\ {\rm cm\,s^{-1}}$. The SNR age is $\tau^{\rm snr} = 50$ kyr. Its maximum rigidity is $R^{\rm max} = 1$ TV. A damping factor $\kappa_B = 16$ is used to enhance the (otherwise) Bohm-like diffusivity at the shock. These properties are typical for SNRs at their late evolutionary stages. For the large-scale population of the Galactic ensemble, represented by younger SNRs with strong shocks and amplified magnetic fields, typical parameters are $u_1 \sim 10^9\ {\rm cm\,s^{-1}}$, $B/\kappa_B \sim 100\ \mu$G, and $R^{\rm max} \sim 5$ PV. No secondary production occurs in SNRs with these properties, and their spectrum, $S^G \sim R^{-\nu}$, is independent on the exact values of the environmental parameters. The spectral indices are taken as $\nu = 2.2$ and 2.1 for $Z = 1$ and $Z > 1$, respectively, while the spectra from the *old* SNR component are softer by 0.5 for all elements. The spectral indices of the SNR ensemble agree with the basic DSA predictions and with γ–ray observations of young SNRs [5]. On the contrary, softer spectra may arise from weak shocks or from environmental effects such as interaction between shock and dense gas or turbulence damping, which may well be the case in *the old* SNRs. The elemental dependence of the spectral indices is a known feature of the CR spectrum, possibly ascribed to a M/Z–dependent injection efficiency in SNR shocks [27]. The source abundances and the cross section for destruction/production processes are those adopted from previous studies [26,28]. The diffusion coefficient is taken as a universal function in rigidity, $K(R) = \beta K_0 (R/R_0)^\delta$, with $K_0/L = 0.1/5\ {\rm kpc\,Myr^{-1}}$ and index $\delta = 1/2$, as expected from an Iroshnikov-Kraichnan turbulence spectrum and tested to the new B/C data from PAMELA. The ISM is assumed to be composed by 90% H and 10% He, with surface density $2h \times n^{\rm ism} = 200\ {\rm pc} \times 1\ {\rm cm^{-3}}$. The solar modulation is described under the *force-field* approximation [29]. The proton spectrum is shown in Fig. 1 using a modulation potential $\Phi = 800$ MV to describe the new AMS data. The spectrum is described a superposition of two source components $\phi_p = \phi_p^L + \phi_p^G$, shown as dashed lines, that amounts to 85% for the nearby SNR and 15% for the ensemble, at 1 GeV/n.

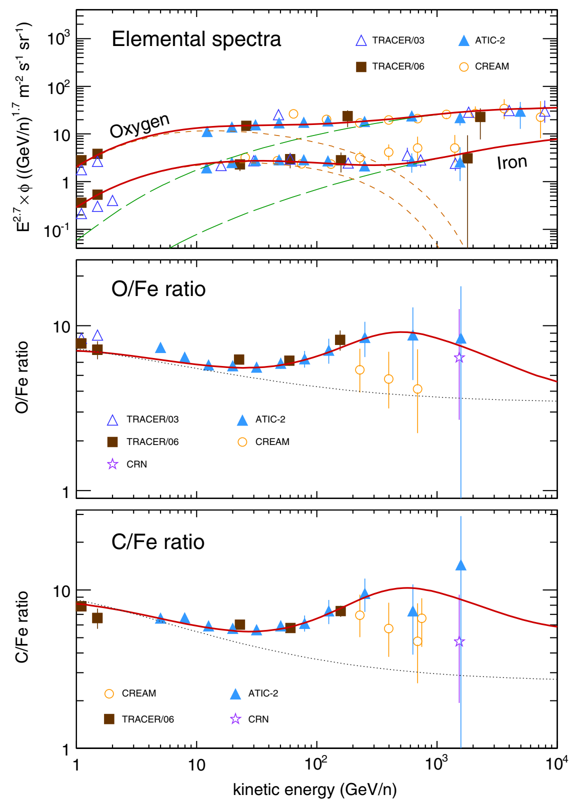

FIG. 3 (color online). Energy spectra of O and Fe multiplied by $E^{2.7}$, and nuclear ratios C/Fe and O/Fe as function of kinetic energy per nucleon. The solid lines indicate the model calculations. The contributions arising from the nearby source (short-dashed lines) and from the Galactic ensemble (long-dashed lines) are shown. The data are from ATIC-2 [8,9], CREAM [30], CRN [31], and TRACER [32,33]. The TRACER data on nuclear ratios are those obtained in Ref. [9]. Standard model predictions are also shown for the C/Fe and O/Fe ratios (dotted lines).

To account for the propagation/spallation effect described above, the source term for the Galactic SNR component, $S_j^G(E)$, is replaced by the *effective source term* $\hat{S}_j^G \equiv F_j(E) \times S_j^G(E)$ for all j-type nuclei, where $F_j(E) \equiv F(\lambda_j^{\rm sp}(E))$ is the fraction of Galactic SNRs contributing the nuclear species jth. In the high-energy limit one has $\hat{S}^G \to S^G$ for all species, but lighter CR nuclei experience a more rapid convergence than heavier nuclei, due to interactions. Typical cross sections for collisions with the ISM are $\sigma^{\rm sp} \sim 40$ mb for protons, ~300 mb for C-N-O, and ~900 mb for Fe. The function $F(R)$ is shown Fig. 2 (bottom) as function of rigidity for C, O and Fe.

III. RESULTS

The model predictions are shown in Fig. 3 for the O/Fe and C/Fe ratios and for the spectra of Fe and O. The two flux components are shown as dashed lines. The

C spectrum, not shown, is very similar to the O spectrum. Owing spallation, the Fe spectrum of the Galactic SNR population is slightly reshaped due to a "missing flux" from distant SNRs that *do not* contributed to its total flux at Earth. This effect is maximized in the primary/primary ratios C/Fe and O/Fe that, as seen in the figure, experience a remarkable spectral upturn above a few tenths of GeV/nucleon energies. The ATIC-2 data are described very well by the model. These features are also present in the TRACER data, as shown in Panov *et al.* [9], but not in the CREAM data. For the two ratios the upturn is similar and, in fact, the C/O ratio is featureless. At $E \sim 1$–10 GeV/nucleon, the flux is entirely dominated by the nearby component. At energies above ~TeV/nucleon, the spallation effect vanishes and the ratios become asymptotically representative of the spectral properties of the Galactic ensemble. For reference, the C/Fe and O/Fe ratios arising from standard calculations, i.e., using one class of sources, are plotted as dotted lines. As discussed, conventional models are unable to describe any spectral change on these ratios. From this mechanism, similar features are expected for other ratios such as Ne/Fe, Mg/Fe, or Ar/Fe. Interestingly, an upturn in the Ar/Fe and Ca/Fe ratios was observed by HEAO3 [34]. However, these elements require more refined elaborations due to the presence of secondary components in their flux. Also the effective approach used here, only suitable for primary/primary nuclear ratios, suffers from several limitations. For instance, the dilution factor h/L used to estimated the average interaction rate is probably a too crude simplification that leaves an uncertainties on the absolute scale of $\lambda^{\rm sp}$. In fact, since the observed CRs are both injected/detected from/in the disk, it is improbable that during their past history they have spent much time in the halo. Furthermore, due to possible inhomogeneous diffusion or convection processes, the CR transport may be either more confined in the disk or swept out in the halo, respectively [19,22,28]. A rigorous treatment of the problem has to account for all these unknowns which, however, require the use of better quality CR data. In particular, the Fe spectrum deserves more experimental investigation. Fortunately, we are in a proficient era for CR physics. Ongoing and planned space experiments such as AMS, ISS-CREAM [35], or CALET [36] will measure these elements over a large energy range.

IV. ON THE NEARBY SOURCE

In this interpretation of the C/Fe and O/Fe ratios, the presence of a source placed near the Solar System is a key ingredient. From the model presented here, such a source is identified as a local SNR ($d \sim$ few100 pc) with low magnetization ($B \sim \mu$G), slow shock speed ($u_1 \sim 5 \times 10^7$ cm s^{-1}), and a high gas density in comparison to that of the ISM $n \sim 1$ cm^{-3}. The accelerated spectra are rather steep ($\nu \sim 2.7$) and limited to a maximum rigidity $R^{\rm max} \sim$ TV. These properties are appropriate for *old* SNRs of type Ia. Remnants of this type may be not be detectable in γ rays any longer, unless the rate of p − p collisions is enhanced by the presence of denser media such as molecular clouds. In this case, the emission might be sufficiently high to be detected by the *Fermi*-LAT observatory. Possible examples are SNRs W44, W28, W51C or IC-443 [37–40]. Indications of nearby sources in the CR spectrum are found in several recent studies [17,27,41–43] and noticed from independent studies in connection with the local bubble [41,44,45]. Concerning the secondary production mechanism, antiprotons are also emitted from such a SNR but, similarly to the case of Li-Be-B nuclei [15], no striking signatures are expected after accounting for both source components. In fact, the $\bar{p}/p$ ratio "excess" predicted in related studies [12,46,47] arises from one-component scenarios. The diffuse γ-ray emission can be used to test models involving nearby sources. Roughly, one may expect a diffuse spectrum which is harder than that predicted by standard models, at least in the Galactic plane where the emission is dominated by the π^0 production from p − p collisions. However, the appearance of individual sources in the CR spectrum demands a different calculation scheme, possibly beyond the usual steady-state description [48–50]. This description might be, in fact, an oversimplification of reality which does not reflect the *stochastic nature* of SNR events and their influence on the surrounding CR flux. Interestingly, indications of CR flux variations in the Galaxy are found by recent *Fermi*-LAT observations of the diffuse γ-ray emission [51] and were also noted in previous studies [52,53]. The *Fermi*-LAT data show harder γ-ray spectra in the inner Galaxy which are at odds with standard calculations. While these observations might be explained in terms of SNR properties [51,53], a complete calculation—possibly accounting for their space-time discreteness—has never been attempted for γ rays.

V. CONCLUSIONS

This work is motivated by the search of a comprehensive, agreeable model for Galactic CRs that is able to account for the several puzzling features recently observed in their spectrum. Without the presence of nearby sources, it is difficult to interpret the ATIC-2 data in the context of known models of CR propagation. The only alternative interpretation of the spectral upturn is the one proposed by the ATIC-2 Collaboration, the *closed Galaxy model with bubbles* [9]. In my opinion, their model may represent a viable solution of the puzzle, but it suffers from some problems. In particular, it predicts a too weak rise of the elemental ratios, while requiring too steep source spectra and a too flat B/C ratio. On the contrary, the interpretation presented here accounts well for the basic observations on primary spectra and secondary/primary ratios. Despite the approximate calculation method employed in this work, it is remarkable that the spectral upturn arises under a scenario that is able to simultaneously account for important features in the CR spectrum, namely, the rise in the positron fraction and the spectral hardening of proton and nuclei.

ACKNOWLEDGMENTS

I am grateful to D. Maurin and L. Derome for discussions, and to A. Panov for kindly providing me with the ATIC-2 data. Other data are extracted from the CRDB database [54]. This work is supported by the ANR LabEx grant ENIGMASS at CNRS/IN2P3.

[1] O. Adriani *et al.*, Nature (London) **458**, 607 (2009).
[2] P. D. Serpico, Astropart. Phys. **39–40**, 2 (2012).
[3] O. Adriani *et al.*, Science **332**, 69 (2011).
[4] H. S. Yoon *et al.*, Astrophys. J. **715**, 1400 (2010).
[5] P. Blasi, Astron. Astrophys. Rev. **21**, 70 (2013).
[6] M. Aguilar *et al.*, Phys. Rev. Lett. **114**, 171103 (2015).
[7] L. Accardo *et al.*, Phys. Rev. Lett. **113**, 121101 (2014).
[8] A. D. Panov *et al.*, J. Phys. Conf. Ser. **409**, 012036 (2013).
[9] A. D. Panov, N. V. Sokolskaya, and V. I. Zatsepin, Nucl. Phys. B, Proc. Suppl. **256–257**, 233 (2014).
[10] I. A. Grenier, J. H. Black, and A. W. Strong, Annu. Rev. Astron. Astrophys. **53**, 199 (2015).
[11] P. Blasi, Phys. Rev. Lett. **103**, 051104 (2009).
[12] P. Mertsch and S. Sarkar, Phys. Rev. D **90**, 061301 (2014).
[13] P. Mertsch and S. Sarkar, Phys. Rev. Lett. **103**, 081104 (2009).
[14] I. Cholis and D. Hooper, Phys. Rev. D **89**, 043013 (2014).
[15] N. Tomassetti and F. Donato, Astrophys. J. **803**, L15 (2015).
[16] M. Kachelrieß, S. Ostapchenko, and R. Tomàs, Astrophys. J. **733**, 119 (2011).
[17] A. E. Vladimirov, G. Jóhannesson, I. V. Moskalenko, and T. A. Porter, Astrophys. J. **752**, 68 (2012).
[18] T. Delahaye, J. Lavalle, R. Lineros, F. Donato, and N. Fornengo, Astron. Astrophys. **524**, A51 (2010).
[19] R. Taillet and D. Maurin, Astron. Astrophys. **402**, 971 (2003).
[20] A. D. Panov *et al.*, Bull. Acad. Sci. USSR, Phys. Ser. (English Transl.) **73**, 564 (2009).
[21] Y. Genolini, A. Putze, P. Salati, and P. D. Serpico, Astron. Astrophys. **580**, A9 (2015).
[22] F. Jones, Astrophys. J. **222**, 1097 (1978).
[23] J. R. Letaw, R. Silberberg, and C. H. Tsao, Astrophys. J. **51**, 271 (1983).
[24] M. Ahlers, P. Mertsch, and S. Sarkar, Phys. Rev. D **80**, 123017 (2009).
[25] D. Camargo, C. Bonatto, and E. Bica, Mon. Not. R. Astron. Soc. **450**, 4150 (2015).
[26] N. Tomassetti and F. Donato, Astron. Astrophys. **544**, A16 (2012).
[27] M. A. Malkov, P. H. Diamond, and R. Z. Sagdeev, Phys. Rev. Lett. **108**, 081104 (2012).
[28] N. Tomassetti, Astrophys. J. **752**, L13 (2012).
[29] L. J. Gleeson and W. I. Axford, Astrophys. J. **154**, 1011 (1968).
[30] H. S. Ahn *et al.*, Astrophys. J. **707**, 593 (2009).
[31] D. Muller, S. P. Swordy, P. Meyer, J. L'Heureux, and J. M. Grunsfeld, Astrophys. J. **374**, 356 (1991).
[32] M. Ave, P. J. Boyle, F. Gahbauer, C. Höppner, J. R. Hörandel, M. Ichimura, D. Müller, and A. Romero-Wolf, Astrophys. J. **678**, 262 (2008).
[33] A. Obermeier, M. Ave, P. Boyle, Ch. Höppner, J. Hörandel, and D. Müller, Astrophys. J. **742**,14 (2011).
[34] W. R. Binns, T. L. Garrard, M. H. Israel, M. D. Jones, M. P. Kamionkowski, J. Klarmann, E. C. Stone, and C. J. Waddington, Astrophys. J. **324**, 1106 (1988).
[35] E. S. Seo *et al.*, Adv. Space Res. **53**, 1451 (2014).
[36] O. Adriani *et al.*, Nucl. Phys. B, Proc. Suppl. **256–257**, 225 (2014).
[37] A. A. Abdo *et al.*, Science **327**, 1103 (2010).
[38] A. A. Abdo *et al.*, Astrophys. J. **712**, 459 (2010).
[39] A. A. Abdo *et al.*, Astrophys. J. **718**, 348 (2010).
[40] A. A. Abdo *et al.*, Astrophys. J. **706**, L1 (2009).
[41] I. V. Moskalenko, A. W. Strong, S. G. Mashnik, and J. F. Ormes, Astrophys. J. **586**, 1050 (2003).
[42] M. Kachelrieß, A. Neronov, and D. V. Semikoz, arXiv: 1504.06472.
[43] A. E. Nierstenhoefer *et al.*, in *Proceedings of ECRS 2014, Kiel, Germany*, arXiv:1501.06434.
[44] N. Benitez, J. Maíz-Apellániz, and M. Canelles, Phys. Rev. Lett. **88**, 081101 (2002).
[45] A. D. Erlykin and A. W. Wolfendale, Astropart. Phys. **35**, 449 (2012).
[46] P. Blasi and P. D. Serpico, Phys. Rev. Lett. **103**, 081102 (2009).
[47] K. Kohri *et al.*, arXiv:1505.01236
[48] P. Blasi and E. Amato, J. Cosmol. Astropart. Phys. 01 (2012) 010.
[49] G. Bernard, T. Delahaye, Y.-Y. Keum, W. Liu, P. Salati, and R. Taillet, Astron. Astrophys. **555**, A48 (2013).
[50] S. Miyake, H. Muraishi, and S. Yanagita, Astron. Astrophys. **573**, A134 (2015).
[51] M. Ackermann *et al.*, Astrophys. J. **750**, 3 (2012).
[52] S. W. Digel, I. A. Grenier, S. D. Hunter, T. M. Dame, and P. Thaddeus, Astrophys. J. **555**, 12 (2001).
[53] I. Büsching, A. Kopp, M. Pohl, R. Schlickeiser, C. Perrot, and I. Grenier, Astrophys. J. **619**, 314 (2005).
[54] D. Maurin, F. Melot, and R. Taillet, Astron. Astrophys. **569**, A32 (2014).