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Critical Aspects of the Nested Leaky-Box Model

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Anomalies in cosmic-ray (CR) fluxes, such as the rising positron flux and the flat antiproton-to-proton ratio, have called into question the standard halo model of CR transport and supposedly support alternative models, such as the nested leaky box model. Here, we test such a model in terms of both primary cosmic-ray spectra, spectra of stable and unstable nuclei and antimatter production. We find the standard version of the model should be considered as ruled out as it is in direct conflict with several observational facts and current data. We further show that the flat antiproton-over-proton ratio proves that the Galactic residence time cannot be energy-independent.

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1. Introduction

The discovery of the rising positron fraction by PAMELA [2] and AMS-02 [4] is in conflict with the naive expectation of the standard cosmic-ray (CR) transport model in which the accumulated grammage in the Galaxy decreases with energy, as indicated by secondary-to-primary ratios. To reconcile the measurement with the model, one has to introduce pulsars as primary positron sources [15, 16]. Another approach is to conceive an alternative transport model in which the rising positrons can be explained by purely secondary positrons [8, 18]. One such model is the nested leaky box model (NLBM) which recently claimed to provide a natural explanation of B/C and similar secondary/primary ratios, as well as of positrons [9] and antiprotons [10, 11]. The underlying idea is that CRs accumulate an energy-dependent grammage around CR sources while being trapped in so-called cocoons. Low-energy secondary CR nuclei are then mainly produced while being trapped in these cocoons and secondary-to-primary ratios, such as B/C, are sensitive to the energy dependence of the cocoon grammage. At large enough energies, the cocoon grammage becomes negligible compared to the grammage accumulated on Galactic scales which is assumed to be energy independent. This transition can naturally explain the observed hardening of secondary-to-primary ratios at 300 GV seen in AMS-02, DAMPE and CALET [3, 6, 12]. Furthermore, positrons and antiprotons are produced by primary nuclei with $\sim 10-20$ times more energy. Hence, their fluxes are mainly sensitive to the energy independent Galactic grammage even at low energies. As a result, a flat $e^+/\bar{p}$-ratio is recovered in the NLBM as long as the energy losses of positrons are negligible during Galactic transport. The steepening in the electron plus positron flux at $\sim$ 1 TeV [7] can then be interpreted as the onset of losses which leads to a Galactic propagation time of $\sim$ 1 Myr. This picture could potentially shake the pillars of the standard model of CR transport in the Galaxy, developed through decades of theoretical investigation.

The formation of low-diffusivity zones around CRs is supported both theoretically via streaming instabilities around CR accelerators [21, 23] and observationally by the discovery of TeV halos [1], extended regions of TeV gamma-ray emission around some pulsars explained by a diffusion coefficient much smaller than in the standard model of Galactic CR transport. Given these developments, we critically evaluated the NLBM by comparing its predictions with data on primary and secondary nuclei, unstable isotopes, positrons, and antiproton fluxes. Our findings expose fundamental conflicts between the NLBM framework and observations, questioning its viability as a replacement for the standard CR transport model: 1. The observed spectral hardening of primary nuclei contradicts NLBM predictions, requiring artificial modifications to reconcile the data. 2. AMS-02's preliminary ^{10}Be/^{9}Be measurements are inconsistent with NLBM predictions. 3. The flatness of the $e^+/\bar{p}$ ratio cannot be reproduced when positron energy losses are included. 4. New antiproton cross-section data and observed spectra invalidate energy-independent propagation, a core NLBM assumption. 5. Grammage estimates necessary to explain B/C ratios are incompatible with those required for positrons and antiprotons.

The article is organized as follows: we describe the model in Sect. 2. In Sect. 3, we present the results of our calculations in terms of spectra of primary and secondary nuclei, unstable nuclei, positrons and antiprotons. Our conclusions are drawn in Sect. 4.

2. Model

In this section, we summarize the most important aspects of our model, while a full description can be found in Ref. [22]. The NLBM envisions CRs diffusing in a hierarchy of two nested zones. In each zone, CRs accumulate a given grammage $\chi_i = m_p n_i c \tau_j$ with the proton mass m_p, the speed of light c, the gas density n_i and CR escape time τ_i of zone i. As discussed above, a crucial assumption of the NLBM is that the Galactic residence time τ_G is energy-independent and ~ 1 Myr to explain the observed steepening in the electron-positron flux at 1 TeV. On the other hand, the cocoon time scale is energy dependent. We assume the same energy dependence as in prior studies [11] leading to a cocoon grammage of the form of

$$\chi_c(E) = \chi_0 \left(\frac{E}{10\ \mathrm{GeV}} \right)^{-\zeta \ln\left(\frac{E}{\mathrm{GeV}}\right)} . \tag{1}$$

Similar to the standard transport model, the Galactic gas disk is modeled as a cylinder with a radius $R_\mathrm{G} \approx 10$ kpc and a half-height $h \approx 100$ pc and is uniformly populated with CR sources that accelerate nuclei following a nearly universal power-law spectrum. However, in the NLBM, the same region corresponds to the whole Galactic propagation volume, namely there is no extended halo around the disk.

The equilibrium density of a CR species i in the Galaxy is given by

$$N_{\mathrm{G},i}(E) = \left(1 + \frac{\chi_\mathrm{G}}{\chi_i} + \frac{\tau_G}{\tau_d} \right)^{-1} \tau_\mathrm{G} Q_{\mathrm{G},i}(E), \tag{2}$$

where $\chi_i = \frac{m_p}{\sigma_i}$ is the critical grammage of nucleus i, τ_d is the lifetime in case of radioactive isotopes and the source term $Q_{\mathrm{G},i}(E)$ contains the CRs leaking from the cocoons into the Galaxy as well as secondary production in the Galaxy. For a primary nucleus, the energy dependence is solely determined by the injection spectrum. Hence, in order to obtain a spectral break in H and He fluxes as the one observed, one needs to inject these nuclei with a broken power law:

$$q_i(E) \;=\; q_{0,i} \left(\frac{E}{E_0} \right)^{-\alpha_i} \left[1 + \left(\frac{E}{E_{b,i}} \right)^{\frac{\Delta\alpha}{s}} \right]^{s} , \tag{3}$$

where $E_{b,i}$ is the break energy, α_i is the spectral index, $\Delta\alpha$ is the spectral difference and s is the smoothness of the transition, fixed at $s = 0.05$. Here, the position and amount of the break have no connection to the similar feature observed in B/C while, in the halo model, both features can be related to the same origin.

Since secondary antimatter, such as positrons and antiprotons, do not retain the kinetic energy of their primaries, one needs the full differential cross-section to calculate their production. The flux of antiprotons due to a primary i (here protons and He) follows as:

$$N_{\mathrm{G},\bar{p}} = \frac{1}{m_p} \int_{E_{\bar{p}}^{\mathrm{th}}}^{\infty} dE' N_{\mathrm{G},i}(E') \left[\chi_\mathrm{G} + \chi_c(E') \right] \frac{d\sigma_{i,\bar{p}}(E,E')}{dE}, \tag{4}$$

where $E_{\bar{p}}^{\mathrm{th}}$ is the minimum energy to produce an antiproton of energy E.

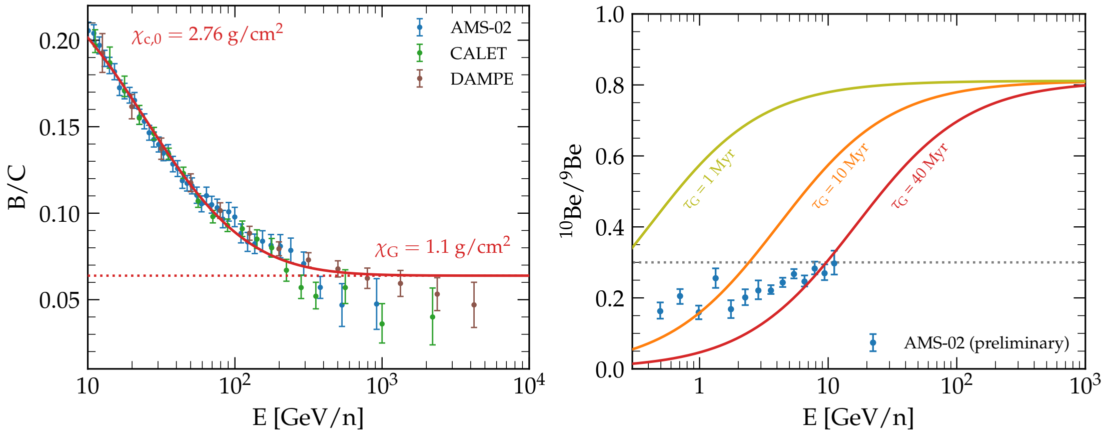

Figure 1: Left panel: Flux ratio of Boron-to-Carbon as a function of kinetic energy per nucleon, measured by AMS-02 [5, 6], DAMPE [12], and CALET [3]. The results are compared with our best-fit model predictions. Right panel: Flux ratios of beryllium isotopes (^{10}Be/^{9}Be) as a function of kinetic energy per nucleon. The plot displays preliminary measurements from the AMS-02 experiment. Predictions from the NLBM are overlaid for comparison, illustrating different galactic residence timescales (τ_G). The curves, from top to bottom, correspond to τ_G = 40, 10, and 1 Myr, respectively.

Furthermore, for positrons, energy losses might become important at high energies. Hence, their flux is given by:

$$N_{G,e^+} = \frac{1}{m_p}\left(1+\frac{\tau_G}{\tau_{\rm loss}}\right)^{-1}\int_0^\infty dE' N_{G,i}(E')\,[\chi_G + \chi_c(E')]\,\frac{d\sigma_{i,e^+}(E,E')}{dE}, \tag{5}$$

where the losses inside the cocoons are considered negligible.

With these ingredients, we can calulate secondary-over-primary ratios and antimatter fluxes in the NLBM. For sake of simpicity and without loss of generality, we limit our analysis to nuclei lighter than O.

3. Results

3.1 Nuclei

We obtain our best-fit grammage by fitting the NLBM predictions to the data of the B/C ratio, see left panel of Fig. 1. The hardening at ~ 300 GeV/n is due to the transition from being dominated by the cocoon grammage to the Galactic one.

While ratios such as B/C are only sensitive to the grammage, radioactive nuclei can constrain the residence time itself. The right panel of Fig. 1 shows the NLBM prediction for different τ_G with a grammage fixed by B/C compared to preliminary AMS-02 data of the radioactive ^{10}Be over ^{9}Be flux ratio. While at low energies, other effects, such as cross-section uncertainties and ionization losses, might be important, the model should reproduce the data around 10 GeV/n. The data of radioactive nuclei seems to suggest Galactic residence times $\gtrsim$ 10 Myr, much larger than usually advocated for in the NLBM.

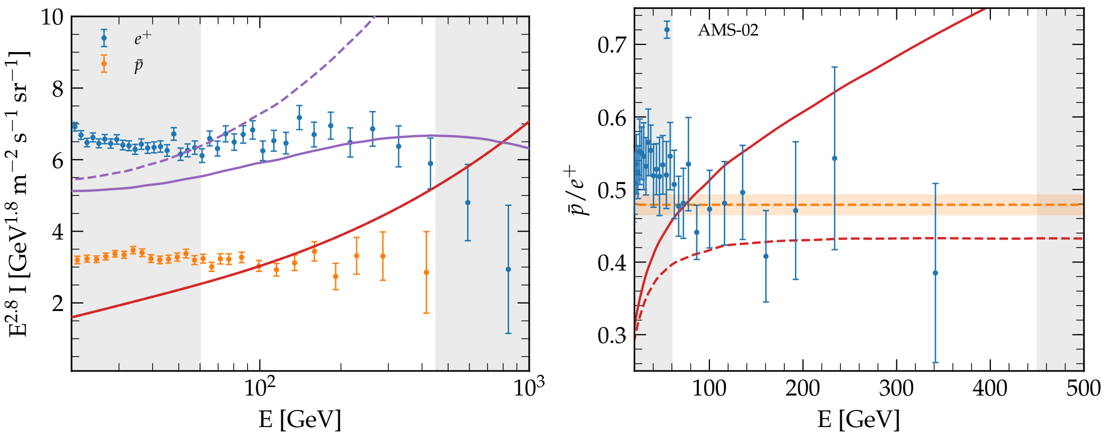

Figure 2: Fluxes of antiprotons ($\bar{p}$) and positrons (e^+) (left panel), along with their flux ratio (right panel) as functions of energy, compared with the predictions of the NLBM. The model representations are as follows: dashed lines for predictions without energy losses in the positron model and solid lines for energy losses with τ_G = 1 Myr in the positron model. The model fluxes have been rescaled by a factor of $\eta = 2$, as detailed in the text. The gray shaded areas highlight energies outside the validity range of the constant fit, depicted in both panels.

3.2 Antimatter

An independent check of the grammage and residence times can be obtained from antimatter fluxes, especially antiprotons and positrons. Both are mainly produced by protons and He nuclei with energies ~ 10 times their energy. As a result, their fluxes at the energies measured by AMS-02 are mainly sensitive to the Galactic grammage. However, because high-energy positrons suffer considerable energy losses, their flux gives an independent way to constrain the Galactic residence time that must give consistent results with the constraints from unstable nuclei.

After fitting both the protons and He fluxes measured by AMS-02 [6], the corresponding positron and antiproton fluxes and their ratio are shown in Fig. 2. In the right panel, one can see that the flat Galactic grammage indeed leads to a flat e$^+$/$\bar{p}$-ratio compatible wiith the measurement of AMS-02. However, as soon as energy losses are included, the positrons lose considerable energy even at residence times of $\tau_G \sim 1$ Myr. This indicates that in order to reproduce antimatter flux ratios, τ_G needs to be shorter which is in direct conflict with the trend inferred from unstable nuclei fluxes.

The problems of the NLBM to explain antimatter and nuclei data at the same time become even more severe when looking at the absolute fluxes. The left panel of Fig. 2 illustrates that using a constant grammage leads to fluxes that are harder than the measurements. Furthermore, using the same grammage as inferred from B/C, the NLBM actually underpredicts the positron and antiproton fluxes by a factor $\gtrsim 2$ (fluxes in the figure are multiplied by 2). The reason for the discrepancy is the fact that antimatter fluxes are only sensitive to the Galactic grammage in the NLBM. A more detailed derivation can be found in Ref. [22] and it agrees well with the results of Ref. [14]. Hence, the NLBM fails to reproduce nuclei and antimatter fluxes self-consistently using the same grammage, a severe shortcoming that is absent in the standard propagation model.

3.3 The Energy Dependence of the Galactic Residence Time

One of the key predictions of the NLBM is the energy-independent Galactic residence time that potentially explains the flat antiproton-to-proton ratio. However, here we argue, that the measured energy independence actually proves the residence time to be energy dependent, ruling out the NLBM in its standard form.

The argument goes as follows: Let's assume that CR primaries are injected by their sources with a power-law spectrum $\propto E^{-\alpha}$. With a Galactic residence time $\tau_G \propto E^{-\delta}$, the flux ratio of a secondary over its primary would typically scale as $E^{-\delta}$. Based on this naive expectation, the flat antiproton-to-proton ratio seems to be a problem for the standard CR transport model and is potentially solved by the NLBM. However, for the $\bar{p}/p$-ratio, two additional effects are important: 1. Recent reevaluations of the antiproton production cross sections unveiled a cross section that increases with energy as E^{β} [13, 17]). 2. Antiprotons are produced by protons with an energy ~ 10 times larger than the parent proton. Hence, spectral features, such as the hardening of the proton flux at 300 GV, will appear at 10 times lower energies in the antiproton flux. As a result, the flux ratio at energies between 30 and 300 GV will rise with energy by the amount of the hardening $\Delta\alpha$.

The final antiproton-to-proton ratio scales then as $E^{\Delta\alpha+\beta-\delta} \propto E^{0.35-\delta}$. It follows that, for this ratio to be flat, the Galactic residence time needs to be energy dependent. The required δ is in good agreement with the standard model of CR transport and is incompatible with one of the most critical assumptions of the NLBM. Our finding aligns well with the extensive literature that reproduces the the normalization and the shape of the antiproton flux in the standard CR transport model (see e.g. [20]).

4. Conclusions

The standard model of Galactic CR transport has recently been questioned due to the unexpected behavior of the CR positron flux. While it could be understood by introducing pulsar wind nebulae as primary positron sources [15, 16], other explanations propose to substantially modify the transport model in order to bring secondary positrons in agreement with the data [8, 18, 19]. One such model is the NLBM which found further support by the flat energy dependence of the $\bar{p}/p$ and e^+/p ratios [10, 11] and the discovery of low diffusivity zones around sources [1].

In this work, we scrutinize the model against light CR nuclei, unstable isotope and antimatter fluxes. We find that CR primaries need to be injected with broken power-law spectra in order to reproduce the hardening of H and He fluxes. Within this framework, this hardening has no relation to the similar hardening observed in secondary-to-primary ratios and their position and change of slope coincide purely coincidentally. Furthermore, preliminary measurements of unstable isotopes seem to prefer residence times, that are much larger than what is typically assumed in the NLBM. However, the $e^+/\bar{p}$-ratio indicates much smaller residence times, rendering it impossible to reconcile the two measurements in the NLBM.

Once the grammage is fixed by B/C, we find that the NLBM fails to reproduce positron and antiproton fluxes. Using an energy-independent Galactic escape time, the model is incapable of reproducing these measurements consistently in a unified picture. Lastly, we show that new evaluations of the antiproton production cross sections together with the hardening of the proton flux require an energy-dependent Galactic residence time that is in good agreement with the standard CR transport model but incompatible with the assumption of the NLBM.

We conclude that the NLBM in its current form is incompatible with the data and should be ruled out or requires substantial revisions. Interestingly, the required modifications of an energy-dependent, larger residence time make the NLBM resemble more and more the standard CR transport model. Nonetheless, even if subdominant, effects like the grammage accumulated near sources must leave signatures in the data and once detected, will play an important role in clarifying the global picture of Galactic CR transport.

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