Spectrum of antiprotons confined in the Earth’s magnetosphere

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Abstract. We have demonstrated a reasonably satisfactory agreement between the theoretically simulated geomagnetically confined antiproton fluxes and the Pamela experimentally observed antiproton fluxes within the Earth’s magnetosphere. The antiprotons were considered created partially in nuclear reactions of direct proton/antiproton production ($p+p$, $p+p\bar{p}+p+p$) and to an even larger extent in nuclear reactions of neutron/antineutron (indirect) pair production ($p+p$, $n+n\bar{p}+p+p$) both processes resulting from cosmic rays interactions with the Earth’s upper atmosphere. Although the theoretically predicted spectrum of trapped antiprotons is not a perfect match in all details with the in-situ observed flux spectra, we do note an excellent antiproton flux match around 1 GeV kinetic energy. Thus, we conclude that what we earlier had largely predicted, the Pamela antiproton detection experiment has now observed.

1. Introduction
In the August 2011 issue of the Astrophysical Journal there was published the paper “The discovery of geomagnetically trapped cosmic ray antiprotons” by O. Adriani et al., 2011, ApJL 737, number 2, L29, PAMELA collaboration [1]. In connection with the appearance of that paper we would like to make some remarks concerning the citation done in the paper regarding results of theoretical studies of geomagnetically confined antimatter (antiprotons) made in our publication [2].

1.1. Direct antiproton production source
In our early theoretical papers devoted to the study of antimatter trapped in planetary magnetospheres [3,4] we first showed that the Earth’s magnetosphere can indeed contain and possess an antiproton radiation belt. This is caused by interaction of galactic cosmic rays (GCR) with the Earth’s residual upper atmosphere at altitudes of about 1000 km in nuclear reactions that yield direct antiproton production ($p+p$, $p+p\bar{p}+p+p$). This particular source mechanism produces antiproton fluxes of one to two orders of magnitude greater than that of the interstellar antiproton flux (created by the same GCR on 5 to 7 g/cm\textsuperscript{2} of the residual matter encountered by GCR during its lifetime in the Galaxy). The maximum of this terrestrial antiproton belt flux is typically located on $L$-shells of 1.20-1.25. The antiproton pitch angle distribution in this belt has a classic maximum at 90° equatorial pitch-angle.

In that one particular paper [2] cited by Dr. Adriani and coworkers we had searched how terrestrial radial diffusion influences the space distribution and the flux values of the antiproton belt created by the mechanism of direct antiproton production source only. The flux captured within the plane of the geomagnetic equator were considered in frame of the radial diffusion model.
\[ Q_{2p}(L, E_p) + Q_{3p}(L, E_p) = \frac{f(L)}{\lambda_{\text{inel}}} - L^2 \frac{\partial}{\partial L} \left( \frac{1}{L} D_{LL}(L, E_p) \frac{\partial f}{\partial L} \right) + \frac{1}{\sqrt{\mu}} \frac{\partial}{\partial \mu} \left( \sqrt{\mu} \left( \frac{d\mu}{dt} \right) f \right). \]  

(1)

where \( \mu \) is the antiproton magnetic moment, \( L \) is the McIlwain \( L \)-shell parameter in \( R_{\text{Earth}} \), \( f(L, \mu) = F(L, E_p)/P(E_p) \) represents the phase space distribution function, \( \langle d\mu/dt \rangle \) describes antiproton energy losses analogous to \( \langle dE/dx \rangle \) and \( \lambda_{\text{inel}} \) describes inelastic and annihilation interactions as in the equation 1, and \( D_{LL} \) is the radial diffusion coefficient. The source functions \( Q_{2p} + Q_{3p} \) are secondary and tertiary antiproton production spectra for antiprotons born in the direct antiproton production reaction. The results of the simulations shown in figure 1 demonstrate that the radial diffusion process spread the belt from its source at \( L \approx 1.2 \) up to \( L = 2 \) and higher.

1.2. An indirect antiproton source from albedo antineutrons decay

In the same paper [2] in paragraph 5 titled “External antiproton belt and the total trapped antiproton belt mass” there was mentioned another source of terrestrial magnetosphere antiproton belt: it stems from decay of antineutrons born in another channel of the pair production reaction \( (p+p, n+n\bar{p}+p+p) \) of GCR with the Earth’s atmosphere constituents. This particular antimatter source mechanism creates thousands of times greater antiproton flux and at greater \( L \)-shells in comparison with direct antiproton production source.

This quantitatively more important process was first considered in detail by Bickford [5] under a project supported with NASA’s grant for developing effective fuel for space rockets. The mechanism of formation of antiproton flux from albedo antineutron decay (CR\( N \)D source) is quite similar to the well-established idea of decaying albedo neutrons produced by GCR in the Earth’s atmosphere to create the innermost proton radiation belt in the magnetospheric trapping region (known as the classic CRAND source). As it was mentioned in the paragraph 5 of [2], the decaying albedo antineutrons create most of the antiproton radiation belt with resulting maximum flux located on \( L = 1.4 \pm 1.5 \). In the paper this more populous belt was called “external antiproton belt” in relation to spatial position of antiproton belt named as the “inner antiproton belt” from the in situ source described above. Maximum flux of the “external belt” exceeds by about thousands of times the maximum flux of the
“inner antiproton belt”, and so the total observable antiproton content in the Earth’s magnetosphere is substantially greater than in the inner region of the belt alone.

To illustrate, the distribution of total antimatter mass in these two belts is shown in figure 2 [5,6]. The inner belt has antimatter mass maximum at \( L \approx 1.25 \), and the external antiproton belt (due to transport while still antineutrons) has maximum near \( L \approx 2 \).

![Figure 2. Distribution antiproton mass near the Earth.](image)

Bickford estimated integral flux of antiprotons from the CRAND antiproton source accounting for the production of albedo antineutrons relative to albedo neutrons an energy dependent ratio of 1 antineutron for every \( \sim 10^5 - 10^9 \) neutrons [5,6]. The flux shows significant dependence on \( L \)-shell number at \( L < 1.4 \) (see figure 1.5 from [5]).

2. Comparison measured and calculated antiproton flux

In these circumstances it is insufficient to compare the spectra measured in SAA region with antiproton spectra calculated from only one weaker source (as it was done in Adriani et al. 2011 paper in figure 1 of that paper), where the antiproton fluxes are calculated to be significantly lower than those from greater antiproton source. From a theoretical point of view, one should not compare without pointing out for which antiproton source those fluxes were calculated. Another problem with the comparison is the fact that the antiproton spectra measured at different \( L \) shells were being compared with calculated spectra for a certain specific \( L \)-shell of 1.2, and that makes little sense since one must pay attention to the strong \( L \)-dependence of the trapped antiproton fluxes and their spectra [5,6]. The theory-observation comparison as given by Adriani et al. 2011 is thus not entirely proper, and the authors of the theoretical work [2] have been somewhat mis-cited.

In figure 3 we would like to demonstrate a proper comparison of results of the theoretical predictions made before the Pamela spacecraft observations of antiprotons. Here we show prior theoretical simulations of the total antiproton fluxes in the magnetospheric SAA region in direct comparison with the PAMELA experimental data. One can see a reasonably satisfactory agreement of the theoretically simulated and the experimentally observed antiproton fluxes. Although this is certainly not a perfect match in all details, we do note an excellent flux magnitude match around 1 GeV antiproton kinetic energy. Thus, we had earlier largely predicted what Pamela has now observed.

The South-Atlantic Anomaly region where the Pamela antiproton flux results were obtained is characterized by strong \( L \)-dependence of the trapped flux [5].
At the same time the CRAND source antiproton fluxes possess a significantly narrow pitch angle distribution. This probably explains at least some of the differences, seen in figure 3, between experimental and simulated antiproton fluxes.

3. Conclusion

Due to these two reasons more exact comparison simulated and measured fluxes should be done in future in SAA region, and especially with careful accounting for the pitch angle dependencies and the $L$-shell location of incident antimatter particles.

Misquotation of our work can be also just corrected by the inscription of the curve related to our work in figure 1 [1]: "$L=1.2$, direct antiproton production source ($p+p, p+p\bar{p}+p+p$)".

Of course we are very happy that the quality Pamela antiproton detector space experiment was carried out, and we commend the experimenters for the technical achievement of unambiguously distinguishing between highly energetic protons and antiprotons at MeV and GeV energies in the Earth’s magnetosphere.

References
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