Detailed analysis of observed antiprotons in cosmic rays

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Abstract

In the present work, the origin of antiprotons observed in cosmic rays (above the atmosphere) is analyzed in details. We have considered the origin of the primaries, (which their interactions with the interstellar medium is one of the most important sources of antiprotons) is a supernova type II then used a diffusion model for their propagation. We have used the latest parameterization for antiproton production cross section in pp collisions (instead of well known parameterization introduced by Tan et al.) as well as our calculated residence time for primaries. The resulted intensity shows the secondary antiprotons produced in pp collisions in the galaxy, have a high population as one can not consider an excess for extragalactic antiprotons. Also there is a high degree of uncertainty in different parameters.

1. Introduction

A large part of the observed antiprotons are galactic secondaries which are produced in collisions between primary cosmic rays with interstellar medium nuclei.

Our aim was computing the observed antiprotons excess into galactic secondary antiprotons using a new antiproton production cross section [1] and considering the supernova origin for the primaries. Although the observed antiprotons energy range is confined ($\sim 0.1-10\,\mathrm{GeV}$), we did not see a considerable excess. But it must be noted that we can not rule out the extragalactic origin for antiprotons with higher energies if observed.

Now, there are many models to clarify as to how cosmic rays propagate in the interstellar medium [2,3] but the actual propagation processes are believed to be diffusion processes in which irregularities in magnetic field are used as scattering centers; this point is the basis of different types of diffusion models. [4, 5, 6]
To describe the propagation of cosmic rays in the Galaxy we used a diffusion model presented by Ginzburg and Syrovatskii [7] (see also [4]). In the case of a stationary solution, the number density $N_S(E,\vec{r})$ of a stable cosmic ray species whose distribution of sources is defined by the function of energy and space, $Q_S(E,\vec{r})$, is given by [2,4]:

$$\frac{\partial}{\partial t} N_S(E,\vec{r}) = 0$$

$$= Q_S(E,\vec{r}) - \vec{\nabla}\cdot\left[\left(\vec{u} - D\vec{\nabla}\right)N_S(E,\vec{r})\right] \qquad (1)$$

$$- \frac{1}{\tau_i} N_S(E,\vec{r}) - \frac{\partial}{\partial E}\left[b(E)N_S(E,\vec{r})\right].$$

We mainly follow the approach of Gaisser et al. [4]. The main feature is that the propagation region is assumed to have a cylindrical symmetry: the interstellar density ρ drops off outside the disk, and diffusion occurs in a region that includes both the gaseous disk and part of a halo.

On the right hand of side of the first term, the source term, is the production rate of secondary particles (with Index S) from primaries (with Index P) which can be written as:

$$Q_S(E,\vec{r})$$
$$= 4\pi \int \frac{d\sigma_{P\to S}(E,E')}{dE} \frac{\rho(\vec{r})}{<m>} J_P(E',\vec{r})dE', \qquad (2)$$

in which $J_P(E,\vec{r})$ is the flux of primaries at position $\vec{r}$ in the galaxy (which is assumed to be uniform throughout the Galactic disk), ρ is the density of the interstellar medium and $<m>$ is the average mass of an interstellar atom.

For antiprotons, the source term is written as:

$$\frac{Q_{\bar{p}}(E)}{4\pi} = 2\frac{\rho}{m_H}\varepsilon\int\frac{d\sigma_{pp\rightarrow\bar{p}}}{dE_{\bar{p}}}J_p(E_p)dE_p \ , \qquad (3)$$

where $\sigma_{pp\rightarrow\bar{p}}$ is $\bar{p}$ production cross section for $pp\rightarrow\bar{p}X$. The factor ε shows the effects of nuclei in the interstellar medium and in the cosmic rays, and the factor of 2 accounts for antiprotons produced by antineutron decay.

Here we have considered on the averaged values of the secondary flux.

In antiproton case, the diffusive-convective term in the right hand side of formula (1) reduces to $N_{\bar{p}}(E)/\tau_e(E)$; $\tau_e(E)$ in diffusion model is the residence time in the gaseous disk. The third term represents the loss due to inelastic collisions, with characteristic time τ_i. The fourth term will be omitted (the energy loss or gain of secondaries as they propagate, respectively) because the only significant energy losses for antiprotons are from plasma scattering and ionization, both of which are irrelevant for antiprotons at kinetic energies ≥ 1 GeV [4]. With these simplifications we have:

$$\frac{\partial}{\partial t}N_S(E,\vec{r}) = 0$$

$$= Q_S(E) - \frac{1}{\tau_e(E)}N_S(E,\vec{r}) - \frac{1}{\tau_i}N_S(E,\vec{r})$$

which leads to $N_S(E,\vec{r}) = \dfrac{\tau_e(E)}{1+\tau_e(E)/\tau_i}Q_{\bar{p}}(E)$. It could

be seen that in this solution, $N_S(E,\vec{r})$ is not related to space and is just a function of the secondary particle energy. Using $J_{\bar{p}}(E) = \upsilon N_{\bar{p}}(E)/(4\pi)$:

$$J_{\bar{p}}(E) = \frac{\upsilon\tau_e}{1+\tau_e/\tau_i}\frac{Q_{\bar{p}}(E)}{4\pi} \ , \qquad (4)$$

where, υ is the antiproton velocity.

2. Computations

The factor ε which is computed with rewriting relation (2) for antiproton production in pp collisions, for a pure hydrogen interstellar medium has the amount of [4]:

$$\varepsilon^H = 1.20 \qquad (5)$$

After some simplification [8], we have the suitable form for secondary antiprotons flux in a pure hydrogen interstellar medium [8] :

$$J_{\bar{p}}(E_{\bar{p}}) = \frac{2\lambda_e^H}{m_H}\varepsilon^H\int\frac{d\sigma_{pp\rightarrow\bar{p}}}{dE_{\bar{p}}}J_p(E_p)dE_p \ , \qquad (6)$$

where $\lambda_e^H = \upsilon\rho_H\tau_e$ is the escape length of antiprotons in a pure hydrogen interstellar medium. Using this concept we need to find τ_e for secondaries (here antiprotons).

Here we have used the primary protons flux by Saha et al. [9]:

$$J_p(E_p)dE_p = 1.32\ E_p^{-2.65}dE_p \ . \qquad (7)$$

As Supernova remnants (SNRs) are considered to be the main source of cosmic rays (CRs) in the Galaxy, we have used models introduced by Axford et al. [10] and Berezhko et al. [11,12] to calculate a residence time for primary cosmic rays.

Diffusive shock acceleration process can convert sufficient amount of the explosion energy into CRs and produce CR spectrum with necessary shape and amplitude [11].

If the observed CRs flux is assumed as a power law (i.e. $E^{-\eta_0}$), and production flux at the position of source (i.e. at the position of supernova) as be $E^{-\eta}$; we can find CRs residence time, τ_R (i.e. τ_e in diffusion model), as a function of Energy:

$$E^{-\eta_0} \propto \tau_R E^{-\eta} \rightarrow \tau_R \propto E^{-(\eta_0-\eta)} \ . \qquad (8)$$

Here one must note that we can use this formula just in the case that we consider primary CRs to be protons. The exact relation must be a function of rigidity rather than energy.

λ_e^H in relation (6), which accounts for "the traversed matter" (i.e. grammage) then could be written as: [8]

$$\lambda_{A,B} = 10(E\ \text{GeV}/10)^{-0.63\pm0.02}\text{g}/\text{cm}^2 \qquad (9)$$

where A and B denotes for Axford and Berezhko supernovae models.

As mentioned before, we considered a supernovae origin for primary cosmic rays. We also used Axford and Berezhko models to reproduce the production flux at the position of source ($E^{-\eta}$). Considering $E^{-\eta_0}$ from relation (7) (i.e. $\eta_0 = 2.65$) and using calculated indexes from Axford and Berezhko models (2.02 ± 0.02) [8], leads to $\tau_R \propto E^{-0.63\pm0.02}$. To write this formula we noted that $\lambda \propto \tau_R$, and used the fact that a CR primary with energy 10 GeV traverses ~ 10 g of matter in the Galaxy [2].

Below the Knee region, Axford and Berezhko models produce similar fluxes for primaries which are mentioned as index A and B in relation (9).

When charged particles move in the interstellar medium, they move in different paths through the interstellar magnetic fields which causes different residence times. $\lambda_{A,B}$ or λ_e^H which is calculated above, is the "traversed matter" by primary cosmic rays. Here we assume that the residence time has the same value for protons and antiprotons and as a result; protons and antiprotons traverse equal amounts of matter in the interstellar medium because their only difference is in the charge sign.

To compute $\bar{p}$ production cross sections in

Table 1. D_1 to D_7 [1].

Parameters	D_1	D_2	D_3	D_4	D_5	D_6	D_7
Value (errors)	3.4610(20)	4.340(20)	0.007855	0.5121(3)	3.6620(27)	0.023070(1)	3.2540(77)

$pp \to \bar{p}X$, $\sigma_{pp \to \bar{p}}$, we have used the latest parameterization [1] to reproduce experimental $\bar{p}$ production cross sections in pp collisions. This parameterization is offered by Duperray et al. [1]

In their paper by using the method first introduced by Feynmen [13] and later continued by Tan et al. [14] using a radial scaling variable, they offered a formula to describe $\bar{p}$ production cross section in $pA \to \bar{p}X$ reaction [1].

The formula can be simplified as below to show $\bar{p}$ production cross section in $pp \to \bar{p}X$ [1]:

$$E_{\bar{p}} \frac{d^3\sigma}{dP_{\bar{p}}^3} = \sigma_{in}(1-x_R)^{D_1} e^{-D_2 x_R}$$
$$\times \left[D_3 \left(\sqrt{s}\right)^{D_4} e^{-D_5 P_{\bar{p},\perp}} + D_6 e^{-D_7 (P_{\bar{p},\perp})^2} \right]. \tag{10}$$

The seven parameters, D_1 to D_7 and their errors are listed in table 1 [1].

The values of these parameters obtained by fitting the experimental $\bar{p}$ production cross sections for proton-proton collisions and the corresponding error following the PDG standard conventions.

In relation (10), $d^3\sigma / dP_{\bar{p}}^3$ is the triplet differential cross section for detecting $\bar{p}$ in within the phase space volume element $dP_{\bar{p}}^3$, $E_{\bar{p}}$ the total energy of produced antiproton and σ_{in}, x_R, $\sqrt{s}$ and $P_{\bar{p},\perp}$ are respectively [15]:

$$\sigma_{in}(mb) =$$
$$\sigma_0[1 - 0.62\exp(-K_p / 200)\sin(10.9 K_p^{-0.28})], \tag{11}$$

where K_p is the kinetic energy of incident proton in lab frame (in MeV):

$$K_p = (E_p - m_p) \times 10^{-3} \text{MeV} \tag{12}$$
(E_p and m_p both in GeV)

and σ_0 is equal to

$$\sigma_0(mb) = 45 \times A^{0.7}[1 + 0.016\sin(5.3 - 2.63\ln(A))] \text{ [15]}.$$

For $pp \to \bar{p}X$, σ_0 is equal to

$$\sigma_0(mb) = 45 \times 1^{0.7}[1 + 0.016\sin(5.3)] \approx 45.0665.$$

$$x_R = \frac{E_{\bar{p}}^*}{E_{\bar{p},\max}^*} \tag{13}$$

(Where $E_{\bar{p}}^*$ and $E_{\bar{p},\max}^*$ are the total energy of the inclusive particle, $\bar{p}$, and its maximum possible value in Center of Mass frame respectively. One can find a complete review in [8])

$\sqrt{s_{pp}}$ is the total energy of the center of mass:

$$s_{pp} = m_p^2 + m_p^2 + 2m_p E_p$$
$$= 2m_p(m_p + E_p), \tag{14}$$

and $P_{\bar{p},\perp}$, is the transverse components of $\bar{p}$ momentum in Lab frame:

$$P_{\bar{p},\perp} = P_{\bar{p}} \sin\theta_L, \tag{15}$$

where θ_L is the angle of emission in Lab frame.

to calculate $\bar{p}$ production cross section, needs to approximate:

$$d\sigma(E_{\bar{p}}, E_p) = 2\pi \int_{P_{\bar{p},\perp}} (E_{\bar{p}} \frac{d^3\sigma}{dP_{\bar{p}}^3}) d\theta_L. \tag{16}$$

We need $d\sigma(E_{\bar{p}}, E_p)$ for each E_P and $E_{\bar{p}}$. The upper limit of θ_L is $\sin^{-1}(P_{\bar{p},\max}^* / P_{\bar{p}})$ [15] and all the calculated $d\sigma(E_{\bar{p}}, E_p)$ for different E_P and $E_{\bar{p}}$ then will be used to approximate the integral in relation (6). (Figure 1)

The flux of cosmic rays reduces with energy rapidly. Here we have used the relativistic approximation for converting the quantities from lab frame to C.M. frame and vice versa [8, 16, and 17].

By reproducing differential $\bar{p}$ production cross sections as a function of incident proton and produced antiproton energies and using relation (7) and (9), with a numerical method we calculated relation (6) for $\bar{p}$ energies (Figure 1).

3. Conclusion

Estimates of the primary spectra of cosmic ray components [9], nuclear parameters [4], and the latest parameterization of $\bar{p}$ production cross section [1] together with considering a supernova origin for the primaries in a simplified diffusion model and considering a suitable form for residence time [8] is used to calculate $\bar{p}$ spectra.

The result is compared with the observed antiproton spectrum for $E\sim$1GeV up to $\sim$10 GeV (Figure 1). Though in upper energies one can see the difference of observed flux (or $\bar{p}$ excess) increases by energy, but lack of experimental values in upper energies makes the decision uncertain. Lower than $\sim$ 1 GeV the solar modulation is obvious and its effect must be considered.
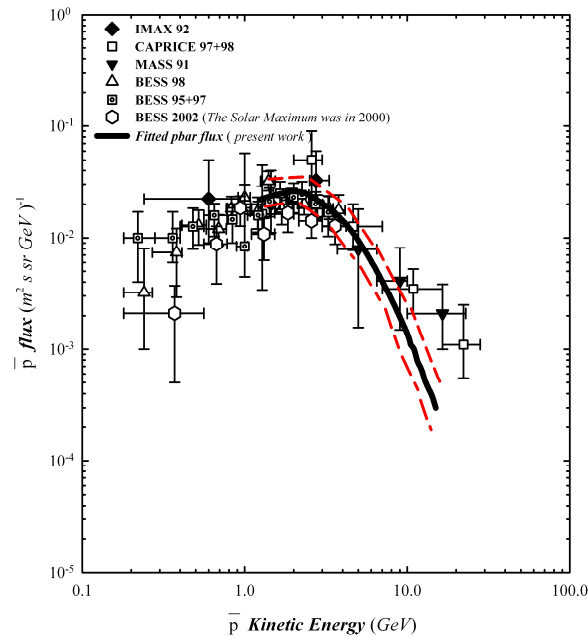
Figure 1. Computed $\overline{p}$ Intensity for pure hydrogen interstellar medium (solid line) compared with experimental data. Upper and lower limits (dashed lines) are account for uncertainties in our computations.

We have shown data from BESS 2002 [18] in figure 1 which it shows the effect of solar modulation two years after solar maximum.

The upper and lower limits (dashed lines) accounts for approximated uncertainties which are produced by changing ε and λ parameters.

Solid curve calculated for pure hydrogen interstellar medium (i.e. $\varepsilon^H = 1.20$).

From figure 1, one can see that antiprotons above the atmosphere (at least in our analyzed range with more experimental data) are most likely from the Galactic origin.

We must note here that, as these calculations are related to CRs propagation model and many other parameters (i.e. ε and λ), and considering the fact that there is a lack of experimental data especially in upper energies, still there is a possibility for extragalactic antiprotons [19] (although unlikely).

References
1. R P Duperray, C Y Huang, K V Protasov and M Bu´enerd, *Physical Review* D **68** (2003) 094017.
2. T K Gaisser, "*Cosmic Rays and Particle Physics*", Cambridge University Press (1990)
3. R Schlickeiser, "*Cosmic Ray Astrophysics*", Springer (2002).
4. T K Gaisser, R K Schaefer, *Astrophysical Journal*, **394** (1992) 174-183.
5. L Bergström, J Edsjö, P Ullio, *Astrophysical Journal*, **526** (1999) 215-235.
6. C Evoli, D Gaggero, D Grasso, L Maccione, arXiv: 0807.4730v2 (2008).
7. V L Ginzburg, S I Syrovatskii, "*The origin of cosmic rays*", Pergamon Press, London (1964).
8. P Davoudifar, "*Origin of antiparticles in cosmic rays*", M.Sc. thesis, Kerman University, Iran (2005).
9. R K Saha, R Majumdar, P Pal, and D P Bhattacharyya, *Modern Physics Letters* A **13** (1998) 1997-2011.
10. I W Axford, et al., 17th *International Cosmic Ray Conference*, **2**(1981) 155.
11. E G Berezhko, et al., 25th *International Cosmic Ray Conference*, **4**(1997) 417.
12. E G Berezhko, et al., *Zh. EKSP. Teor. Fiz.* **116** (1999) 737.
13. R P Feynman, *Physics Review Letters*, **23** (1969) 1415.
14. L C Tan, L K Ng, *Physical Review* D, **26** (1982) 1179.
15. S A Stephens, *Astrophysics and Space Science*, **76** (1981) 87-103.
16. C J Joachain, "*Quantum Collision Theory*", Elsevier (1983).
17. M Longair, "*High Energy Astrophysics*", Cambridge University Press (1992).
18. S Haino, et al., 29th *International Cosmic Ray Conference*, Pune, **3** (2005) 13-16.
19. J Szabelski, J Wdowczyk, W A Wolfendale, *Nature*, **285** (1980) 386-388.