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ON THE ORIGIN OF LOW ENERGY PROTONS IN COSMIC RAYS

ԵՐԵՎԱՆ 1982 ЕРЕВАН

1. Introduction

The first measurements of the flux of 2 - 10 GeV antiprotons in primary cosmic radiation [1,2] turned out several times greater than the fluxes predicted by earlier calculations. In these calculations the production of antiprotons in nuclear inelastic collisions of cosmic rays (CR) with interstellar gas was investigated, assuming that the mean column density (grammage) traversed by primary CR is $\sim 2 \div 5$ g/cm^2 as it follows from the CR mass composition analysis. The discovery of anomalous abundance of antiprotons in CR has stipulated new, more accurate calculations of the production and propagation of antiprotons in the Galaxy [3-6], based on the recent accelerator data on the cross section of inclusive reaction $p+p \rightarrow \bar{p}+$anything. It follows from the comparison of these calculations with the measured abundance $\bar{p}/p \sim 5 \cdot 10^{-4}$ that the CR, responsible for the production of high energy antiprotons, should traverse the grammage ~ 20 g/cm^2. Note that for the explanation of the intensity of 10 GeV positrons, when their secondary origin is meant, a $5 \div 10$ g/cm^2 grammage is needed.

Thus, we face quite a "spectrum" of grammages required for the explanation of the fluxes of secondary nuclei, antiprotons and positrons by the interaction of CR with the interstellar gas[3]. The presence of such a "spectrum" of grammages apparently testifies the production of antiprotons in the sources different from those of positrons and heavy nuclei of CR.

The one important feature of the energy spectrum of antiprotons that are produced in p-p collisions is the presence of a pronounced maximum at ~ 2 GeV with an abrupt decrease of intensity to both high and low energies. This feature is the result of the reaction kinematics and it depends weakly on the shape of the spectrum of interacting protons as well as on the energy loss (~ 100 MeV) at traversing ~ 20 g/cm^2 of interstellar matter [4]. Therefore, the recently measured CR antiproton-proton ratio at $T \sim 200$ MeV [7] appeared quite unexpected, as from these data follows the approximate stability of the ratio $\bar{p}/p$ in 0.2 - 10 GeV interval, whereas the predicted relation in the homogeneous model of CR propagation in the Galaxy (Leaky Box Model) changes in this interval by three orders. Moreover, such a high $\bar{p}/p$ ratio at low energies isn't yet explained in various modifications of the CR propagation models discussed in literature. Even in the limiting case of a Closed Galaxy Model the predicted flux of low energy antiprotons is much less than the one observed [4,5]. Therefore, it seems more probable that antiprotons are produced in the main in compact sources. In particular, the possibility of CR antiproton production in supernova shells surrounding young pulsars was discussed by Ginzburg and Ptuskin [8]. It is then

assumed that the anomalous abundance of low energy antiprotons may be explained by the adiabatic loss in the expanding turbulent plasma of the active region. However, due to the absence of numerical calculations it isn't clear whether this mechanism would provide the observed spectrum of antiprotons.

The alternative explanation of experimental data is the assumption on the existence of antimatter on the level 10^{-4}. Since the hypothesis on the presence of antimatter in the present epoch in such quantity is rather radicel, the study of other models, which do not lead to so far-reaching consequences, seems justified.

2. Formulation of the model

Remaining in the framework of models that imply the secondary origin of antiprotons, one may obtain a high $\bar{p}/p$ ratio of low energies ($100 \div 300$ MeV) introducing additional energy loss $1 \div 2$ GeV in the source. If the energy dumping is caused by ionization, then it should be assumed that antiprotons pass 250 g/cm^2 of hydrogen, which is much more than the absorption mean free path of antiprotons not exceeding 30 g/cm^2.

The basic feature of the model considered in this investigation consists in tha fact that the formation of antiproton spectra occurs in the plasma with a concentration of electron-positron pairs exceeding that of nuclei. The strong interaction matter traversed by accelerated particles is as now admitted 20 g/cm^2. The presence of additional electron-positron pairs in the plasma should allow 1 - 2 GeV energy loss for protons and antiprotons, i.e., in this very plasma $n_{\pm}/n_p \gtrsim 10$[*].

Such a plasma with an increased concentration of $(e^+ - e^-)$ pairs may exist near relativistic astrophysical objects: in accretion disks around black holes, in magnetospheres of pulsars, in strong supernova shock waves etc. All the enumerated objects are widely discussed in literature as CR sources.

Let the accelerated proton beams traverse the plasma layer. Consider two limiting cases:

a) the region of the production of antiprotons and antineutrons and the region occupied by $(e^+ - e^-)$ pairs where protons and antiprotons in the main loose their energy are spatially separated;

b) the production of antiparticles and the energy loss occur in the same region of space.

Let us denote the proton primary beam intensity by $J_p^0(T)$. In the case a), after traversing the layer x , the intensity of protons will be

$$J_p(T,x) = J_p^0(T)\exp(-n_p \sigma_{pp} x), \qquad (1)$$

where n_p is the proton concentration in plasma in the production region, σ_{pp} is the total cross section of inelastic p-p collisions.

The production spectrum $q(T,x)$ of antiprotons is associated with the relation

$$q(T,x) = 4\pi n_p \int_{T_0}^{\infty} \sigma_{\bar{p}}(T,T') J_p(T',x)\, dT', \qquad (2)$$

where $\sigma_{\bar{p}}(T,T')$ is the inclusive cross section, and $T_0 = 6 m_p c^2$ is the $\bar{p}$ production threshold energy. Here and later we neglect nuclear cascade processes, which is quite permissible for the grammages considered (20 g/cm^2).

The distribution function $N_{\bar{p}}(T,x)$ of antiprotons satisfies equation

$$v_{\bar{p}} \frac{\partial N_{\bar{p}}}{\partial x} = q(T,x) - n_p v_{\bar{p}} (\sigma_{\bar{p}p} + \sigma_a) N_{\bar{p}}, \qquad (3)$$

$N_{\bar{p}}(T,0)$ being zero. Here $\sigma_{\bar{p}p} + \sigma_a$ is the total cross section of inelastic p-p collisions, σ_a is the cross section of antiproton annihilation, $v_{\bar{p}}$ is the velocity. Solving (3) we find the intensity $J_{\bar{p}}$ of antiprotons

$$\begin{aligned} J_{\bar{p}}(T,x) &= \frac{v_{\bar{p}}}{4\pi} N_{\bar{p}}(T,x) = \\ &= \frac{1}{4\pi} \exp\left[-(\sigma_{\bar{p}p} + \sigma_a) n_p x\right] \int_0^x dx' \exp\left[-(\sigma_{\bar{p}p} + \sigma_a) n_p x'\right] q(T,x'). \end{aligned} \qquad (4)$$

One may assume with a good accuracy that the intensity of antiprotons is equal to that of antineutrons: $J_{\bar{p}}(T,x) \simeq \simeq J_{\bar{n}}(T,x)$. Thus, the expressions (1)-(4) determine the intensities $J_p(T,x_1)$ of protons and $J_{\bar{p}(\bar{n})}(T,x_1)$ of antiprotons (antineutrons) escaping from the production region.

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[*] When this work was completed, S.G.Matinyan called our attention to a series of theoretical and experimental investigations under a guidance of G.I.Budker (see e.g. [9]) on the electron cooling of charged particles in storage rings of heavy particles. The key assumption of our model on large energy loss of antiprotons in the electron-positron plasma is similar to Budker's basic idea of the heavy particle beam cooling at energy transfer due to Coulomb collisions to the accompanying electron beam[10].

One should next take into account the charged particles energy loss in plasma. After traversing the depth x_2 in plasma the charged particle spectra take the form

$$J_{p,\bar{p}}(T)=\frac{\varepsilon(T_1)}{\varepsilon(T)}J_{p,\bar{p}}(T_1,x_1) \qquad (5)$$

where $\varepsilon(T)=-dT/dx$ is the energy loss; the value T_1 is defined by the relation

$$\int_{T}^{T_1}\frac{dT}{\varepsilon(T)}=x_2 \qquad (6)$$

When calculating we have assumed $\sigma_{pp}\simeq\sigma_{\bar{p}p}\simeq\sigma_{\bar{n}p}\simeq \simeq 30\,\mathrm{mb}$; $\sigma_a\simeq 24/\beta\,(\beta=v/c)$; $m_p n_p x_1 = 20$ g/cm^2; the plasma parameters are chosen so that the energy loss of high energy particles make 1 - 2 GeV. In the calculations the antiproton production cross section presented by Stephens [4] was used. The proton initial spectrum was taken in the form

$$J_p^0(T)=\frac{A}{(T+m_pc^2)^{2,5}} \qquad (7)$$

with the normalization $\int_{T_0}^{\infty}J_p^0(T)\,dT=1$.

In the problem considered the shape of the initial proton spectrum well up to $T\leq 6$ GeV apparently doesn't affect the spectrum of secondary antiprotons.

The energy loss rate of protons and antiprotons is determined by the concentration $n_\pm$ of electrons and positrons and by their temperature θ. The stopping power in the ionized cold gas is [11]

$$\varepsilon_c(T)\cong\frac{4\pi e^4 n_\pm}{m_ec^2\beta^2}\ln\left(\frac{2m_ec^2}{I}\beta^2\gamma^2\right), \qquad (8)$$

where $I\simeq 3{,}7\cdot 10^{-11}\sqrt{n_\pm}$ eV; $\gamma=1/\sqrt{1-\beta^2}$, while in the hot plasma (see e.g. [12])

$$\varepsilon_h(T)=\frac{4\pi e^4 n_\pm}{m_ec^2\beta^2}\left[\Psi(y)-y\Psi'(y)\right]\ln\left[\frac{3}{2e^3}\left(\frac{k^3\theta^3}{\pi n_\pm}\right)^{1/2}\right], \qquad (9)$$

where $y^2=\frac{m_ec^2}{2k\theta}\beta^2$, $\Psi(y)$ is the error function.

From (9) follows a strict decrease of energy loss in the low energy region ($T<\frac{m_p}{m_e}k\theta$) as compared with the case of cold plasma.

The case b) (the production and loss in the same region of space) mathematically is more complicated. The distribution functions $N_p(T,x)$ of protons and $N_{\bar{p}}(T,x)$ of antiprotons are found from the simultaneous equations

$$v_p\frac{\partial N_p}{\partial x}-\frac{\partial}{\partial T}\left(v_p\varepsilon(T)N_p\right)=-v_pn_p\sigma_{pp}N_p, \qquad (10)$$

$$q(T,x)=4\pi n_p\int_{T_0}^{\infty}\sigma_{\bar{p}}(T,T')J_p(T',x)\,dT', \qquad (11)$$

$$v_{\bar{p}}\frac{\partial N_{\bar{p}}}{\partial x}-\frac{\partial}{\partial T}\left(v_{\bar{p}}\varepsilon(T)N_{\bar{p}}\right)=q(T,x)-n_pv_{\bar{p}}(\sigma_{\bar{p}p}+\sigma_a)N_{\bar{p}}. \qquad (12)$$

The limiting conditions are the same as in the case a). The approximate solution of eqs. (10-12) has the form

$$J_p(T,x)=\frac{\varepsilon(T_1)}{\varepsilon(T)}J_p^0(T_1)e^{-n_p\sigma_{pp}x}, \qquad (13)$$

$$J_{\bar{p}}(T,x)=\frac{1}{4\pi\mathcal{E}(T)}\int_{T}^{T_1} dT'\, q(T',x)\, e^{-\varphi(T,T')} \tag{14}$$

where $\varphi(T,T')=\int_{T}^{T'}\frac{n_p\sigma_a(T'')}{\mathcal{E}(T'')}\,dT''$; T_1 is defined by the formula (6).

The calculations have shown that the cases a) and b) give practically identical spectra of protons and antiprotons for the same parameters of plasma. Therefore, we shall later present results for the case a) only.

3. Calculation results

The results of the calculation of energy spectra of antinucleons after their escape from the source are shown in fig.1. (The amount of electrons in the source traversed by protons and antiprotons, assuming its independence of the energy of traversing particles, was taken $n_\pm x_2$ = 8,7 · 10^{25} electron/cm^2); the Coulomb logarithm was chosen equal to 20; the plasma temperature is $K\Theta$ = 100 keV. The energy loss of ultrarelativistic protons (antiprotons) at such parameters is ΔT = 1 GeV.

The presence of additional Coulomb energy loss of antiprotons results in the fact that the spectrum for $T \sim$ 0,1GeV is determined by the production spectrum q in the range $T \gtrsim$ 1 GeV, where $q(T)$ has a maximum. This leads to the increase of antiprotons intensity by three orders with respect to antineutrons intensity. In the range $T \gtrsim$ 10 GeV (when the energy loss may be neglected) the spectrum $J_{\bar{p}}$ doesn't much differ from $J_{\bar{n}}$. The spectrum of the part of antiprotons from the antineutron decays is independent of the parameters of electron-positron plasma, since in the discussed model of a compact source they, as is assumed, decay after escaping from the plasma region.

In fig. 2 the energy spectra of antiprotons for the cases of hot and cold plasma are presented. The considerable difference of spectra at low energies is connected with a different behaviour of energy loss: $\mathcal{E}_c \sim \beta^{-2}$ whereas $\mathcal{E}_h \sim \beta^{-2}[\Psi(y)-y\Psi'(y)] \sim \beta$ at $y \equiv \left(\frac{m_e}{m_p}\frac{T}{K\Theta}\right)^{1/2} \ll 1$. The difference of $\mathcal{E}_c$ and $\mathcal{E}_h$ at low energies results also in the increase of low energy protons yield from a hot target as compared with the case of cold plasma.

Fig. 3 presents the calculated and observed energy spectra of protons. The spectrum of protons that have escaped from the source is normalized to the observed one at T = 100 GeV. When comparing the calculated and measured spectra of particles one should take into account the factor of propagation in the Galaxy. We assume that after escaping from the production region the propagation of protons and antiprotons in the Galaxy occurs in the same way as that of CR nuclei. From the analysis of mass composition of CR Ormes and Protheroe [13] found that the interstellar matter traversed by CR depends on the energy as

$$\lambda(T)=\begin{cases}(7\pm1)\ \text{g/cm}^2 & T\leq 2\ \text{GeV/nucl.}\\ (7\pm1)(T/2)^{-0,4\pm0,1}\ \text{g/cm}^2 & T>2\ \text{GeV/nucl.}\end{cases} \tag{15}$$

Such a dependence is confirmed by new data from HEAO-3 [14].

This implies that the time that charged particles spend in the Galaxy

$$\tau(T) = \frac{\lambda(T)}{\beta c} \qquad (16)$$

depends on their energy. Therefore, the observed intensity of particles $I_{p,\bar{p}}(T)$ is proportional to $\tau(T) J_{p,\bar{p}}$. We assume

$$I_{p,\bar{p}}(T) = \eta(T) J_{p,\bar{p}}(T) , \qquad (17)$$

where the propagation factor

$$\eta(T) = \frac{I_p(100\ \mathrm{GeV})}{J_p(100\ \mathrm{GeV})} \, \frac{\tau(T)}{\tau(100\ \mathrm{GeV})} \qquad (18)$$

allows for the dependence of the CR mean lifetime on the energy and provides the normalization of the proton spectrum to the observed value at T = 100 GeV. The proton spectra obtained allowing for the factor of propagation are shown in fig. 3.

4. Discussion of the results

As it follows from fig. 3, at $T \geqslant 2$ GeV there is a good agreement between the calculated spectrum $I_p(T)$ and the measured spectrum of protons $I_p^d(T)$ corrected for solar modulation [15,16]. At $T < 2$ GeV the $I_p(T)$ is less than the demodulated spectrum I_p^d. One may connect this difference with the existence of other sources of low energy protons. However, there is no necessity in such an assumption. In order to obtain the required agreement one may alter the spectrum $J_p^o(T)$ of primary protons in the energy range $T \leqq T_o = 6$ GeV. Apparently, the spectra of antinucleons will then remain the same.

The calculated dependence of the ratio $I_{\bar{p}}/I_p^d$ is shown in fig. 4 a,b. The quantity I_p^d contains at $T < 1$ GeV

an uncertainty of the factor of two, associated with the difficulties of the correct consideration of demodulation parameters.

The agreement with experimental data at $T \sim 2 \div 10$ GeV, as in the case of other models, is provided by the choice of average grammage traversed by protons in the antinucleon production region $m_p n_p x_1 = 20$ g/cm^2. At $T \sim 200$ MeV the divergence is ~ 5 for the hot plasma with $K\Theta = 100$ keV and ~ 10 for the cold plasma. In fact, one may improve the agreement in the hot plasma model assuming that $K\Theta \geqslant 200$ keV.

Note that the calculations made in the assumption that the production of antiprotons takes place as a result of bombarding the interstellar gas by CR, do not account for experimental data. In particular, the Leaky Box Model, where CR traverse 5 g/cm^2, doesn't agree with observations at all, and the Closed Galaxy Model, accounting for the data at $T \sim 2 \div 10$ GeV, predicts a ratio of $\bar{p}/p$ by three orders smaller that that observed at T = 200 MeV.

When comparing the calculated and observed ratios $\bar{p}/p$, one should possibly introduce a correction taking into account the adiabatic cooling of CR in heliosphere. According to Protheroe [5] in the period of solar activity maximum, when the experiment of Buffington et al. [7] was carried out, the modulation may be described by mean energy loss $\sim$ 600 MeV. Therefore, the measured ratio $\bar{p}/p$ at $\sim$ 200 MeV may, in fact, correspond to $T \sim 800$ MeV. If we shift the point in fig. 4 onto 600 MeV, we shall obtain quite a satisfactory agreement with the calculations.

We have so far admitted that the existence of electron-positron plasma in CR sources without considering its formatio mechanisms. Such a plasma may form near a compact object with a strong electric or magnetic field, in particular, in a magnetosphere of a pulsar [17]. In hot plasma, however, the effective pair production is also possible at the absence of external strong fields. In the optically thin plasma at $k\Theta \leq m_e c^2$ the equilibrium ratio $\frac{n_+}{n_-}$, determined mainly by direct positron production processes in (e-e) and (e-p) collisions, equals [1

$$\frac{n_+}{n} \simeq \alpha^2 \exp\left[-\frac{2 m_e c^2}{k\Theta}\right] \ll 1 \quad .$$

At a great optical depth with respect to the Tompson scattering $\tau = \sigma_T \cdot R \cdot n_e > 1$ more substantial becomes the pair production in (γ - γ) collisions, which may result in (e^+-e^-) plasma formation: $n_\pm / n_p \gg 1$ [18-21]. In particular, in the limiting case of optically thick plasma, being in thermodynamic equilibrium, beginning with $\Theta \geqslant 3 \cdot 10^9$ K the pair pressure and their density may be well over the density of initial electrons [22].

The optically thick plasma with $\Theta \geqslant 10^9$ K may be formed behind the front of a strong shock wave arising at the initial stage of a supernova explosion[23]. At this stage there possibly occurs a shock acceleration of ejected matter [24], and the accelerated particles, according to the Colgate model, appear in interstellar madium, traversing a plasma layer with an increased content of (e^+-e^-) pairs.

Another alternative of the CR origin is the old idea of particles acceleration at the Galactic centre explosions [25].

According to [26], the (basic) fraction of the proton-nuclear component of CR may have got acceleration during the last powerful explosion in the nucleus, that has apparently occurred about 10^7 years ago. It is mentioned in [8] that within the framework of this model it is possible to explain the observed flux of high energy antiprotons provided the accelerated protons traverse the required grammage 20 g/cm^2 in the source. An additional assumption on the existence of electron-positron plasma in the source allows to satisfactorily explain also the measured ratio $\bar{p}/p$ at low energies. Apparently, there are no principle arguments against the possibility of the formation of hot (e^+-e^-) plasma (by analogy with supernova explosions) in the Galactic nucleus during its active phase.

In the considered model the accelerated nuclei won't be able to escape from the source due to a practically complete spallation in 20 g/cm^2 of matter and due to high energy loss in the electron-positron plasma.

When accelerated protons pass through 20 g/cm^2 of matter, a great number of γ -rays and electrons are produced from the decay of secondary π -mesons. However, the escape of these particles from the active region is very much complicated due to processes of pair production and the Compton scattering on the plasma thermal photons. Indeed, assuming that the plasma is in thermodynamic equilibrium, it is not difficult to relate the plasma optical depth with respect to photoproduction with the quantity $n_\pm x_2 \simeq 10^{26}$ electron/cm^2 required to provide the energy loss of protons and antiprotons of the order 1 GeV (see above):

$$\tau_{\gamma\gamma} = \sigma_{\gamma\gamma}\cdot R\cdot n_\gamma = \sigma_{\gamma\gamma}\, n_\pm\, x_2 (n_\gamma/n_\pm)\cdot K^{-1}$$

where $n_\gamma/n_\pm \simeq (k\Theta/m_e c^2)^{3/2} e^{m_e c^2/k\Theta}$ is the ratio of the concentration of photons to that of pairs, depending on the plasma temperature only [22] ; K is the coefficient characterizing "the entanglement" of particle trajectories in plasma and defined as a ratio of the time during which the charged particle passes through the plasma shell to the time of the free flight.

For E_γ = 100 MeV and $k\Theta$ = 100 keV the photoproduction cross section is $\sigma_{\gamma\gamma} \sim 3\cdot 10^{-26}$ cm^2, i.e., the optical depth is $\tau_{\gamma\gamma} \simeq 40K^{-1}$ if $K \ll 10$.

The plasma will also absorb ultrarelativistic electrons due to the Compton loss on the plasma X-ray photons. Nevertheless, high energy π-mesons, having a path exceeding the plasma thickness, decay in the ambient space, producing high energy electrons and protons.

In conclusion one of the authors (F.A.A.) expresses his gratitude to S.G.Matinyan for discussions stimulating this paper.

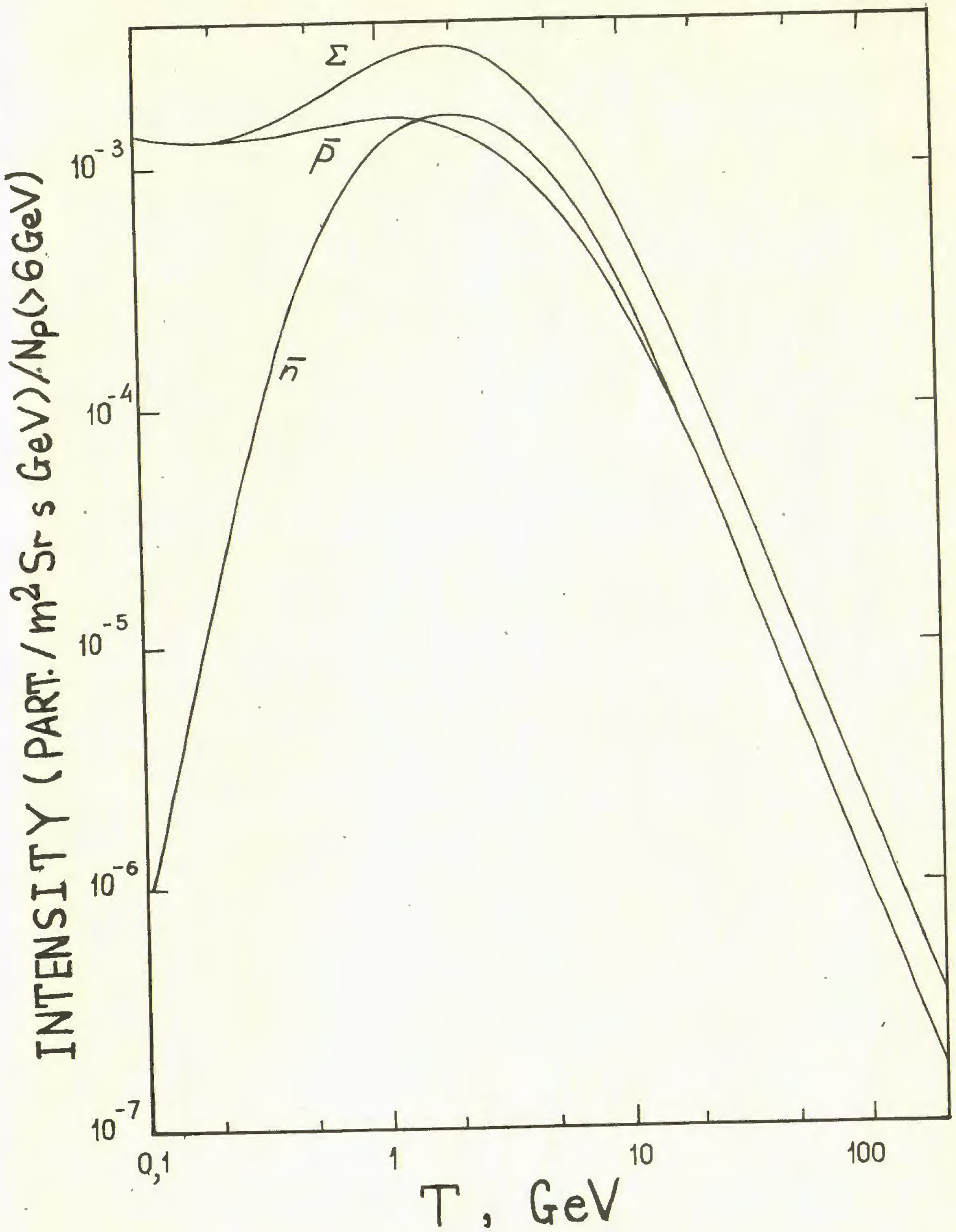


Fig. 1

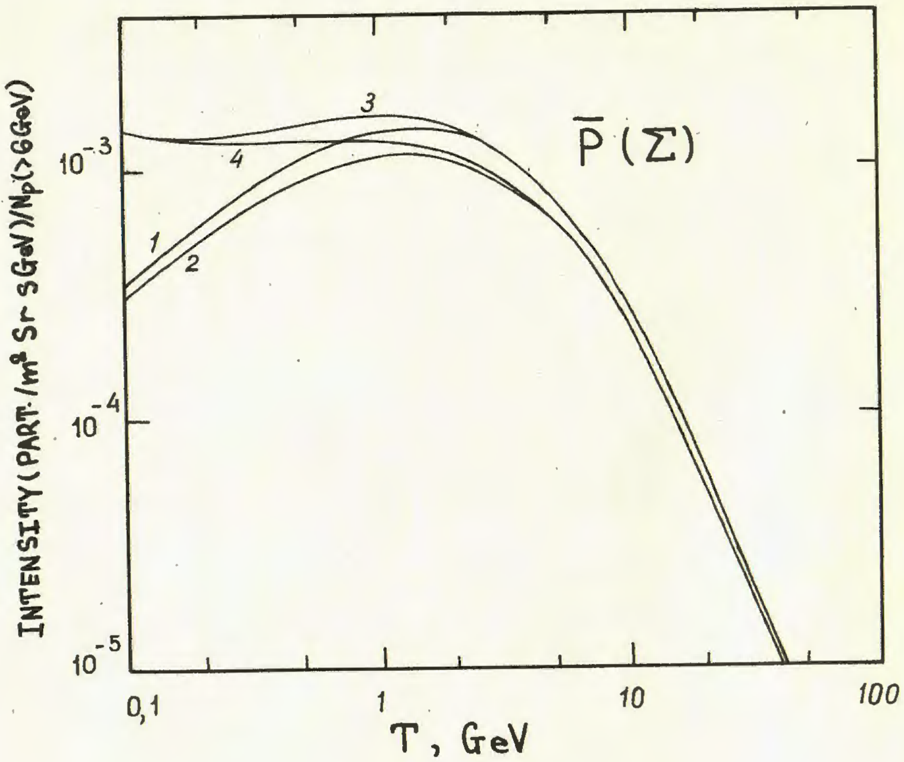
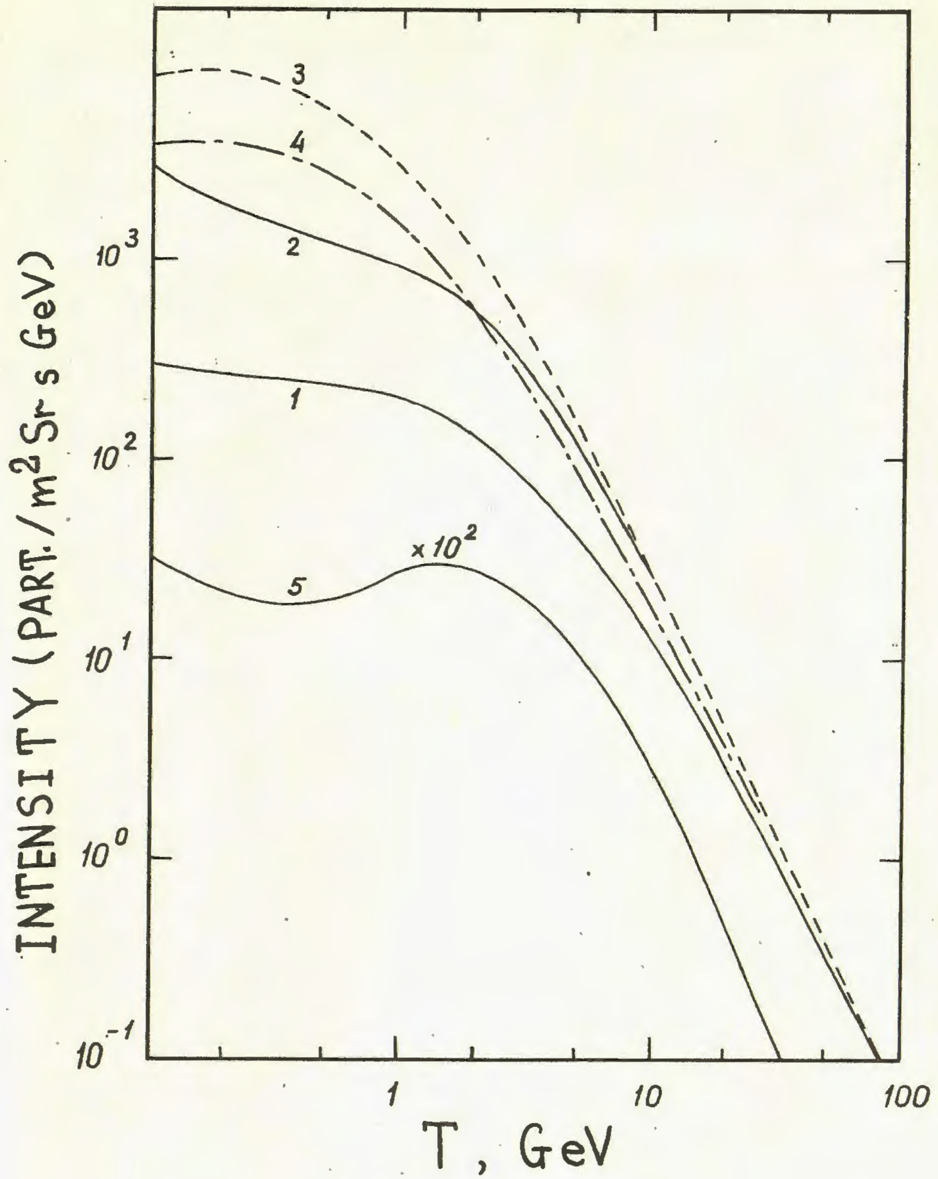

INTENSITY (PART./m² Sr s GeV)/Np(>6 GeV)
10^-3
10^-4
10^-5
0,1
1
10
100
T, GeV
P̄(Σ)
1
2
3
4

Fig. 2


INTENSITY (PART./m² Sr s GeV)
10^3
10^2
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10^-1
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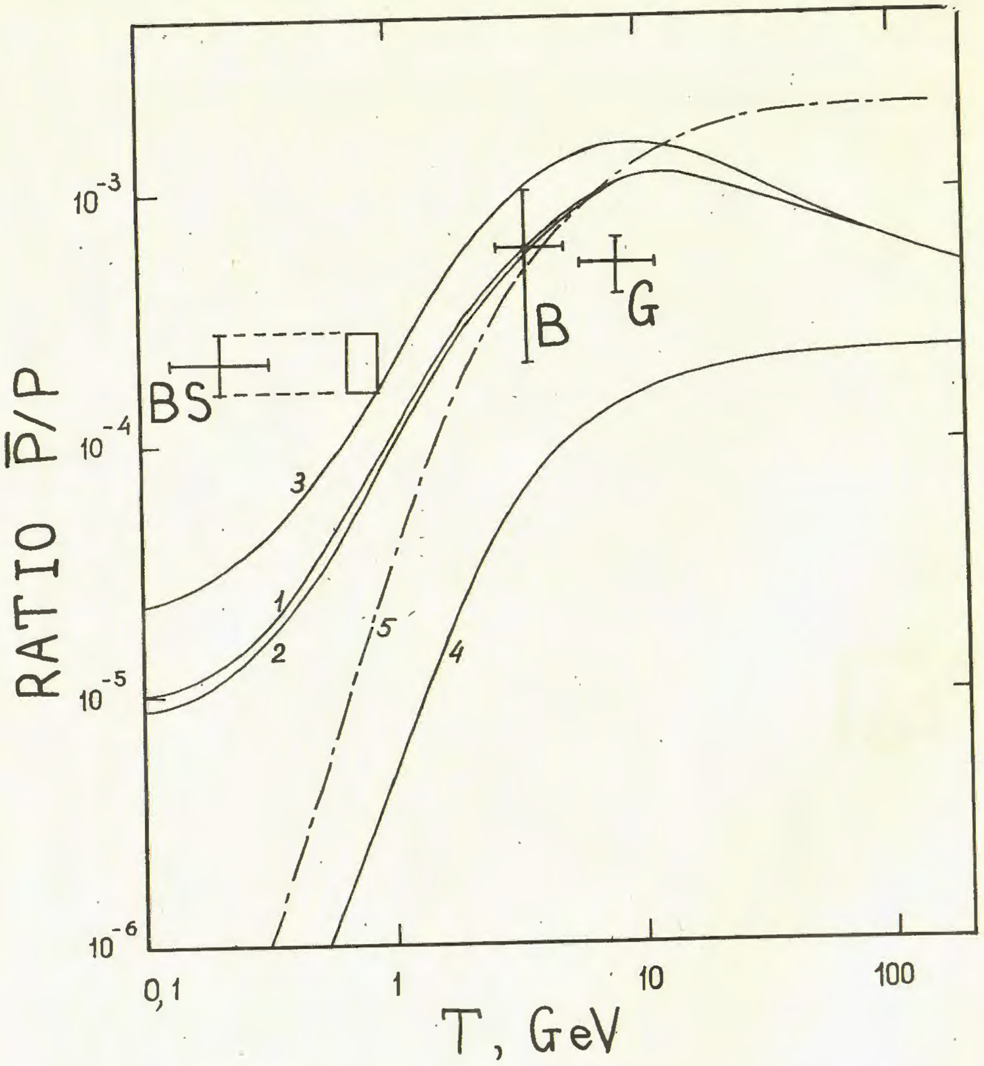
10
100
T, GeV
3
4
2
1
5
×10²

Fig. 3


10^-3
10^-4
10^-5
10^-6
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BS
B
G
1
2
3
4
5
0,1
1
10
100
T, GeV

Fig. 4a

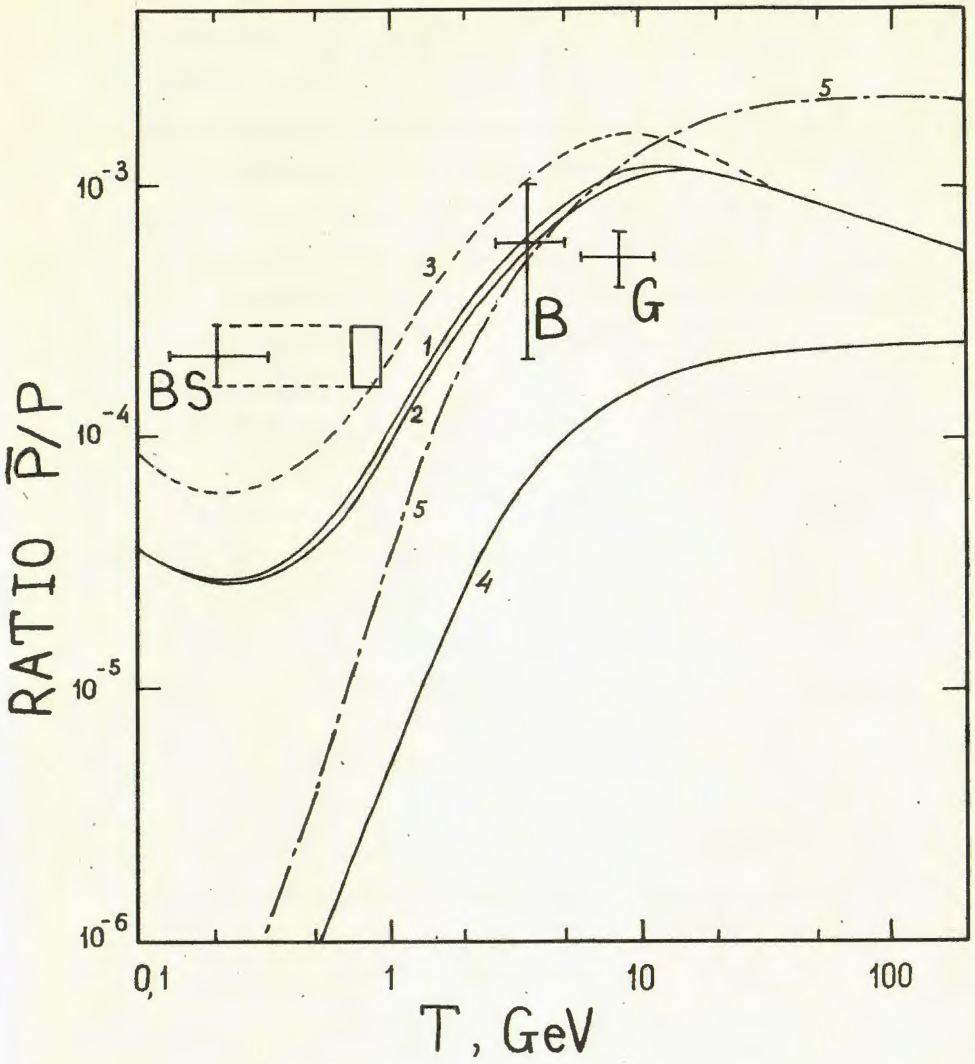
10^-3
10^-4
10^-5
10^-6
RATIO P̄/P
BS
B
G
1
2
3
4
5
5
0,1
1
10
100
T, GeV

Fig. 4b

Figure Captions

Fig. 1 Energy spectra of antiprotons $\bar{p}$ and antineutrons $\bar{n}$. Σ is the total spectrum of antiprotons after the decay of antineutrons. The initial spectrum of protons is given by the expression (7); $K\Theta = 100$ keV, $\Delta T = 1$ GeV.

Fig. 2 Energy spectra of antiprotons for various parameters of plasma. Curves 1 and 2 correspond to the cold plasma with $\Delta T = 1$ GeV and $\Delta T - 2$ GeV, respectively; 3 and 4 correspond to the hot plasma with $\Delta T = 1$ GeV and $\Delta T = 2$ GeV, respectively.

Fig. 3 Comparison of proton energy spectra obtained in this paper with that of primary protons. $K\Theta = 100$ keV and $\Delta T = 2$ GeV.

1 - the spectrum of protons escaping from the source;

2 - the expected proton spectrum taking into account the propagation factor;

3,4 - demodulated proton spectra according to [15,16] ;

5 - the expected antiproton spectrum taking into account the propagation factor.

Fig. 4 Observed and predicted $\bar{p}/p$ ratios near the Earth.

a) cold plasma; b) hot plasma

1 - $\Delta T = 1$ GeV, 2 - $\Delta T = 2$ GeV; measured proton spectrum from [15]; 3 - $\Delta T = 1$ GeV, measured spectrum of protons [16]; 4,5 - $\bar{p}/p$ ratio in Leaky Box and Closed Galaxy Models.

Experimental points: B - [1] , G - [2] , BS - [7] .

The dotted line rectangle shows the possible effect of adiabatic cooling in heliosphere.

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