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ANOMALOUS PAMELA EFFECT AND ITS POSSIBLE EXPLANATION

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Abstract

Anomalous effect discovered in PAMELA experiment includes the unusual dependence of ratio r of galactic positron flux to (electron + positron) one as a function of energy E of these particles. According to the theory and calculations the ratio $r(E)$ has to be decreased with the growth of E. However, experiment shows that in the energy range of $0.1 < E < 5$ GV the value of r decreases and after that from $E > 5$ GeV the ratio r increases up to $E \approx 150$ GeV (till this energy there are the measurements). In this paper the explanation of this anomalous effect is given. The explanation includes the suggestion that galactic cosmic rays (GCRs) are generated not only supernova remnants but active dwarf stars also. The latter produce particles with $E < 10^{14}$ eV. During powerful flares on these stars high energy protons are generated. Part of these particles propagates into interstellar space, some part falls on the stellar photosphere, interacts with the stellar matter and produces charged and neutral pions. The charged pion decays (π^+ μ^+ e^+) give additional flux of e+ (and e^-). Also, neutral pion decays will produce 2γ and these gammas will give (e^+e^-) pairs. The Sun is a yellow dwarf and during powerful solar flares we observe such processes. High-energy positrons and electrons will have the possibility to escape from the active flare region with strong magnetic fields and come to the interstellar medium. Thus, we will have an additional source of positrons that can explain anomalous effect observed in the PAMELA experiment.

Introduction

It is accepted that our Galaxy consists of the matter (not antimatter) and such particles as antiprotons and positrons are produced in the nuclear interactions of cosmic particles with the nuclei of interstellar medium. The energy spectrum of antiprotons obtained in PAMELA experiment in a wide energy region of $0.5 \leq E \leq 100$ ГэВ is in agreement with the mechanism mentioned above [1].

However, we observe another situation for positrons when we consider the ratio r of fluxes of galactic e^+ to the sum of galactic e^- and e+.

It is accepted that main source of cosmic rays in Galaxy is shock waves of supernova remnants. These shock waves accelerate particles up to $E \approx 10^{17}$ eV [2]. As our Galaxy consists of the matter, the shock waves from supernovae accelerate protons, nuclei and electrons. The spectrum of accelerated particles has the form $J(E) \sim E^{-\gamma}$ where $\gamma \approx (2.2 - 2.5)$. As the propagation of these particles in Galaxy, losses of energy and outlet from the Galaxy, the detected spectrum of protons has $\gamma \approx 2.7$ and electrons $\gamma \approx 3.1$.

The GCRs interact with interstellar gas of Galaxy and produce charged and neutral pions. The decays of positive pions ($\pi^+\mu^+e^+$) and neutral ones (($\pi^o 2\gamma e^+e^-$) give the positrons. The flux of positrons $J_{e+}(E)$ (and electrons), generated by this mechanism gives less than 1% from the flux of galactic electrons accelerated by shock waves of supernovae. The positron spectrum has a form $J_{e+}(E) \sim E^{-\gamma}$ with $\gamma_{e+} \approx 2.7$. When the propagation of these particles in Galaxy they loss part of energy in the processes of inverse Compton effect and synchrotron irradiation. Some part of them leaves Galaxy. As a result of these processes, we have $\gamma_{e+} \approx 3.5$. Then the ratio r of $J_{e+}(E)$ to the total electron and positron flux $[J_{e-}(E) + J_{e+}(E)]$ will depend on energy as $r = A_{e+} E^{-\gamma e+} / (A_{e-}E^{-\gamma e-} + A_{e+}E^{-\gamma e+})$. As $A_{e-} >> A_{e+}$, we have $r \sim E^{(-\gamma e+ + \gamma e-)} \sim E^{-0.4}$. However, the experimental data obtained in the PAMELA experiment and shown in Fig. 1 give another dependence: the value of $r(E)$ increases with the increase of particle energy for $E > 5$ GeV. It is the main meaning of the anomaly effect discovered in the PAMELA experiment.

Let us consider the other possible sources of cosmic rays in Galaxy besides supernova remnants.

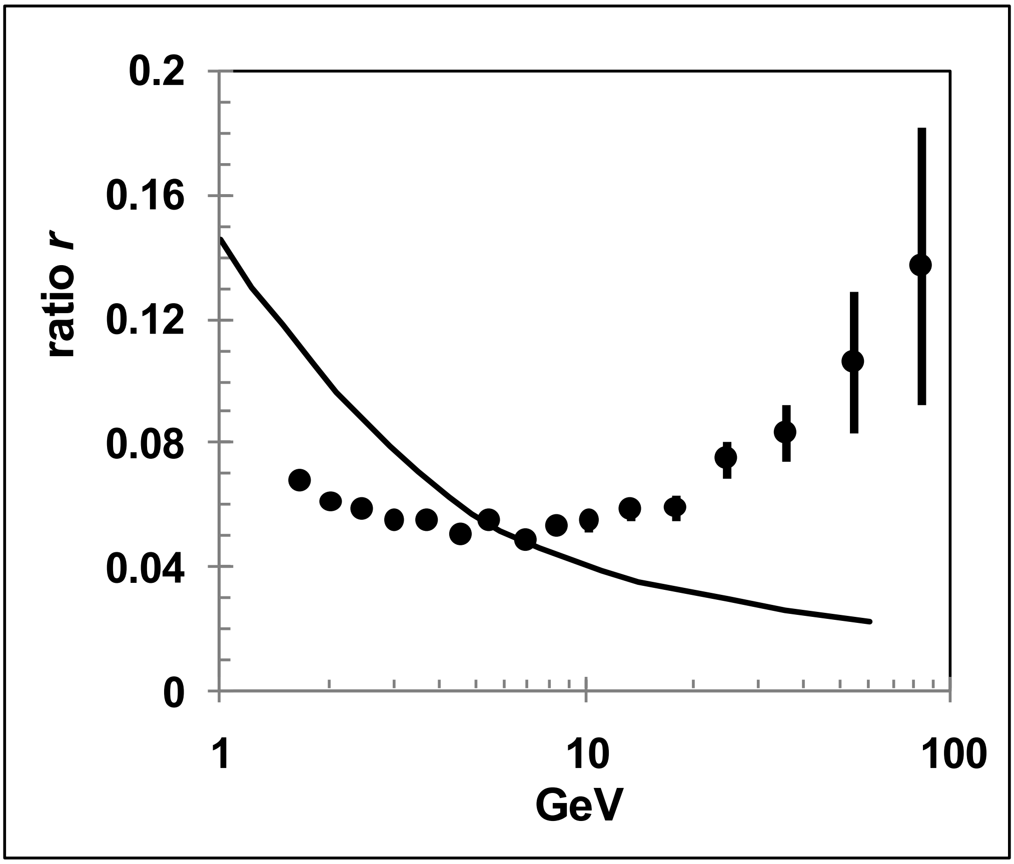

Fig. 1. The ratio *r* of positron flux to the sum of fluxes of electrons and positrons vs. energy measured in the PAMELA experiment (black points with standard errors). Solid curve is the calculated ratio *r*. The calculations were made with the assumption that all positrons are born in the nuclear interactions of GCRs with interstellar gas [4].

Active dwarf stars – sources of cosmic rays

Are there other comic ray sources in our Galaxy besides supernovae? Between huge variety of stars in our Galaxy (there are ~ $2 \cdot 10^{11}$ stars) the dwarf stars of G-M spectral classes amount of 95% [5]. These stars are at the bottom right part of Hertzsprung-Russell diagram. The most part of these stars is very active and gives stellar flares. The powerful stellar flares release huge energy up to 10^{36} ergs. It exceeds the energy released the most powerful solar flares in ~ 10^4 times [6]. Such stellar flares can accelerate particles up to the energy of $E \approx (10^{13} - 10^{14})$ eV [7].

Could stellar flares provide the energy of cosmic rays observed in Galaxy? Let us take that ~ 10% of dwarf stars produce stellar flares, then its number is $n_{\rm dw} \approx 2 \cdot 10^{10}$. Let us take that the average energy released by one flare is $P \approx 2 \cdot 10^{35}$ ergs and frequency of such flares is $\nu \approx 36$ year^{-1}. It means that one stellar flare occurs each 10 days. Under these assumptions the energy of GCRs produced in the stellar flares will equal to $W_{GCR} \approx 1.4 \cdot 10^{54}$ ergs. This value is comparable with the accepted evaluation of GCR energy in galactic disk $W_{GCR} \approx 2 \cdot 10^{54}$ ergs.

Thus, stellar flares observed on dwarf stars are capable to provide necessary energy of cosmic rays in the Galaxy and to give essential contribution to GCR spectrum up to $E \approx (10^{13} - 10^{14})$ eV [7].

Production of additional positron flux

Several times during powerful solar flares the γ-ray radiation from the decay of neutral pions was recorded [8, 9]. The powerful solar flares accelerate solar proton up to $E \sim 30$ ГэВ. Part of these accelerated particles goes to the Sun and interact with the solar material. In these nuclear interactions neutral and charged pions are produced. The π^o-decay gives 2γ observed at the Earth's orbit. Together with the neutral pions the charged ones are produced also. The latter via process of ($\pi^{\pm}\mu^{\pm}e^{\pm}$) decay produce $e^{\pm}$. The solar flares arise in the regions with strong and complex magnetic fields (about 10^3 G or more). If the energy of $e^{\pm}$ is rather high they have a chance to leave flare region with strong magnetic fields and escape to the interplanetary space. Also the additional flux of e+ is generated by the decay of π^o. The same process of $e^{\pm}$ production takes place during powerful stellar flares on red dwarf stars.

Let us consider the process of $e^{\pm}$ production during flare processes on active red dwarf stars and suggest that spectrum of accelerated protons has the form $J_p(E)=AE^{-\gamma}$ (such spectrum we have in solar flares). Some part of these flare particles will enters to the stellar photosphere and make nuclear interactions with stellar matter generating charged and neutral pions. The decays of pions give an additional fluxes of $e^{\pm}$. In the energy range of $E > 1$ GeV the spectrum of $e^{\pm}$ can be presented as $J_{e-}(E) = J_{e+}(E) = BE^{-\gamma}$, where B is constant.

The energy of $e^{\pm}$ generated by this mechanism is less than energy of parent protons in ~ 25 times. If the maximum energy of flare protons is $E_{max} \sim 10^{13}$ eV, then the maximum energy of $e^{\pm}$ produced in such flares will be ≤ 400 GeV. It is worth to note that the bulk part of electrons (as and protons) will be accelerated during stellar flare process and the additional flux of electrons from the mechanism of $\pi^{\pm}$ $\mu^{\pm}$ $e^{\pm}$ and π^o decays will be a small additional part of main electron flux.

The additional fluxes of $e^{\pm}$ are generated in the external stellar photosphere where there are strong magnetic fields. As sequence of it, the part of particles only will escape to interstellar space and the probability of escape (escape function) F will depend on the energy of $e^{\pm}$. In that case the $e^{\pm}$ spectrum coming out from stellar flare region to the interstellar space will have the form $J_e(E) = F(E) \cdot BE^{-\gamma}$. We chose the escape function as $F(E) = [1 + m\exp(-k(E - E_0))]^{-1}$, where m, k and E_0 are constants. This function with the values of m, k and E_0 used in this paper is shown in Fig. 2. One can see that the escape probability of $e^{\pm}$ with energies $E > 100$ GeV from the flare stellar region is 100%.

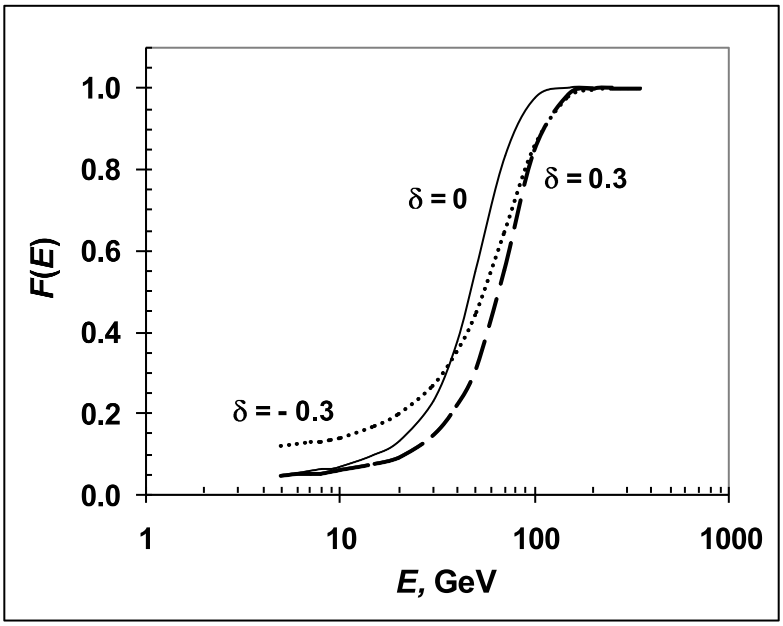

Fig. 2. Probability of escape of secondary electrons and positrons from stellar flare region $F(E)$ for the 3 cases considered in this paper: $\delta = -0.3$, $\delta = 0$ и $\delta = 0.3$. The value of δ is the difference of the exponents of electron and positron spectra. For $\delta = -0.3$ (dotted curve) the constants equal to $m = 0.25$, $k = 0.04$ and $E_0 = 90$ GeV, for $\delta = 0$ (thin curve) $m = 0.05$, $k = 0.07$ and $E_0 = 90$ GeV, for $\delta = 0.3$ (black dashed curve) $m = 0.3$, $k = 0.05$ and $E_0 = 90$ GeV.

Discussion

Let us consider the ratio of e^+ to the total flux of $(e^- + e^+)$, taking into account that the fluxes of these particles are produced from GCRs $J_{e-(GCR)}$, $J_{e+(GCR)}$ and from stellar flares on dwarf stars $J_{e-(Flare)}$, $J_{e+(Flare)}$: $r = [J_{e+(GCR)} + FJ_{e+(Flare)}] / [J_{e-(GCR)} + FJ_{e-(Flare)} + J_{e+(GCR)} + FJ_{e+(Flare)}]$. As it follows from the PAMELA data (see Fig. 1) with the increase of energy of leptons at $E >$ several GeV the additional flux of positrons becomes higher than the flux of these particles produced by the GCRs in the nuclear interaction with interstellar gas.

We can propose that $FJ_{e+(Flare)} > J_{e+(GCR)}$ for particles with $E >$ several GeV. Then $r \approx [FJ_{e+(Flare)}) / (J_{e-(GCR)} + 2FJ_{e+(Flare)}]$. We take that $J_{e-(GCR)} = AE^{-\gamma 1}$ и $J_{e+(Flare)} =$

$BE^{-\gamma 2}$. Then $r \approx F(E) / [CE^{\delta} + 2F(E)]$, where C is constant and the value of δ is the difference of exponents of positron spectrum produced by stellar flares and electron spectrum produced by GCRs, $\delta = \gamma 2 - \gamma 1$. From the experimental data presented in Fig. 1 one can find the value of C. After that using the function $F(E)$ given in Fig. 2 the values of $r(E)$ can be calculated. The results of calculations for $\delta = -0.3$ ($C = 18$), $\delta = 0$ ($C = 5.5$) and $\delta = +0.3$ ($C = 1.2$) are shown in Fig. 3. It is seen that the increase of r with the increase of particle energy E observed in the PAMELA experiment is satisfactory described by suggested mechanism.

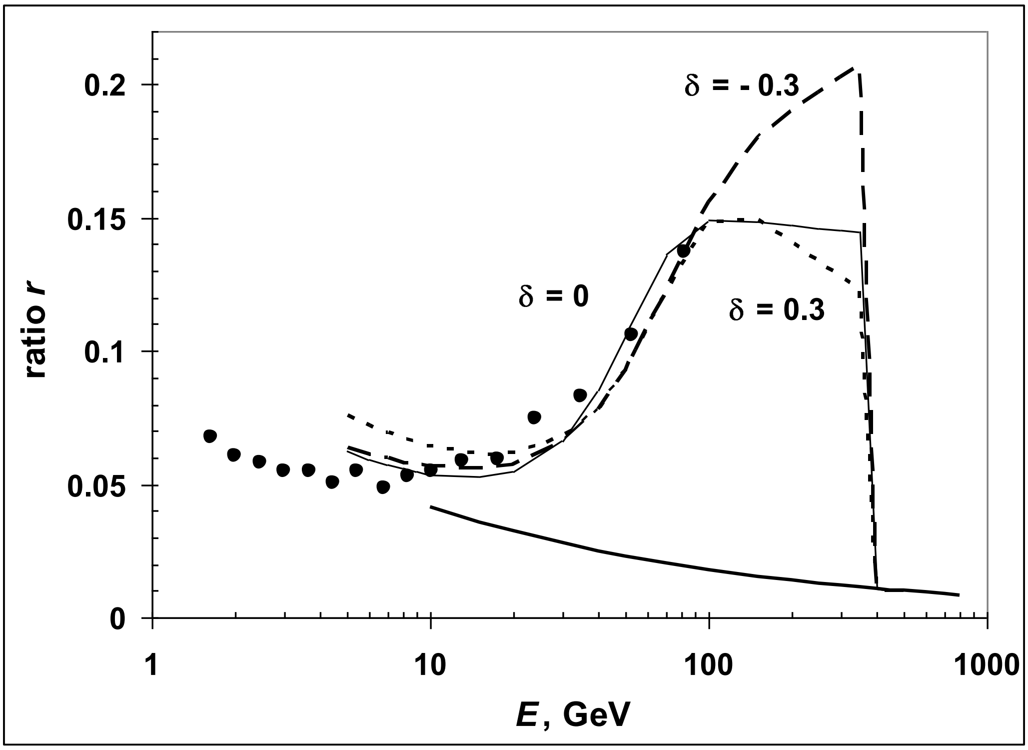

Fig. 3. The ratio r of positron flux to the sum of electron plus positron fluxes vs. energy E of these particles. Dark points are experimental data from the PAMELA spectrometer. The bottom thick curve is the calculation made at the suggestion that the all positrons are produced in the nuclear interactions of GCRs with interstellar gas. The other curves were calculated for the function $r = F(E) / [CE^{\delta} + 2F(E)]$ (see text): dashed curve - for δ = - 0.3 and C = 18, thin solid curve - for δ = 0 and C = 5.5, and dotted curve - for δ = 0.3 and C = 1.2. The function $F(E)$ is shown in Fig. 2.

The feature of this mechanism is the abrupt decrease of r (down to $r = J_{e+(GCR)} / [J_{e-(GCR)} + J_{e+(GCR)}]$) when the energy of $e^{\pm}$ becomes near ~ $(E_{max}/25)$ where E_{max} is the maximum energy of protons accelerated in stellar flare. Most likely that stellar flares on active red stars can accelerate protons up to energy

$E_{max} \approx 10^{13}$ eV and the abrupt decrease of *r* will be observed at $E \approx 300$ GeV.

Currently the several mechanisms explaining the anomalous PAMELA effect were suggested. Some of them are considered and mentioned in [3]. They include the production of additional flux of positrons as via known processes of interaction of particles, via decay of radioactive nuclei [10], so via processes of dark matter particle annihilation.

Conclusion

The international PAMELA experiment discovered the new anomaly effect in the ratio *r* of positron flux to sum fluxes of positrons and electrons. According to the theory the value of *r* has to be decreased with the increase of particle energy *E*. However, the experiment showed the decrease of this ratio in the energy interval of $0.1 < E < 5$ GeV but beginning from $E > 5$ GeV up to $E \approx 150$ GeV (till this energy the measurements were made) the value of *r* is increased.

The explanation of the effect observed is given. The base of this explanation is the suggestion that active dwarf stars together with supernovae produce GCRs. More than 95% of all stars in our Galaxy belong to the dwarf stars. During powerful stellar flares high energy protons are generated (the same process we observe on our Sun during solar flares). The maximum energy of accelerated protons is expected to be about $E < 10^{14}$ eV. The part of accelerated protons propagates into interstellar space, another part goes to the stellar photosphere and interacts with its material. As a result of this process neutral and charged pions are produced. The pion decays produce additional flux of e^+. Such process we observe on the Sun during powerful solar flares (our Sun is the yellow dwarf). The stellar flares occur in the region with strong magnetic fields and only high energy e^+ (in our case e^+ with $E > 5$ GeV) have the chance to leave the region of acceleration and escape to interstellar medium. Thus, we have the source of additional flux of e^+. It is necessary to note that the main bulk of electrons is accelerated during the main stellar flare process and the additional flux of electrons from the pion decays will be a small part of the main electron flux. However, the additional flux of positrons from these decays will provide the main positron flux of these particles in our Galaxy up to energies of $E \approx 300$ GeV.

The evaluations show that the considered mechanism can explain the increase of ratio of positron flux to the sum fluxes of positrons and electrons in the energy range of $E > 5$ GeV. At $E \approx 300$ GeV the abrupt decrease of the ratio down to $r \approx 0.01$ has to be observed.

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