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Pulsar contribution to the cosmic rays between the knee and the ankle

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We calculate energy spectra and mass composition of cosmic rays accelerated by the galactic population of pulsars during their radio and gamma-ray phase. It is assumed that a significant part of the pulsar rotational energy is lost on acceleration of iron nuclei extracted from the surface of the neutron star. It is shown that the best description of the observed cosmic ray spectrum and the mass composition between a few 10^{15} eV and a few 10^{18} eV is obtained for the model B of Lorimer et al., in which the logs of initial pulsar periods and surface magnetic fields are given by the Gaussian distributions with the average values of $< logP[ms] >= 2.6$ and $< logB[G] >= 12.3$, respectively.

1. Introduction

The contribution of particles accelerated by pulsars to the observed cosmic ray spectrum has been more recently discussed in [1, 2, 3]. For example, Bednarek & Protheroe [2] estimate the contribution of heavy nuclei accelerated in the pulsar outer gaps to energies above the knee region. Giller & Lipski [3] derive the initial parameters of the pulsar population inside the Galaxy required to explain the observed shape of the CR spectrum and its intensity. Here we calculate the energy spectra of different types of nuclei injected by the pulsars into the Galaxy, applying a model for their injection and propagation in the expanding pulsar wind nebula (PWNa) surrounding a young pulsar. The model takes into account the energy losses and escape conditions of nuclei during the expansion of the nebula. The results of calculations are compared with the reports on the mass composition in this energy region (see for details [4]).

2. The energy spectra of nuclei injected from the pulsar wind nebulae

It is likely that rotating magnetospheres of neutron stars can accelerate not only leptons but also heavy nuclei, extracted from positively charged polar cap regions. From normalization to the observations of the Crab pulsar, Arons and collaborators [5] postulate that the Lorentz factors of iron nuclei, accelerated somewhere in the inner magnetosphere and the pulsar wind zone and, injected into the pulsar wind nebula should be, $\gamma_{Fe} \approx \chi Ze\Phi_{\rm open}/m_{\rm i}c^2 \approx 8 \times 10^9 \chi B_{12} P_{\rm ms}^{-2}$, where $m_{\rm i}$ and Ze are the mass and charge of the iron nuclei, c is the velocity of light, and $\Phi_{\rm open} = \sqrt{L_{\rm rot}/c}$ is the total electric potential drop across the open magnetosphere, $L_{\rm rot}$ is the rate of rotational energy lost by the pulsar, $B = 10^{12} B_{12} G$ is the surface magnetic field of the pulsar, and $P = 10^{-3} P_{\rm ms}$ is the pulsar period. Due to the rotational energy losses on emission of dipole radiation, the pulsar period evolves in time according to $P_{\rm ms}^2 = P_{0,\rm ms}^2 + 2 \times 10^{-9} t B_{12}^2$, where $P_{0,\rm ms}$ is the initial period of the pulsar, and t is in seconds. Arons and collaborators argue that the acceleration factor χ is not far from unity. $\chi = 0.5$ is taken in the following calculations. Moreover, we assume that these nuclei take significant part, ξ, of the pulsar rotational energy. The unknown value of ξ times the pulsar birth rate in the Galaxy, η, can be obtained from the comparison of contribution of particles injected by pulsars to the observed cosmic ray flux. According to this model the pulsar at a specific time accelerates nuclei monoenergetically. However the energies of freshly produced nuclei change in time due to the change of the pulsar period caused by its rotational energy losses.

The nuclei, injected by the pulsar, propagate in the expanding nebula with parameters changing drastically in time. In order to take properly into account different effects on their propagation (collisions with matter, diffusion inside the nebula, escape from the nebula), we have to consider a time dependent model for the expanding nebula taking into account not only the initial parameters of the expanding envelope but also the energy supplied by the pulsar. The model has to determine such basic parameters as: the expansion velocity of the nebula, the pulsar wind shock radius, the outer radius of the nebula, the average density of matter and magnetic field strength inside the nebula, and others. The details of such a model for the PWNe are described in [6].

The pulsar loses energy in the form of a relativistic wind extending up to the shock at a distance $R_{\rm sh}$. At this distance, the pressure of the wind is balanced by the pressure of the expanding nebula. Rees & Gunn [7] estimate the location of this shock as a function of time by comparing the pulsar wind energy flux, determined by $L_{\rm rot}$, with the pressure of the outer nebula, determined by the supply of energy to the nebula by the pulsar over the whole of its lifetime, $L_{\rm rot}(t)/(4\pi R_{\rm sh}^2 c) \approx 3L_{\rm pul-neb}/(4\pi R_{\rm Neb}^3)$. and $L_{\rm rot}(t) = B_{\rm s}^2 R_{\rm s}^6 \Omega^4/6c^3 \approx 2.5\times 10^{43} B_{12}^2 P_{\rm ms}^{-4}$ erg s^{-1}, where $R_{\rm s}$ and $B_{\rm s}$ are the radius of the pulsar and its surface magnetic field, $\Omega = 2\pi/P$.

The injection spectrum of nuclei can be obtained by summing up over all population of pulsars inside the Galaxy. However, the initial parameters of the pulsars are not precisely known. Therefore, we consider a few different models proposed in the literature. They differ in distributions of the surface magnetic fields and the initial periods of the new born pulsars. The following models are:

1. The surface magnetic fields of the pulsars are described by the distribution derived by Narayan [8], $dN/d(logB) \approx 0.065/(B[10^{12}G])$ yr^{-1}, for $B > 2\times 10^{12}$ G. The distribution of pulsars with the surface magnetic fields below 2×10^{12} G bases on Fig. 13 in Narayan [8]. All pulsars are born with the fixed initial period $P_0 = 40$ ms [9].

2. The surface magnetic fields of the pulsars as in model (1). The initial pulsar periods are correlated with their surface magnetic fields, $P_0[ms] = 63.7/(B[10^{12}G])$, as postulated by Xu et al. [10]. We apply this formula for the pulsar initial periods above 2 ms.

3. Model A of Lorimer et al. [11] postulating the Gaussian distribution of log B of the pulsars with parameters $< logB[G] >= 12.46$ and $\sigma_{\rm logB} = 0.31$. We apply this model for the range of $B = 10^{11.5-13.3}$ G. All pulsars are born with a single initial period, $logP_0[ms] = 1.35$.

4. Model B of Lorimer et al. [11] postulating the Gaussian distributions of log B, with $< logB[G] >= 12.3$ and $\sigma_{\rm logB} = 0.35$, and for log P_0, with $< logP_0[ms] >= 2.6$ and $\sigma_{\rm logB} = 0.35$ above 2 ms.

For these four models of the pulsar population, we calculate the injection spectra of nuclei into the Galaxy applying the values of the normalization coefficients, $\xi\cdot\eta$, which give us the flux of calculated nuclei on the level comparable to that observed in the cosmic ray spectrum.

3. Contribution to the cosmic rays in the Galaxy

Having in hand the injection spectrum of nuclei by pulsars, we can estimate the flux of these nuclei inside the Galaxy, adopting the leaky box model, from the relation $dN/(dEdSdtd\Omega) = dN_{\rm inj}dEdt\cdot c\,\tau_{\rm esc}/4\pi\, V_{\rm gal}$, where $dN_{\rm inj}/dEdt$ is the total injection spectrum of CRs from all the pulsars in the Galaxy, $V_{\rm gal} = 10^{68}$ cm^3 is the volume of the Galaxy (a disk with a radius of 15 kpc and a half-thickness of 3 kpc), and $\tau_{\rm esc}$ is the escape time of hadrons from the Galaxy. The dependence of the escape time of nuclei on their energy and charge is approximated by $\tau_{\rm esc} = 7\times 10^8$ yr$/(E_{\rm GeV}/Z)^{0.54}$, where Z is the charge of nuclei and $E_{\rm GeV}$ its energy in

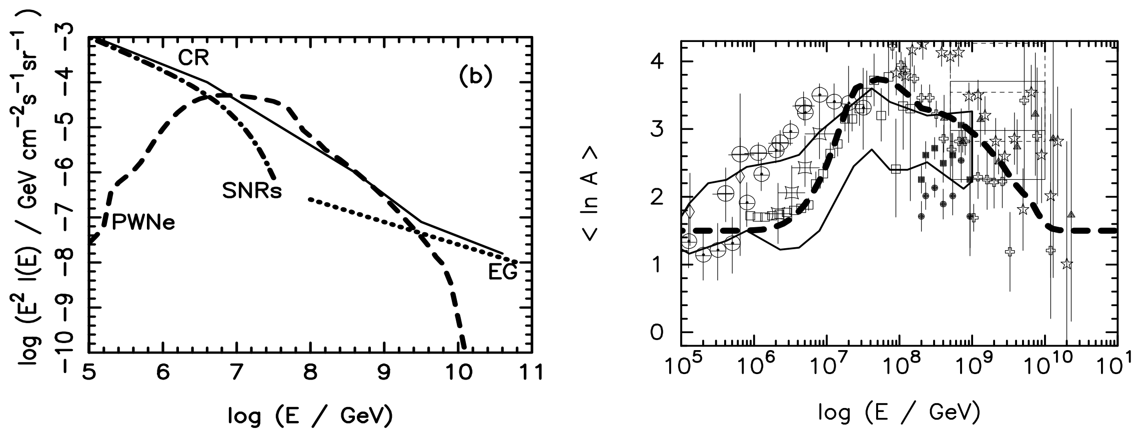

Figure 1. The comparison of the spectrum of particles accelerated by pulsars with the parameters described by the model (4) (dashed curve), with the observed cosmic ray spectrum (thin full curve). It is assumed that at low energies the supernova remnants (SNR) accelerate CRs with the spectrum $dN/dE \propto E^{-2.7} exp(-E/10^7 GeV)$ (dot-dashed curve). At extremely high energies (EG), the spectrum has the form $dN/dE \propto E^{-2.7}$ (dotted line). The comparison of the mass composition of the cosmic rays, $< lnA >$, obtained in terms of the model (4) (dashed curve), with the measurements of the cosmic ray composition reported by different experiments. $< lnA >$ equal to 1.5 is taken for the SNR contribution to cosmic ray spectrum as measured at low energies by direct experiments. Similar composition is also applied for the EG component of CRs above the ankle.

GeV. This formula make use of the energy dependence of the lifetime of particles as obtained in the standard diffusion model [12], and is normalized to the estimated lifetime of protons with energies 3×10^{18} eV equal to 10^4 years (see Fig. 4.18 in Berezinsky et al. [13]).

The calculations have been performed for all four models of the pulsar population, applying the normalization parameter, $\xi \cdot \eta$, as reported above. The comparison with the observed cosmic ray spectrum with the predictions of model (4) is shown in Figs. 1. Particles, accelerated by the pulsars, dominate the spectrum between the knee and the ankle. Only this model gives good consistency of the observed shape of the spectrum with the calculated one. We also calculate the expected mass compositions of the CRs, $< lnA >$, in terms of the model (4) and compare them with the measurements of the mass composition of CRs by different experiments (see Fig. 1). The mass composition of the galactic supernova component is taken as reported by the direct measurements at low energies (JACEE, RUNJOB). The same composition is also applied to the extremely high energy component. Model (4) describes well the general tendency reported by most experiments, i.e. the sharp rise of $< lnA >$ above the knee up to the value of about 4 (which corresponds to almost pure iron), and gradual decrease of $< lnA >$ above $\sim 3 \times 10^{17}$ eV.

4. Discussion and Conclusions

The best fit to the observed cosmic ray spectrum between the knee and the ankle is obtained for the model B of Lorimer et al. [11] (our model iv) which postulates that the observed radio pulsars are born with relatively long initial periods, with the average value of $\sim$ 400 ms, with the Gaussian distribution in log scale, and typical surface magnetic fields, with the average value of 2×10^{12} G and also the Gaussian distribution in log scale. These parameters are similar to those obtained in the work by Giller & Lipski [3], who got the best description of the cosmic ray spectrum, based mainly on the analytical calculations, for the gamma distribution of the initial pulsar periods (which is $\propto P_0^{s-1}$ for small periods) with average value of $P_0 = 500$ ms and s = 3.86, and the Gaussian distribution for log B with average value between $10^{12} - 10^{13}$ G and $\sigma_{\rm logB} = 0.4$. From the normalization of the calculated spectrum of nuclei in terms of the model (4) to the observed cosmic ray spectrum, we obtained the efficiency of conversion of the rotational energy of the pulsar into the energy of iron nuclei multiplied by the pulsar birth rate equal to $\sim 1/120$ yr^{-1}. This value is consistent with the estimated pulsar birth rate $\sim 1/(20-250\ {\rm yr})$ [14, 15, 16]. Therefore, we conclude that the efficiency of acceleration of the iron nuclei should be in the range $\sim (0.2-1.0)$.

The low energy break in the spectrum of nuclei injected by the PWNe is explained in our model by switching off the mechanism of extraction of the iron nuclei from the surface of the neutron star. This is caused by the lack of efficient cascading in the inner pulsar magnetosphere which products impinge on the region of the polar cap and allow efficient extraction of the iron nuclei from the neutron star surface. The cascades stop developing in the pulsar magnetosphere when the pulsar period becomes too low due to the pulsar rotational energy losses. This happens when pulsars reach the age of $\sim 10^6 - 10^7$ yrs, depending on the value of their surface magnetic field. It might be surprising that we postulate a similar order contribution to the cosmic ray spectrum around the knee region from particles accelerated at the outer supernova shock waves and from the pulsars. However, it is likely that the initial parameters of pulsars and expanding supernova envelopes, which originate in this same phenomenon, are in some way related. Pulsars with more extreme parameters (initial periods, surface magnetic fields) seem to be produced by explosions of type Ib/c supernovae which progenitors rotate fast and have relatively smaller envelopes just before explosion.

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