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Is the knee and ankle in cosmic ray spectrum due to its propagation?

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Abstract. The Hillas diagram size-strange of magnetic field allows pulsars as galactic cosmic ray sources. The spectrum of cosmic nuclei outgoing from pulsar is formed by its photo-disintegration in the soft photon bath around the source. The diffusion equations for high-energy nuclei have been solved for various initial conditions. We have assumed that in the source nuclei are accelerated with single power low spectrum and constant mass composition. The sources are distributed in galactic disk. The propagation of high-energy nuclei in galactic magnetic field has been analysed. We have found that the confinement time versus energy changing its shape at the some energy where „knee" and „ankle" in cosmic ray spectrum is observed. The spectra of the particular group of nuclei expected in the cosmic rays spectrum have been calculated. The total (sum over whole nuclei) spectrum is compared with experimental data in wide energy range. The mass composition versus energy also agrees with experimental data.

1 Introduction

A characteristic feature of the cosmic ray spectrum is the steeping that occurs at ~4x10^{15} eV, so called "knee" of the spectrum. Below the "knee" the spectrum has the form of a power law with spectral index about -2.7. Above the "knee" the spectrum again has the form of a power law with its spectral index about -3.1 that persists to about 10^{17} eV. The energy spectrum steppe above 10^{17}eV and again flattens above 5x10^{18} eV. The change in the spectral slope forms a dip where minimum lies among 2×10^{18}eV to 5× 10^{18}eV so called "ankle". After "ankle" the spectrum flattens to power law with index -2.7. It is also found evidence for a change in composition to a lighter component above the ankle that is correlated with the change in spectral slope.

The main goal of this paper is to find connection between the features in the cosmic rays spectrum and magnitudes of parameters characterised local cosmic space (galactic). So we have analysed the photo-dissociation and rigidity processes to explain the observed features in cosmic ray spectrum and variation of mass composition. It shown that in steady state phase (now) the spectrum of cosmic rays is determined by propagation of nuclei in soft background photon field and it is quite natural to assume that the nuclei are continuously injected by galactic cosmic sources (galactic pulsars). Subsequently the nuclei are scattered by galactic magnetic. In the proposed model both the cosmic ray spectrum and mass composition can be very well described with widely accepted parameters of cosmic vicinity. We argue that the features observed in the cosmic ray spectrum are mirroring the properties of cosmic space.

2 The model description

The cosmic rays are galactic origins in whole energy range. Propagation processes in soft photon and magnetic fields form the mass composition and the spectrum of primary cosmic ray.

2.1 Assumptions

We have considered the model of galactic cosmic ray sources with the following assumptions:

- Nuclei are accelerate with mass number A=1÷56 (from hydrogen to iron) continuously with spectrum $Q(E) = k \cdot E^{-\gamma}$ where γ-is the spectral index of accelerate nuclei. We using value γ=2.75 for protons and γ=2.55 for nuclei from helium to iron groups.
- The spectrum of soft photons inside the acceleration region (most probably pulsar) is a type of thermal bremsstrahlung with maximal temperature kT=20 eV. The calculation has been done for the concentration of plasma is equal to unity and photons residential time τ=R/c=1 sec.

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- The relative mass composition of produced nuclei by sources we have took as observe JACEE experiment at energy 10^{14}eV.
- The cosmic ray sources are located in disk. The disk there is inside the spherical Halo with radius R_H =50000 ly.
- The magnetic field in disk composed with regular and turbulent components in the portion $B = (0.07 \cdot B)_{regular} + (0.93 \cdot B)_{turbulent}$. - where B is the total magnetic field in the given point of galactic space.

3 Propagation of nuclei through the radiation fields

The interaction between photons and high energy nuclei has important consequences both for the mass composition and for the energy spectrum of cosmic ray. Three processes should be taken into consideration:

- Pair production $\gamma + A \rightarrow e^{+} + e^{-} + A^{*}$
- Photo disintegration of nuclei $\gamma + A \rightarrow (A-1)^{*} + \left\{ \begin{matrix} n \\ p \end{matrix} \right.$
- Photo production $\gamma + p = n \cdot (\pi^{o}, \pi^{\pm}) + p$

$2\gamma \hookleftarrow$

A summary of the cross-sections and other parameters for photons-nucleus reactions has been give in paper by .Karakula and Tkaczyk (1993). The energy spectra of nuclei with mass number A=56-i outgoing from the source after passing the propagation distance x have been obtained by solving the system of diffusion equations:

$$\frac{\partial N_i(E,x)}{\partial x} = -a_i(E) \cdot N_i(E,x) + a_{i-1}(E) \cdot N_{i-1}(E,x), \quad for\ i = 1,2,\ldots 54 \qquad (1)$$

$$\frac{\partial N_o(E,x)}{\partial x} = -a_o(E) \cdot N_o(E,x), \quad for\ i = 0 \text{ -Iron} \qquad (2)$$

Where $N_i(E, x)$- is the number density of nuclei with index i per unit energy interval after passing the distance x in the source and E-is the energy per nucleon. Equation (1) is used for nuclei from deuterium to iron A=55. The first term in the right side describes the rate of removal of nuclei from the beam due to photo - disintegration process. The coefficients a_i is the reciprocal mean free path of nuclei with mass number A=56-i, where i is integer number. The second term in equation (1) describes production of nuclei with index i by knockoff of one nucleon from heavier nuclei (i-1). The protons in the proposed model are accelerated in the source but these are also secondary ones from photo -disintegration of nuclei.

The differential number of secondary protons $P_i(E,x)$ has been obtained by solving the equation,

$$\frac{\partial P_i(E,x)}{\partial x} = a_i(E) \cdot N_i(E,x), \qquad (3)$$

The total number of secondary protons P(E,x) at the propagation distance x is summa $P_i(E,x)$ over whole indexes i. $P(E,x) = \sum_{i=0}^{54} P_i(E,x),$ (4)

Secondary and primary protons suffer photopion energy

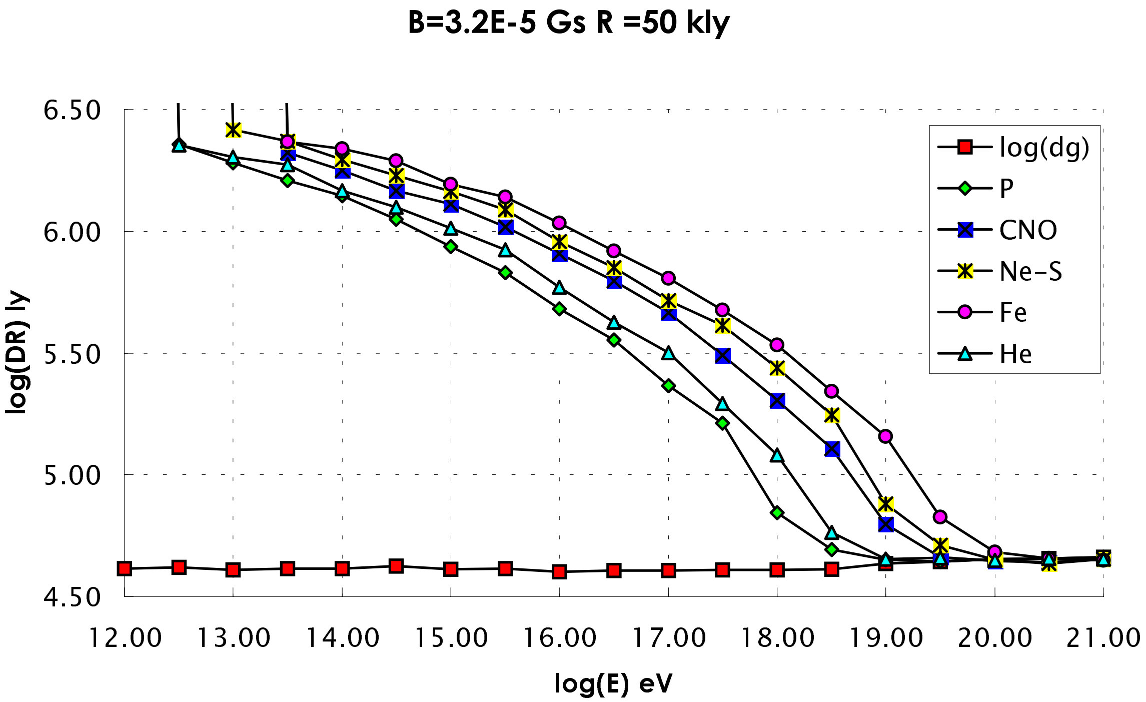

Fig. 1. The mean value of real RD and geometrical dg distances passed by nucleus, versus energy for ring model of regular magnetic field $B_d = 2.1\mu Gs$ and halo radius R_H =50000ly.

losses. The solutions of the diffusion equation for particular nuclei and protons have been found and a computer code has been made using input parameters specified in the assumptions to the proposed model . The best fit to the cosmic ray spectrum has been found by varying these parameters. The spectra of groups of nuclei the same as named by a JACEE are shown as a result of calculation. The groups of nuclei are collected as follows PP-primary protons, PS-secondary protons (from photo - disintegration), He, CNO, Ne-S, Fe.

4 Propagation of nuclei in the magnetic field

To describe the regular galactic magnetic field we simplified the ring model proposed by Rand and Kulkarni (1989), based on pulsar rotation measures. The disk magnetic lines are concentric ring with constant strange inside disk B_d and change the sign up and below plain z=0. The strange of regular component outside the disk decreases following formula $B_{regular} = B_d \cdot \exp(-\frac{z-z_o}{z_o}) \cdot \exp(-\frac{r-R_o}{R_o})$ *where* B_d strange of magnetic field in disk. The diameters of disk are the high z_o=0.2 kpc and the radius R_o=15 kpc.

The bisimmetric spiral model of magnetic field was also used for calculations of nuclei trajectory. No substantial difference has been fund.

The new of proposed model is assumption that the regular component give the minor contribution (7% of total) to the strange of Galactic magnetic field. As it was shown by Karakuła et al.,(1972) the large anisotropy should be observed if cosmic ray origin from galactic sources and disk has regular magnetic field only.

Modelling the turbulent magnetic field we adopt the method of Honda (1987). The main advantage to this method is that it produces a turbulent magnetic field whose divergence is zero. The irregular component has the random direction and strange. The numbers of N=1000 trajectories, for particular energy, of protons or nuclei, starting randomly from the disk, have been calculated. The calculations of trajectory of nuclei were stopped when exceed radius of halo R_H. The calculation has been done for several values of radius of halo 25000, 50000 and 100000 light years. The real distances RD[ly] passed by nuclei and geometrical distance dg[ly] between starting and stopped points are calculated. The average values for RD and dg distances have been calculated as function of energy for groups of nuclei.

Figure 1 shows RD and dg distances for ring model. The value of magnetic field indicated on the fig. 2 is only parameter the real regular magnetic field near the Sun is equal to Bd=7%3.16x10^{-5} =2.1 µGs but amplitude of turbulent component is equal to 93% of 3.16x10^{-5} µGs. The radius of halo is equal to R_H =50000ly. The leakage probability from the halo region is proportional to the reciprocal of RD.

5 Discussion and conclusions

Figure 2 shows the spectra of nuclei, multiplied by E^3,

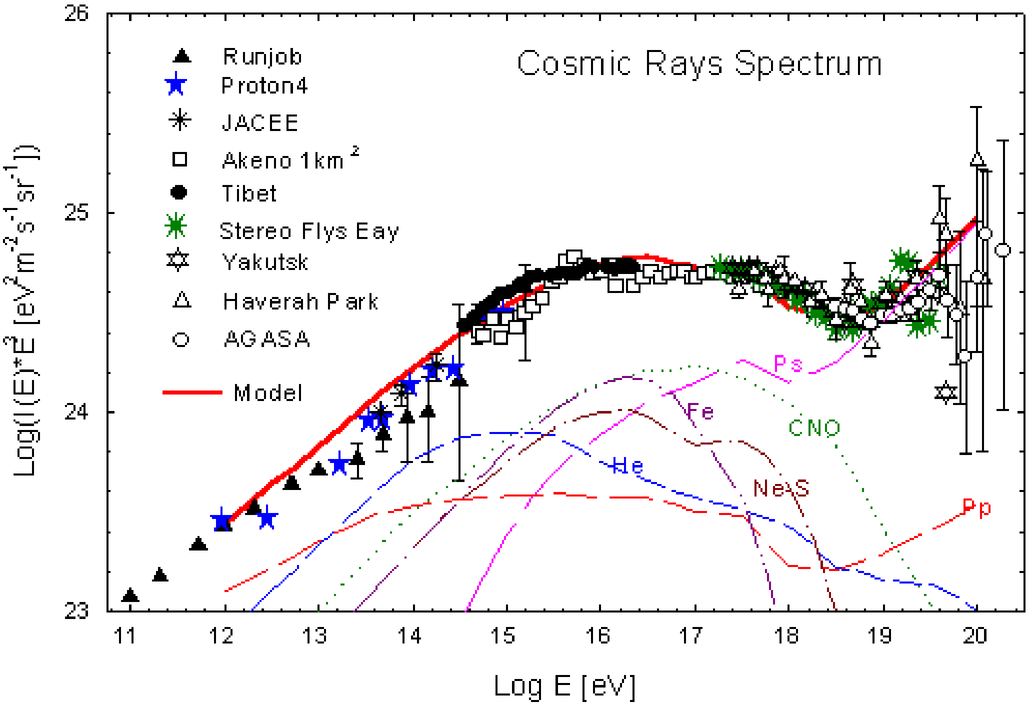

Fig. 2. The cosmic ray energy spectrum data points and predictions by the model, total (full line) and particular group of spectra (dashed lines).

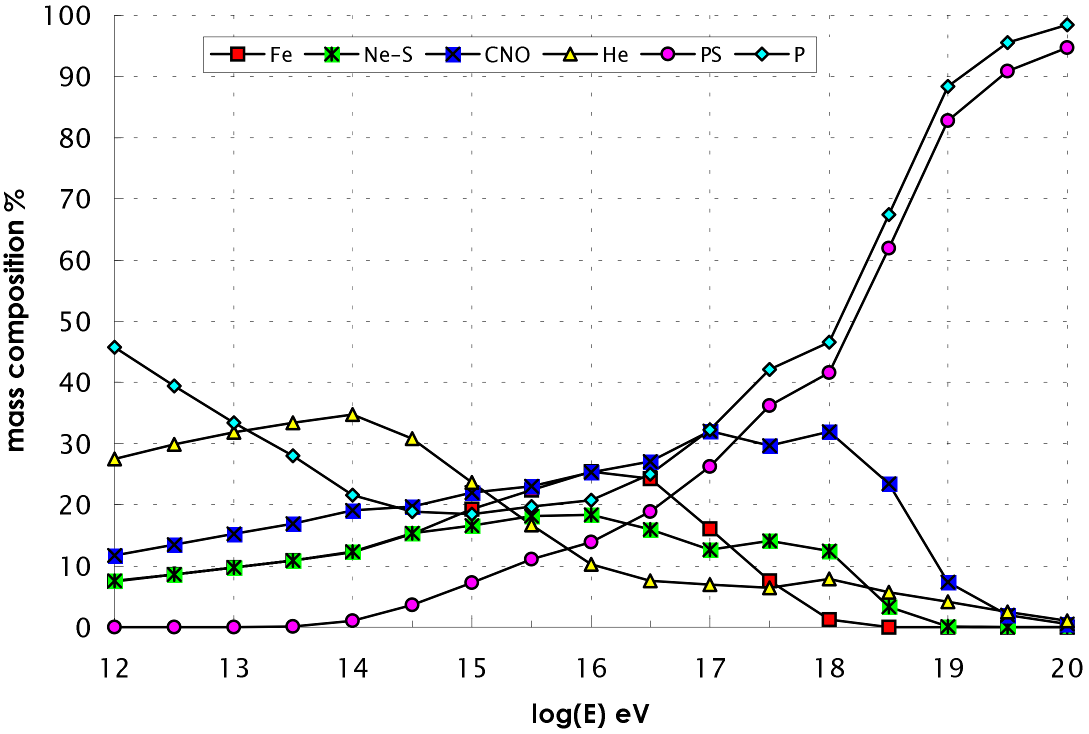

Fig. 3. The expected from model, percentage contribution particular group of nuclei to the cosmic ray spectrum, versus energy.

expected from the model, by full line the total spectrum and by broken/doted lines for group of nuclei labelled respectively. The data points displayed cosmic ray energy spectra measured by well know array indicated on the figure 2.

The calculation have been performed in two steps, first the diffusion equation has been solved. In second step the leakage effect has been taken in to account for the nuclei after its destruction in the photons field (source). We should notice that total spectrum from model is normalised to experimental point at energy 10^{12} eV. The curve from model very well follows the data point in whole energy range. Moreover the knee and ankle in predicted spectrum exists and appeared at this some energy range. Even characteristic dip near the ankle also appeared in spectrum from model. Shortly the features in the spectrum of cosmic rays have the interpretation in my model as follow. The steeping in the spectrum of protons observed at energy ~10^{14}eV is caused by theirs non-diffusive leaked from galaxy. Below this energy the protons and nuclei are effectively trapped even by weak the regular component of magnetic field. In energy region 10^{15} ~$3\text{x}10^{16}$ eV the "knee" in the energy spectrum is due to photo disintegration process of nuclei, in a soft photon field and leaked process. The concave down at energy 3 10^{18}eV is cause by fact that above this energy, protons and nuclei, in average traverses the same path independent from energy in galactic space. So the propagation process do not change the spectrum. The sum of sources output spectrum is galactic spectrum.

In figure 3 we shows the relative mass composition group of nuclei as a function of energy. This picture is in accord with observation. The mass composition is complex in low energy range, its variation is in the frame experimental uncertainty. It is clear that mass composition became lighter above the energy ≈$3\text{x}10^{18}$eV

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