29th International Cosmic Ray Conference Pune (2005) **00**, 101-104

Cosmic ray spectrum above 10^{15} eV (a new approach)

A.A. Petrukhin
Moscow Engineering Physics Institute, Moscow 115409, Russia
Presenter: A.A. Petrukhin (petruhin@nevod.mephi.ru), rus-petrukhin-AA-abs1-og12-oral

A new approach to cosmic ray description based on the model of particle generation and acceleration in plasma pinches and on supposition that a new state of matter appears in cosmic ray interactions above 10^{15} eV is considered. Consequences for various aspects of cosmic ray physics and some possibilities to check this hypothesis are discussed.

1. Introduction

At present, the following basic information about cosmic rays of high energies is known. Their flux is permanent in time and isotropic in space. Their energy spectrum is described by power functions with average slope $\gamma \approx 2.7$. This spectrum has three peculiarities: the knee and the ankle at which its slope is changed, and GZK cutoff (or its absence). The composition below 10^{15} eV corresponds to natural abundance of chemical elements except for so-called secondaries (nuclei of Li, Be, B), which are present in cosmic rays, but are absent in natural abundance. Around the knee the heaving composition is observed, which at further increase of energy begins to return back to a normal state. For description of cosmic ray behaviour many theoretical models were suggested, but there is no model which could explain all observed data and unambiguously predict the slope of energy spectrum. And, at last, all models have limitations on accelerated energies. But there is one model of CR generation in plasma pinches, which is free from these drawbacks. Unfortunately this interesting model is practically unknown among cosmic ray community. It is very important also to remark that all information about cosmic rays above 10^{15} eV was obtained from results of EAS investigations. These results are converted into primary cosmic ray energy spectrum and composition taking into account extrapolation of accelerator data about hadron interaction to higher energies of cosmic rays without any changes. But namely above 10^{15} eV many unusual events in cosmic ray interactions were observed. It is impossible to explain most part of them without inclusion of new physical phenomena. Corresponding ideas were presented at previous ICRCs [1]. Their discussions and some new theoretical models allowed to formulate a new approach to cosmic ray description which is presented in this paper.

2. Present situation and unsolved problems

At present the description of primary cosmic rays is based on the separation of galactic and extragalactic sources of their origin. In particular it is supposed that cosmic rays below the knee have galactic origin. Since all existing models give the slope of energy spectrum less than 2.7 (2.0; 2.2; … 2.5) it is supposed that these cosmic rays are kept in Galaxy by magnetic fields, live in it of the order of 10^7 years, interact with galactic matter (as a result, secondary nuclei are produced) and change the spectrum slope by the necessary value $\Delta\gamma$ (up to 0.5). The maximal energy of particles which can be accelerated and kept in Galaxy gives the position of the knee. Since the maximal energy of nuclei $E_{max}(A)$ is proportional to Z, the observed composition above the knee is heaving. The flux of extragalactic cosmic rays is significantly less and can be observed at ultra-high energies only. The energy at which fluxes of galactic and extragalactic origin are equal gives the position of the ankle. At further increase of the energy GZK cutoff due to interaction with relic radiation must appear. Since experimentally the cutoff apparently is not observed, various theoretical ideas and models were proposed to solve this problem: new sources of CR (topological defects, top-down mechanism etc), various new components of CR, and even Lorenz invariance violation.

The described situation raises the following questions: 1) Why the slope of CR energy spectrum is changed at interactions in Galaxy, whereas at interactions in the Earth's atmosphere it is practically not changed? 2) To keep particles with energies up to 10^{15} eV in Galaxy, regular (but not stochastic) magnetic fields are required. What are sources of such magnetic fields? 3) If particles begin to go out from Galaxy at the knee energies, a noticeable anisotropy must appear, which is not observed. 4) If various nuclei (from p to Fe) participate in the formation of the knee, it must be very wide (1 – 26), while it is rather sharp. 5) If new sources exist, why they are absent in our Galaxy? 6) If they are very rare, we must observe them as local point sources. But, for the present, there are no reliable evidences for that.

3. Generation of cosmic rays in plasma pinches

The content of this section is based on papers [2], the main idea of which is the following. In cosmic plasma (of any origin) electrical discharges – "cosmic lightnings" – can occur, at which cylindrical pinches are formed, similar to laboratory ones. Two basic instabilities of plasma pinches are known: snaky and neck (Figure1). In the latter case plasma jets are squeezed out of pinch neck. These jets are the accelerated particle beams. For description of this process the well-known equations of plasma physics are used only. This model has no free parameters except for absolute intensity. The main results of this model:
1) Energy distribution of particles in jets has the form: $dN/dE \sim E^{-(\gamma+1)}$. 2) This form does not depend on pinch sizes, currents in pinches and other parameters, which determine the coefficient of proportionality only.
3) Integral spectrum slope has unambiguous value $\gamma = \sqrt{3} \sim 1.73$. 4) Accelerated particle energy has no limitation since the density in plasma pinch neck tends to infinity when its radius goes to 0. 5) Composition of accelerated particles will be the same as composition of cosmic plasma which consists mainly of hydrogen.

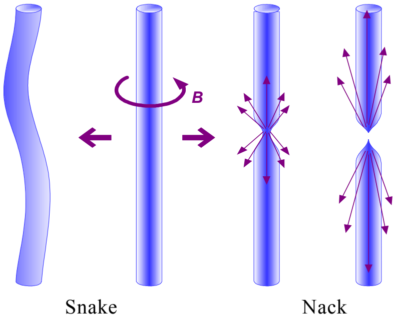

Figure 1. Generation of particles in pinches of cosmic plasma.

Of course, the considered model cannot discard other models of cosmic ray acceleration, but two very interesting (and fantastic) results: unambiguous value $\gamma = 1.73$ and absence of limitation on accelerated energy make it very attractive. Apparently this model can explain the absence of point sources of cosmic rays since plasma pinches, f.e. near Supernova, can be oriented in any direction. Now this fact is explained by the long-time propagation of cosmic particles through weak magnetic fields.

4. New physics in CR interactions with energies above the knee

The second idea of new approach to CR description is based on results of numerous CR experiments in which various unusual events and dependences were observed. These results were discussed at various conferences (see f. e. [3]) and are well-known. Therefore let us list them only. In hadron experiments: halos, alignment, penetrating cascades, long-flying component, centauros and anti-centauros. In muon experiments: excess of VHE (~ 100 TeV) single and multiple muons, observations of VHE muons the probability to detect which is very small. In EAS investigations: excess of young showers, widening of lateral distribution, increasing N_μ/N_e ratio, slowing X_{max} (N_e) dependence which are explained now as a heaving of composition. It is important that all these phenomena appear at primary particle energies above 1 PeV.

To explain a threshold behaviour of observed unusual events, the production of heavy particle or state of matter is necessary. To explain VHE muon excess, a quick mechanism of their generation is required. If to suppose that new physical object can decay into W, Z-bosons, this condition will be fulfilled, and moreover the increasing of transferred momentum will be ensured. To explain the most important unusual phenomen in hadron interactions – alignment – very large angular momentum at the production of new state of matter has to appear, which ensures a possibility of decays into W, Z-bosons, too. Really, resonance state of hadronic matter decay into hadrons for the nuclear time. To give an opportunity of decays into W, Z-bosons, it is necessary to decrease the probability of hadron decays, and potential barrier of angular momentum is very suitable reason for that. Appropriate theoretical model was considered in paper [4], in which it was shown that in non-central ion-ion collisions a globally polarized quark-gluon plasma with large orbital angular momentum L, value of which increases with energy as $\sqrt{s}$, must appear.

Of course, potential barrier will exist also for W, Z-bosons, and some comments are required. In the center-of-mass system the massive object can be considered classically. In this case the potential barrier $V(L) = L^2/2mr^2$, and its value is less for heavy particles. In alternative consideration $\vec{L} = \vec{r} \times \vec{p} = \vec{r} \times (m\vec{v})$, and particles with larger mass (f. e. W, Z-bosons) can take away considerably larger angular momentum than more light particles (f. e. pions, nucleons).

5. Consequences for CR spectrum, composition and others

If to suppose that acceleration of particles in plasma pinches is the main mechanism of cosmic ray generation, then many difficult problems will be solved very simply. Since this mechanism can work any time and at any place, it is clear why the flux of cosmic rays is permanent in time and isotropic in space. Serious perturbations in this flux can appear during any catastrophical phenomena, f. e. supernova explosion, at not so long distances.

Since the spectrum in the source has 2.7 slope, it is not necessary to drive cosmic rays from place to place in Galaxy during tens million years and, generally, to divide galactic and extragalactic CR. The observed flux of CR is the single flux in the Universe! In this case, secondaries will be produced not by the same particles but by different ones, and the change of the spectrum slope is not required.

The knee problem in this approach is connected with generation of new state of matter. This question was discussed in detail at previous ICRCs [1], therefore it is necessary to do some comments only. The production of new state of matter with a large angular momentum in non-central collisions solves both important problems: gives a large cross section and ensures decays into W, Z-bosons.

More interesting and may be at that unexpected is transformation of our knowledge about the composition. At present, the information about composition is extracted from results of EAS investigations, namely from data on the number of muons and elongation rate, taking into account results of simulations. If new state of matter with mass ~ 1 TeV is generated, the number of secondary particles will be increased due to decays of W, Z-bozons into hadrons (on average 20 in each). This leads to a more quick development of shower (decreasing of elongation rate) and to increasing N_μ. As a result, instead of proton shower with energy E_0, "iron" shower with lower energy will be observed.

The ankle problem. With increasing energy, the mass and excitation energy of the new state of matter will be increased. This can broke the synchronization in polarization of partons and correspondingly of quarks, as it was considered in [4], and decrease global angular momentum. The new state begins to decay into hadrons, and EAS will return to normal development. It is important that the number of decaying W, Z – bosons can be changed only discretely, therefore large fluctuations in EAS development are expected.The GZK cutoff problem. Figure2 illustrates the difference in values of CR fluxes at highest energies. In the considered approach the energy spectrum must return to the initial line, the flux around the cutoff will be higher than in the traditional picture, and such phenomena as bump and dip appear naturally.

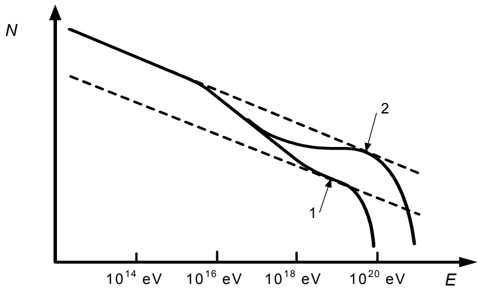

Figure 2. Cosmic ray energy spectrum: 1) with the knee, the ankle and GZK-cutoff, 2) without the knee and the ankle

6. How to check this approach

Very often it is proposed to wait for LHC results, and if new physical processes (states of matter) are observed then to reconsider the propagation of cosmic rays through the atmosphere and EAS development. But, firstly, as the NEEDS Workshop showed [5] the requirements of cosmic ray physics and possibilities of LHC experiments coincide in small number of points only. And, secondly, there are many problems of cosmic rays: composition, the knee, the ankle, cutoff etc. which cannot be solved at any accelerator.

As it was shown in [1] the very good method to find new state of matter and to solve the knee problem is investigation of VHE (> 100 TeV) muons, but unfortunately there is no appropriate detector. More perspective idea is the investigation of changes of zenith-angular dependence of muons in EAS on primary particle energy. The change of muon flux absorption and its divergence at various zenith angles can show the changes in muon component formation.

At last, investigations of the behavior of UHECR spectrum (Figure2). To solve this problem, measurements of CR energy spectrum in a maximal wide interval of energies, at least beginning essentially below the ankle with a single EAS array to avoid numerous systematic uncertainties are required. One of possible solutions is to construct the central (or another, more near to fluorescence detectors) part of North site of Auger Observatory with smaller distance between Cherenkov water tanks.

7. Conclusions

Presented approach allows to solve many problems of VHECR from a single point of view. Of course, some contradictions with modern theoretical conceptions and interpretation of existing experimental data remain, and their re-analysis is required. Nevertheless the ideas and results of this approach are very attractive and, at least, stimulate the further development of non-traditional approaches to CR origin and interaction.

8. Acknowledgements

First of all I would like to thank participants of various meetings, who took part in discussions and assisted in the development of new approach. Many thanks to B.A.Trubnikov for numerous very fruitful discussions, to A.Insolia for warm hospitality and useful discussions, which promoted the serious progress of this work, and to my colleagues N.S.Barbashina, R.P.Kokoulin and I.I.Yashin for help at various stages of work and in preparation of this paper. The work was partially supported by CRDF Award RP2-2557-MO-03.

References

[1] A.A.Petrukhin, Proc. 27th ICRC, Hamburg, 5, 1768 (2001); 28th ICRC, Tsukuba, 1, 275 (2003).

[2] B.A.Trubnikov, V.P.Vlasov, S.K.Zhdanov, Proc. Intern. Conf. on Plasma Physics, Delhi, eds. A.Sen and P.K.Kaw, 1, 257 (1989); "Hydrodynamics of Unstable Media", CRC Press Inc., Boca Raton, New York, London, Tokyo, 114 (1996).

[3] S.A.Slavatinski, Nucl. Phys. B (Proc. Suppl.) 122, 3 (2003).

[4] Zuo-Tang Liang and Xin-Nian Wang, Preprint LBNL-56383 arXiv: nucl-th/0410079 v.4 26 Apr 2005.

[5] NEEDS Workshop Discussion, Nucl. Phys. B (Proc. Suppl.) 122, 433 (2003).