# SINGLE SOURCE MODEL AND ULTRA HIGH-ENERGY COSMIC RAY ORIGIN*

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The energy spectrum of Cosmic Rays (CR) is a perfect example of a situation when the subject of studies is unique. Thus, trying to explain it, one does not have to relay on the 'most probable' or 'average' solution. The phenomenon as we see it, here and now, could be the result of the particular chain of coincidences. If only this chain is not 'very impossible' it can be just the right solution. In this paper we would like to examine the idea of the Single Source Model (SSM) of Erlykin and Wolfendale for the whole CR spectrum. We will show that the origin of extremely high energy particles is quite consistent with the model. Our main conclusion is that no new physics 'beyond the GZK energy' is needed.

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## 1. Introduction

The spectrum of energies of CR particles extends over 10 decades. The respective figure can be found in Ref. [1]. On the first sight it is surprisingly boring preserving over whole this energy range the power low shape with the index close to 3 (intensity decreases about 3 orders of magnitude when the energy of the particle increases 10 times). Although a closer inspection shows two points which deserved more attention. The first is called the knee. About the energy of $10^{15}$ eV the spectrum becomes slightly steeper (the index changes from 2.7 below this point to about 3 above). The second, following the anatomical analogy, is called "the ankle". At about $10^{18}$ eV there can be seen a slight dip and subsequent flattering of the spectrum just before the statistics of all existing data vanishes and the measured spectrum

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ends. If any theory of the CR origin (and propagation) pretend to be *right* it should explain both these features. We would like to show that Single Source Model fulfills this requirement satisfactorily. It was introduced by Erlykin and Wolfendale few years ago (Ref. [2]). It was established to explain the shape of the so-called 'knee' in the CR energy spectrum seen in many experiment for almost 50 years (Ref. [3]).The most complete recent and careful analysis of the very accurately measured Extensive Air Shower size (the number of charged particles) spectra (40 data sets), muon size spectra (11), hadron size spectra (2) and Cherenkov photon size spectra (5) collected by different experiments made in Ref. [4] shows the existence of sharp fine structures around the estimated primary CR particle energy of few times $10^{15}$ eV. In the papers by Erlykin and Wolfendale (Ref. [5]) it was shown that SSM can be used to explain number of other observed CR phenomena.

In this paper we would like to follow this line and look for the consequences of SSM for Ultra High-Energy Cosmic Rays (UHECR). The highest energies of CR particles exceed $10^{20}$ eV what is believed to violate the Greisen–Zatsepin–Kuzmin (GZK) cutoff, which is the consequence of interactions of UHE nucleons with 3 K cosmological microwave background photons (Ref. [6]). The very detailed recent review of this interesting energy area is given in Ref. [7] (for some theoretical implications see, *e.g.*, Ref. [8]).

## 2. Review of the CR spectrum

Before doing this we would like to examine the whole CR spectrum from the SSM point of view.

### *2.1. Below the knee ($E < 10^{15}$ eV)*

Starting from the energy of few GeV, which is high enough to neglect the Solar modulation effects, it is known that the measured CR spectra as well as chemical and isotopic compositions are in surprisingly good agreement with the simple so-called 'leaky box' model proposed by Cowsik in Ref. [9]. In this model CR particles originate and are confined within some region of space (Galaxy). Infinite number of infinitesimal sources are distributed uniformly each with the same injection energy spectrum (presumed to be of the power-law form $I(E) = E^{-\gamma_0}$). CR particles after leaving the source continue random walk determined by the scalar diffusion coefficient which, in principle, can depend on particle energy, but they could also leak out from the confinement region crossing the boundaries (however spatially distributed) which are only partially reflexive. Thus, the time of confinement of the particle of given energy (rigidity) is determined by the value of the diffusion coefficient. It depends on particular distribution of magnetic fields irregularities in interstellar medium. For example, the Kolmogorov turbulence spectrum of the form $F(k) \sim k^{-5/3}$ gives $D \sim E^{1/3}$, other possibilities give index of $D(E)$ 1/2 and even 5/3.

The leaky box model can be modified in many ways. One of our special interests is to put, instead of infinite, the large but finite number of CR sources, which could be identified later as some astronomical objects as *e.g.* SuperNovae (SN). In Fig. 1 (from Ref. [10]) we present the variety of 50 spectra calculated by Erlykin and Wolfendale assuming $\gamma_0 = 2.15$ (as it comes out from theoretical prediction of the acceleration model given by Axford) and $D(R) \sim R^{1/2}$ and reasonable choice of other propagation and acceleration parameters. Each line represents the result of the particular set of 50 000 standard SNs distributed randomly in space and time. It is seen that the fluctuations of the resulting slope are quite large and detailed analysis shows that it is quite likely that observed spectrum below the knee can be produced by the model.

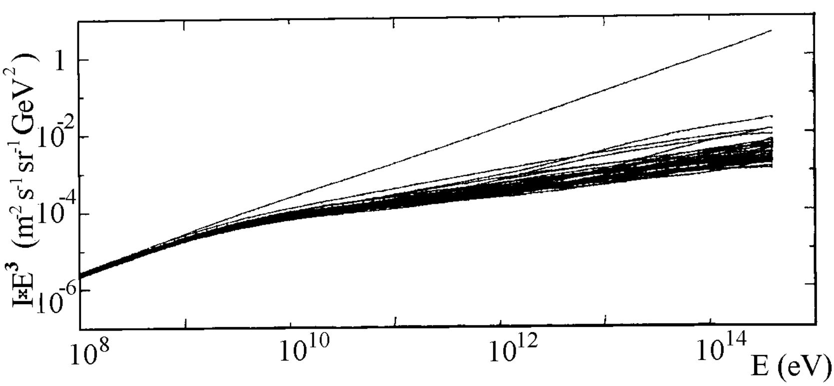


Fig. 1. 50 examples of spectra from particular distribution of CR sources in the Galaxy.

### *2.2. The knee ($10^{15}$–$10^{16}$ eV); the Single Source Model*

The CR of energies around the knee ($3\times10^{15}$ eV) propagate in Galactic magnetic field of strength and size of irregularities which cannot exceed some limits determined by the structure of the Galaxy. It is obvious that at some energy they can be no longer confined within the Galaxy volume. Rough estimation is to correlate the energy at which this process starts with the minimum length scale of magnetic field irregularities. If one takes this length to be 1 pc than it gives energy of just about $3 \times 10^{15}$ eV for protons. However, such explanation of the breakup of the CR spectrum ('knee') gives the change of the spectrum index quite smooth. The sharpness parameter defined as maximum of the $\partial^2 I/\partial(\log E)^2$ (where $I = I(E)$ is the differential CR energy spectrum at Earth) found in Ref. [11] for Galactic modulation mechanism is $\simeq 0.3$ while observed spectra give values (in most cases) of 1–3.

In Fig. 2 the idea of SSM is shown. The rather smooth, Galactic modulated CR spectra from many SNs forming the 'background' flux is enriched by the additional component from the one nearby and quite recent SN. The SS spectra are not affected by the modulation just because 'by pure coincidence' we are within the expanding shell confining just accelerated high energy CR particles: 'the local bubble' — region of hot ($10^6$ K) plasma. The likely topography of the region of interest coming from the astronomical observations is shown in Fig. 3 and confirms such 'coincidence' (Ref. [12]). The 'local bubble' could be produced by the typical SN explosion (of $\sim 5 \times 10^{50}$ erg) roughly $10^5$ years ago giving the sharp cutoffs of different mass component shown in Fig. 2 distributed according to the different particle rigidity (different $Z$) which can be seen in the data as mentioned fine structures.

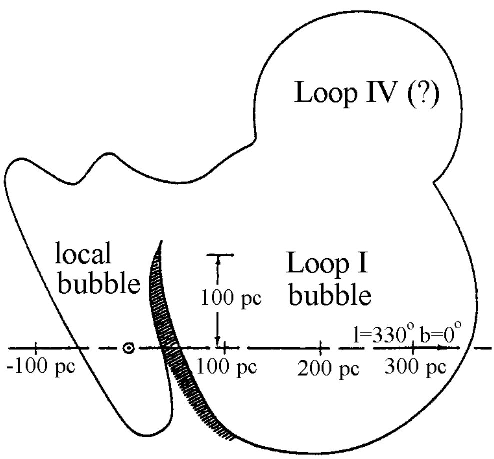


Fig. 2. The nearby region of the Galaxy and the 'local bubble' structure.

The SSM gives not only the overall spectrum of CR around the knee but also direct predictions concerning the chemical composition in this energy region, and they are also in agreement with the observations.

### *2.3. Between the 'knee' and the 'ankle' ($E = 10^{16}$–$10^{18}$)*

In the energy range $10^{16}$–$10^{17}$ the 'background' spectrum, *i.e.* the sum of many modulated SNs contributions, is smooth. However, one remark is needed here. The 'standard' SN are believed not to be able to accelerate CR to energies much higher than the energy of the knee, but it is quite

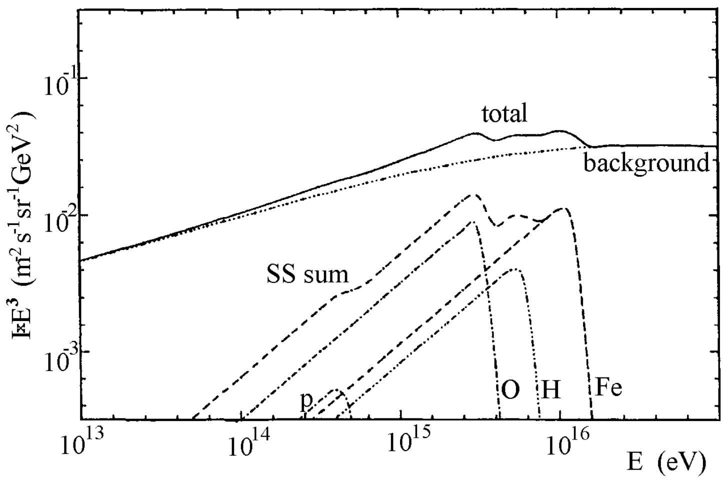


Fig. 3. The SSM of CR spectrum around the 'knee'. The recent local source contribution is shown separately for different mass components: Fe — iron, H — heavy elements, O — oxygen and $p$ for protons.

likely that there is a special population of SNs with very high initial shock velocities and magnetic fields which can shift this energy limit even up to $10^{21}$ eV for iron nuclei. We can call them hereafter Super-SuperNovae SSN.

At the energy of about $3 \times 10^{17}$ eV the background component should fall down anyway. The Galactic magnetic fields are not strong enough to keep such energetic particles. It is interesting that in the measured UHECR spectrum this is the region where the second substantial change of spectral index appears: the 'ankle'.

### *2.4. The 'ankle' and above ($E > 10^{18}$ eV)*

Many of experimentally observed features in the UHECR domain (as, *e.g.*, anisotropy studied in Ref. [13]), confirm that we actually see there the vanishing Galactic component and the new Extra-Galactic (EG) one which starts to dominate above the energy of $3 \times 10^{18}$ eV. The analysis of the whole available data made in Ref. [14] shows that the EG component could start as power-law with the index of about 2 and than, above $\simeq 10^{19}$ eV, continues with spectral index of $\sim 3$ up to the end of measurements (*i.e.*, $10^{20}$ or slightly higher). This EG spectrum is the subject of our analysis in the present paper.

## 3. EG component — origin and spectra at Earth

If we assume that other galaxies are similar to our own, it is obvious that the CR of ultra-high energies which cannot be confined fill the extra-galactic space. They traveled there in magnetic fields which are, of course, much weaker and extended than that within Galaxy. Astronomical measurements show that the averaged field could be of the order of 10 nGs and the scale of its irregularities is of the order of 100 pc. These values make the propagation of UHECR rather complicated because, just in the energy region of the 'ankle', their transport through the intergalactic space changes from diffusive regime to (almost) rectilinear. Thus, CR below, say, $5 \times 10^{18}$ eV can reach the Earth after traveling over billions of years, while those of $3 \times 10^{19}$ eV can do this much faster. Taking into account the fact that the space is not empty, but full of background low energy photons (cosmological microwave (CMB) radiation and infrared light photons produced by stars and hot gas in galaxies), the UHECR particles can sometimes interact with them loosing some portion of their energy. The processes involved here are rather well known and cross sections measured in laboratory experiments can be used to estimate the effect.

In Fig. 4 we present results of such calculations. We assumed that in each galaxy the birth rate of SSN is 1 per 100 years and each of them produces the spectrum $I(E) = E^{-2.15}$ with total energy of given CR (from 1 GeV to

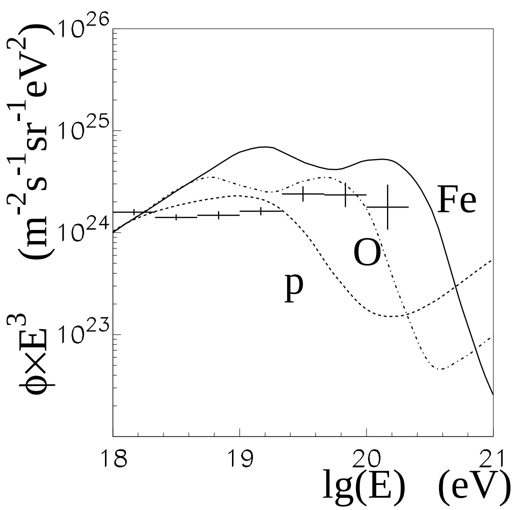


Fig. 4. Fluxes of UHECR observed at Earth for iron, oxygen and proton primaries produced in sources uniformly distributed over the whole Universe. Points show the 'world average' data.

$10^{21}$ eV) of $10^{51}$ erg. The density of galaxies is equal to 1 per 100 Mpc$^3$ and constant over the whole Universe (with Hubble radius of 3000 Mpc), what gives us the CR production rate. The propagation is then introduced by full 3D Monte Carlo. Modification of the CR energy spectrum is caused by $e^+e^-$ pair production, pions production (the famous GZK process related to significant $\Delta$ resonance cross section for reaction with CMB photons at proton energies above $\sim 5 \times 10^{19}$ eV) and photo-disintegration in the case of nuclear CR (iron and oxygen as typical examples were used). Points in Fig. 4 are from Ref. [14] and represent the 'world average' measured UHECR spectrum.

As it is clearly seen data can be satisfactorily explained by the mixture of heavy elements (oxygen and iron) in SSN sources in distant galaxies.

Further examinations are in progress and results concerning details of the 'best fit' source composition, including perhaps some modifications in the galaxy distribution, will be published somewhere else soon.

## 4. Summary

We have shown that the idea of SSM works well for the whole CR spectrum. The EG component seems to originate from the same processes as those producing CR in our Galaxy. Effects of intergalactic propagation reproduce the shape of the 'ankle' in a natural way without introducing any new parameters and no new physics 'beyond the GZK energy' is needed.

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