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Extragalactic cosmic rays and their signatures

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ABSTRACT

The signatures of UHE proton propagation through CMB radiation are pair-production dip and GZK cutoff. The visible manifestations of these two spectral features are ankle, which is intrinsic part of the dip, beginning of GZK cutoff in the differential spectrum and $E_{1/2}$ in integral spectrum. Observed practically in all experiments since 1963, the ankle is usually interpreted as a feature caused by transition from galactic to extragalactic cosmic rays. Using the mass composition measured by HiRes, Telescope Array and Auger detectors at energy (1–3) EeV, calculated anisotropy of galactic cosmic rays at these energies, and the elongation curves we strongly argue against the interpretation of the ankle given above. The transition must occur at lower energy, most probably at the second knee as the dip model predicts. The other prediction of the dip model, the shape of the dip, is well confirmed by HiRes, Telescope Array (TA), AGASA and Yakutsk detectors, and, after recalibration of energies, by Auger detector. Predicted beginning of GZK cutoff and $E_{1/2}$ agree well with HiRes and TA data. However, directly measured mass composition remains a puzzle. While HiRes and TA detectors observe the proton-dominated mass composition, as required by the dip model, the data of Auger detector strongly evidence for nuclei mass composition becoming progressively heavier at energy higher than 4 EeV and reaching Iron at energy about 35 EeV. The Auger-based scenario is consistent with another interpretation of the ankle at energy $E_a \approx 4$ EeV as transition from extragalactic protons to extragalactic nuclei. The heavy-nuclei dominance at higher energies may be provided by low-energy of acceleration for protons $E_p^{\max} \sim 4$ EeV and rigidity-dependent $E_A^{\max} = ZE_p^{\max}$ for nuclei. The highest energy suppression may be explained as nuclei-photodisintegration cutoff.

1. Historical review: galactic or extragalactic origin?

Do observed cosmic rays (CR) have galactic or extragalactic origin?

Since late 1950s this question divided theorists in two groups. Ginzburg [1] and Syrovatsky [2], defended the Galactic origin, while Hoyle [3], Burbidge [4,5] and their collaborators suggested the extragalactic origin. In 1963 in book [6] Ginzburg and Syrovatsky presented the strong arguments in favor of galactic origin, but hot discussions between these two groups continued at all International Cosmic Ray Conferences (ICRCs) until late 1980s.

The main issues of extragalactic origin have been acceleration, diffusive propagation of extragalactic particles and magnetic fields in galaxies and clusters. The main point of extragalactic models was proposal of Active Galactic Nuclei (AGN) as the sources, and explanation of observed isotropy of cosmic rays. Much attention was given to acceleration of protons to highest energies above 10^{19} eV, impossible in Galactic model. An upper limit to the maximum energy of acceleration was found in [5] from condition of equality of the Larmor radius and dimension of the accelerating site, which later was used in the famous "Hillas plot" [7]. As a plausible model in [4] was proposed the Local Supercluster with AGN observed there.

V.L. Ginzburg suggested the rigorous test for extragalactic origin, predicting the lower-limit for gamma-ray flux from Small Magellanic Cloud (SMC). The gas density in this source is fairly well known, while the CR flux in extragalactic model is that measured in Milky Way (MW). Therefore, the produced gamma-ray flux at energies $E_\gamma \gtrsim 100$ MeV is well predicted. The calculated gamma-ray flux from $pp \to \pi^0$ production gives the lower limit, because part of the detected flux can be produced by electrons and by the point-like sources. In 1993 EGRET [8] put the upper limit to gamma-ray flux from SMC well below the Ginzburg lower limit, which means that extragalactic CR flux is lower than that observed in MW. In 2008 Fermi/LAT [9] measured gamma-ray flux from SMC with a high accuracy, reliably excluding extragalactic origin of the bulk of CRs observed in our galaxy. The exclusion obtained by EGRET and FERMI/LAT is not valid for very high CR energies where transition to extragalactic CRs may be expected.

The Standard Model (SM) for Galactic Cosmic Rays was first put forward by Ginzburg and Syrovatskii [6] in 1963 and in the main features it was accomplished in 1977–1978 by discovery of diffusive shock acceleration [11]. The SM is based on (i) supernova

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remnants as sources, (ii) SNR shock acceleration, and (iii) diffusive propagation of CR in the Galactic magnetic fields.

The book [6] was not a review. It described an original and detailed construction of Galactic model of cosmic rays and their propagation in magnetic fields. The book included the theoretical issues of synchrotron radiation relative to astrophysics, and diffusion equations for propagation of particles with their analytic solutions. In particular, the remarkable Syrovatsky analytic solution of diffusion equation for point-like sources [10] was included there. However, most important results were obtained phenomenologically. The authors put forward the disk-halo model and estimated the magnetic fields B there, suggesting equipartition relation $\omega_{cr} \sim B^2/2\pi \sim \rho u^2/2$, where the first term is energy density of cosmic rays and the last one is turbulent energy density of plasma. Magnetic field in the disk was estimated as $B_d \sim 3 \times 10^{-6}$ G. Two versions of halo were suggested and analyzed: the spherical one with $R_h \sim 10 - 15$ kpc and with flattening halo with $h \sim 3$ kpc. The set of diffusion equations for protons and nuclei was solved analytically and, using the data on anisotropy and mass composition, diffusion coefficient for disk was estimated as $D \sim 1 \times 10^{29}$ cm^2/s, close to presently known value. The authors recognized the problem of Li, Be, B as the secondary nuclei and using the solutions of diffusion equations for many nuclei and galactic models, determined the thickness traversed by cosmic rays as $x \sim 10$ g/cm^2, also close to the present value. Finally, the authors estimated the galaxy luminosity in cosmic rays L_{cr} using two formulae which at present can be unified as

$$L_{cr} \sim c\omega_{cr} M_g / x \quad (1)$$

where M_g is the mass of galactic gas. Eq. (1) gives $L_{cr} \sim 2 \times 10^{40}$ erg/s in a good agreement with energy release of SN in our Galaxy.

The most interesting and dramatic story in development of SM is connected with acceleration.

In 1977–1978 four works on acceleration at shocks [11] appeared almost simultaneously. The particles are accelerated due to multiple reflections from the shock front and may acquire maximum energy high enough for galactic cosmic rays. In 1983 Laggage and Cesarsky [12] demonstrated that the time of acceleration cycle increases during process of acceleration and E_{max} remains below the observed knee, which is galactic feature. It was really a dramatic moment, when most reliable and beautiful acceleration mechanism seems to be not viable. Revival came back not very soon: in 2001 Bell and Lucek [13] convincingly confirmed the early proposal of Bell [11] about strong amplification of magnetic field upstream by cosmic rays themselves due to streaming instability. A highly turbulent field with strength up to $B \sim 10^{-4}$ G is produced and increases maximum energy up to needed value $E_{max} \sim 4Z$ PeV.

2. Spectral features and signatures

The observed energy spectrum of Cosmic Rays (CR) has approximately a power-law behavior for 11 orders of magnitude in energy with several features that can be linked with particles propagation and acceleration.

The most prominent spectral feature is the *knee* in all-particle spectrum at energy 3–4 PeV, discovered first at the MSU (Moscow State University) array in 1958 [14]. At the knee the spectrum $E^{-\gamma}$ steepens from $\gamma \approx 2.7$ to $\gamma \approx 3.1$. This knee is provided by the light elements, protons and Helium, and is explained in the framework of the Standard Model (SM) for Galactic Cosmic Rays (GCRs) by the maximum energy E_{max} of acceleration in the Galactic Sources (Supernovae Remnants, SNR). In the case of the rigidity-dependent acceleration $E_{max} \propto Z$, where Z is charge number of a nuclei, the maximum acceleration energy is reached by Iron nuclei, and thus the Iron knee is predicted to be located at energy by factor 26 times higher than for proton knee, i.e. at energy $E_{max}^{Fe} \sim (80\text{—}100)$ PeV. Recently, the Iron knee was found indeed at energy 80 PeV in KASCADE-Grande experiment [15] in a good agreement with rigidity-acceleration prediction.

Above the knee, at energy $E_{skn} \approx (0.4\text{—}0.7)$ EeV, there is a faint feature in the spectrum [16] called the *second knee*. It is seen in many experiments (for a review see [17]). This feature is often interpreted as a place of transition from galactic to extragalactic CRs. However, for the last forty years the standard place for transition from galactic to extragalactic CRs is considered at *ankle*, a very prominent spectral feature, observed first in 1960s by Volcano Ranch detector at energy $E_a^{obs} \sim 10$ EeV, and it was immediately interpreted by Linsley [18] as transition between these two components of CRs. This interpretation was further confirmed by detection a particle with energy about 100 EeV [19] The ankle as presented by Linsley in 1973 [20] is shown in Fig. 1 according to data of Volcano-Ranch and Haverah-Park. (Fig. 1 is taken from paper by Gaisser [21].) At present beginning of ankle is found at $E_a^{obs} \approx 4.5 \pm 0.5$ EeV according to HiRes observations [22], at (4.9 ± 0.3) EeV in Telescope Array (TA) [23], and at (4.2 ± 0.1) EeV in Auger (PAO) [24,25].

What makes us think that CR at highest energies are extragalactic and that transition occurs at ankle?

If CRs at highest energies are galactic heavy nuclei up to Iron, anisotropy can be not easily observable. However, SNRs as the sources cannot provide particles with energies as high as 100 EeV, and for all-galactic-CR model one needs additional class of sources which are able to accelerate particles to much higher energies than SNR. These sources can be hypernovae explosions (GRBs) which occur very rarely, e.g. one per million years in our galaxy. Such a model was developed in [26]. More recently another galactic model [27] also with GRBs as the sources was studied, with protons and Iron nuclei as accelerated particles and assuming diffusion of Iron nuclei in the galactic magnetic fields. The calculated energy spectrum explains well the observed PAO spectrum.

To prove that observed particles at highest energies are extragalactic, one must know their signatures, and these signatures have

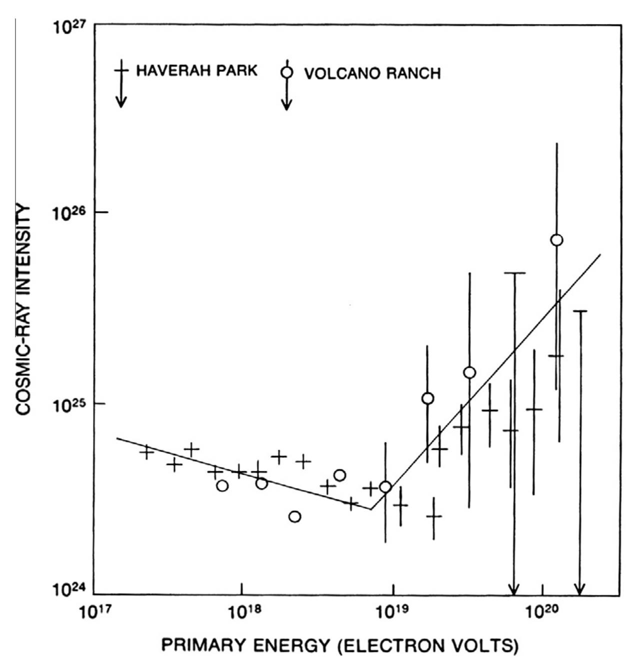

Fig. 1. The ankle as presented by Linsley in review [20] and taken from paper by Gaisser [21].