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The Energy Spectrum of Ultraheavy Nuclei above 10^{20} eV

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Abstract

A major feature of the energy spectrum of the cosmic radiation above 10^{19} eV is the increasing fraction of heavy nuclei with respect to light nuclei. This fact, along with other simple assumptions, is adopted to calculate the energy spectrum of the cosmic radiation up to 2.4×10^{21} eV. The predicted spectrum maintains the index of 2.67 observed at lower energies which is the basic, known, empirical well-assessed feature of the physical mechanism accelerating cosmic rays in the Galaxy. Indeed above 10^{19} eV the injection of nuclei is inhibited by some filter and this inhibition causes a staircase profile of the energy spectrum. It is argued that particle injection failure versus energy commences with protons, followed by Helium and then by other heavier nuclei up to Uranium. Around 7.5×10^{20} the cosmic radiation consists solely of nuclei heavier than Copper and the estimated intensity is 1.8×10^{-30} particles/GeV s sr m^2.

Keywords

Ankle Energy, Ultra-High Energy, GZK Effect, Ultraheavy Nuclei

1. Introduction

In the year 2007 came to light the unexpected and severe result [1] that a large fraction of the cosmic radiation above the ankle energy of 3.1×10^{18} eV consisted of heavy nuclei and not only of proton and Helium. The outcome was confirmed by another two independent methods of measurements [2] [3] feasible with the unsurpassed Auger instrument. After the year 2013 the chemical composition resulting from $X_{\max}$ and the width of the $X_{\max}$ distribution observed by the Auger Collaboration has become unmatchable with that reported in the period 2007-2011 as argued in Section 3. Presently (2017) the preponderance of heavy nuclei above 5×10^{18} eV is based more on the $X_{\max}$ measured by the Telescope Array (hereafter TA) detector rather than on recent data of the Auger Group.

The evolution of the chemical composition of the cosmic radiation toward heavy nuclei is of paramount importance since it entails the reorientation of some basic concepts in Cosmic Ray Physics. One of these concepts is that cosmic rays of maximum observed energies 10^{19} - 3.0×10^{20} eV do not come from extragalactic sources but are domestic, of galactic origin. Cosmological nuclei would be photodissociated and destroyed before harbouring in the Milky Way Galaxy and hypothetical cosmological protons will be decelerated via photopion reactions, ultimately stranded in local ambients without intercepting terrestrial instruments.

According to this study the increasing fraction of heavy nuclei above 10^{19} eV observed by TA and Auger experiments (see **Figure 3**) will continue as energy ascends, becoming irresistible; for example, above the energy of 6.76×10^{20} eV the cosmic radiation is expected to consist only of nuclei heavier than Iron. Nuclei are predicted to disappear from the cosmic-ray flux because the injection to the acceleration process is inhibited by a filtering process, or something equivalent to a filtering process, operating at the galactic sources. The sieve does initiate at the energy of 2.6×10^{19} eV [4]. The Galactic sources are located in the cold boundaries wrapping up the H II regions embedded in the O B star associations of the Milky Way Galaxy (as it will be described in *The rule governing cosmic ray abundances prior to acceleration* paper in preparation).

2. The Features of the Energy Spectrum Above 10^{19} eV

The domestic origin of ultrahigh cosmic rays has been assumed in a recent calculation [4] of the energy spectrum of the cosmic radiation in the interval 10^{19} - 2.4×10^{21} eV. The part of the computed spectrum where experimental data are available *i.e.* 10^{19} - 3.0×10^{20} eV is shown in **Figure 1** (green squares) along with the fluxes measured by Telescope Array [5] and Auger experiments [6]. **Figure 2** shows the fluxes measured by the Fly's Eye experiment [7] that took data in the period 1997-2006 with a final exposure of 4500 km^2/year sr and now dismantled and recycled.

The energy spectrum in **Figure 1** and **Figure 2** (green squares) shows a distinctive silhouette, visible in the appropriate variables: the energy E in a linear scale and the flux multiplied by E^γ which mitigates the steep fall of the spectrum with energy (E is the particle energy and γ the spectral index of 2.67). While a linear scale of energy to visualize the spectrum is rare, the multiplication of the flux by E^γ with the desired γ is routine. Notice that a logarithmic scale on energy would have compressed the data points, belittling the distinctive and unique silhouette of the spectrum in the interval 10^{19}-1.8×10^{20} eV gleaned by the Auger apparatus [6]. The spectrum profile (green squares) is echoing the abundances of quiescent interstellar atoms at the sources prior to acceleration (see **Figure 3** of ref. [4]) and the universal index γ of the Galactic Accelerator (Part 3 of ref. [8]).

Calculation details are found in a previous paper [4] and here only the basic

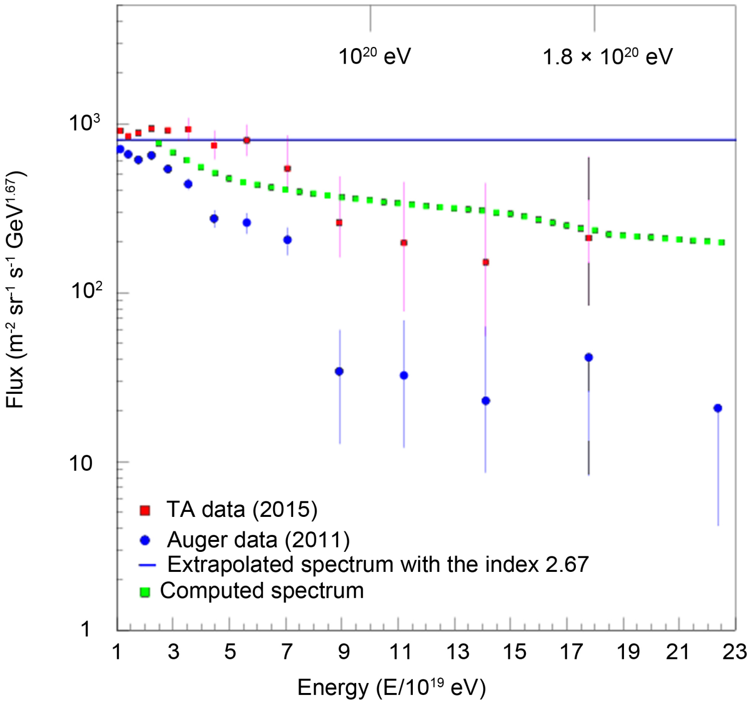

Figure 1. The computed energy spectrum is represented by green squares in the range 10^{19} - 2.3×10^{20} eV which is the highest energy interval where experimental data are available. The data measured by Telescope Array (red squares) [5] and Auger Collaborations (blue dots) [6] are shown for comparison with the predicted spectrum. The two Auger data points at the highest energies are upper limits to the flux.

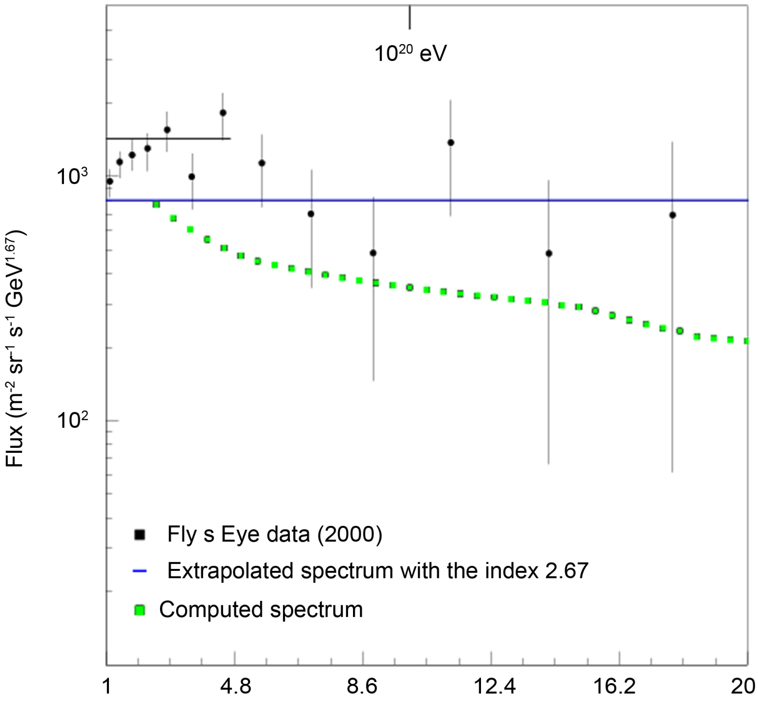

Figure 2. Comparison of the computed spectrum (green squares) with the flux data of the Fly's Eye Experiment (black dots) [7] in the same frame of **Figure 1**.

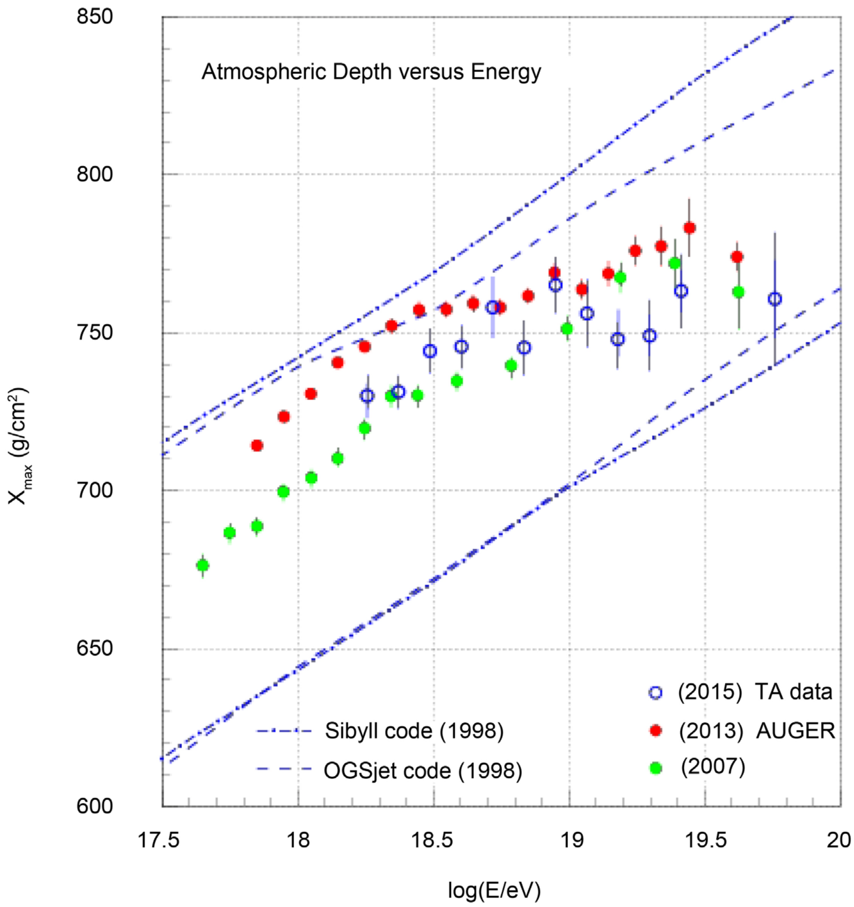

Figure 3. Atmospheric depth versus energy measured by the Telescope Array [14] [15] and auger collaborations [1] [16]. Theoretical depths for purely H and Fe cosmic nuclei (blue lines called rails) result from classical calculations [17].

tenets of the spectrum calculation are summarized: 1) the physical process accelerating cosmic rays takes place in the Galaxy and is not known; to designate the unknown acceleration process the term *Galactic Accelerator* is used. Although the acceleration mechanism is unknown it has some identified, constrained features: 2) it delivers cosmic rays with a constant spectral index of 2.67 up to the energy of 2.4×10^{21} eV. 3) The acceleration process is not localized in any celestial bodies but it is ubiquitous in the Galactic volume.

The event suppression in the spectrum discovered by the HiRes Group in 2004 [9] is interpreted as the maximum energy attainable by protons in the Galaxy. The physical mechanism causing the break is called *LIGA* effect (for *Lack of particle Injection to the Galactic Accelerator*). All the important tenets above are nested in a reasoning (Section 3, ref. [4]) leading to the predicted spectrum shown in **Figure 1** and **Figure 2**.

The interpolation of the spectral break [9] above 3×10^{19} eV via a power law with a single ultrasoft slope, (≈3.5 - 5.5) has been performed by HiRes, Auger and TA experiments in the investigation of the highest energy cosmic-ray events, a few dozens of events. According to these three groups, as explicitly stated in many papers, the break interpolation via an ultrasoft index proves the existence the hypothetical GZK effect. But this interpretation plainly conflicts with the experimental data reported by the same experiments as described a few years ago [10].

3. Empirical Basis of the Calculation of the Energy Spectrum

The derivation of the computed spectrum (green squares in **Figure 1** and **Figure 2**) is based on the important assumption (A): the chemical composition of the cosmic radiation evolves from light to heavy in the range 5.0 × 10^{18} - 10^{20} eV. This Section deals with the empirical foundation of this assertion (A) which was omitted in the preceding paper [4] due to its small size. From the Auger Group: "as can be seen measurements favour a mixed composition." Michael Unger (2008) [11].

From the published results [1] [2] [3] of the Auger experiment in the years 2007-2012 emerges the picture that the chemical composition of the cosmic radiation in the interval 4.0 × 10^{18} - 4.0 × 10^{19} eV consists of a substantial fraction of intermediate and heavy nuclei. On the contrary, the TA Collaboration believes that, in this energy range, the cosmic radiation is dominated by protons as explicitly expressed in a number of papers. This last credence simply reiterates that of the HiRes Group [12] that previously operated a florescence detector on the same geographical site (Dugway, Utah, North America, 39 Nord, 120 West).

In essential terms, the TA and HiRes Groups affirm the contrary of the assertion (A) e.g. almost all cosmic rays are protons with no evolution of the chemical composition toward heavy nuclei. Explicit awareness of this assertion is documented in many places; for instance: "…to resolve outstanding differences in the interpretation of conflicting $X_{\max}$ data." (William F. Hanlow, 2013 [13]) where $X_{\max}$ data refer to both Auger and TA data; on the same token: "…A comparison with $X_{\max}$ distribution with model simulations (QGSjet-II-03), we showed the primary composition is consistent with 100% proton and inconsistent with 100% iron for energies $10^{18.2}$ eV < $10^{19.2}$ eV." (Masaki Fukushima, 2015 ref. [14]).

From these premises an unequivocal conclusion on the tendency of the chemical composition is neither easy nor restful because the only florescence instrument which can compete with the exposures of Auger detector is that operated by the TA Group. As it emerges in a moment the moot point hinges on the simulation codes of atmospheric cascades and not on the $X_{\max}$ data themselves.

The errors of the $X_{\max}$ in TA and Auger detectors are, respectively, 16.3 g/cm^2 [15] and 20 g/cm^2 [2] [11]. Event selection, event reconstruction, atmospheric condition and telescope calibration are major sources of the systematic error. Notice that separation of the H-Fe rails of 80 - 95 g/cm^2 in the band 10^{18} - 10^{19} eV (see **Figure 3** and **Figure 4**) is close to the systematic and statistical error, and hence, only the tendency of the chemical composition versus energy can be

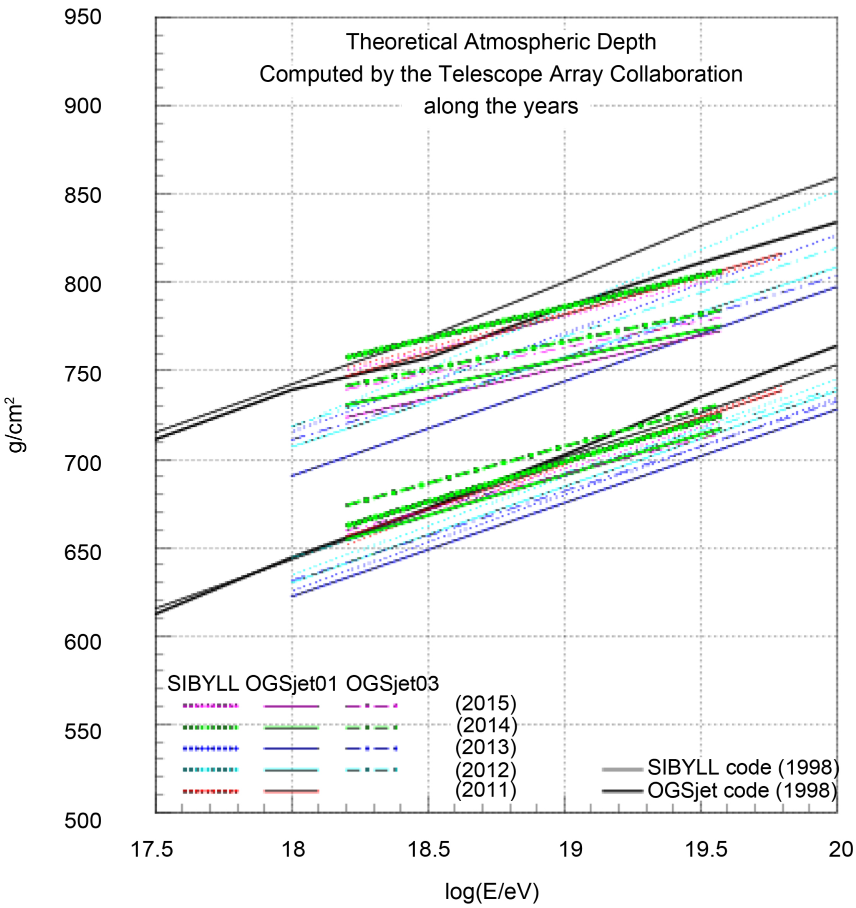

Figure 4. Mean atmospheric depth $X_{\max}$ versus energy computed by the TA Group in the years 2011-2015 and the hadronic simulation code used in the calculation. The separation between H and Fe rails depends on the hadronic model and the energy. The absolute values of $X_{\max}$ depend primarily on the ensemble of proton-air cross sections.

reliably assessed.

Figure 3 shows the atmospheric depth $X_{\max}$ versus energy measured by the TA [14] [15] and Auger [1] [16] experiments detecting florescence light produced in giant air cascades.

The two rails (blue curves) in **Figure 3** are theoretical atmospheric depths for pure cosmic protons (upper rail) and pure cosmic Iron (lower rail) and provide an aid to visually and instantly reckon the chemical composition. These rails are classical predictions of atmospheric shower simulations [17] that have been upgraded along the years, close and wide, by new inputs on nucleus-air cross sections, hadronic fragmentation algorithms, inelasticities and other variables. The abnormal lifting of the Auger $X_{\max}$ data in the interval $10^{17.9}$ - 10^{19} eV toward a light chemical composition (see **Figure 3**) from year 2007 [1] to the year 2013 [16] is embarrassing for a number of reasons. The first one is that heavy ions cannot disappear from the spectrum within the small energy interval $10^{17.5}$ - 10^{18} eV. In fact many experiments around $10^{17.5}$ eV reported a dominant fractions of heavy nuclei including HiRes-MIA [18] and HiRes detectors [19]. Secondly, detailed calculations giving nuclear species versus energy in the interval 10^{17} - 10^{19} eV thoroughly disagree with Auger data of the year 2013 (see figure 4 and figure 7 of ref. [20]).

Figure 4 shows the bunch of rails computed and adopted by the TA Group in the data analysis in the years 2011-2015. Patently, the computed TA atmospheric depths are so scattered that almost any interpretations of the experimental data in **Figure 3** become viable and legitimate. As a vivid example, consider the Auger data (red dots) [16] and the theoretical depth in **Figure 5** represented by thick green rails. The upper thick green rail (labelled 2014, for clarity) is one of the many rails computed by the TA Group (also shown in **Figure 4**) and it converts the $X_{\max}$ Auger data in the range 10^{19} - 2.0×10^{20} eV into purely proton cosmic-ray composition. But if so, around the ankle energy e.g. $10^{18.2}$ - $10^{18.6}$ eV, the Auger data would become unphysical! Conversely, if the Auger data (red

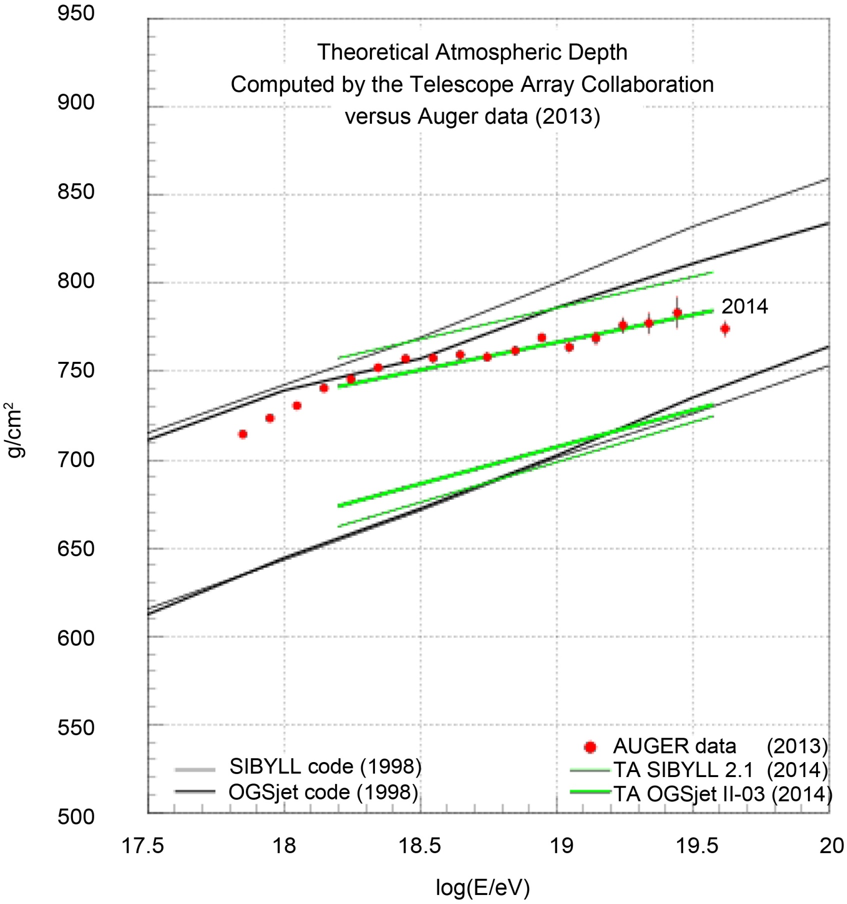

Figure 5. Measurements of the $X_{\max}$ performed by the Auger experiment (red dots) [16] framed in the H and Fe atmospheric depths (rails) evaluated by the TA Group. The figure reports the classical atmospheric depths via QGSjet and Sybill codes [17] (black rails) and those of the TA Group (thick and thin green rails). Above $10^{18.6}$ eV data would be compatible with a purely proton cosmic-ray component except the last data point. The aim of this figure is to draw attention to the ankle energy band e.g. $10^{18.2}$ - $10^{18.6}$ eV, where the Auger $X_{\max}$ data are unphysical if the thick green rails of the QGSjet II-03 code are reliable calculations. The thick green rail is labelled 2014 for clarity.

dots) in **Figure 5** are reliable measurements, then the theoretical atmospheric depths are suspicious (thick green line 2014, via QGSjet-II-03). A third possibility, the most real one according to this and a previous study [20], is that both Auger $X_{\max}$ data in the limited range $10^{18.2}$ - $10^{18.6}$ eV of the year 2013 [16] and the QGSjet-II-03 outcomes over the entire energy range of **Figure 3**, are essentially incorrect and misleading. Notice that recent measurements of proton-air cross sections are below those of the QGSjet-II-03 code.

The trend of increasing fractions of heavy nuclei with increasing energy in the band 4.0×10^{18} - 10^{20} eV is well substantiated by both TA and Auger experiments as shown in **Figure 3** with the classical H and Fe rails [17]. No empirical evidence discrediting the H and Fe rails in **Figure 3** is known. Progress and refinements in hadronic codes simulating atmospheric showers did take place but no upheaval regarding the main, critical parameters emerged in recent years. For example, new data on proton-air cross section in the range 10^{12} eV - 5×10^{18} eV lie on a straight line (see, for example, **Figure 1** of ref. [21]). This feature suggests that intimate substructures of hadrons smoothly coexist while colliding, regardless of the energy, implying no bumps or dips in the cross sections, and plausibly, in the theoretical $X_{\max}$ versus energy. Nevertheless, deficiencies in the codes remain (for example, muon deficit on the ground of about 25 per cent). It is concluded that above 10^{19} eV the assertion (A) is empirically founded, not only on the $X_{\max}$ measurements shown in **Figure 3**, but also on the other two independent methods of measuring the chemical composition [2] [3] feasible with the Auger instrument.

4. Premises of the Spectrum Calculation and Their Empirical Basis

The domestic origin of cosmic rays up to very high energy, 10^{20} eV and above, is not a predominant concept recurrent in the present and past literature [8]. As a consequence, it is useful to enumerate those facts suggesting that ultrahigh cosmic rays are galactic. The first one is the heavy composition of the cosmic radiation above 2.6×10^{19} eV. The second fact is based on measurements of arrival directions of ultrahigh cosmic rays.

The evidence for the galactic origin of ultrahigh energy cosmic nuclei comes from the nuclear photodisintegration cross sections $\sigma(\gamma, A)$ and measured features of ubiquitous cosmic photons with density ρ of 411 particles/cm^3 and mean energy of 6.76×10^{-4} eV. Important reactions are the ejection of one or two neutrons, $\gamma A \to (A-1)n$ or $\gamma A \to (A-2)2n$ where γ represents the ubiquitous photon, A is the mass number of the cosmic nucleus and n is the ejected neutron. In the laboratory energies 15 - 20 MeV the cross section $\sigma(\gamma, A)$ has one or more peaks and it is in the range 10^{-25} - 10^{-27} cm^2, sharply descending at higher energies. The resulting characteristic path L of a long wandering extragalactic nucleus is, $L = 1/\rho\sigma(\gamma, A)$, too tiny for a cosmic world of gigaparsec size.

Had cosmic rays above $E_L = 2.6 \times 10^{19}$ eV been extragalactic, a tight correlation between backwardly extrapolated arrival directions and locations of particular celestial bodies (for example active galactic nuclei) would have been discovered. This correlation has never been detected though cherished [22] and expected.

No celestial bodies within 25 Mpc from the Earth, believed to be potential cosmic-ray sources, intercept the backward extrapolated trajectories of the most energetic cosmic rays as charted by numerous measurements with fairly good direction resolutions (see, for example, ref. [23]). This assertion becomes highly constraining, imperious, by the absence of a correlation between the direction of Virgo cluster of galaxies and arrival directions of ultrahigh cosmic rays.

For sake of completeness, another important hypothesis of the calculation, designated as assumption (B) in the preceding paper [4], is mentioned. It regards the existence of the spectral break discovered by HiRes Collaboration in 2004 [9]. Presently it has an undisputed, well assessed, empirical evidence and no data scrutiny is necessary.

5. Concluding Remarks

As argued in Sections 3 and 4 the hypotheses of the calculation of the cosmic ray-spectrum above 10^{19} eV [4] are empirically founded and dodge the dominant, toxic theoretical prejudice (see ref. [8]).

The predicted spectrum shown in **Figure 1** and **Figure 2** (tiny green squares) in the range (2 - 9) × 10^{19} eV is comprised between the Auger flux (too low) and the TA flux (too high). Above 9 × 10^{19} eV the Auger data (**Figure 1**) lie below the predicted spectrum. On the contrary the Fly's Eye flux shown in 2 (black dots) is above the predicted spectrum up to the maximum energy of 3 × 10^{20} eV.

According to this study, the existence of a fifth stigma in the cosmic-ray spectrum is correctly interpreted assuming the existence of a preferential selection mechanism which sieves quiescent particles in the interstellar medium prior to acceleration. More precisely, the mechanism is expected to operate in the cold interstellar territories surrounding the H II regions inside the O B star associations of the Milky Way Galaxy. In previous papers [4] [10] this filtering effect was termed *Lack of particle Injection to the Galactic Accelerator* (concisely, liga effect) and the particular energy where the liga effect materializes designated by E_L.

In the near future a conclusive validation of the predicted spectrum of **Figure 1**, besides precise and reliable measurements of the fluxes, could come from the measurements of the chemical composition above 10^{20} eV. At the energy of 6.76 × 10^{20} eV the atmospheric depth $X_{\max}$ is predicted to lie below the theoretical Fe rail (imagine **Figure 3**, with extrapolated rails up to 10^{21} eV) since no nucleus lighter than Iron composes the cosmic radiation above this energy.

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