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Origin of the ultrahigh-energy cosmic rays and their spectral break

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Summary. — The energy spectrum, composition and arrival directions of ultrahigh energy cosmic rays (UHECRs) with energy above the cosmic ray ankle, measured by the Pierre Auger Observatory, appear to be in conflict if their origin is assumed to be extragalactic. Their spectrum and composition, however, are those expected from Galactic UHECRs accelerated by highly relativistic jets such as those producing short hard gamma ray bursts (SHBs). If this alternative interpretation is correct, then the observed break in the energy spectrum of UHECRs around 50 EeV is the energy threshold for free escape of UHE iron nuclei from the Galaxy and not the Greisen-Zatsepin-Kuzmin (GZK) cutoff for protons, and the arrival directions of UHECR nuclei with energy above their UHE breaks must point back to their Galactic sources rather than to active galactic nuclei (AGN) within the GZK horizon.

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Cosmic rays (CRs), discovered by Victor Hess [1] almost a century ago, have an observed spectrum extending from $E \leq 10^6$ eV to extremely high energies, $E \geq 10^{20}$ eV. At low energies the primary CRs contain all the stable elements. At very high energies, their all-particle spectrum has not been resolved into separate elements. Their energy spectrum is well represented by a broken power law $E^{-\beta}$, with $\beta \approx 2.7$ above ~ 10 GeV until the "CR knee" at $\sim 3 \times 10^{15}$ eV, where it steepens to $\beta \approx 2.9$ up to a "second knee" near 2×10^{17} eV where it changes to $\beta \approx 3.3$. Above the "ankle" at $\sim 3 \times 10^{18}$ eV the ultrahigh energy cosmic ray (UHECR) flux has been accurately measured by the Fly's Eye High Resolution (HiRes) experiment [2,3] and the Pierre Auger Observatory (PAO) [4,5]. Its energy spectrum is well described by a power-law with $\beta \approx 2.7$ until a "break" near 5×10^{19} eV where it changes to $\beta \approx 4.3$, as shown in fig. 1, which shows the energy domain we are here concerned with.

While the origin of the CR knees of different elements is still debated, the CR ankle is generally identified as the energy beyond which the deflection of CRs in the Galactic magnetic field can neither isotropise them nor prolong significantly their residence time in the Galaxy, see, *e.g.*, [6-9] and references therein, and [10] for an alternative.

A free escape of UHECRs from the Galaxy implies that they essentially suffer an angular spread $\langle\theta^2\rangle \ll 1$ by magnetic deflections on their way out of the Galactic cosmic ray halo whose typical radius is $R_G \sim 10\,\mathrm{kpc}$. For CRs of charge Z, this happens at an energy for which their Larmor radius, $R_L = E/Z\,e\,B_r$, becomes much larger than the coherence length, l_c, of the random component of the Galactic magnetic field $B_r \sim 3\,\mu$ Gauss [11,12] and their small deflections $\delta\theta \simeq l_c/R_L$ add up to

$$\langle\theta\rangle \simeq \left[\frac{R_G}{l_c}\right]^{1/2} \left[\frac{l_c}{R_L}\right] \leq \frac{\pi}{2}\,. \tag{1}$$

For a typical $l_c \sim 0.1\,\mathrm{kpc}$, $R_L = E/e\,Z\,B$ and $\theta = \pi/2$, eq. (1) yields a threshold energy for escape, and consequently a spectral break at $E_{break}(A,Z) = Z\,E_{break}(p) = 1.8\,Z\,\mathrm{EeV}$. For Fe nuclei, $E_{break}(Fe) = 46.8\,\mathrm{EeV}$, which roughly coincides with the break-energy measured by HiRes [2,3] and PAO [4,5].

The observed ultrahigh-energy (UHE) break at $E \approx 5\times10^{19}$ eV was identified by both HiRes and PAO as the so-called "GZK cutoff". This effective threshold for energy losses of CR protons by pion production in collisions with the cosmic microwave background (CMB) radiation, which exponetially suppresses the extragalactic flux of UHECR protons with energy above 5×10^{19} eV, was predicted by Greisen [13] and by Zatsepin and Kuzmin [14] in 1966, right after the discovery of the CMB.

Further support for the identification of the UHE break with the GZK cutoff for UHECR protons came from the arrival directions of UHECRs with energy above the GZK threshold observed in the early PAO data [15]: if the UHECRs are protons, half of those with $E \geq E_{GZK}$ must come from distances $< 70\,\mathrm{Mpc}$. Indeed, PAO reported that a large fraction of these UHECRs (measured between 1 January 2004 and 31 August 2007) had arrival directions pointing back within $\leq 3.1\,\mathrm{deg}$ to active galactic nuclei (AGNs) closer than $\sim 75\,\mathrm{Mpc}$, while the directions of those with smaller energies were isotropic [15,16].

The conclusion that most UHECRs with $E \geq E_{GZK}$ are protons was expected: extragalactic UHECR nuclei disintegrate in collisions with the infrared background radiations and the CMB, with a mean free path much shorter than that of UHE protons for π production above the GZK threshold [7,17-20].

However, this early evidence for a directional correlation with AGNs, obtained by PAO from a sample of 27 UHECRs was not present in a sample of an additional 42 events seen through 31 December 2009 and has diminished significantly in the joint sample [21]. In addition, the HiRes collaboration reported [22]. that their sample of 13 events with energy above 57 EeV ($1\,\mathrm{EeV} = 10^{18}$ eV), is incompatible with directional correlation with AGNs at 95%.

Moreover, PAO recently reported the measured depth of shower maximum of UHECRs and its root-mean-square fluctuations, which indicate that the composition of UHECRs changes progressively with energy from proton-dominated below the CR ankle to Fe-dominated as one approaches the GZK cutoff [4,23]. The GZK cutoff for Fe-dominated composition is $\approx \mathrm{A} = 56$ times larger than that for protons, $E_{GZK}(\mathrm{Fe}) \approx 3\times10^{21}$ eV. Thus, the PAO composition of UHECRs seems to be in conflict with the identification of the UHE break at 50 EeV as the GZK cutoff of UHECR protons. Also the spectral shape around the UHE break seems not to be compatible with that expected from the GZK cutoff [24]. Note, however, that a proton dominated composition [25] and the spectrum of UHECRs [22] that were measured by HiRes are those expected from extragalactic UHECRs [7].

All together, it appears that either the UHECRs are mainly extragalactic protons, the UHE break is due to the GZK cutoff and the Fe-dominated composition of UHECRs near the GZK cutoff that was inferred by the PAO is not correct, or the UHECR composition becomes Fe-dominated near the UHE break and the UHE break is not the GZK cutoff of UHECR protons. This composition controversy, as well as the UHECR-AGN association controversy should be resolved experimentally. But, if the UHECR composition inferred by PAO [4,23] turns out to be the correct one, is there a consistent and simple explanation for both the energy spectrum and composition measured by PAO?

In this short paper we present such an explanation. We show that, with small modifications in the assumed relative Galactic and extragalactic fluxes, the comprehensive theory of cosmic rays presented in [7] correctly predicts the energy spectrum and composition of the PAO UHECRs. All one has to do is to go back to the original assumption that the UHECRs are dominantly of Galactic origin [6]. We show that a rough knowledge of the properties of the Galactic accelerators of UHECRs without an exact knowledge of their identity can reproduce the spectrum and composition of UHECRs which were reported by PAO.

In [7] we posited that CRs are a mixture of Galactic and extragalactic fluxes, accelerated in gamma ray bursts (GRBs) [26]. They are the GRB-ionized interstellar medium (ISM) collissionally accelerated by the highly relativistic jets of plasmoids (cannonballs) that produce Galactic and extragalactic GRBs, most of which are beamed away from Earth [6]. The ones trapped in the Galactic magnetic field have produced its CR halo. In a steady state, the escape rate from the CR halo equals its filling rate. The two CR populations are steadily injected into the Galactic CR halo and the intergalactic medium (IGM) with roughly the same energy spectrum and composition. But they suffer different losses in the host galaxies of the GRBs and in the IGM due to the different environments and residence times.

The CR energy spectrum and composition above the second knee reflect the A-dependent threshold energy (roughly proportional to A) for photo-dissociation of extragalactic CR nuclei in collisions with the CMB and the infrared background radiations during their long residence time in the IGM [7]. The second knee is the threshold for photo-dissociation of ^{4}He. The CR composition changes progressively from that of low-energy CRs near the second knee to almost a pure protons below the CR ankle, as more heavy nuclei and their fragments disintegrate. The photo-disintegration of the primary nuclei and their fragments changes the power-law index of the all-particle energy spectrum from ~ 2.9 below the second knee to ~ 3.3 above it. We do not discuss in detail this calculationally complex subject here (DADO and DAR, in preparation) since we are focusing on the understanding of UHECRs above the ankle. The Galactic component, whose residence time in the Galaxy is too short to imply a significant photo-disintegration in the ISM, starts to dominate before the energy reaches the CR ankle.

Above $E = E_{break}(p) \approx 1.9\,\mathrm{EeV}$, UHECR protons are not isotropised and their free escape is not delayed by the Galactic magnetic field. Their flux predictably decreases with increasing energy beyond the proton UHE break. The CR nuclei of ^{4}He, that at fixed particle energy are only slightly less abundant than protons (by a factor ~ 0.8), have a UHE break at $E_{break}(^4\mathrm{He}) \approx 2 \times 1.9\,\mathrm{EeV}$, beyond which Fe dominates the CR composition. The UHE Fe break is at $\approx 26\times 1.9 \approx 50\,\mathrm{EeV}$. We shall interpret the UHE all-particle break as the UHE Fe break beyond which Fe CRs are not isotropised nor confined. In order to validate this possibility, we proceed to derive the corresponding spectrum of UHECRs.

At the energies at which CR nuclei are isotropised by the Galactic magnetic field, their density is enhanced by their energy-dependent residence time in the Galaxy. At relatively low (sub TeV) energies this time was empirically estimated [27] to behave as $\tau(E,Z)\propto (E/Z)^{-\beta_r}$ with $\beta_r \approx 0.5\pm 0.1$, yielding a CR number density [7]

$$\frac{\mathrm{d}n_{_A}}{\mathrm{d}E} \propto \tau(E,Z)\frac{\mathrm{d}n^{inj}_{_A}}{\mathrm{d}E} \propto X(A,Z)\,A^{\beta-1}\,E^{-\beta}\,, \tag{2}$$

where $n^{inj}_{_A}$ are the injection rates of nuclei, $X(A,Z)$ are their relative abundances in the ISM and $\beta=\beta_{inj}+\beta_r$. For Fermi acceleration in highly relativistic jets, $\beta_{inj}=13/6$ for all CR nuclei [7], while β_r is not known above the spectral knees. If β_r is E-independent, using its low-energy value one obtains [7] a spectral index of Fe UHE nuclei $\beta=2.67\pm 0.1$, for $E<E_{break}(\mathrm{Fe})\sim 50\,\mathrm{EeV}$, *i.e.*,

$$\frac{\mathrm{d}n_{_{Fe}}}{\mathrm{d}E}\propto E^{-2.67\pm 0.1}. \tag{3}$$

Consider now the arrival of CR nuclei with $E>E_{break}(A,Z)$ from Galactic sources. Their small deflections by the Galactic magnetic field along their path to Earth spread their arrival directions according to eq. (1) and their mean arrival times by

$$\langle \tau_d(E,Z)\rangle \sim \frac{R_G\langle\theta^2\rangle}{2\,c} \tag{4}$$

and their residence time in the Galaxy as a function of E approaches rapidly their energy-independent free escape time, $\langle\tau_r(E,Z)\rangle \sim (R_G/c)\,[1+\langle\theta^2\rangle/2]\to R_G/c$. A distribution of N_s Galactic transient sources of UHECRs that *isotropically emit* CRs can produce a quasi-isotropic distribution of arrival directions provided their Galactic rate satisfies $\dot N_s\,\tau_d > 4/\langle\theta^2\rangle$. Their spectral index, however, will remain $\beta=\beta_{inj}\approx 13/6$.

In our theory [7] the injection of CRs is *narrowly beamed*: CRs are accelerated by highly relativistic very narrow jets emitted in the birth or death of compact stars, in supernova explosions, in phase transitions in compact stars, in their mergers, and in accretion episodes onto compact stars, all of which produce observable GRBs when their jets point towards Earth.

For collimated sources eq. (1) implies that the probability for an UHECR to reach Earth is $\langle\theta^2\rangle/4\propto E^{-2}$. Consequently, if the effective number of sources during $\tau_d(E)$ satisfies $N_{eff}=\dot N_s\,\tau_d(E)\ll 4/\langle\theta^2\rangle$, the probability that the rays reach us during a time $\delta t\ll\tau_d(E)$ is $\propto E^{-2}$. The flux of UHECR nuclei beyond their $E_{break}(Z)=Z\,E_{break}(p)$ then satisfies

$$\frac{\mathrm{d}n_{_A}}{\mathrm{d}E}\propto E^{-\beta_{inj}-2}\sim E^{-4.17}. \tag{5}$$

This result is valid in the cannonball model of GRBs [28] where the jets have typical bulk-motion Lorentz factor $\gamma\sim 10^3$ and the UHECRs are beamed into a cone with an opening angle $\theta\sim 1/\gamma\sim 10^{-3}$ much smaller than their angular spread by Galactic

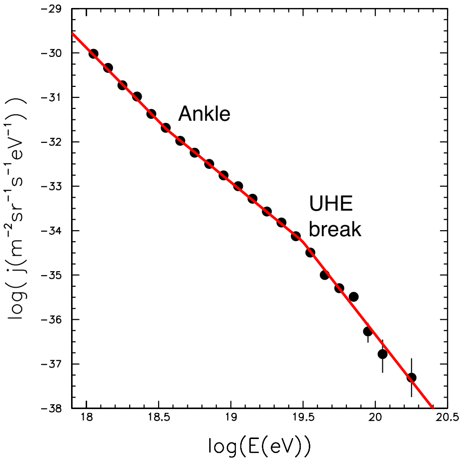

Fig. 1. – Comparison between the predicted slopes of the broken power-law spectrum of UHECRs and the PAO data [5]. The overall normalization and the energy of the cosmic ray ankle which depend on poorly known astrophysical parameters, were adjusted by a best fit to the data.

magnetic deflections. It is not valid in GRB fireball models with spherical ejecta or conical jets of opening angle much larger than the angular spread due to deflections by the Galactic magnetic field.

In fig. 1 we compare the PAO spectrum [5] of UHECRs (multiplied by E^3 in fig. 2 for clarity) and the approximate power-law spectrum with the predicted indexes $\beta = 3.3$ between the second knee and the ^{4}He UHE break (Dado and Dar, in preparation), $\beta = 2.67$ between this energy and the Fe break and $\beta = 4.17$, as given in eqs. (3), (5), which follow from our current update of [7]. The broken power-laws is a best fit to the data. The theoretical power-law indexes and break points agree well with their best fit

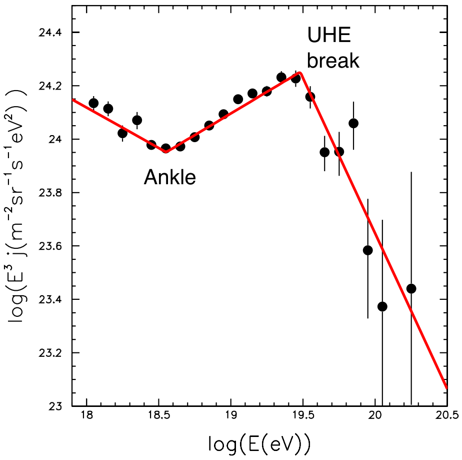

Fig. 2. – The predicted broken power-law spectrum of UHECRs, compared to the PAO data [5], both multiplied by E^3.

values: a best fit yields power-law indixes 2.68 and 4.16 below and above the UHE break at 50 EeV, and 3.3 below the ankle at 3.6 EeV.

A similar interpretation of the spectrum and composition of UHECRs has been proposed [29]. It is based on the assumption that the origin of UHECRs is Galactic GRBs, as first suggested in [6]. Yet, we maintain that their derivation in [29] of the spectrum at energies above the UHE iron break is flawed(1).

In conclusion, if the UHECRs with energy above the UHE break are mostly iron nuclei, as inferred from the PAO measurements, then the spectrum and composition of the UHECRs are those expected from CRs that are accelerated by the highly relativistic jets emitted in Galactic GRBs, most of which are mercifully beamed away from Earth. In particular, the UHE break in the spectrum of UHECRs around 50 EeV is not the GZK cutoff, but the energy threshold for "free" escape of UHE Fe nuclei from the Galaxy. The energy spectrum of UHECRs above the UHE break is a trivial consequence of the energy dependence of the magnetic deflection of Galactic UHE Fe nuclei: It is the steepening by two units of the spectrum at the break, eq. (5) that reflects the "rigidity" of a UHECR trajectory in the randomly directed domains of the Galactic magnetic field. Finally the UHECR nuclei above their respective UHE breaks should point back towards young remnants of Galactic GRBs. These may be supernova remnants, magnetars, young neutron stars and accreting compact objects in close binaries (the expected angular-clustering properties of UHECRs will be discussed elsewhere).

If the UHECRs are extragalactic protons, as implied by the Fly's Eye HiRes observations, then the UHE break near 50 EeV is the GZK cutoff, and the UHECRs must be accompanied by the UHE neutrinos and photons from the decay of the charged and neutral GZK pions. Their expected spectral index between the CR ankle and the GZK cutoff is their injection index below the CR ankle, *i.e.* $\beta = 3.2 - \beta_r \approx 2.7 \pm 0.1$, their spectrum above the UHE break is the GZK spectrum, and their arrival directions should point towards their nearby extragalactic sources.

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(1) The number density of Galactic CRs is roughly their injection rate times their residence time in the Galaxy. At energies beyond which they are not isotropised by the Galactic magnetic field, their mean residence time in the Galaxy tends to their free escape time $\sim R_G/c$, which is constant and does not decrease like E^{-2} as was assumed in [29] in order to argue that $\beta = \beta_{inj} + 2$ for $E(A,Z) > E_{break}(A,Z)$. At energy well above the UHE break, the random angular deflections are in steps $|\delta\theta| \sim l_c/R_L \propto (Z/E)^2$ perpendicular to the motion and the magnetic field, while the advance along the direction of motion is not by random walk but in steps of an approximate lengthh l_c yielding $\tau_r \approx R_G/c$. Quite generally, theoretical estimates of the diffusion coefficient below the escape breaks, like that in [29] did not yield an energy dependence of the Galactic residence time of CRs consistent with measurements at low CR energies [27].

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