Transition from Galactic to Extra-Galactic Cosmic Rays

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Abstract. In this paper we review the main features of the observed Cosmic Rays spectrum in the energy range $10^{17}$ eV ÷ $10^{20}$ eV. We present a theoretical model that explains the main observed features of the spectrum, namely the second Knee and Dip, and implies a transition from Galactic to Extra-Galactic cosmic rays at energy $E \simeq 10^{18}$ eV, with a proton dominated Extra-Galactic spectrum.

1. Introduction
The CR spectrum observed on Earth extends over many orders of magnitude from GeV energy up to energies larger than $10^{20}$ eV. This spectrum is a steeply falling power law with almost no structure apart from four still not well understood features. These features can be summarized as follows: (i) at energy of about $4 \times 10^{15}$ eV there is a change in the spectral index, called the Knee; (ii) at energy around $4 \times 10^{17}$ eV, the spectral index changes again with a steeper spectrum, this feature is called the 2nd Knee; (iii) in the energy range $10^{18}$ eV ÷ $8 \times 10^{19}$ eV the spectrum presents a smooth suppression called the Dip, with a flattening around $E \simeq 10^{19}$ eV called the Ankle; (iv) finally, the debated Greisen-Zatsepin-Kuzmin (GZK) feature [1] could be present in the spectrum starting from $8 \times 10^{19}$ eV. Leaving aside the GZK, whose presence will be soon clarified by the Auger detector [2], the other features can be well recognized in the experimental data of all the CR detectors. The two knees structure as well as the presence of the Dip is firmly established by different detectors [2]. While, from an experimental point of view, the presence of the 2nd Knee and Dip is not questionable their theoretical interpretation is still under debate.
A key ingredient in any theoretical model explaining the 2nd Knee and Dip is the CR chemical composition at the Dip energies, namely in the energy range $10^{18}$ eV ÷ $8 \times 10^{19}$ eV. From an experimental point of view this chemical composition is still not well understood, there are opposite indications that favor different scenarios: the HiRes, HiRes-MIA and Yakutsk detectors favor a proton dominated flux at energies $E > 10^{18}$ eV [2], while, in the same energy range, Fly’s Eye, Haverah Park and Akeno detectors indicate a mixed composition with protons and heavy nuclei (most probably Iron nuclei) [2]. Another important piece of information comes from the energy range below the 2nd Knee, namely at $E < 10^{17}$ eV. The origin of CR in this energy range is clearly galactic and the Kascade data [2], that are in good agreement with all other measurements, show a gradual transition from light to heavy nuclei starting from the first knee. This behavior is well explained in the rigidity propagation/acceleration models (for a review see [3], and references therein) according to which every spectrum of each galactic nuclear species presents a steepening at the energy $E_Z = Z E_p$, with $E_p = 2.5 \times 10^{15}$ eV associated to protons.
In these models the first knee coincides with the energy at which the proton spectrum shows a steepening and the subsequent behavior of the spectrum results from the convolution of the spectra of heavier nuclei, each characterized by a knee (steepening energy). According to this picture above the Iron knee $E_{Fe} = 6.5 \times 10^{16} \text{ eV}$ the Galactic Cosmic Rays (GCR) spectrum should be suppressed.

The observed behavior of the all-particle spectrum at the Ankle energy ($E \approx 10^{19} \text{ eV}$) was traditionally interpreted as the transition from GCR to Extra-Galactic Cosmic Rays (EGCR) [4]. Nevertheless, this interpretation presents several problems as discussed in detail in [5] mainly related to the difficulty in extending the GCR flux, thought to be dominated by heavy nuclei, up to very high energies ($10^{19} \text{ eV}$). In this paper we briefly present an alternative model that places the transition GCR-EGCR at lower energies, namely around the 2nd Knee energy ($10^{18} \text{ eV}$). This model is based on an alternative explanation of the all-particle spectrum at the Dip energies. In the next section we will present the main features of our model.

2. Transition from Galactic to Extra Galactic Cosmic Rays

Following [6] (see also references therein) there are convincing evidences that the presence of the observed Dip, in contrast to the traditional interpretation, signals a proton dominated spectrum at energies $E > 10^{18} \text{ eV}$. As in [6] we will use the formalism of the modification factor $\eta(E)$ defined as the ratio of the spectrum $J_p(E)$, with different channels of energy losses taken into account, and the unmodified spectrum $J_p^{unm}$, where only adiabatic energy losses (red-shift) are included: $\eta(E) = J_p(E)/J_p^{unm}(E)$. In figure 1 we report three different modification factors: the total one $\eta_{tot}$, in which $J_p(E)$ is the proton spectrum with all channels of energy losses taken into account, $\eta_{ee}$ in which $J_p(E)$ includes only adiabatic and pair production energy losses and the observed modification factor $\eta_{obs}$ that uses $J_{obs}(E)$ as in the AGASA data [2]. The injection spectrum used in figure 1 is a single power law, with spectral index $\gamma_g = 2.7$, and a source total emissivity per unit of comoving volume $\mathcal{L}_0 = 1.5 \times 10^{44} \text{ erg/Mpc}^3 \text{s}$. This value of the total emissivity is very high because of our assumption of a single power law at injection (with $\gamma_g = 2.7$) from $E_{min} = 1 \text{ GeV}$ up to $E_{max} = 10^{21} \text{ eV}$. To reduce the required emissivity one can assume that the acceleration mechanism works only from a somewhat higher minimum energy [5]. The behavior of the modification factor $\eta_{ee}$, as reported in figure 1 reaches a very good agreement with experimental data (as reported in [6] $\chi^2/\text{d.o.f.}=1.12$). This is a strong indication that the Dip can be explained as the effect of the pair production process in the interaction of UHE protons with the CMB radiation. From the behavior of the observed modification factor $\eta_{obs}$ it follows that at energies around the 2nd Knee this quantity, which is bound to be $\leq 1$ by definition, exceeds unity (see figure 1). This is the indication that a new component, of different origin, is dominating the spectrum. We interpret this new component as due to GCR. In this context the 2nd Knee energy can be interpreted as the energy where, going from high to low energy, the GCR component starts to enter the all-particle spectrum, in agreement with the Kascade data [2] and with the rigidity acceleration/propagation models [3]. The details of the transition between GCR and EGCR, namely the exact mixed composition in the energy range $10^{17} \text{ eV} \div 10^{18} \text{ eV}$, depends, on the GCR side, on the specific model of propagation/acceleration chosen [3] and, on the EGCR side, on the details of the proton propagation. The EGCR proton propagation at energy between $10^{17} \text{ eV}$ and $10^{18} \text{ eV}$ is affected mainly by the presence of an Intergalactic Magnetic Field (IMF), that provides a steepening of the EGCR flux at energies $E \leq 10^{18}$ [7]. The energy scale of this steepening has a universal nature, being the energy scale at which adiabatic and pair production energy losses occur at the same rate [7]. On the other hand, the behavior of the spectrum at lower energies (i.e. $10^{17} \text{ eV} \leq E \leq 10^{18} \text{ eV}$) is related also to the magnetic field strength chosen [7]. The transition scenario outlined is described by figure 2 with the all-particle spectrum of Kascade and Akeno [2] and the EGCR spectrum obtained in the Bohm diffusive approximation with an IMF of 1 nG and a source minimal distance from the
observer of 50 Mpc. In figure 2 the dashed line represents the GCR component and is obtained as a result of subtracting the EGCR spectrum from the observed all-particle spectrum.

Summarizing, the firm experimental detection of the 2nd Knee and Dip founds a compelling explanation in terms of composition and origin of CR particles. In this context we propose the following model: (i) The detection of the Dip implies a proton EGCR component that dominates the CR spectrum starting from the 2nd Knee energy $E \simeq 10^{18}$ eV; (ii) the 2nd Knee energy assumes a universal meaning being related only to the protons energy losses mechanism; (iii) The expected transition from GCR to EGCR in the all particle spectrum, signaled by an observed modification factor $\eta_{\text{obs}}$ larger than one, sits between the detected Iron Knee $E_{26} = 6.5 \times 10^{16}$ eV and the 2nd Knee energy, the details of this transition being related, on the EGCR side, to the IMF. Finally, we can conclude stressing that a clear cut indication about the validity of the proposed models for the GCR-EGCR transition seems mainly related to a precise determination of the UHECR chemical composition at the Dip energies.

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