A review on ground-based measurements of cosmic rays

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Summary. — This paper summarises recent results on the cosmic ray energy spectrum, composition and anisotropy from the knee region to the GZK cutoff [1, 2] of the spectrum by means of ground-based experiments. Most of the information reported in this contribution is taken from [3, 4].

PACS 95.55 – Vj.
PACS 96.50 – sd.

1. – Introduction

The cosmic ray energy spectrum above 10^{14} eV has a power-law like behaviour ($\propto E^{-\gamma}$, with $\gamma \sim 2.7$) with features which are known as the 'knee' at $3-4\times10^{15}$ eV, where the spectrum steepens to $\gamma \sim 3.0$, the 'ankle' at $2-8\times10^{18}$ eV, which is characterised by a flattening of the spectrum by roughly the same change of the spectral index, i.e. back to $\gamma \sim 2.7$, and the GZK cut-off around 5×10^{19} eV.

The shape and composition of the primary spectrum as well as the large-scale anisotropy in the arrival direction of cosmic rays are key elements to understand the origin, acceleration and propagation of the Galactic radiation. The paradigm of the origin of Galactic cosmic rays (CR) are supernovae, as their shock waves can provide the required power to explain the intensity of the CR radiation at least up to 10^{15} eV [5]. This paradigm has been recently confirmed well below the knee by the observations of AGILE [6] and FERMI satellites [7]. However, the possibility for supernovae to accelerate CRs at energies above 10^{15} eV is quite challenging, therefore, different populations of sources have been envisaged as responsible for the radiation in galactic and extragalactic energy ranges [8, 9]. Those sources would be subject to a rigidity cutoff in the maximum energy at which the various elements are accelerated, as proposed originally by Peters [10]. In this approach, the knee at $\sim 4\times10^{15}$ eV would represent the end of the spectrum of CRs accelerated by supernova remnants in the Milky Way and the ankle at $\sim 4\times10^{18}$ eV the transition to particles from extragalactic sources. However, the ankle structure could be explained also in a completely different way, such as a consequence of the physical process of pair production by protons during propagation through the cosmic microwave background radiation [11]. In this case, the Galactic-extragalactic transition occurs below 10^{18} eV.

A refined study of the CR primary spectrum and composition is, therefore, extremely important to address the above questions. As acceleration and propagation mechanisms in magnetic fields would lead to the same rigidity dependence, the study of large scale anisotropies in the arrival direction could provide relevant information to distinguish source and propagation effects.

The direct study of CRs by means of satellites or balloon-borne detectors is performed only at energies below 10^{15} eV. Close to the knee, the flux becomes of the order of 1 particle m^{-2} sr^{-1} yr^{-1}. This fact prevents the possibility of a direct observation of its structure by currently planned satellites or balloon experiments. Indeed, at least hundred of events above the knee are necessary to determine its existence with enough significance. Around the knee and at higher energies, CRs are studied by means of large arrays located at ground that measure the secondary particles produced by the primary CR cascading in the atmosphere, the so-called Extensive Air Showers (EAS). Typically, the energy is proportional to the total number of secondaries sampled at ground, while the composition is inferred either through a multi-component measurement, such as the electromagnetic and muonic components, or through the measurement of the emitted light (Cherenkov or fluorescence lights) along the longitudinal development of the shower. Despite the fact that shower arrays allow one to collect high statistics, the interpretation of the results is based on the comparison with expectations from simulation describing the EAS development in atmosphere, which are at some level inaccurate. This introduces a systematic uncertainty on the results, especially on the mass composition.

Interestingly, the TeV region allows some partial overlap between direct and indirect measurements. Several techniques have been employed recently on ground detectors that are sensitive to specific components of the CR radiation to overcome those uncertainties [12]. Among them, it is worth mentioning the measurement of the light component (p alone, or p+He) using hadron calorimeters [13], or Cherenkov light measurements in coincidence with TeV muons [14], and RPC counters at high altitude [15]. Those results are in quite good agreement with measurements by CREAM [16] balloon. In particular, the ARGO results allow one to cross-check the fluxes on an extended energy range (5-250 TeV). These results show that, when indirect measurements have the opportunity of selecting almost pure beams, their findings are in reasonable agreement with direct ones and confirm a fair representation of the EAS development in the atmosphere by simulation codes such as CORSIKA [17].

A fundamental ingredient of the CORSIKA simulation is the hadronic interaction model which generates the hadronic cascade at the origin of the electromagnetic cascade. Since 2009, the Large Hadron Collider (LHC) provides a lot of very precise data which have been used to improve two of the hadronic models used for air shower simulations, EPOS [18] and QGSJetII [19], giving birth to the most updated versions: EPOS-LHC and QGSJetII-04. Remarkably, interaction models employed in air shower simulations provided a somewhat better prediction of global observables (multiplicities, p_T-distributions, forward and transverse energy flow, etc.) than typical tunes of HEP models, such as PYTHIA or PHOJET [20]. The cross-section is particularly important for the EAS development and the depth of shower maximum. The proton-proton scattering total cross-section measured by TOTEM [21] at $\sqrt{s} = 7$ TeV allowed to reduce to 20 gr/cm^2 the difference in X_{max} position of the two models, which is comparable to the systematic uncertainties in the measurement by experiments. The muon number depends on the ratio between particles producing hadronic sub-showers and the total number of particles. LHC data allow constraining the (anti)baryon and strangeness production at mid rapidity as well as the forward production of π^0 in fixed target experiments [22]. Taking into account these data, EPOS-LHC and QGSJetII-04 provide now quite similar results [23].

2. – The knee region up to the ankle

The 'knee' is a distinct feature of the all-particle CR energy spectrum at $\sim 4 \times 10^{15}$ eV, where the power index suddenly changes from $\gamma \sim -2.7$ to $\gamma \sim -3.1$. Since its discovery the origin of this feature is still under debate. From the experimental point of view, measurements indicate that such a break is observed in the hadronic, muonic, and electromagnetic components [24, 25, 26, 27], as well as in Cherenkov light [28]. These results give a clear indication that the knee is a peculiarity of the primary spectrum, disfavouring a hypothesis based on changes of the interaction characteristics of the primaries with air nuclei. This conclusion has been reinforced by the first comparisons of the predictions from hadronic models and LHC data [29].

Several experimental results associate the knee with the bending of the light component, and are compatible with a rigidity dependent cut-off [26, 25]. Unfortunately, the flux of the different components vary significantly depending on the interaction model used to interpret the data [26]. However, if this interpretation is correct, the heavy component should show a similar bending in the energy range $5 \times 10^{16} - 10^{17}$ eV. This is indeed the experimental finding of KASCADE-Grande [30] confirmed by TUNKA-133 [31] and IceTop [32] experiments. In detail, the measured all-particle energy spectrum by KASCADE-Grande exhibits a less pronounced but still clear deviation from a single power law between the knee and the ankle, with a spectral hardening at $\sim 2 \times 10^{16}$ eV and a steepening at $\sim 10^{17}$ eV [33]. The average mass composition gets heavier after the knee till $\sim 10^{17}$ eV, where a bending of the heavy component is observed [34] . An indication of a hardening of the light component just above 10^{17} eV has been measured as well [35]. The flux of heavy and light components depends on the hadronic interaction model used to interpret the experimental data [36] as previously mentioned. The above results are summarised on the left side of Fig. 1.

The right side of Fig. 1 compares the results of several experiments in terms of $< lnA >$, as it is often reported in literature to describe the evolution of the composition as a function of energy. Only QGSJet-II model is considered. A more detailed description including the role of interaction models in composition is reported in [37]. Use of different models introduces a shift in the average mass comparable to the dispersion of the data in Fig. 1. Despite the large uncertainty in the absolute composition, a common general trend is visible. Composition gets heavier through the knee region and becomes lighter approaching the ankle. The solid line in the plot is used as a guidance line to show how the average $< lnA >$ from the data in the plot evolves with energy. This result is compatible with the concept that the galactic component of the cosmic ray radiation reaches an end following a rigidity cut-off at $\sim 10^{17}$ eV and that the ankle indicates a transition to a population dominated by extra-galactic sources.

The search for anisotropies in the arrival direction of CR around the knee region can provide relevant information to distinguish source and propagation effects. The anisotropy varies with energy but the topological structure remains the same till $\sim 10^{14}$ eV where it has an abrupt change as pointed out by IceCube [38]. Such a change is confirmed till knee energies. This result seems to be inconsistent with the amplitude and phase expected according to the Compton-Getting prediction due to the relative motion of the Earth in the Galaxy. KASCADE-Grande published recently [39] an update on the anisotropy study based on the East-West method [40]. By investigating the variation of the amplitude as a function of energy it was found that the amplitudes were not

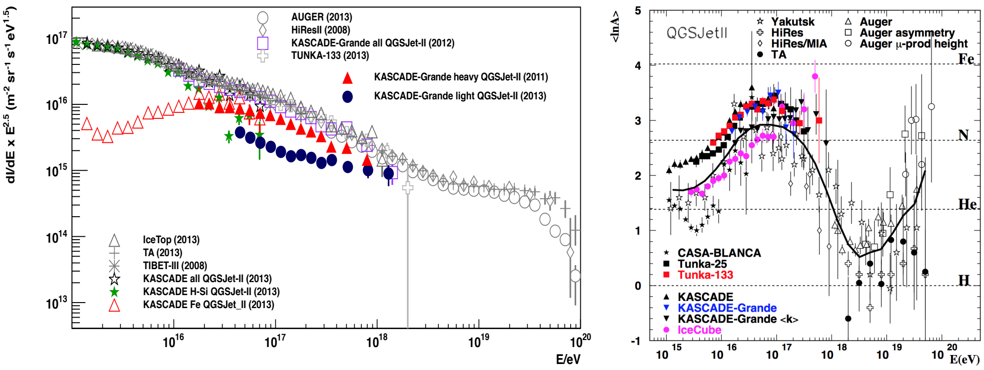

Fig. 1. – Left: The measurement of the CR spectrum by EAS experiments from the knee till the end of the spectrum. The main knee is explained as the bending of the light, followed by the medium, component. The fainter knee around 10^{17} eV is attributed to the bending of the heavy one. An ankle-like feature is observed in the light component just above 10^{17} eV that might be related to the lightening of the composition approaching the ankle. Right: Average logarithmic mass of CRs as a function of energy derived from X_{max} and particle detector measurements using QGSJet-II interaction model. Most of the data are taken from [37] and references therein. The solid line is drawn as a guidance and is obtained by averaging, in each energy bin, the values of $< lnA >$ reported in the figure. The plots are taken from [3].

significant, however, the phases were in almost all energy bins centred around 250 ± 25 degrees. This is interesting in itself because it points towards the Galactic Center. Moreover, it agrees inside the statistical uncertainties with the results of the anisotropy studies of the Pierre Auger Observatory [41] in the energy range 3×10^{17} – 10^{18} eV.

3. – From the ankle to the end of the spectrum

Fig. 1 shows that the features at the Ultra High Energies (UHE), the ankle and the cutoff, have been established beyond doubt. The spectral slopes before and after the ankle have been measured and agree between Pierre Auger Observatory (PAO) [42] and Telescope Array (TA) [43]. The positions of the ankle also agree within the quoted errors, and are compatible with the existing model(s). The parameters of the break at the highest energies are known less accurately. There seems to be some discrepancy concerning the shape of the spectrum around the break; however more statistics is needed for a firm conclusion. The position of the break is compatible with the GZK cutoff for protons in TA, but the PAO spectrum fits better the case of a limit in the UHECRs acceleration by the sources.

As far as the mass composition is concerned, the situation is less definite, and a consistent picture has not yet emerged [37]. While PAO sees a change in the composition towards a heavier one at the highest energies, the TA observes no such a trend and is compatible with a pure proton composition. This difference in the data has profound consequences: the Auger data suggest that we see the maximum energy of sources, similarly to what is observed at the knee in the cosmic ray spectrum, while the TA data suggest we observe the GZK effect. Moreover, the different compositions in the GZK- and maximum-energy scenario will affect the level of anisotropies expected to be seen in the data.

Despite the major advances in the understanding of UHECRs nature, the current experiments face the limit in the statistics they can accumulate due to the extremely low flux of 1 particle km^{-2} $year^{-1}$ above 5×10^{19} eV. For this reason future space-based observatories, such as JEM-EUSO, that reach much higher and uniform exposures [44], could help in sheding light on the mystery of the most energetic radiation of the Universe.

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