Measurement of the cosmic ray spectrum and chemical composition in the 10^{15}-10^{18} eV energy range

Andrea Chiavassa[1,⋆]

[1] *Dipartimento di Fisica dell'Universitá degli Studi di Torino & INFN*
Via Pietro Giuria 1, 10125, Torino, Italy

Abstract. Cosmic ray in the $10^{15} - 10^{18}$ eV energy range can only be detected with ground based experiments, sampling Extensive Air Showers (EAS) particles. The interest in this energetic interval is related to the search of the knee of the iron component of cosmic ray and to the study of the transition between galactic and extra-galactic primaries. The energy and mass calibration of these arrays can only be performed with complete EAS simulations as no sources are available for an absolute calibration. The systematic error on the energy assignment can be estimated around 30 ± 10%.
The all particle spectrum measured in this energy range is more structured than previously thought, showing some faint features: a hardening slightly above 10^{16} eV and a steepening below 10^{17} eV. The studies of the primary chemical composition are quickly evolving towards the measurements of the primary spectra of different mass groups: up to now we are able to separate (on a event by event basis) light and heavy primaries. Above the knee a steepening of the heavy primary spectrum and a hardening of the light ones have been detected.

1 Introduction

Experiments studying primary cosmic rays in the $10^{15} - 10^{18}$ eV energy range are ground based arrays, typical active surface $\sim 4 \times 10^4 m^2 < \Sigma < 10^6 m^2$, detecting either the Cherenkov light emitted during Extensive Air Showers (EAS) development (TUNKA-133[1], TALE[2]) either the electromagnetic and muon EAS components (KASCADE-Grande[3], Ice Top[4]). Pros and cons of both techniques are well known and can be briefly summarized: Cherenkov arrays are limited by statistical problems (their duty cycle being $\sim 10 - 15\%$) but can detect the light emitted during the whole shower development, thus performing an almost calorimetric measurement of the primary energy and are sensible to the depth of the shower maximum. While surface arrays (100% duty cycle) detecting the electromagnetic and muon EAS components are mainly limited by the systematic errors on their energy and mass calibrations, that are necessarily based on a full EAS simulation. Recently experiments based on the detection of the radio signals emitted during EAS developments are giving first physics results like the LOFAR ones about primary chemical composition[5].

Lately in spite of these limitations important improvements have been obtained, mainly because of the increased resolution in the detection of the shower parameters, reaching, with experiments covering very large active surfaces, the level of 15-20% on the shower size (i.e. the number of electrons

⋆e-mail: achavas@to.infn.it

at observation level) and on the total muon number. In parallel to the increased array resolution the hadronic interaction models have evolved after the results of the LHC experiments, covering an energy range reaching the knee energy, even if collider experiments data cover a kinematic range different from the one relevant for EAS development.

In section 2 I will discuss the main sources of systematic errors in the energy and mass calibration and finally in section 3 I will review recent results on the measurement of the cosmic ray spectrum and chemical composition in the $10^{15} - 10^{18}$ eV energy range.

2 Systematic errors in the energy and mass calibration

Experiments operating in the $10^{15} - 10^{18}$ eV energy range cannot be calibrated with known sources, therefore we must use full EAS simulation introducing systematic errors due to arbitrary choices that must be made running simulation codes.

Surface arrays evaluate the energy of the primary particle measuring the number of particles (either electrons or muon) at observation level, while cherenkov experiments determine the photon's one. The correlation between these experimental parameters and the cosmic ray energy is obtained by means of EAS simulations.

The center of mass energy of the interaction between the incoming cosmic ray and atmospheric nuclei is similar (in the considered energy range) to the one of LHC proton-proton interactions, but LHC experiments give precise informations in the central pseudo-rapidity region, while EAS develop in the very forward one. Therefore the experimental results of LHC experiments are in the energy range of interest but in a different kinematic region; the high energy hadronic interaction models used in the EAS simulation codes are tuned to these data.

The so-called "post-LHC" hadronic interaction models more widely used in the EAS simulation are: EPOS-LHC[6], QGSJetII-04[7] and SIBYLL2.3c[8]. The EAS description we obtain from all of them is not reproducing all the experimental data (for instance the muon development in atmosphere[9]) therefore we still don't have a completely reliable and exact EAS simulation. Nevertheless the differences between models (in this energy range) have been reduced with respect to the situation before the LHC data taking. For instance the behavior of the particle number versus the pseudo-rapidity: all interaction models give similar results in the central region, while their prediction are different in the forward one.

Running EAS simulation codes (the more widely diffused in the community is CORSIKA[10], that can be considered as the reference one) we must choose an hadronic interaction model. We can evaluate the differences in the energy assignments, for the same value of the experimental parameter, running the EAS simulation with the same input values and different hadronic interaction models. This difference was estimated around 20% by the KASCADE-Grande experiment [11] for the pre-LHC models.

The EAS parameters used to evaluate the energy of the primary particle depend also on its mass. EAS experiments cannot (because of the shower development fluctuations) measure the mass of the particle originating the shower, that is therefore a free parameter of the EAS simulations. To derive the so called "all particle" cosmic ray spectrum we can estimate the, energy dependent, mean value of the primary mass[12, 13] and use this value to calculate the calibration curve correlating the experimental observable and the primary energy. The models, describing the mean value of the cosmic ray mass dependence on energy, are usually constructed starting from the abundance and the spectral slopes of each element measured at low energy by direct experiments. Then different hypothesis are made about the change of slope of the single element spectra.

Concluding the energy calibration of EAS experiments (around knee energies) can only be performed by means of a complete EAS simulation, systematic errors, roughly about $\sigma_{sys}(E)/E \sim$

30 ± 10%, are introduced by the (arbitrary) choice of the hadronic interaction model and of the primary particle mass.

3 All particle spectrum measurements

Figure 1 shows a summary[1, 2, 4, 11, 14–21] of the all particle spectrum measurement. In this plot the results obtained by different experiments, operating at different heights above sea level, with different techniques and using different hadronic interaction models for the absolute energy calibration, have been collected.

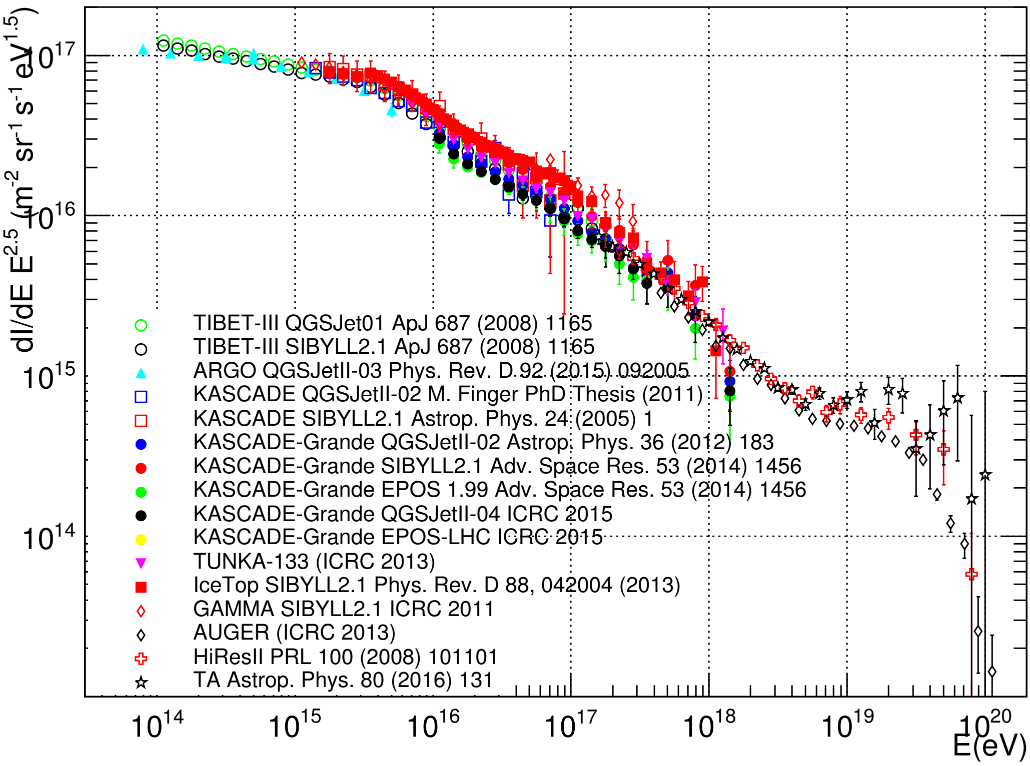

Figure 1. Compilation of all particle spectrum measurements.

Already from this plot covering large energy and flux ranges we can see that the primary spectrum shows more features than the two well known and established ones called the "knee" and the "ankle". Other two faint features (a hardening slightly above 10^{16} eV and a steepening around 10^{17} eV) have been observed in the all particle spectrum. These features have been claimed by the KASCADE-Grande experiment[18] and then confirmed by Ice Top[4], TUNKA-133[1] and TALE[2]. The spectral shapes agree quite well, the differences in the corresponding energies are smaller than the systematic error due to the energy calibration. In figure 2 the same marker is used for the results of a single experiment, while the same color is used for data calibrated with the same hadronic interaction model. We can appreciate that differences between markers with the same color are smaller than those between the same marker with different colors. Thus showing that differences between measurements can be mainly ascribed to the data energy calibration.

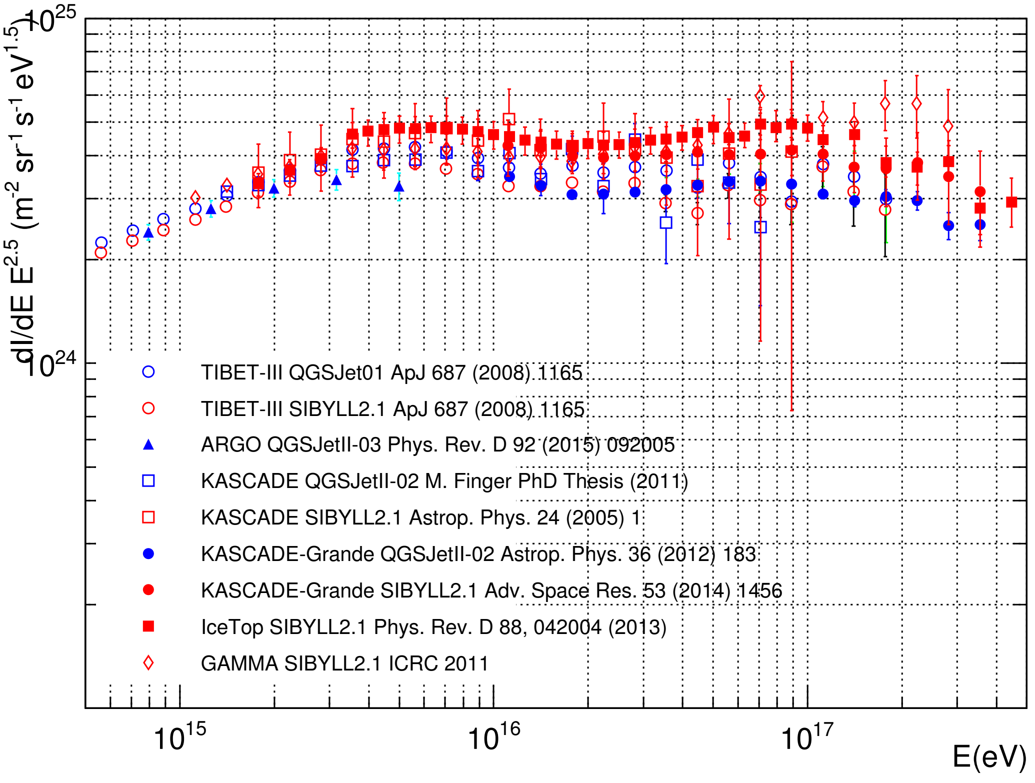

Figure 2. All particle spectra measurements around the knee. Results from the same experiment but calibrated with different hadronic interaction models are shown by the same marker with different colors. While different markers with the same colors represent the results of different experiments calibrated with the same hadronic interaction model.

The origin of these spectral features are object of discussion in the community (as an example see[22]) and can be partly explained by containment inside magnetic fields (either in the acceleration region or during the primary particles propagation). It is important to check whether these features can be ascribed to a particular primary component and therefore all analysis techniques aiming to the measurement of the spectra of different mass groups are very important.

4 Measurement of the cosmic ray mass group spectra

The last generation of surface EAS arrays has reached a resolution allowing studies separating events in mass groups: light (represented by Hydrogen and Helium), intermediate (Carbon or Oxygen) and heavy (Silicon and Iron). We can divide analysis techniques in two families: event by event classification and statistical methods.

Statistical analyses are performed either unfolding, from the number of events measured in each bin of the N_e vs N_μ plots, the spectra of the primary mass groups[17], or by machine learning approach like the neural network technique[23]. Both techniques allow the separation of four or even five primary mass groups, but their results heavily depend on the hadronic interaction model used in the EAS simulation. The spectra of the different mass groups, published by the KASCADE[17], KASCADE-Grande[24] and Ice Top[23] experiments, show sudden and correlated flux jumps, limited to very small energy intervals, in the spectra of different primary components indicating that these features are artificially introduced by the method.

Event by event classifications are performed defining experimental observables depending on the mass of the primary particle. The KASCADE collaboration introduced a selection method based on the ratio of the muon and electron numbers converted (applying the constant intensity cut technique) to a reference value of the zenith angle (i.e. to the same atmospheric depth)[25]. This method has then been used by the KASCADE-Grande experiment at higher energies ([26] and [27]). While the ARGO-YBJ experiment separated light and heavy primaries using a parameter obtained combining the number of particles measured by the surface detector with those describing the shape of the Cherenkov light images obtained by a prototype of the LHAASO Cherenkov telescopes[15].

Event by event classification allows the separation of two mass groups (light and heavy primaries). The choice of the hadronic interaction models influences the absolute flux values, all experiments claim that the event selection is not artificially introducing spectral features.

The KASCADE experiment published[25] the differential spectra, not energy calibrated, of the light and heavy primaries mass groups. The light elements spectrum shows a clear steepening, at the same value of the experimental observable (i.e. the muon density at $45.5m$ from the shower core) also the all particle one shows a (less enhanced) steepening. From the integral flux above this spectral feature we can argue that this change of slope corresponds with the knee.

The main results of the KASCADE-Grande experiment are shown in figure 3: the steepening observed in the all particle spectrum at 8×10^{16} eV is detected, with enhanced statistical significance, in the spectrum of heavy primary[26]. This feature was expected at a similar energy by models attributing the knee of the primary spectrum (at $E \sim 2-4 \times 10^{15}$ eV) to light primaries and explaining the knee as a feature due to containment inside magnetic fields. A hardening of the light primaries is observed in the all particle spectrum at $10^{17.08}$ eV[27], this feature is not visible in the all particle spectrum because this component is not the dominant one at these energies.

The ARGO-YBJ experiment published the spectrum of the light primaries showing a very sharp knee-like feature around $7 \pm 2.3 \pm 0.7 \times 10^{14}$ eV[15]. This feature is hardly conceivable with the KASCADE results, either showing an unexpected spectral feature or an incorrect monte-carlo description of the EAS development. ARGO-YBJ and KASCADE were located at very different heights above sea level (4300 m and 130 m), therefore showers were measured at different development stages. The all particle spectrum published by the ARGO-YBJ is not showing a steepening at the same energy, even if the fraction of light primaries below the knee is very high: this is not fully understood yet.

In figure 4 the EAS experiments measurements of the light primaries spectrum are shown together with the results of the CREAM[28] balloon experiment.

Recently it has been shown that the detection of the radio emission during EAS development is sensible to the atmospheric depth of the shower maximum. The LOFAR collaboration published

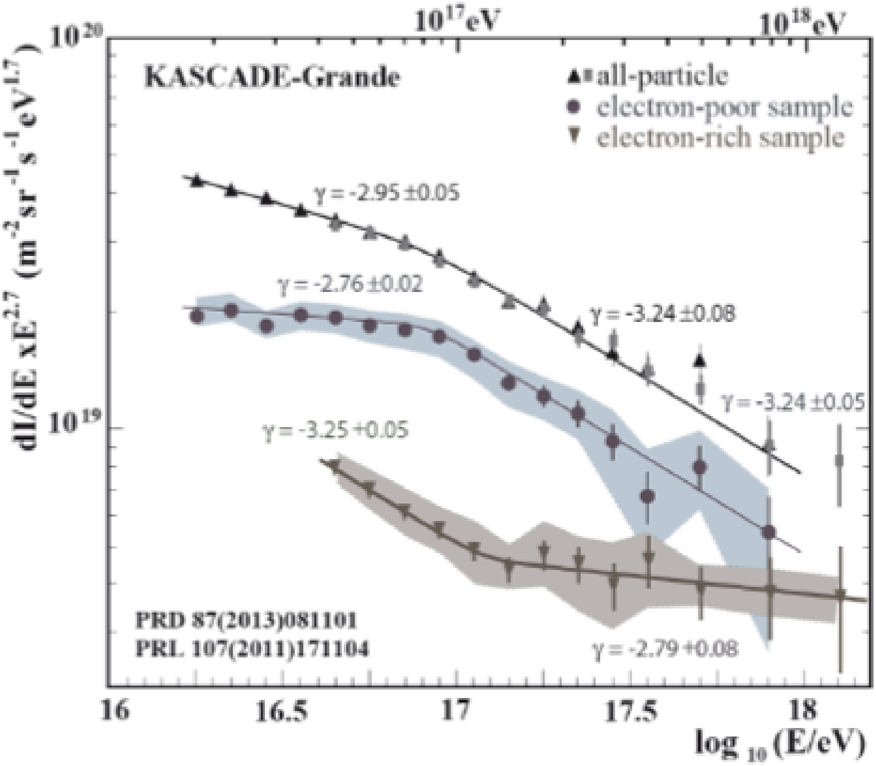

Figure 3. All particle spectrum measured by the KASCADE-Grande collaboration shown together with the spectra of the light and heavy primary components (from[27]).

interesting results[5] obtained with a good X_{max} precision but with small statistics. These results, interpreted with post-LHC hadronic interaction models, indicate a chemical composition dominated by light elements even above the knee of the spectrum. In the LOFAR publication a difference with respect to the results of the traditional surface arrays is claimed, in my opinion this difference can be mainly attributed to the hadronic interaction models used in the EAS simulation: all published results by traditional surface arrays are calibrated by pre-LHC hadronic interaction models and we know that post-LHC models (predicting an higher μ number) foresee an increase of the light elements fraction.

5 Concluding Remarks

The high resolution reached by last generation EAS experiments and the developments in the EAS simulation, due to the increased knowledge of hadronic interactions, brought relevant improvements in the study of primary cosmic rays in the 10^{15}-10^{18} eV energy range. The main limitation of current experiments is due to the absolute energy and mass calibration: a detailed study of their implications is necessary to reach a deeper understanding of this energy range. In my opinion it is important to evaluate not only the effects due to high energy hadronic models but also those due to the analysis strategies followed by experiments.

We can summarize the major recent experimental achievements:

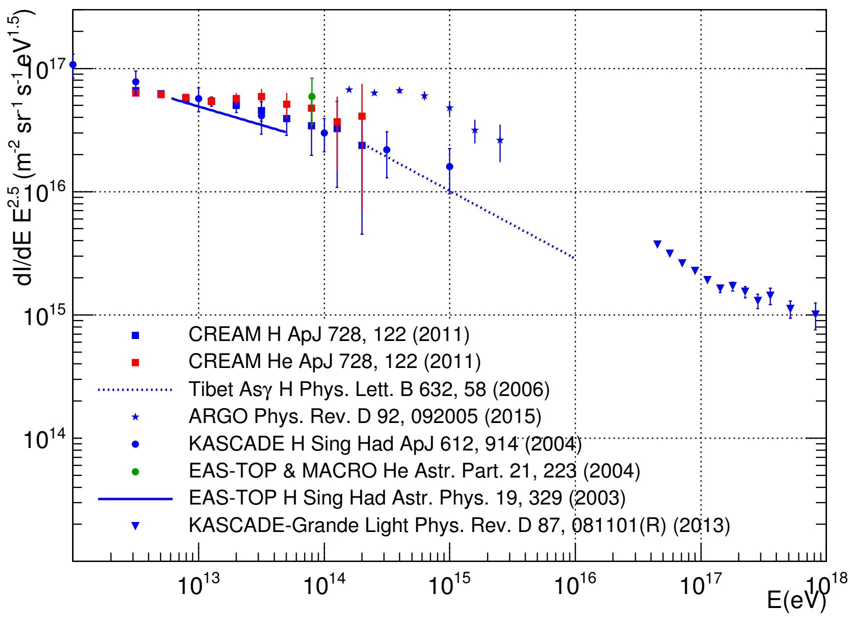

Figure 4. H and He spectra measured by the CREAM[28] experiment compared with light primaries spectra measured by EAS experiments. The KASCADE results[25] are not shown in this plot as they are presented in a not energy calibrated form.

- the primary all particle spectrum above the knee cannot be described by a single slope power law, faint but significant structures have been identified.
- The knee of the primary spectrum, from the KASCADE and KASCADE-Grande results, is attributed to the light primary component, but high altitude experiments (e.g. TIBET-III and ARGO-YBJ) published results that are not in full agreement with this claim.
- A knee-like feature in the spectrum of the heavy primary component and a hardening of the spectrum of light primaries have been observed.

Future experiments will improve the situation if they will explain the differences between current results (mainly those about the light primaries spectrum) and will measure the anisotropies of the arrival directions for different mass groups. To obtain these results future experiments must combine high resolution ($< 15\%$ on both electron and muon numbers), high statistics ($\sim$ km^2 effective areas) and large dynamic range (at least 2-3 orders of magnitude in energy).

References

[1] V.V. Prosin et al., Nucl. Instr. and Meth. A **756**, 94 (2014).
[2] R.U. Abbasi et al., Astroparticle Physics. **80**, 131 (2016).

[3] W.D. Apel et al., Nucl. Instr. and Meth. A **620**, 202 (2010).
[4] M.G. Aartsen et al., Phys. Rev. D **88**, 042004 (2013).
[5] S. Buitnik et al., Nature **531**, 70 (2016).
[6] T. Pierog at al., Phys. Rev. C **92**, 034906 (2015).
[7] S. Ostapchenko, Phys. Rev. D **83**, 014018 (2011).
[8] F. Riehn et al., EPJ Web Conf. **99**, 12001 (2015).
[9] W.D. Apel et al., Astroparticle Physics **95**, 25 (2017).
[10] D. Heck et al., Report FZKA 6019, Forschungszentrum Karlsruhe (1998).
[11] W.D. Apel et al., Advances in Space Research **53**, 1456 (2014).
[12] J.R. Höerandel, Astropart. Phys. **19**, 193 (2003).
[13] T.K. Gaisser et al., Astroparticle Physics **35(12)**, 801 (2012).
[14] M. Amenomori et al., ApJ **678**, 1165 (2008).
[15] B. Bartoli et al., Phys. Rev. D **92**, 092005 (2015).
[16] M. Finger, PhD Thesis, Karlsruhe University (2011).
[17] T. Antoni et al., Astropart. Phys. **24**, 1 (2005).
[18] W.D. Apel et al., Astropart. Phys. **36**, 183 (2012).
[19] A.P. Garkaya et al., J. Phys. G: Nucl. Part. Phys. **35**, 115201 (2008).
[20] A. Aab et al., arXiv:13075059v1, (2013).
[21] R.U. Abbasi et al., Phys. Rev. Lett. **100**, 101101 (2008).
[22] T.K. Gaisser et al., Front. Phys. **8(6)**, 748 (2013).
[23] K. Rawlins for the IceCube collaboration, Journal of Physics (conference series) **718**, 052033 (2016).
[24] W.D. Apel et al., Astropart. Phys. **47**, 54 (2013).
[25] T. Antoni et al., Astropart. Phys. **16**, 373 (2002).
[26] W.D. Apel et al., Phys. Rev. Lett. **107**, 171104 (2011).
[27] W.D. Apel et al., Phys. Rev. D **87**, 081101(R) (2013).
[28] Y.S. Yoon et al., ApJ **728**, 122 (2011).