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Indirect measurements of High Energy Cosmic Rays

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Abstract

In this review I will shortly discuss some of the latest results obtained by indirect measurements of High Energy Cosmic Rays. The field covers a wide energy range, from $10^{13}eV$ up to $10^{20}eV$: the measurement techniques, the dimension of the arrays and the scientific goals of experiments are completely different. The main experimental achievements of the last years can be shortly summarized as follows. In the energy range below the knee of the primary spectrum ($E < 4 \times 10^{15}eV$) an anisotropy in the arrival direction of primary particles has been discovered. Around knee energies (i.e. from $3 - 4 \times 10^{15}eV$ to $\sim 10^{17}eV$) relevant new results have been obtained with the detection of a change of slope in the spectrum of heavy primaries. And finally at higher energies (above $10^{18}eV$) a flux suppression around $\sim 5 \times 10^{19}eV$ and also an indication of a large scale anisotropy in the cosmic ray arrival directions, for energies greater than $\sim 5 \times 10^{19}eV$, have been measured.

Keywords: Cosmic rays, Detection, Spectra, Anisotropy, Mass groups

1. Introduction

The energy range that could be studied with experiments directly detecting the primary cosmic rays, either with balloon or satellite borne experiments, is limited because of their dimensions. Their surface does not allow to accumulate enough statistics while their weight is not sufficient to contain, and thus directly measure, the whole energy of the primary particle.

Thus above $E \sim 10^{14}eV$ primary cosmic rays must be studied by large area arrays located on the earth surface, measuring the secondary particles generated in the shower development in atmosphere. These particle showers (usually named Extensive Air Showers, EAS) are the result of the interaction of a primary particle with atmospheric nuclei. Sampling the particles reaching the detection level, the characteristics of the primary cosmic rays must be inferred: i.e. energy, mass (or chemical composition) and arrival direction.

The main features of the EAS development are described by the Heitler model [1]. Most of the primary cosmic ray energy is transferred through π^0 decays, already after the earliest phases of EAS development, in the electromagnetic component of the shower (i.e. photons and electrons). The decay of charged pions generates muons.

The energy of the primary particle is usually determined measuring the size (i.e. the total number of particles) of the electromagnetic component at detection level. But, if the detector is located well beyond the maximum shower development, the size of the muonic component, fluctuating less than the electromagnetic one, gives a more precise estimation of the primary energy. Both techniques must be calibrated by means of complete EAS simulations. These are based on hadronic interaction models that, above $10^{15}eV$ and before the LHC experiments results, are extrapolations of the experimental results obtained at lower energies. Moreover the accelerator experiments are not studying the very forward regions of the interactions, that are the more relevant for the shower development.

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The atomic mass number of the primary particles cannot be determined by the detection of only one EAS component; the usual choice is to compare the electron and muon size at detection level. Due to EAS development fluctuations, it is not possible to have an event by event measurement of the mass of the primary particles. The evolution of the primary chemical composition with energy can only be obtained comparing the measured distributions of the experimental observables with those expected by EAS complete simulation.

Concluding the data interpretation critically depends on the hadronic interaction models used in the simulation codes, relevant improvements are expected (at least up to $10^{17} eV$) following the results of the LHC experiments.

The previous discussion is valid for the experiments sampling the EAS at observation level. In this case it is thus critical the choice of the height above sea level where to locate the experiment. In fact near the maximum development of the shower the number of particles is almost independent from the primary chemical composition and the fluctuations of the EAS development are minimized. An experiment detecting the shower at its maximum thus has a good sensitivity to primary energy but it is almost blind to the chemical composition. While an experiment operating at an atmospheric depth beyond the shower maximum has a lower resolution in the primary energy determination, while is more sensible to the primary chemical composition.

The case is different for the experiments that are able to measure the longitudinal development of the shower. Up to now only the experiments based on the fluorescence light detection are able to perform such measurements. These arrays allow for each event the determination of the number of particles in the EAS as a function of the atmospheric depth. Integrating these numbers the energy of the event is obtained. Measuring the whole shower development, these experiments can determine the atmospheric depth of the maximum EAS development (X_{max}), that, at fixed primary energy, depends on the mass of the primary particle (lighter primaries give deeper maximum depths compared to heavier ones).

The determination of the primary energy is quasi calorimetric and weakly depends on EAS development simulations (used only to evaluate the invisible energy), while in order to calibrate the X_{max} measurements in terms of the primary mass simulations are needed.

The weakness of the fluorescence light measurements are: the high detection threshold (the signal are weak and can only be detected for $E > 10^{17} eV$) and the low duty cycle ($\sim 10\%$, as these experiments can only take data during clear, moonless nights).

Dividing the energy range covered by indirect measurements in three intervals we can thus summarize the main features of the present experiments:

a) $10^{13} - 10^{15} eV$. Experiments are usually located at mountain levels, the surface covered is of the order of $\sim 10^4 m^2$ in case of full-coverage arrays (MILAGRO [2], ARGO [3]) and one order of magnitude bigger in case of sampling detectors (TIBET Air Shower Array [4]).
b) knee energies from $10^{14} eV$ to $10^{18} eV$. The experimental sites chosen in this energy range spans from sea level (KASCADE [5], KASCADE-Grande [6]), to the 675 *m a.s.l.* of the Tunka experiment [7], up to mountain level (GAMMA [8] 3200*m a.s.l.*, ICE-TOP [9] 2835*m a.s.l.*). The surface sampled by these arrays spans from 10^4 to $10^6 m^2$.
c) Ultra high energies, $E > 10^{18} eV$. Here the main feature of the experiments is the huge surface covered by the arrays: from the 700km^2 of the Telescope Array [10] to the 3000km^2 of the Pierre Auger Observatory [11].

In the following sections the main results will be summarized, for a detailed description of the analysis and for the related plots a detailed list of references is given.

2. Energies below the knee

In this energy range a very important result was the detection by the MILAGRO experiment of an excess of counts, on an angular scale of 10°, from two localized regions [12]. These excesses are found analyzing all events, i.e. with no cuts to select events generated by gamma rays. The median energy of these events is $\sim 1 TeV$, the significance of the two excesses found have peak significances of 15.0σ and 12.7σ. The spectra of the events coming from these regions are not consistent with the spectrum of isotropic cosmic rays.

The same structures were then investigated by the ARGO-YBJ experiment [13] with an higher resolution and as a function of the primary energy (from 0.9 TeV to 23 TeV), confirming the MILAGRO results. Moreover smoothing the sky maps on a lower, compared to MILAGRO, angular scale further structures appear.

In the southern hemisphere, the under ice muon experiment ICE-CUBE detected the existence of structures in the sky map of the cosmic ray arrival directions [14]. Combining their sky maps with those of MILAGRO the regions of the excesses detected by the two experiments show continuity.

These excesses are unexpected as the galactic magnetic field should randomize the arrival directions of primaries at these energies. Possible explanations have been proposed, for instance see [15].

Below $10^{14} eV$ a comparison between the results obtained by direct and indirect measurements can be performed. This is a very interesting point that could be used to check the calibrations of the indirect EAS experiments.

The ARGO-YBJ experiment [16] published the light primary (H and He) spectrum derived from the event hit multiplicity (i.e. the number of pads fired in an event). With the event selection used in this analysis they could show (by a full monte carlo simulation) that the contribution of the CNO group primaries is lower than 2%. The measured spectrum is compared with the one directly measured, for these two primaries, by the balloon experiment CREAM [17]: the agreement found is very good. In the future the ARGO-YBJ will extend its energy range using the analogic informations coming from the RPC detectors. Moving to higher energies we can expect that the contribution due to heavier elements will increase and thus, to separate the light component, some criteria based on the detected observables may be required. Being the experiment located at high altitudes ($4300 m\ a.s.l$) it detects EAS near their maximum and, as mentioned before, the separation of the events in samples originated by different primaries became more difficult. A very important result would be the measurement of the spectra of H and He separately up to knee energies, that would definitively show which is the dominating element at the knee. This measurement at the moment is only possible for the ARGO-YBJ experiment provided that it will be able to separate the events in the samples generated by the two elements.

3. Knee energies

The knee is a steepening of the primary cosmic ray spectrum observed at $\sim 3-4 \times 10^{15} eV$, more than fifty years ago by Kristhiansen et al. [18], consisting in a change of slope of the primary spectrum from $\gamma \sim 2.7$ to $\gamma \sim 3.1$. The explanations of this spectral feature are not yet completely understood, but in the last decade different experiments showed that this change of slope can be attributed to the light component of the primaries [19, 20] and that the change of slope of different elemental spectra is observed at an energy increasing with the atomic number [21], even if the resolution is not enough to discriminate between an A or Z dependence of the knee energy.

These experiments were tuned to measure around knee energies, thus their surface did not allowed to get enough statistics to reach $10^{17} eV$, i.e. the energy where

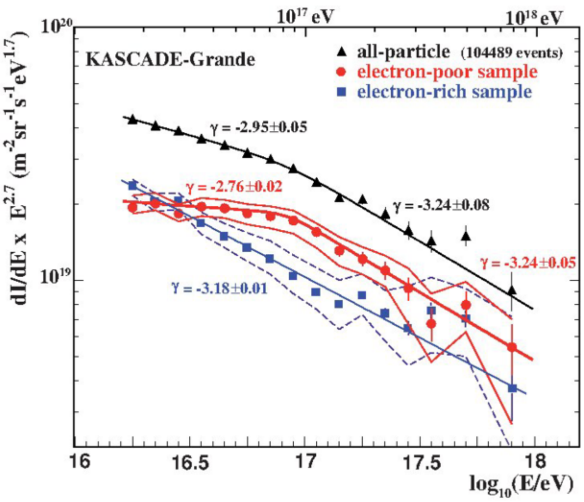

Figure 1: Energy spectra, measured by the KASCADE-Grande collaboration, dividing the events into the electron poor (i.e. heavy elements) and elctron rich (i.e. light primaries) samples

the change of slope of heavy elements (iron) was expected in the hypothesis that the knee energy scales with the mass of the primary particle. The next generation of experiments is focused on the study of the $10^{16} - 10^{18} eV$ energy range.

The KASCADE-Grande experiment [6] is an enlargement of the former KASCADE array obtained arranging the plastic scintillation detection previously used in the EAS-TOP experiment. The data taking lasted since 2003 to 2012. For each event the experiment determines: the arrival direction, the number of charged particles (N_{ch}) and the number of muons (N_μ) at observation level. These observables are used to estimate the primary energy on an event by event basis and to classify the events into samples generated by light and heavy primaries, according to the ratio between the muon and charged particle numbers (evaluated at a reference angle by the constant intensity cut method). The measured all particle spectrum [22] cannot be described by a single power law. Two faint, but statistically significant, structures are observed: a hardening for energies slightly above $10^{16} eV$ and a steepening around $10^{17} eV$.

This steepening has been further investigated measuring the spectrum both for the light and heavy primaries event sample: figure 1 shows the results of the KASCADE-Grande collaboration [23]. The steepening is only present in the spectrum of the heavy primaries, while the one of the light primaries can be described by a single power law.

The $10^{16} - 10^{18} eV$ energy range is also studied by the Tunka-133 [7] and ICE-TOP [9] experiments. These

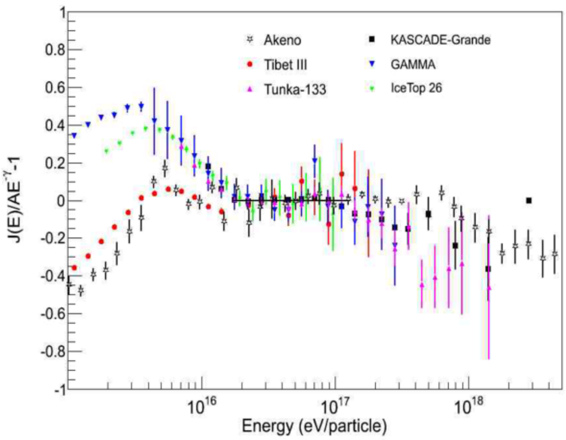

Figure 2: Residual plot of the spectra measured by different experiments with respect to a single power law fit, to the same data set, in the energy range above the spectral feature claimed by the KASCADE-Grande experiment.

arrays operate with different techniques (atmospheric cherenkov light detection and cherenkov light emitted in ice respectively) and, as mentioned before, are located at different altitudes above sea level. Moreover the data analysis are based on different hadronic interaction models (at the moment essentially QGSJetII-03 [24] and SIBYLL2.1 [25]). The hardening around $10^{16} eV$ and the steepening around $10^{17} eV$, claimed by KASCADE-Grande, have been also detected in the spectra of both these experiments.

The agreement between the shapes measured by different experiments is shown in figure 2 by a residual plot obtained comparing each data set with a single power law fit performed, on the same data set, in the energy range between the two features claimed by KASCADE-Grande ($1.7 \times 10^{16} < E < 1.3 \times 10^{17} eV$). In the same plot, the residuals of the Akeno [26] and Tibet-III [27] experiments are also shown. The first one does not show such features; we can, probably, attribute such difference to the resolution of this experiment belonging to a former generation of arrays, while the second one show a less pronounced, but still observable, hardening around $10^{16} eV$.

All these results point towards an explanation of the knee based on astrophysical mechanisms, i.e. either the achievement of the maximum energy obtainable by galactic sources or the limit of the containment inside local galactic magnetic fields. Both explanations implies that the energy of the knee of the spectrum of single elements scales with the charge of the nuclei, to disentangle between these two hypothesis further measurements are needed, for instance the anisotropy of primaries arrival directions. Moreover it is not yet clear if at the knee the spectrum is dominated be H or He primaries, as direct or high altitude experiments have not yet reached a primary energy above $10^{15} eV$.

Analysis improvements are expected in the near future when the hadronic interaction models will be tuned with the LHC experiment results and will not be based on the extrapolation of lower energies results. It will be thus important to store and be able to analyze again the experimental data obtained by already stopped arrays, whose resolution is lower than the fluctuations due to the shower development in atmosphere.

4. Energies above the knee

This energy range is presently studied by two different experiments: the Pierre Auger Observatory and the Telescope Array. Both experiments are realized combining a detector sampling the EAS at detection level (plastic scintillators in case of Telescope Array and water cherenkov tanks for Auger) with a detector measuring the fluorescence light emitted during the EAS development in atmosphere. Thus the high statistics sampling detector, operating with a 100% duty cycle, is calibrated by means of the fluorescence telescopes, operating with 10% duty cycle, measuring in a quasi calorimetric way the energy of the primary particle. In this way the energy measurements performed by a sampling detector are calibrated without an EAS simulation (that as previously discussed depends on hadronic interaction models that, at these energies, are not known).

Beside the difference of the technique adopted for the sampling detector the two arrays differ for the surface covered: the Pierre Auger Observatory extends over 3000 km^2 while the Telescope Array is distributed over $\sim 700 km^2$. The systematic errors, quoted by the two collaborations, on the energy determination are around 20%, one of the main contribution being the one due to the knowledge of the fluorescence yield. This contribution will be reduced in the near future by the results of new dedicated experiments [28].

The spectra measured by the experiments agrees inside the quoted errors as far as the absolute flux is concerned. The shapes of these spectra coincide even better showing the same features: the hardening around $4 \times 10^{18} eV$ (known as the ankle) and the flux suppression around $4 \times 10^{19} eV$. The suppression observed at $\sim 4 \times 10^{19} eV$ can be interpreted as a sign of the so called GZK effect [29], i.e. the flux suppression caused by the interaction of primary cosmic rays with CMB photons.

This feature was first observed by the HiRes collaboration [30] and then confirmed, with an higher statistics, by the Auger experiment [31]. The Telescope Array experiment also detected such spectral features [32].

The situation is more controversial concerning the primary chemical composition measurements. All the experiments study the chemical composition behavior by means of the X_{max} distributions in bins of primary energy. Measurements are performed by the fluorescence detectors and thus suffer of statistical problems and no informations are yet available for energies greater than the flux suppression. The Hires, Auger and Telescope Array experiments have published the mean values and RMS of the X_{max} distributions as a function of the primary energy comparing their results with the expectations obtained by monte carlo simulations (based on various hadronic interaction models). The Auger collaboration results [33] show a light primaries dominated composition between $10^{18}eV$ and $\sim 4-5\times10^{18}eV$ while for higher energies a tendency toward a heavier composition is preferred. The HiRes [34] and Telescope Array experiments [35] results indicate a composition dominated by light primaries in the whole energetic range. Nevertheless, due to limited statistics, the incompatibility between these results is not strong.

At these energies the influence of galactic and extragalactic magnetic fields on the trajectories of the primary particles are expected to be very small, in this case the field of astronomy by means of charged particles could be opened. In these sense all experiments looks for correlations between the arrival directions of primary cosmic rays and nearby astrophysical objects.

A first claim of a statistically significant correlation between the arrival directions of the events with energy greater than 57 EeV and the AGN located at a distance lower than $71 Mpc$ (taken from the Vernon Cettis catalogue) was claimed in 2007 by the Auger collaboration [36]. Unfortunately these correlation has became less significant when the analysis was repeated, with an event sample increased from 27 to 55 events. In this second sample 21 out of the 55 events have an arrival direction correlating with an AGN [37]. Following the 2007 Auger claim, this search was repeated by the HiRes and Telescope Array collaborations. The Auger Observatory is located in the southern hemisphere while HiRes and the Telescope Array are in the northern one, thus they observe different regions of the sky. The HiRes result is that 2 events out of 13 correlate (3.2 expected from background) [38], the Telescope Array one is consistent with no correlation [39].

5. Conclusions

Indirect measurements of primary cosmic rays are the only possibility to study the energies above $\sim 10^{14}eV$. The field is very active with experiments covering several orders of magnitudes in the primary energetic spectrum. Recent experiments have obtained important results in the study of primary cosmic rays mainly due to their unprecedented resolution and dimension.

In the near future a big step forward will be made on the analysis of the experimental results as the hadronic interaction models will be tuned by means of the LHC experiment results.

On the experimental side, some of the experiments are presently in data taking and future improvements are already planned. New measurement technicques such as the detection of signals in the radio frequency range (aimed to measure the longitudinal EAS development with a high duty cycle) are giving promising results, but are not yet mature for a standalone running.

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