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High energy cosmic rays: sources and fluxes

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ABSTRACT

We discuss the production of a unique energy spectrum of the high energy cosmic rays detected with air showers by shifting the energy estimates of different detectors. After such a spectrum is generated we fit the spectrum with three or four populations of cosmic rays that might be accelerated at different cosmic ray sources. We also present the chemical composition that the fits of the spectrum generates and discuss some new data sets presented this summer at the ICRC in Rio de Janeiro that may require new global fits.

1. Introduction

The direct measurements of the cosmic ray spectrum have to end at energies not much higher than 100 TeV. The cosmic ray flux has a generally steep power law shape and the relatively small devices on balloons and satellites cannot collect much statistics at higher energy. The measurements during the last 20 years have established some of the major features of the spectrum at lower energies. ATIC [1], CREAM [2], and Pamela [3] have extended the measurements of JACEE [4]. All of them measure a proton (H) spectrum that is steeper than the spectra of different nuclei. Above 100 TeV the spectrum of He nuclei approaches (and even exceeds) the H spectrum. Still heavier nuclei tend to have even flatter energy spectrum. Apart from the new results of the AMS 02 experiment on the Space Station, that are somewhat different from the results of CREAM and Pamela and which we will briefly discuss later, the behavior of different nuclei in the TeV region is considered well established [5].

The situation at higher energy, where the spectrum measurements come from air shower arrays, is very different. The air shower array analyses have to estimate the energy of the primary particle that generated the shower from the air shower outprint at the observation level. This involves the use of Monte Carlo calculations involving different hadronic interaction models. The models used for air shower analysis have to describe well the interaction properties in an extremely wide energy range and to predict the interaction characteristics at energies higher than the accelerator measurements. In a couple of years the LHC will reach an equivalent Lab energy of 10^8 GeV. These uncertainties lead to differences among spectra measured by different experiments.

Experiments using scintillator counters measure mostly the electrons content of the air showers. Some experiments also have shielded scintillator counters that measure the muon content of the showers. The ratio of the number of muons to the number of electrons (N_μ/N_e) is used to study the nature of the primary cosmic ray nucleus. The heavier it is, the higher the N_μ/N_e ratio is. A couple of contemporary experiments, Auger [6] and IceTop [7] use water (or ice) tanks in which the shower particles emit Cherenkov photons that are measured by photomultipliers. If these tanks are deep enough they measure not only the shower electrons and muons, but also the gamma rays that produce electron–positron pairs in the tanks. Extracting the muon fraction from the observed signals is not easy but it is possible, at least at some distance from the shower core.

At higher energy the primary cosmic ray energy is estimated by integration of the *shower profile*, the longitudinal development of the number of charged particles in the atmospheric cascade by measurements of the fluorescent light that the charged particles create in the atmosphere. This way of estimating energy is considered less model dependent than the measurement of the shower components with an air shower array. In practice, however, this method is only possible for showers of primary particle energy about 10^8 GeV and is more efficient at higher energy.

The shower depth of maximum (X_{max}), i.e. the position in the atmosphere was the number of charged particle is at its maximum is used to evaluate the mass of the primary particle. Heavier nuclei have less energy per nucleon (E_0/A) and each one of them creates a shorter cascade in the atmosphere. What we observe is the sum of all cascades that has earlier X_{max} in the atmosphere. The value of X_{max} can also be observed in the shower Cherenkov light. Recently there are many attempts at radio detection of the signals that air showers create in the atmosphere. While fluorescence and Cherenkov detection is only possible at night (and in good weather) the radio data are always available. This method may become very useful in the future.

We will start with a description of the method that we used to make different air shower spectrum similar to each other in the attempt to create a *unique* cosmic ray spectrum at high energy. In

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the next section we fit this spectrum using the power laws and cutoff energy for each element involved. Since the spectral features change as a function of the primary energy the fits reveal more than three generations of primary nuclei that may correspond to different types of sources. In the discussion section we comment on the newest sets of data presented at the 2013 International Conference on Cosmic Rays in Rio de Janeiro which may affect the fits made earlier.

2. Shifting the air shower energy spectra

There are obviously two types of errors in the cosmic ray energy spectrum by air shower experiments. The first one is the statistical error that depends only the number of showers detected in an energy bin. At the lower energy of each measurement the statistical error is usually very small, while at the highest energy it is significant. This is obvious in Fig. 1 where the error bars of the highest energy air showers represent only a couple of (or single) events [13–15]. The other type of errors are the *systematic* errors of an experiment that do not have a similar energy dependance.

At relatively low energy the systematic errors depend on the experimental efficiency of shower detection. At higher energy, where the efficiency is of order (1), the biggest contribution is from the ability of the hadronic interaction model used to correctly predict the hadronic interactions of the shower particles. Another contribution is the ability of the shower analysis method to assign correctly the primary energy as a function of the mass of the primary nucleus and the zenith angle of the primary particle. Most recent experiments use the shower signal at certain distance from the shower core (that depends on the experimental configuration) where the difference between showers of nuclei with different primary mass is at minimum, as suggested by Hillas et al. [8]. Usually the systematic errors are higher in the beginning of the energy range and in its end and relatively small in its middle range of each experiment.

In our attempt to obtain a unique cosmic ray spectrum at higher energy we started *shifting* the energy estimates of different experiments until the differences between them in an energy bin reaches a minimum. This technique has been used in the past by a couple of theoretical groups [9,10] that shifted the energy estimates of different experiments so that they agreed on the energy at which the cosmic ray spectrum has a *knee* or an *ankle*.

It is rarely obvious from the publications, especially in older experiments, how big the systematic errors are. Even when a numerical table of the spectrum is included in the publication the error bars are the quadratic sum of the statistical and systematic errors. We were careful enough not to shift the energy of individual experiments by more than 10%, but this was not always possible. The spectra resulting after the shifts are shown in Fig. 2 where the shift factors are also shown. The biggest shifts are on the spectra of the CASA/MIA detector [12] and of the Agasa [18] and the Auger Observatory [6] at the very high energy. The Agasa energy is shifted down to 70% of the original estimate and the Auger energy is shifted up by 20%. In the case of Auger one could shift down the HiRes [19] and TA [20] energy estimates and achieve similar agreement between these experiments. Shifting up the Auger energy within its systematic error (set to 22% in the publication) was chosen because it minimizes the shift of the Agasa energy spectrum.

Since the fluxes are multiplied by E^3 in these graphs the relatively small shifts of the energy assignments create a big visual change. One can now start thinking of a unique representation of the cosmic ray spectrum studied with air shower detectors. The problem for such a representation is that the spectrum we obtained after the shifts does not appear to agree with our classical image of the cosmic ray spectrum. This classical image is that the spectrum has a power law index of -2.7 up to the knee, where the spectrum becomes steeper with an index of -3.0 or even -3.1. It continues with the same slope up to the point at about $10^{18.5}$ eV, where the cosmic ray sources become extragalactic.

Now it appears that all experiments that measure the spectrum between 10^{16} eV and 10^{17} eV observe another change in the spectrum shape as first suggested by the GAMMA experiment [17]. The peak seen in Fig. 2 is not as sharp as the GAMMA experiment claimed but its position seems to be at the same energy. The IceTop energy spectrum gives the power law indexes as a function of the primary energy. Below the cosmic ray knee (log E 6.20–6.55) the index is -2.65 and changes to -3.14 for log E (6.80–7.20). There is another change to -2.90 for log E (7.30–8.00). Above log E of 8.15 and up to 8.90 the index is -3.37 with a relatively large error bar because of the low experimental statistics. We do not know for certain what the reason for these changes is, but they give us the idea that cosmic rays in these energy ranges are accelerated at different types of sources and to different acceleration spectra.

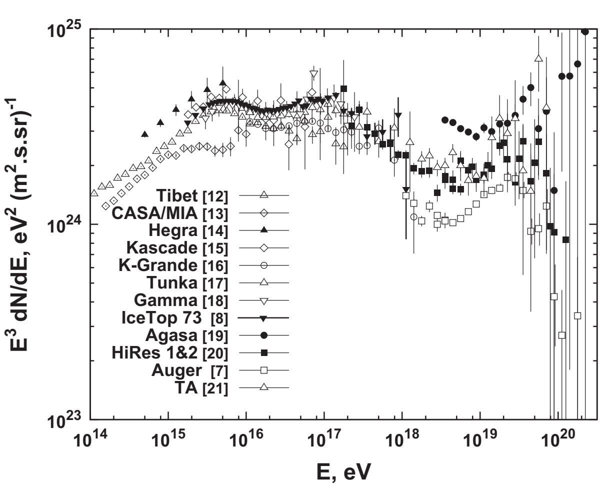

Fig. 1. Comparison of the cosmic ray energy spectra published by different experiments. The reference numbers for the publications are shown in the figure with small numbers in square brackets.

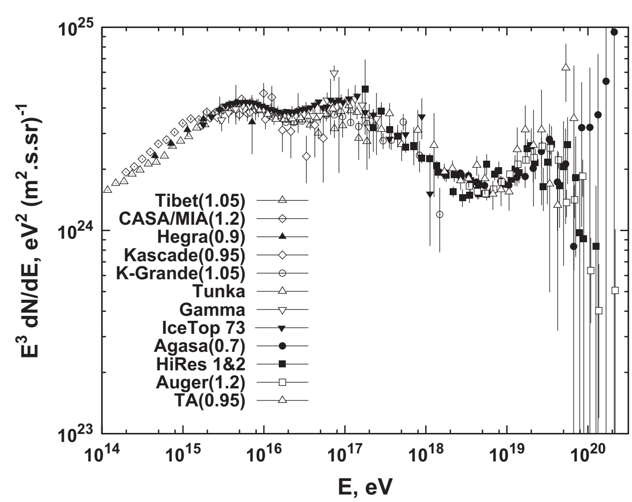

Fig. 2. The cosmic ray energy spectra from the same experiments after shifting the energy estimates. The amount of shifting is shown by the experiment name. If there is no number the original energy assignment is used.