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Analysis of shower size as estimator of extensive air shower energy

Vitor de Souza[a], Jeferson A. Ortiz[a], Gustavo Medina-Tanco[a] and Federico Sanchez[b]
(a) Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, Brasil
(b) Dipartimento di Fisica, Universitá degli Studi di Milano e I.N.F.N.
Presenter: V. de Souza (vitor@astro.iag.usp.br), bra-desouza-V-abs2-he14-oral

The fluorescence technique has been successfully used to detect ultrahigh energy cosmic rays by indirect measurements. The underlying idea is that the number of charged particles in the atmospheric shower, i.e, its longitudinal profile, can be extracted from the amount of emitted nitrogen fluorescence light. However the influence of shower fluctuations and the very possible presence of different nuclear species in the primary cosmic ray spectrum make the estimate of the shower energy from the fluorescence data analysis a difficult task. We investigate the potential of shower size at maximum depth as estimator of shower energy. The detection of the fluorescence light is simulated in detail and the reconstruction biases are carefully analyzed. We extend our calculations to both HiRes and EUSO experiments. This kind of approach is of particular interest for showers that are not fully contained inside the field of view of the detector.

1. Introduction

The total amount of emitted fluorescence light in a shower is a very good approximation to the total number of charged particles $N(X)$, where X is the atmospheric depth. In this sense the number of particles at shower maximum can serve as an estimator of the shower energy. The total energy that goes into electromagnetic charged particles is obtained by integration of the shower longitudinal profile

$$E_{\text{em}} = \alpha \int_0^\infty N(X)dX \tag{1}$$

where α is the average ionization loss rate and the integral on the right-hand side represents the total track length of all charged particles in the shower projected onto the shower axis.

As an alternative proposal [1] the electromagnetic energy can also be calculated by using the fluorescence light intensity and the fluorescence efficiency, without the obligation to reconstruct the number of particles as a function of the atmospheric depth. Such approach is taken as a very precise measurement of the primary shower energy because it is supposed to be weakly dependent of the simulation models and the primary particle type. However, when details of the shower development are taken into account the calorimetric measurement can lead to high systematic uncertainties. A not less important concern is that the fluorescence efficiency as a function of air pressure, density and humidity is only known up to a certain extent. According the approach given by equation 1, the average ionization loss rate is used in the air shower reconstruction and hence the energy spectrum of the electron in the shower must be known via Monte Carlo simulation.

Although the electrons and positrons constitute the majority of the charged particles in a shower and contribute most to the fluorescence light, an important fraction of the shower energy is carried by particles which are invisible to fluorescence telescopes. Such "missing energy" is estimated using Monte Carlo air shower simulation and contributes to the uncertainties involved in this method, being sensitive to the primary composition.

Theoretical works have shown the existence of a clear relation between the primary energy and the maximum number of particles in the shower. Recently, Alvarez-Muñiz et al. [2] have studied the N_{max} shower quantity as an estimator of the primary shower energy, confirming the efficiency of this technique. However, telescopes particularities and reconstruction procedures must be considered due to the introduction of biases and fluctuations in the calculation of N_{max}.

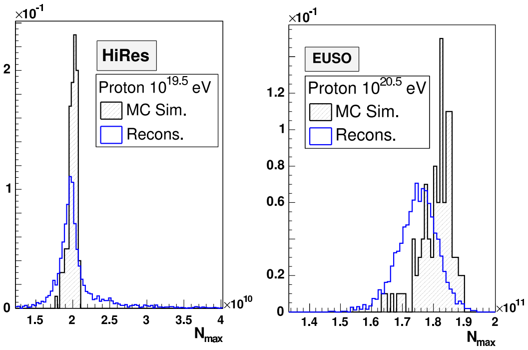

Figure 1. Normalized distribution of the simulated and reconstructed $N_{\max}$.

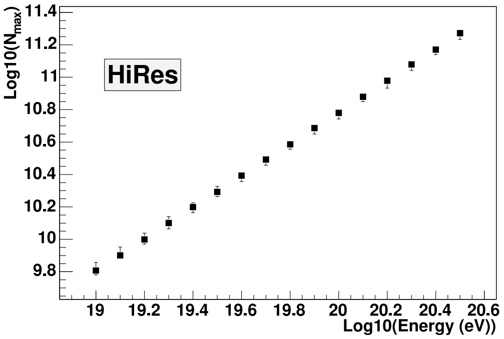

Figure 2. Relation between the reconstructed $N_{\max}$ and the simulated energy for the HiRes telescope.

We explore the possibility of estimating the primary shower energy using the $N_{\max}$ shower quantity for the HiRes [3] and EUSO [4] fluorescence experiments, i.e., ground and space based experiments, respectively. The telescopes particularities and the reconstruction procedures are included in our analysis, predicting more realistic results.

2. Event analysis

The importance of the fluorescence technique in measuring air showers has been demonstrated along the years by the Fly's Eye and HiRes collaboration and now is also being successfully used by the Pierre Auger Observatory [5], all ground based experiments. At the same time, projects are under development and intend to use the fluorescence approach from space observatories. In such projects, fluorescence telescopes would be installed at the International Space Station or in satellites which would increase by at least a factor of 10 the aperture reached by the current ground based telescopes.

In this work we study the possibility of using the $N_{\max}$ parameter as an estimator of the primary energy, employing HiRes and EUSO telescopes as case studies to test its quality in two different setups: ground and space based experiments.

The HiRes telescope specifications were considered and simulated in complete accordance with [3]. The program explained in reference [6] has been used again to obtain the comparisons between our simulations and the HiRes data and simulations. Such program scheme was adapted to mimic in details the EUSO telescope according to the technical configuration given in [4].

The longitudinal air shower profiles were generated by CORSIKA [7] and CONEX [8] simulators. From the obtained longitudinal particle profiles the number of fluorescence photons can be calculated and propagated to the telescopes, being in agreement to the general procedure specified in [9].

Once the simulation of the shower and the telescopes has been done, the shower longitudinal profile is reconstructed in the standard procedure [3]. The number of fluorescence photons measured as a function of time is converted to the number of particles as a function of depth and then a Gaisser-Hillas profile is fitted. One of the parameters fitted in the Gaisser-Hillas function was $N_{\max}$. Only showers which survived the HiRes-II cuts as published in [3] were used in the following analysis.

The EUSO collaboration has not defined quality cuts yet and therefore we have imposed very loose ones

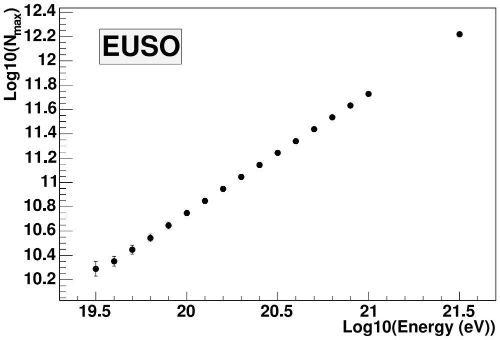

Figure 3. Relation between the reconstructed $N_{\max}$ and the simulated energy for the EUSO telescope.

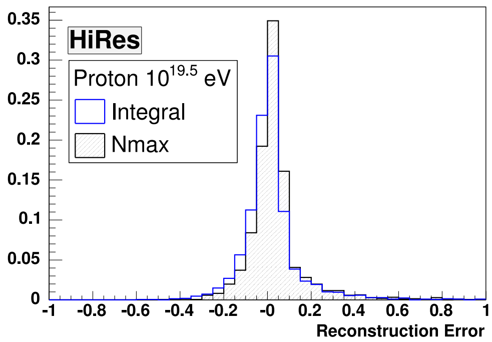

Figure 4. Normalized distribution of the error in the energy reconstruction for both methods.

requiring total path length greater than $0.6°$ and greater than 200 g/cm^2 and $X_{\max}$ in the field of view of the telescope.

We have simulated 100 showers with CORSIKA for energies varying from $10^{19.0}$ to $10^{20.5}$ eV for the HiRes analysis and with CONEX for energies varying from $10^{19.5}$ to $10^{21.5}$ eV for the EUSO. Each shower was used 50 times by drawing a different geometry. For the HiRes calculations we have randomly distributed the showers with zenith angle smaller than 60° over an area with radius of 50 km. For the EUSO calculations we have drawn core positions in a circle with radius of 430 km and zenith angle smaller than $89°$.

Fig. 1 illustrates on the left hand the $N_{\max}$ distribution as simulated by the Monte Carlo program and the distribution of the same reconstructed quantity on the right hand. One can easily verify how the detection and reconstruction procedures distort the distribution producing a wider distribution and a shift in the values. Any reconstruction method based on $N_{\max}$ should take these biases into account.

Fig. 2 shows the relation between the primary energy simulated by the Monte Carlo schemes for the HiRes and EUSO telescopes specifications with the average reconstructed $N_{\max}$. The small error bars show the one sigma confidence level for the $N_{\max}$ distribution. The relation between $N_{\max}$ and energy in Fig. 2 can be well fitted by a straight line

$$Energy = A + B \times N_{\max} \tag{2}$$

The values of A and B parameters were determined to be -1.03×10^{18} and 1.73×10^{9}, respectively, for the HiRes experiment and -5.65×10^{18} and 1.86×10^{9} for the EUSO telescope.

3. Results

Using equations 2 and 2 (with the A and B parameters as given above) we simulated a second set of showers and reconstructed the energy using both procedures: a) the standard integral of the Gaisser-Hillas profile (integral) and b) the $N_{\max}$ relation (equation 2).

Fig. 4 illustrates the error distributions related to the energy reconstruction obtained by using the $N_{\max}$ relation and the integral procedure for the HiRes experiment, for proton-induced showers at 10^{19} eV. For the HiRes telescopes the reconstruction error was calculated to be around 20% at 10^{19} eV reducing to 15% above 10^{20} eV. To this range of energy the $N_{\max}$ reconstruction showed an average reconstruction error 1.5% smaller than the integral procedure.

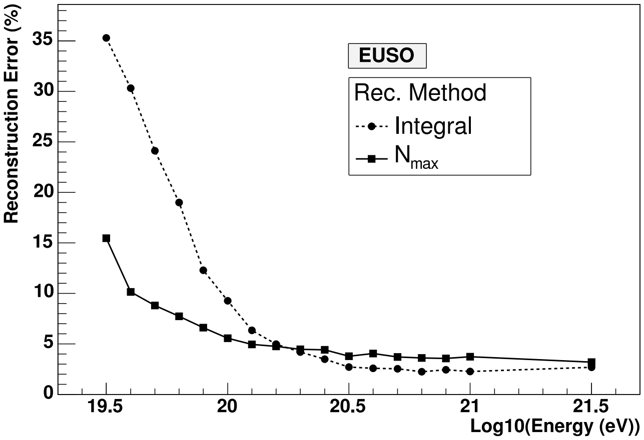

Figure 5. Error in the reconstructed energy for the integral and $N_{\max}$ procedures as a function of energy for the EUSO telescope.

Fig. 5 shows the dependence of the energy reconstruction as a function of energy for the EUSO telescope. For energies below $10^{20.3}$ the reconstruction error related to the $N_{\max}$ method was smaller. However, for higher energies, the EUSO telescope is able to detect the entire development of the shower leading to a good fit of the Gaisser-Hillas at all depths and a better efficiency of the energy reconstruction.

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