29th International Cosmic Ray Conference Pune (2005) **8**, 351-354

Air shower functioning as an autonomous Light Detection and Ranging (LIDAR) for cloudy weather in EHECR observations from space

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Cherenkov albedos of air showers off cloud-tops produce very high intensity signals for air shower observations from space within the regular fluorescence wavelengths of 330 - 400 nm range. This signal stands out in the shower curve as a sharp local peak and allows cloud identification just like a laser-based lidar. In addition, the density-dependent track length provides the cloud and the shower maximum heights to a satisfactory resolution. Monte Carlo studies have been carried out to reconstruct fluorescence and albedo-Cherenkov signals for air shower observations by EUSO. The results clearly reproduced any type of the primary energy spectrum with energy resolution better than 35% at 10^{20} eV using an individual air shower event itself alone.

1. Introduction

The EUSO mission[1, 2] has been in Phase A (Preliminary Design Study) of the European Space Agency (ESA) program and in the NASA Explorer program. Its purpose is to observe high statistics of cosmic rays with extreme energies by detecting fluorescence lights, especially, those of UV lines at 337, 357 and 391 nm that are created in an atmospheric shower event. The optical interferences in the atmosphere by Mie scattering (by aerosols and dusts), Rayleigh scattering (by air molecules), and the existence of clouds, have been significant problems for observation on the ground-level observatories, particularly, when these factors are not monitored all the time. EUSO also considered that these uncertainties of atmospheric conditions could be significant, and designed a lidar sub-system to monitor the Field of View whenever needed.

However, it turned out that the observation of showers and fluorescence lights from space is very different. In particular, for its uncertainty level of atmospheric transmission. Moreover, there is no problem of close proximity issue from space. This close proximity issue makes the fluorescence data (observed from ground) an order of magnitude uncertain, if the impact parameter of the shower is not known. It can sometimes be uncertain to three optical lengths (30 km) if the true optical length is 10 km and without precisely measuring it by a lidar. This can happen in horizontal observations on ground that had to see signals through thick atmosphere of low altitude that is sometimes highly populated by interfering aerosols and dusts.

Observation of showers from space significantly differs from those of the ground stations in many aspects:

(a) There is no proximity problem. The uncertainty of the source luminosity is less than 3% even if we don't know the height of the shower at all. This frees the EUSO observation from a stereo requirement.
(b) Air showers with EUSO act as an autonomous lidar and the detector. High Cherenkov albedos and inverse-density elongation of the track length provides the height of the showers and clouds.
(c) Powerful signal of Cherenkov albedos off clouds barely fails to indicate the existence of clouds.
(d) Shower analysis is feasible even when varieties of cloud existed. It gives a high value for duty cycle.

2. The "Autonomous method" from Space

The "Autonomous Method" (AM) without lidar is based on simple properties of the EUSO detection method being made only possible by the characteristics of observations of showers from space:

1. The non-proximity of EUSO with respect to the EHECR showers.
2. Uncertainties of Rayleigh scattering loss are less than a few to several %. (The absolute column density for transmission loss is less than ~ 1 attenuation length). Mie scattering loss is relevant only in the much lower atmosphere; negligible for space observations for shower max ~ 700 g/cm^2.
3. The relative constancy of fluorescence production yield for altitudes below 15km.

This non-proximity ensures that the solid angles and atmospheric transmission properties will only affect the detection at the negligibly small percent level.

The number of photons arriving at the EUSO detector can be expressed by the following formula:

$$N_{\max} = \left(\frac{\Delta\Omega}{4\pi} \bullet Y \bullet \eta \bullet \frac{E}{E_1} \bullet e^{f(t)} \bullet \Delta L\right), \qquad (1)$$

where $\Delta\Omega$ is the EUSO solid angle, Y is the fluorescence yield (photons/m), and η is the atmospheric transmission coefficient. $E\, e^{f(t)}/E_1$ is the number of photons at the shower maximum of a shower with energy E normalized by $E_1 = 10^{20}$ eV. ΔL is related to the geometrical properties of the shower to the EUSO detector and to the time extent (ΔT) of the shower considered, around the shower maximum. It is given by:

$$\Delta L_i = \frac{c \bullet \Delta T}{1 + n_i \bullet \Omega}, \qquad (2)$$

where **n** and **Ω** are the unit vectors related to the direction through which the shower maximum is seen by EUSO and to the angular direction of the shower.

Because of the relation (1), N_{max} is, at first approximation, only a function of the shower energy E.

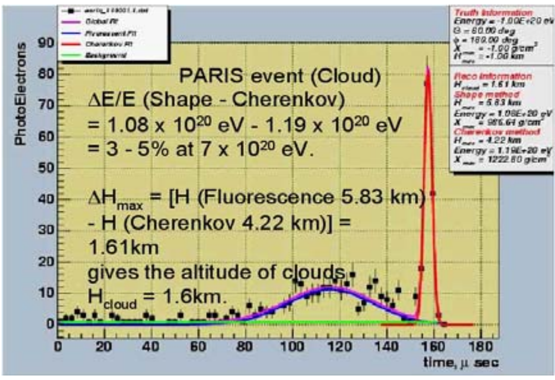
As stated above, all the geometrical factors are only slowly varying functions of the altitude. For example, η will only vary by 4% when there is an error of 1km for the altitude. This error can be diminished further by the following relation that links N_{max}, the total number of photoelectrons in the shower N_{tot} and the density $\rho(h_{max})$:

$$\frac{N_{\max}}{N_{tot}} = \frac{\rho(h_{\max})\Delta L}{2x_0\sqrt{\pi t_{\max}}\, erf\left(\sqrt{\ln\left(\frac{N_{\max}}{N_{threshold}}\right)}\right)}. \qquad (3)$$

The precision is further enhanced by the fact that the shower max altitude is, essentially, a function of the shower inclination and depends little on the shower energy. Because of this, if a cloud is present and detected by an analysis of the shape of the shower signal, the time difference between the observed shower maximum and the cloud peak produced by the cloud albedo gives a reasonable estimate of the cloud top altitude, as well as that of the shower maximum. Hence, clouds favorably work for EUSO as a nice help.

The AM method was applied to the random event simulations incorporating the varieties of clouds. We adopted a double Gaussian shape analysis: one for the shower signal and another, for a possible cloud presence. The energy of the shower was deduced using the formula (1). No a priori information on the shower energy or on the cloud presence was used in this "blind-fold analysis". Figs. 1a and 1b show examples of the shower analysis in the presence (and absence) of a dense cloud for $E \approx 10^{20}$ eV showers inclined at ≈ 60°. The results of the primary spectrum obtained by this study are shown in figures 2a.(GZK subset) and 2b. (Super-GZK subset). The black dots and the grey line represent the initial flux, which are kept unknown during the analyses. As can be seen, the main features of the physics are well reproduced. The energy resolution FWHM ~ 35% obtained at 10^{20} eV can be inferred form the shape of the flux spectra below the minimum energy of the original data (6.0×10^{19} eV and 10^{20} eV).

Fig. 3a. shows the 10^{20} eV spectra obtained with the *"Autonomous Method"*. The energy resolution given by the FWHM is of the order 65% (RMS = 27%), somewhat understandably poorer than that with the lidar methods (perfectly-functioning lidar in three wavelengths). Fig. 3b shows the energy resolution (RMS, blue points) obtained with the *"Autonomous Method"* (without clouds) as a function of the number of photo-electrons in the signal and compared to the error predicted from the statistical error alone (blue line). The green point gives the resolution (at 10^{20} eV) with clouds and the red point shows the value obtained with the ASD methods (Atmospheric Sounding Device, namely, by a "perfect" lidar) at 10^{20} eV. The straight line represents the limits expected from the statistical errors.



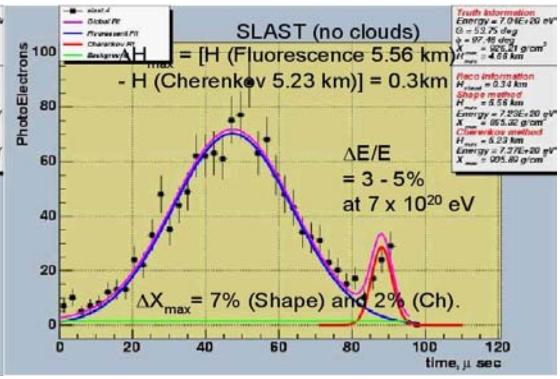
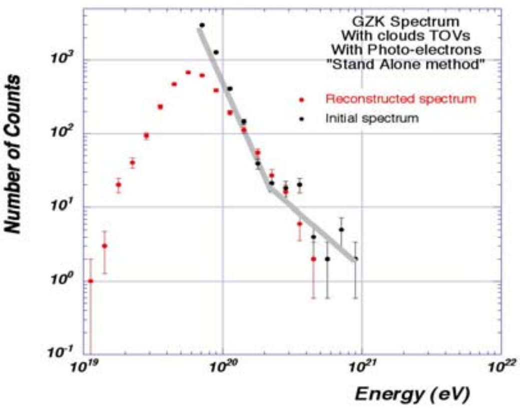


Fig.1a: Example of the "Autonomous Method" analysis of an inclined shower in the presence of a dense cloud.

Fig.1b: Example of the "Autonomous Method" analysis of an inclined shower without any cloud presence.



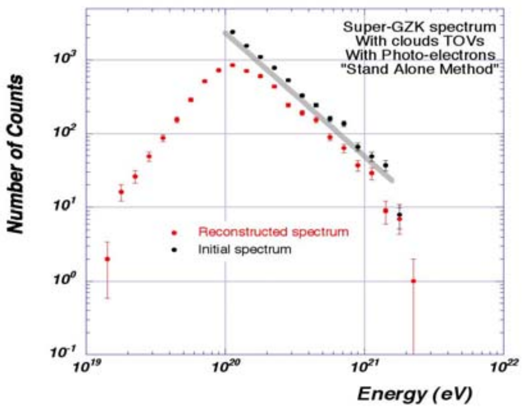


Fig. 2a: Reconstruction of the GZK subset by the Autonomous Method analysis.

Fig. 2b: Reconstruction of the super-GZK subset by the Autonomous Method analysis.

3. Discussions

Monte Carlo analyses that incorporated various cloud situations and rich characteristics of atmospheric shower diagnoses demonstrated the following findings for observation of EHECR showers from space.

. *(a). Air showers with EUSO (fluorescence-detecting space telescope) act as an autonomous lidar.*
(b) Powerful signal of Cherenkov albedos off clouds barely faidsl to indicate the existence of clouds.
(Cf. ground-based experiments do not allow any observation when clouds exist).
(c) Shower analysis is quite feasible for many events even when cloud existed, providing the shower energy and the shower maximum height. They are well fit by the shower curves that linearly elongate with decreasing atmospheric density (1/ρ(z)) in the observation of the shower tracks from space
(d) Cloud-covered aperture will be known in EUSO by using high and prominent peaks of Cherenkov albedos coming off the intervening clouds. As a consequence, EUSO duty cycle can include all weather conditions with and without clouds, which is approximately a factor of 2 higher than the ground-based fluorescence observations.
(e) No systematic uncertainties known to cause an over-estimation of the shower energy (e.g., Cirrus clouds only affect to under-estimate the shower energies < (5-20%).
(f) Air showers with EUSO (space fluorescence-detecting telescope) act as a cost-free autonomous lidar.

Figure 3a: Energy spectra obtained with the "Autonomous Method" for 10^{20} eV events.

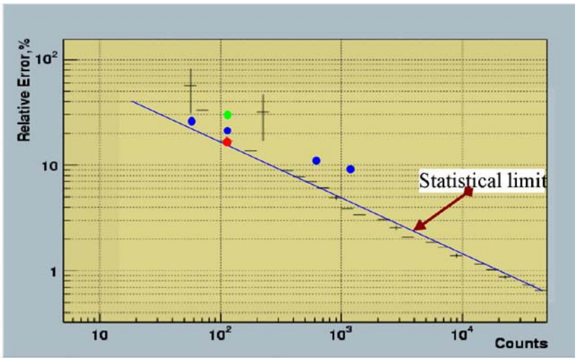


Figure 3b: Energy resolution (blue points) for the "Autonomous Method" as a function of the number of photoelectrons in the shower.

4. Conclusions

The details of the shower observations from space have been studied and revealed that the observation from space is much different from those from ground. The lack of proximity problem, and other characteristics of Cherenkov albedos and density-dependent shower curves, proved in the present Monte Carlo simulations and shower analyses, that neither binocular instrumentation or lidars are required to make an efficient space observation of EHECRs.

5. Acknowledgements

We thank E. Plagnol for providing the Monte Carlo generated events with varieties of clouds for our blind-fold test, and also for discussions.

References

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