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Cosmic-ray mass composition investigations through atmospheric Cerenkov technique – a simulation study

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Abstract. The 4-element TACTIC Cerenkov telescope array at Mt. Abu comprises a central Imaging Element equipped with a 349- pixel Cerenkov imaging camera and three Vertex Elements, each of which is equipped with a special duplex detector array for recording spectral, temporal and polarization characteristics of the atmospheric Cerenkov pulses initiated by primary gamma-rays and cosmic-ray hadrons. It is proposed to use the array for cosmic-ray mass-composition studies above 10 TeV energy during partially moonlit conditions. In order to assess the capability of the TACTIC array for these studies, detailed Monte Carlo simulations, using the CORSIKA code, are being carried out for four primary species (gamma-rays, protons, Neon and Iron), in the energy range ~ 10 – 400 TeV, to estimate the spectral parameters like UV (λ ~ 250 – 310 nm) to Visible (λ ~ 310 – 600 nm) intensity ratio, energy dependence of U / V ratio for each species and the lateral distribution of Cerenkov light for primaries of different energies.

1. Introduction

The study of cosmic-ray mass-composition in the energy range ~ 10^{13} – 10^{15} eV has become important because of the observed spectral steepening around 10^{14} eV (knee feature) in the primary cosmic ray spectrum. While one school of thought ascribes the spectral knee feature to a compositional change (more heavy nuclei), another school attributes it to a basic change in the cosmic-ray interaction modes at these energies (Wolfendale, 1995). Several attempts have been made to study cosmic-ray composition in the knee region by exploiting the air shower array technique where the distinguishing features of extensive air showers initiated by primary cosmic rays of different mass are utilized to infer the primary mass composition. In the present communication, we study the possibility of cosmic ray mass composition studies using the atmospheric Cerenkov technique, in particular, the TACTIC imaging Cerenkov telescope array set up by the BARC at Mt. Abu. Rajasthan (Bhat et al. 1997; Koul et al. 1997). We use The CORSIKA air shower simulation code, with appropriate back-up software to identify potentially useful diagnostic characteristics of the atmospheric Cerenkov pulses initiated by four representative cosmic ray primaries, namely, gamma-rays (γ) protons (p), Neon (Ne) and Iron (Fe) nuclei. The basic motivation for this work is provided by the fact that, when operated at large zenith angles (~ 50°), the TACTIC imaging telescope array can be operated at a threshold detection energy ~ 50 TeV for cosmic ray protons and an effective collection area of $\geq 10^9$ cm^2. The larger collection area results in reasonably high detection rates for the four species, inspite of the steep cosmic-ray power-law spectrum (Wieble-Sooth et al., 1998). Our calculations show that for a 4° field-of-view of the TACTIC system, the hourly event rates vary in the range of 200 (50), 8 (3) and 17 (5) for protons, Ne and Fe primaries of energy 100 (200) TeV, 150 (300) TeV and 200 (400) TeV respectively. The TACTIC system is, thus, potentially useful for mass composition studies if a proper diagnostic algorithm, based on the atmospheric Cerenkov pulses initiated by these primaries, is established on the basis of detailed Monte Carlo simulations.

2. Monte Carlo simulations

The CORSIKA (version 5.61) program based on Monte-Carlo air-shower simulation has been used to derive the following characteristics of the atmospheric Cerenkov events initiated by γ (850 showers; 10 TeV – 100 TeV), Proton (721 showers; 20 TeV – 200 TeV), Ne (880 showers; 30 TeV – 300 TeV) and Iron (870 showers; 40 TeV – 400 TeV) primaries isotropically incident on the atmosphere from a 4° diameter cone centered on a zenith angle of 50°.

(i) Lateral distribution of Cerenkov photon density ϕ_c

(ii) Ratio of UV to visible (U/V) light intensity of the Cerenkov pulses for different core distances

(iii) Average distribution of U/V for core distance ~ 85-125m

& (iv) Dispersion measure (reduced χ^2 values) of the individual lateral distribution curves of all simulated showers with respect to the corresponding average lateral distribution generated by each species ('template' matching).

3. Results

Fig. 1 shows the lateral distribution of Cerenkov photon density ϕ_c for showers initiated by 50 and 100 TeV gamma primaries, 100 and 200 TeV protons, 150 and 300 TeV Neon and 200 and 400 TeV Iron nuclei. The lateral distributions are found to be essentially identical for the three hadron species. The gamma-ray lateral distribution curves, however, show that the well-known 'hump' feature in the lateral distribution appears quite strongly at a gamma-ray energy of ~ 100 TeV at a core distance of ~ 180 m and weakens with further increase in the primary gamma-ray energy (Krys and Wasilewski, 1989). The reappearance of the hump feature is probably connected with the large zenith angle (~ 50°) of the gamma-ray primaries considered in our simulations and offers a possible means of distinguishing between photon and hadron primaries in data collected in the large zenith angle mode of operation.

Fig. 2 shows a comparison of the U/V intensity ratio distribution for primary gamma-rays with the average distributions obtained for the three hadron species. While the average values of the U/V ratio are found to be essentially indistinguishable from each other for the three

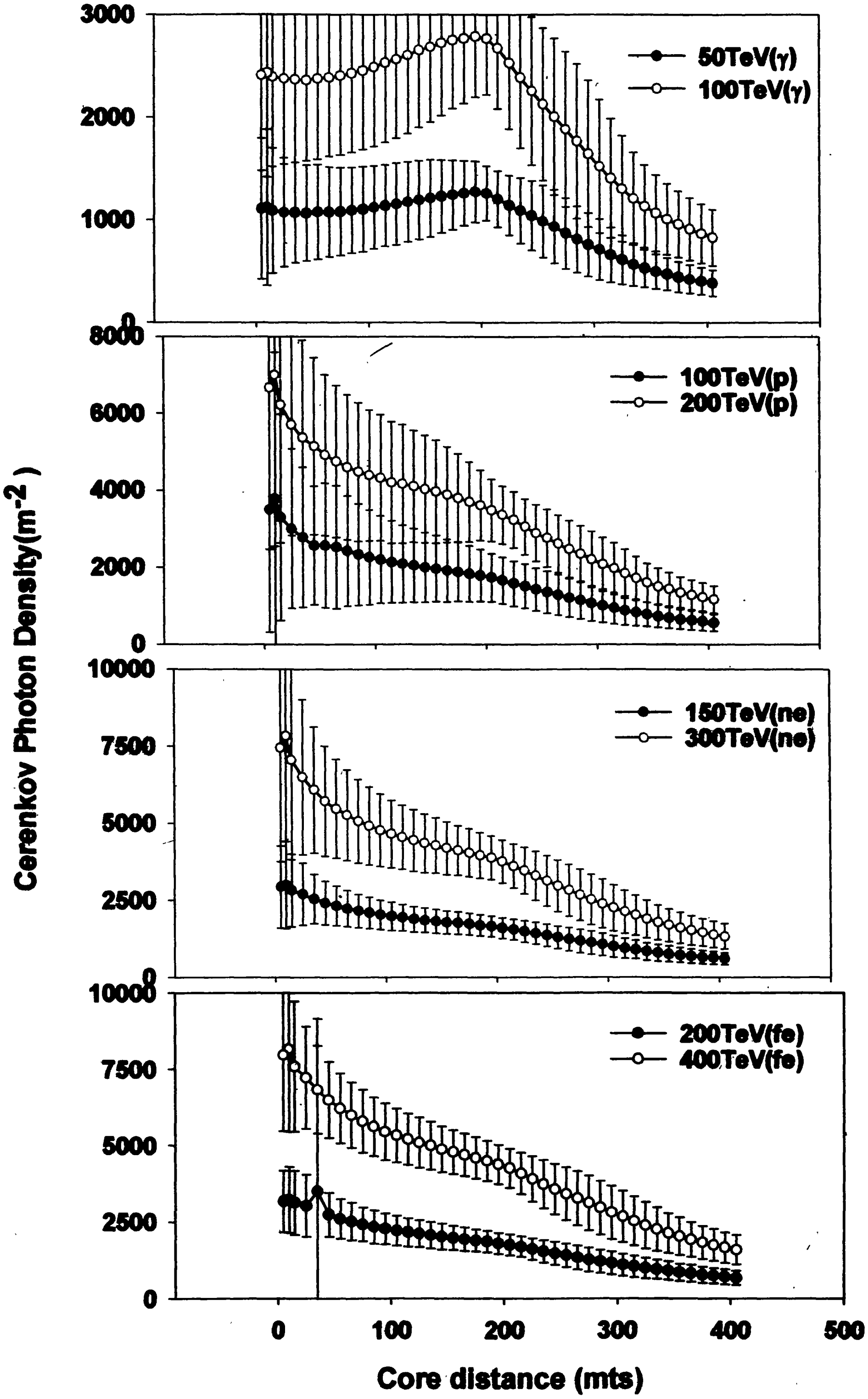

Figure 1. Lateral distribution of Cerenkov photon density ϕ_c for showers generated by 50 and 100 TeV gamma-rays, 100 and 200 TeV protons, 150 TeV and 300 TeV Neon and 200 TeV and 400 TeV Iron nuclei. The 'hump' feature in ϕ_c at ~ 180 m core distance is prominently seen for 100 TeV gamma-ray showers.

hadron species, there is a significant difference between the average U/V values for γ- and p- initiated showers (0.20 ± 0.17 for gamma-rays and 0.40 ± 0.12 for protons). The U/V distributions reveal that gamma-showers, in general, have U/V $\leq$ 0.3. Apart from the possibility of distinguishing between photon and hadron primaries (for U/V $\leq$ 0.3, 85% γ-rays retained and 50% protons rejected), the parameter U/V does not offer much hope for mass segregation.

We have also investigated the possibility of using the observed lateral distributions of Cerenkov photon density (ϕ_c) for primary mass segregation. For this purpose, the percentage of individual showers whose lateral distribution yields a reduced χ^2 value of ~ 1 with respect to an expected distribution ('standard template'), represented by the average lateral distribution of ϕ_c for showers generated by that primary species, has been estimated. Our results show that the average lateral distributions of ϕ_c for the three hadron species are almost identical and mass segregation based on a cut on the estimated χ^2 value is not possible. However, a clear segregation between gamma-ray and hadron primaries is still possible as only 24% of the hadron events show a Cerenkov light density (ϕ_c) lateral distribution which matches with the gamma-ray template (cf. 19% γ-ray events match the hadron template). The possibility of using image parameters for primary mass segregation is under investigation at present and the results will be presented elsewhere.

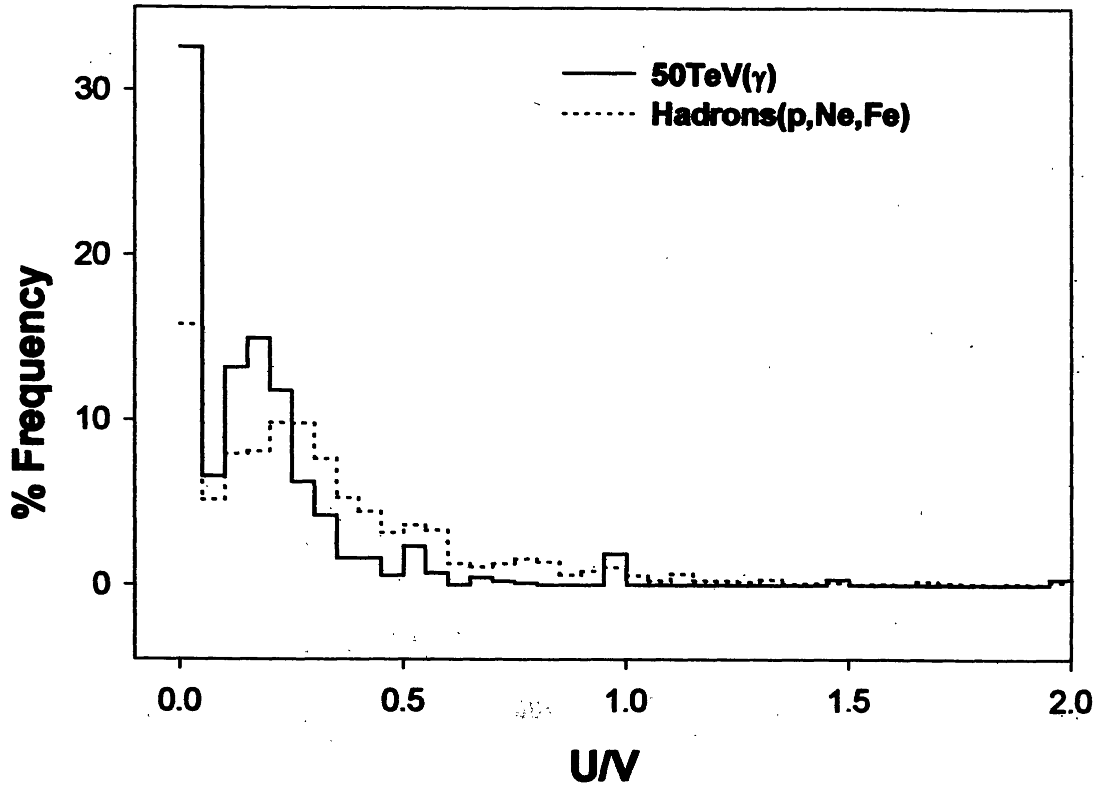

Figure 2. Frequency distribution of the U/V parameter for 50 TeV gamma-ray showers and the < U/V > for showers generated by 100 TeV protons, 150 TeV Ne and 200 TeV Fe nuclei. The four representative energy values are selected to ensure roughly the same Cerenkov photon density for each shower.

4. Conclusions

The simulation results, obtained so far, indicate that, while Cerenkov light lateral distribution, U/V intensity ratio and the corresponding reduced χ^2 distributions, can be used effectively to segregate primary photons from primary hadrons, it may not be possible to separate the hadrons sufficiently in terms of their mass using these parameters. The study is being extended to identify Cerenkov image parameters which can possibly be used in mass segregation at the energies considered here. Some encouraging results of this exercise have been reported elsewhere (Haungs et al., 1999).

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