IL NUOVO CIMENTO Vol. 24 C, N. 4-5 Luglio-Ottobre 2001

Polarization state of atmospheric Čerenkov events —guidance from simulation studies(*)

V. N. Gokhale(2), S. Bhattacharyya(2), R. C. Rannot(2), D. Dumora(1)
J. Procureur(1), A. K. Tickoo(2) and C. L. Bhat(2)

(1) *Centre d'Etude Nucléaire de Bordeaux-Gradignan, Université de Bordeaux 1*
rue du Solarium, 33175 Gradignan Cedex, France
(2) *Bhabha Atomic Research Centre, Nuclear Research Laboratory - Mumbai 400085, India*

(ricevuto il 6 Novembre 2000; approvato il 12 Febbraio 2001)

Summary. — We have been systematically carrying out experimental and simulation studies of the polarization properties of atmospheric Čerenkov events (ACE) produced by very high energy (VHE) and ultrahigh energy (UHE) γ-ray and cosmic ray proton progenitors. We present here an interim report on the work, based on some recent simulation investigations.

PACS 96.40 – Cosmic rays.
PACS 96.40.De – Composition, energy spectra, and interactions.
PACS 96.40.Pq – Extensive air showers.
PACS 01.30.Cc – Conference proceedings.

1. – Introduction

It is expected from elementary considerations of the development of extensive air showers (EAS) in the atmosphere that the accompanying atmospheric Čerenkov events (ACE) should be significantly linearly polarized, with polarization vector ($\vec{p}$) oriented towards the impact point of the EAS core on the ground. If so, as was pointed out first by [1], simultaneous measurements of $\vec{p}$ of an ACE at 2 or more locations on the ground can provide an independent method for locating EAS cores and hence estimating, among other things, the primary energy. Equally interestingly, the two "information-bits" associated with the $\vec{p}$, viz., degree and angle of polarization, may have a useful diagonistic potential and may help to classify the progenitor type—an important requirement for VHE and UHE γ-ray astronomy and cosmic ray mass composition studies through the atmospheric Čerenkov detection technique.

(*) Paper presented at the Chacaltaya Meeting on Cosmic Ray Physics, La Paz, Bolivia, July 23-27, 2000.

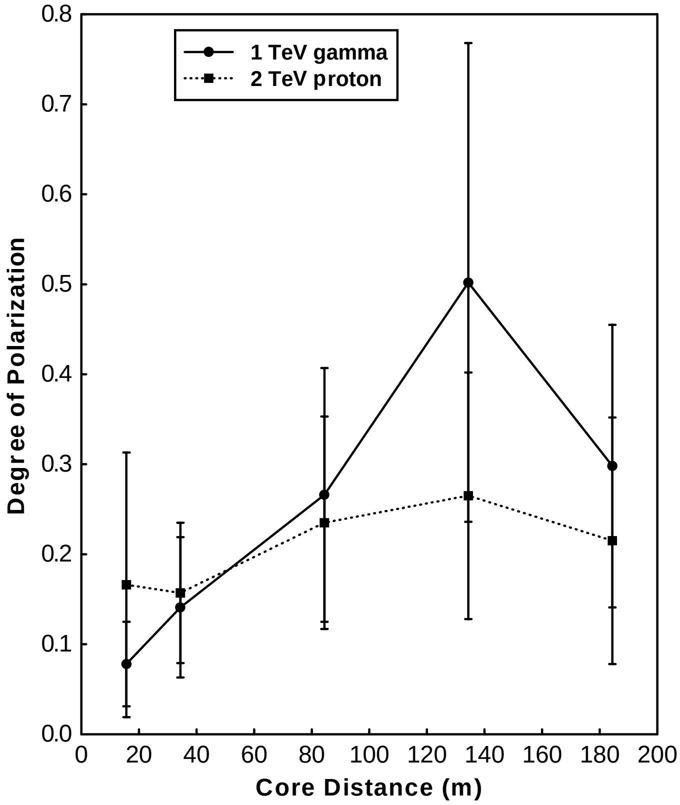

Fig. 1. – $\langle p \rangle$ as a function of core distance for 1 TeV gamma and 2 TeV proton.

Previous work on the potentially important subject has primarily concentrated on the degree of polarization information through estimation or actual measurement of relative radial and transverse ACE flux components. Thus, first experimental work by Galbraith and Jelley [2] led them to the qualitative conclusion that the Čerenkov photon flux with electric vectors (polarization directions) along the direction of an EAS core is comparatively more than that along the perpendicular direction, implying a non-negligible degree of linear polarization, at least for the overall event population. More quantitative simulation and experimental measurements on degree of polarization of ACE produced by protons and iron primaries of $\sim 10^{17}$ eV energies have been done by [3]. They concluded that both the types of ACE are significantly polarized, with a peak degree of polarization $\sim 30\%$ at ~ 125 m from the associated EAS core, beyond which ACE becomes less polarized, reaching essentially zero degree of polarization at 600 m core distance. More importantly, they concluded rather pessimistically about the possible progenitor classification role of the degree of polarization by underlying the fact that this parameter changes only by 5% for each 100 $\mathrm{g\,cm^{-2}}$ change in the depth of cascade maximum. More recently [4] and [5] have discussed the results of their simulation studies of polarization state of ACE produced by γ-ray and proton primaries in the TeV energy region. While again concluding that both the event types are significantly linearly polarized upto a core distance of ~ 125 m or so, they have opined that the differences in the magnitude of this

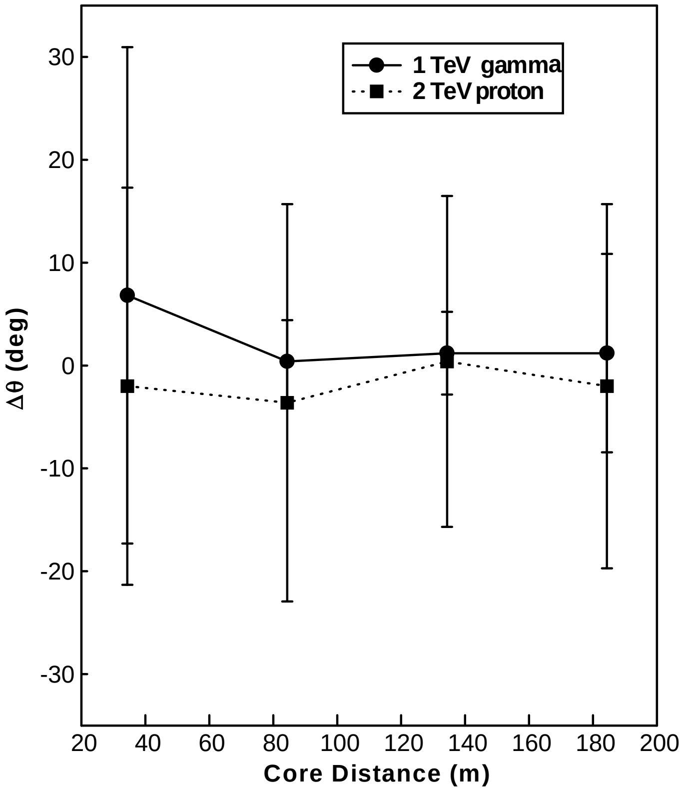

Fig. 2. – $\Delta\theta$ as a function of core distance for 1 TeV gamma and 2 TeV proton.

parameter between the two event types seem to be too small to significantly supplement or enhance the event characterization capability of a typical Čerenkov imaging telescope. In the present work, we would like to report some new results, based on our ongoing studies using VHE and UHE γ-ray photon and cosmic ray proton particle beams.

2. – Data base generation

The CORSIKA air-shower simulation code, suitably modified for the present exercise, has been used for generating data-bases in the VHE and UHE regions, viz., 1 TeV (2 TeV) for γ-rays (protons) in the former case and 200 TeV (400 TeV) for γ-rays (protons) in the latter case. In this specially adapted CORSIKA version, in addition to registering the direction cosines of the propagation vector of each Čerenkov photon reaching our observation level, we also log the arrival direction of each Čerenkov light-producing secondary electron and muon. These two directions together enable to infer the electric (or polarization) vector orientation of a given Čerenkov photon. The azimuthal angle of the projection of this vector on the observation plane with respect to, say, the geographical N-S direction is taken as the effective polarization vector orientation. The data-bases have been generated for our observatory location at Mt. Abu in Rajasthan, Western India (24.62°N, 72.75°E, 1275 m a.s.l.). Both the types of primary particles are made to be incident on the atmosphere along a representative zenith angle of 20°. Čerenkov photons

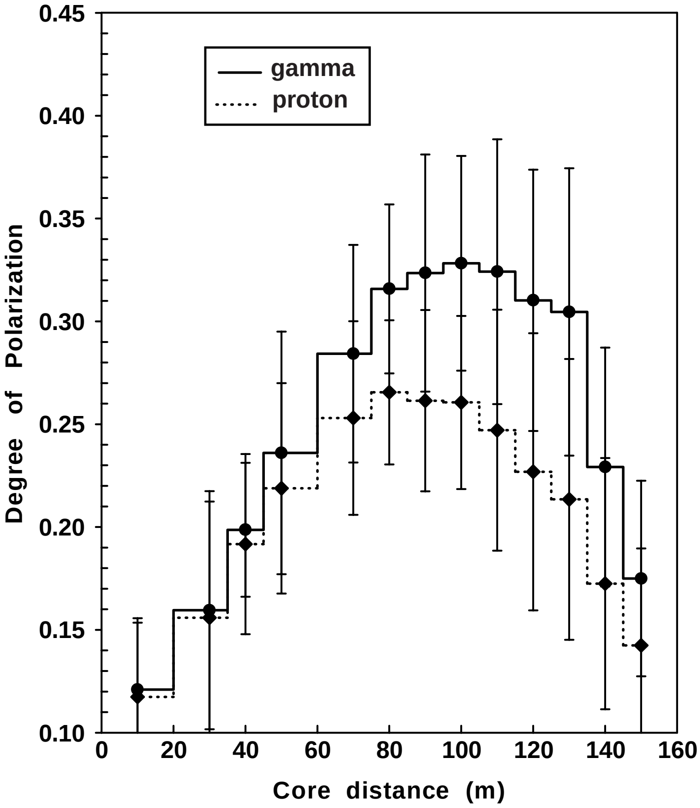

Fig. 3. – $\langle p \rangle$ as a function of core distance for 200 TeV gamma and 400 TeV proton.

produced in the wavelength range $\lambda \sim 300$–600 nm and escaping atmospheric absorption to reach the ground level are recorded along with all related information, viz., coordinates of production point, direction cosines of the Čerenkov photon and or the parent electron or muon, the coordinates of the impact point on the ground, the wavelengh of the detected photon and the Čerenkov photon bunch size, are used in the simulations. In the VHE region the Čerenkov photons are sampled with the help of a linear detector array, comprising 7×2 m $\times$ 2 m light collectors with the nearest-neighbour spacing of 4 m. In the UHE region, on the other hand, the ACE is sampled with the help of a square array of $144 \times 1\,\text{m} \times 1\,\text{m}$ detectors, covering an overall area of 220 m $\times$220 m with an inter-element spacing of 20 m. In both these cases, the shower core is made to be coincident with the centre of the middle detector.

The ACE photons collected by each detector for a given event are divided into 3 equal parts which are assumed to go through 3 ideal linear polarizers (no attenuation) whose axes have been pre-fixed to be shifted by 120° with respect to one another. Each polarizer will thus transmit photons as per $\sim \cos^2 \chi$ functional form, where χ is the angle between the photon electric vector direction (projected) and the polarizer axes. If $I_i (i = 1$–$3)$ are the transmitted fluxes in the 3 cases, the degree (p) and angle (θ) of polarization are

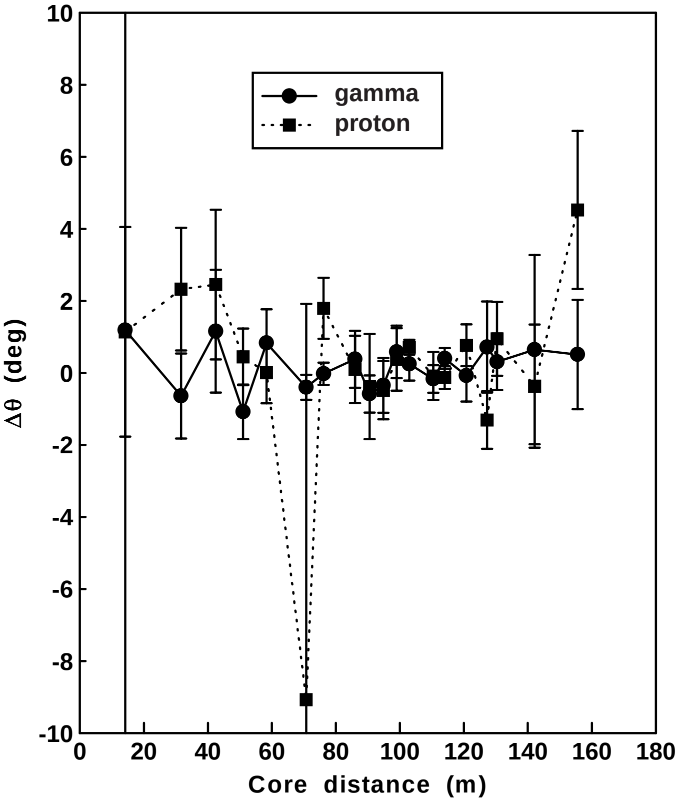

Fig. 4. – $\Delta\theta$ as a function of core distance for 200 TeV gamma and 400 TeV proton.

given by [6]

(1)
$$p = \frac{2\sqrt{I_1(I_1 - I_2) + I_2(I_2 - I_3) + I_3(I_3 - I_1)}}{I_1 + I_2 + I_3},$$

(2)
$$\theta = \frac{1}{2}\tan^{-1}\frac{\sqrt{3}(I_3 - I_2)}{(2I_1 - I_2 - I_3)}.$$

3. – Results and discussion

Figure 1 gives plots of average degree of linear polarization ($\langle p \rangle$) as a function of the core distance R in the VHE case, *i.e.* for γ-rays of 1 TeV energy and protons of 2 TeV energy. For γ-rays, $\langle p \rangle$ is found to increase more or less monotonically from $\sim 10\%$ at $R \sim 15$ m to a peak value of $\sim 50\%$ at $R \sim 130$ m and then decrease to $\sim 30\%$ at $R \sim 180$ m. In case of VHE protons, on the contrary, $\langle p \rangle$ is found to have a weak dependence on R. These results are in good agreement with those obtained by Hillas [4] for comparable primary energies. With regard to the angle of polarization information, it is convenient to define the parameter $\Delta\theta$ as the error in predicting the core direction through measurements of the polarization vector, $\overrightarrow{p}$—it is the difference in the direction

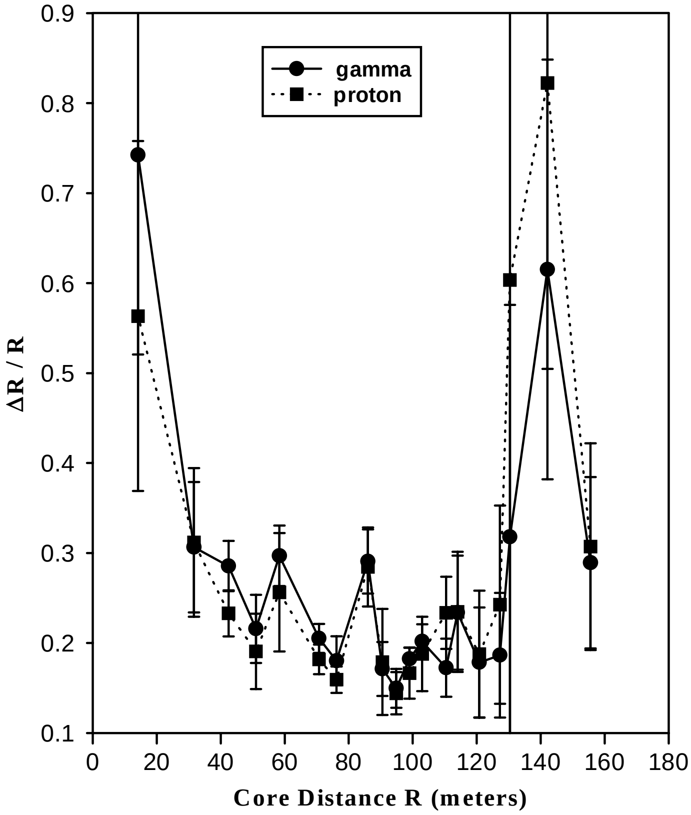

Fig. 5. – Distribution of $\Delta R/R$ as a function of R for 200 TeV gamma and 400 TeV proton.

of $\overrightarrow{p}$ as given by eq. (2) for a given detector element and the actual core direction, *i.e.* the line joining the centre of the element with the array centre, the latter being the known position of the shower core in the present simulation exercise.

Figure 2 gives a plot of $\Delta\theta$ as a function of the EAS core-distance (R), as predicted by measurements made for the 7 element linear array used by us in the VHE case. As is evident from the figure, $\Delta\theta$ is corrrectly predicted to be $\sim 0°$ for both γ-ray and proton progenitors, as would be expected from the above-referred consideration (see sect. **1**) that the polarization vector is oriented along the EAS core, which, in the present case, is known to be coincident with the centre of the linear detector array.

The corresponding behaviours of p and $\Delta\theta$ as a function of R for UHE γ-ray and proton primaries are shown in figs. 3 and 4, respectively. Again, $\langle p \rangle$ is found to increase systematically for both particle species for $R \sim$ 30–100 m range, between 16–32% for γ-rays and between 16-25% for protons. For larger R, $\langle p \rangle$ is seen to decrease, reaching a value of $\sim$ 15% at $R \sim$ 150 m. Figure 4 gives the resulting plots of $\Delta\theta$ as a function of R for, both, γ-ray and proton progenitors. For $R \sim$ 60–130 m, the most "active" core-distance range where most of the ACE are expected to be recorded in actual practice, $\Delta\theta$ is found to be reasonably small for both primary species. $\Delta\theta$ is found to increase for smaller and larger R values lying outside the above referred core-distance interval.

How is this behaviour of $\Delta\theta$ expected to reflect on the corresponding error in the location of EAS core through the ACE polarization technique? To estimate this error, represented by the quantity $\Delta R/R$, we proceed as follows: We take all the array elements which are equidistant from the array centre—the number of such equidistant detector elements varies from 4–128. We determine the point of intersection of all the polarization vectors which are associated with each set of equidistant detector-elements. As each such point of intersection is a possible core position, as follows from the hypothesis that the polarization vectors of a majority of Čerenkov photons in an ACE point towards the EAS core, the error $\Delta R/R$ in the core position is readily obtained by noting the separation of each such point of intersection from the array centre. Figure 5 gives plots of $\Delta R/R$ as a function of the core-position for UHE γ-ray and proton events.

A comparison of this figure with the corresponding plots of fig. 4 shows that $\Delta R/R$ closely mirrors the behaviour of $\Delta\theta$ which is quite understandable. The important thing to note is that for the most important R range $\sim$ 60–130 m, the error $\Delta R/R$ in determining the shower core through polarization technique is expected to be $\leq 20\%$ for both gamma and proton primaries, which is quite reasonable and compares favourably with that expected from the conventional Čerenkov wavefront fitting or lateral distribution function techniques.

We are presently extending these investigations to intermediate energy interval of tens of TeV and are including other cosmic ray nuclei, like neon and iron nuclei in the event progenitor family. Results of our experimental studies on the polarization properties of ACE in the UHE region have been discussed in [7].

4. – Conclusions

Simulation investigations carried out here confirm the work of other authors that ACE produced by VHE and UHE particle-beams (γ-ray and protons) are significantly linearly polarized, the mean degree of linear polarization for γ-ray events being systematically higher than for proton events over the core distance range $R \sim$ 60–130 m. It is also shown that angle of polarization information can be effectively used to locate the shower-core for, both, γ-ray and proton events, the mean error $\Delta R/R$ in the core-location being $\leq 20\%$ over the core distance range 60–130 m.

REFERENCES

[1] Bhat C. L. *et al.*, *Bull. Astron. Soc. India*, **27** (1999) 343.
[2] Galbraith W. and Jelley J. V., *J. Atmos. Terr. Phys.*, **6** (1955) 250.
[3] McComb T. J. L. *et al.*, *Proceedings of the 16th ICRC (Kyoto)*, vol. **9** (1979) p. 53.
[4] Hillas A. M., *Space Sci. Rev.*, **75** (1996) 17.
[5] de la Calle I. *et al.*, *Proc. GeV-TeV Gamma Ray Astrophysics Workshop, AIP Conf. Proc.*, **515** (1996) 515.
[6] Sen A. K. *et al.*, *ICARUS*, **86** (1990) 248.
[7] Tickoo A. K. *et al.*, *Proceedings of the 26th ICRC (Salt Lake City)* OG 4.3.19 (1999).