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Simulation and experimental studies of polarization properties of atmospheric Cerenkov pulses

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Abstract. We present here preliminary results obtained from some simulation and experimental investigations on the polarization state of atmospheric Cerenkov events.

1. Introduction

A qualitative examination of the processes involved in the EAS development suggests that the accompanying atmospheric Cerenkov event (ACE) would be polarized, with the photon electric vector E pointing in the direction of the shower core. In order to get a quantitative confirmation of this idea, we are carrying out Monte Carlo simulation studies with atmospheric cascades induced by gamma-rays and hadron primaries in the VHE range. A specially-adapted version of the CORSIKA simulation code is being used for this purpose (Capdevielle et al., 1992). In parallel, experimental studies are also in progress to measure the polarization state (degree and direction) of ACE induced by cosmic-ray primaries. For this purpose, the prototype MYSTIQUE array, recently set up by us in Mt. Abu, is being utilized (Tickoo et al, 1998). In the event of these exploratory studies turning out to be positive, a promising independent method can become available for the characterization of the EAS primaries as also for locating the shower core and estimating the primary energy. First experimental investigations in this direction have been made by Galbraith and Jelly, 1955. Hillas (1996) recently has presented some results of his simulation investigations on degree of polarization of Cerenkov light from extensive air-showers in the TeV energy range.

2. Simulation studies

The CORSIKA simulation code is used to keep track of each Cerenkov photon reaching a linear array of detector of size 30m × 30m, with an inter-element centre-to-centre distance of 50m, situated at 1700m asl (Gurushikhar altitude where the γ-ray astronomy facility GRACE is being installed; Bhat, 1997). The direction of the progenitor particle (electron/ muon), which produces the detected photon, is also logged, in order to determine the direction of the line joining the instantaneous position of the progenitor particle (in the observations plane) with that of the secondary Cerenkov photon. The azimuthal angle (ϕ) of this line with respect to the array length is estimated; this represents the projected direction of the electric

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vector $\vec{E}$ associated with the Cerenkov photon. For all the simulated events considered here, the shower axis is taken to coincide with the centre of the detector array. As outlined in the Introduction, the distribution of ϕ is found to be pronouncedly peaked towards $\phi \sim 0°$ and $\sim 180°$, in accord with the above-referred expectation that $\vec{E}$ of Cerenkov photons in an EAS should be directed towards the core. To get a quantitative value (magnitude and direction) of the net polarization vector, 3 adjoining (non-collinear) 5m × 5m segments of each detector element are sampled in the following way : Three linear polarizers, with their optical axes oriented along $\phi = 0°$, 120°, and 240°, are assumed to cover the top surfaces of these detector segments. For each incident photon, $\sim \cos^2 \phi$ fraction is taken as being transmitted across the polarizer for detection by the corresponding detector. The resulting polarization vector (degree and angle) is calculated for each Cerenkov pulse at the location of the element from the expressions given by Sen et al (1990).

As shown in Fig. 1 of the Tickoo et al (1998), the above treatment is repeated for each detector element. Figs 1 and 2 give the resulting average picture obtained for γ-ACE and p-ACE of energies 1 and 2 TeV respectively. It is interesting to note that for γ-ACE, the mean degree of polarization $< p >$ increases steadily upto 120m from the shower core and thereafter falls sharply, remarkably mirroring the typical lateral distribution of Cerenkov photons for γ-ray progenitors (Senecha et al. 1992; Rao et al. 1988). On the other hand, in the case of p-ACE, the core distance dependence of the degree of the mean polarization < p > is found to be almost constant at ~ 20%. Equally intersting, the polarization vector is indicated to be preferentially oriented towards the centre of the detector array ($\phi = 0°$), which, it may be recalled, is the position where the shower core is assumed to be pegged in the present simulation exercise. These results are in line with the expectation referred to above that the polarization vector of the ACE can provide an independent method for locating the EAS core. Detailed simulation studies are in progress to seek a general endorsement of this important result.

3. Experimental studies

To check the above predictions on the polarization state of the ACE, the pro-MYST (Tickoo et al. 1998), a prototype experiment consisting of an array of 12 wide-angle photomultiplier detector elements (RCA 8575, 5cm-*dia.*, FOV = 45° semi-angle), spread out over a geographical area of 3500m^2, is being used. Of these, one is the Central trigger Element (CE), 8 surrounding it at distances of ~ 50m are the Timing Elements (TE) and the remaining 3, placed adjacent to TE # 2,5 and 8 are the Polarization Elements (PE). The CE consists of 3 PMT channels operated in a fast coincidence mode (resolving time ~ 10ns), while each TE uses 2 PMT, again operated in a similar mode. Similarly, each PE consisting basically of 3 similar detector channels but with 3 sheet polarizers (type HNB's P-UV2) covering their photocathodes, are used. The polarization axes of the 3 polarizers are displaced with respect to one another by 120°. Whenever an event trigger is produced, the charge contents of 9 gain-calibrated PE channels are logged in charge-to-digital convertors (CDC). The CDC counts are then used to determine the degree and angle of polarization for the event (Sen et al. 1990). The pro-MYST

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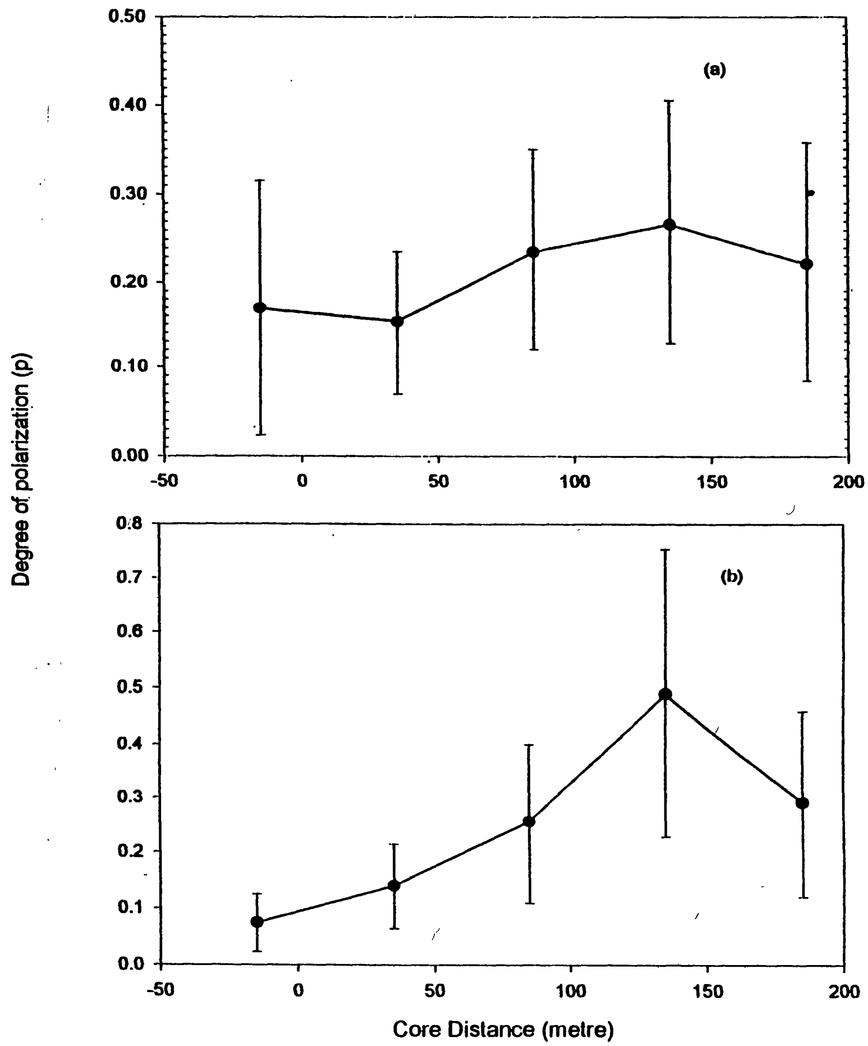

Figure1. Degree of polarization p of atmospheric Cerenkov events plotted as a function of the shower-core distance for a (a) 2 TeV proton and (b) 1 TeV γ-ray photon. The error bars represent standard deviation values and reflect the effect of inter-shower fluctuations.

array is operated at a sufficiently high cosmic-ray primary threshold energy of ~ 5 PeV to ensure that the recorded event is quite robust with respect to the incident Cerenkov photon flux (average event rate ~ $0.05 min^{-1}$). During ~25 h of observations, the three polarization elements PE-2, PE-5 and PE-8 recorded 53, 63and 34 robust events respectively, of which 7 events have been recorded by all the 3 elements. A robust event is defined as one for which the CDC count in any of the PE channels is more than 600, to be compared with $\leq$ 100 counts typically recorded for the sky noise fluctuations. An analysis of the recorded data indicates the degree of polarization p varies from ~ 3% to ~ 65% on an event-to-event basis with a mean $< p >$ ~38%. The results regarding the polarization vector and the resulting shower-core distance estimation for the 7 events common to all the 3 PE's are summarized in Table 1. The core position is taken here as the circumcentre of the triangle with vertices as the

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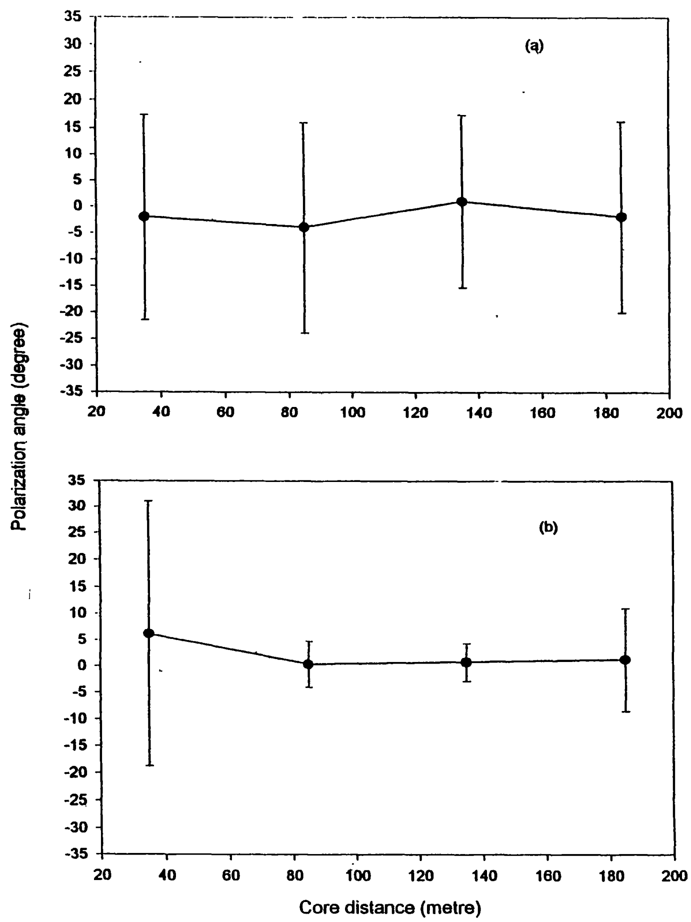

Figure 2. Angle of polarization ϕ of atmospheric Cerenkov events versus shower-core distance for (a) 2 TeV proton and (b) 1 TeV γ-ray photon. ϕ=0 represents the direction of the shower-core $\pm 1\sigma$ error flags, shown in the figure, reflect the effect of shower-to-shower fluctuations.

points of intersection of the 3 polarization vectors given by the 3 PE's. It is evident that in all cases (except event #6 and #7), the estimated core-distances are compatible with what is expected (< 200m) from the known lateral distribution profile of Cerenkov light from proton-primaries in the PeV energy region, with reassuringly reasonable errors of < 35% despite inter-shower fluctuation events. In case of event #6, the physically unacceptable core-distance of ~ 600m (the Cerenkov photon density profile is known to steeply fall beyond a core distance of ~200m at PeV energies) has a comparably large associated error of ~ 100% and is a reflection of extreme shower-to-shower fluctuations. More detailed studies with better-quality sheet-polarizers are presently in progress.

4. Conclusions

To the limited extent that the numbers of Cerenkov photons one is dealing with above are comparable (> a few hundred), in both, the simulation studies at TeV primary energies and

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Table 1. Results on the polarization state of 7 common Cerenkov events registered by the 3 Polarization Elements (PE) of the pro-MYST

Event #	Degree Polarization (p, %)			Angle Polarization (ϕ, deg)			Estimated Core Distance (m)
	PE-2	PE-5	PE-8	PE-2	PE-5	PE-8	
1.	44.4	45.5	24.4	135.9	68.7	110.3	96.7 ± 8.4
2.	16.4	28.4	33.0	147.4	39.1	81.8	71.9 ± 17.8
3.	50.9	18.3	41.5	179.0	15.7	30.5	207.1 ± 67.2
4.	20.2	2.6	18.7	24.4	77.6	130.7	49.0 ± 19.0
5.	21.4	16.8	42.2	143.7	22.3	53.2	93.9 ± 29.2
6.	25.2	28.7	40.1	146.8	138.7	107.7	665.9 ± 690.1
7.	25.9	33.2	29.7	133.8 .	40.1	65.0	116.2 ± 63.9

the experimental investigations with the pro-MYST (at PeV energies for practical constraints), there should be a similar effect from the photon counting statistics on both the aspects of the present exploratory studies. It is interesting to know that the results obtained so far with pro-MYST on both, the degree and direction of polarization state of Cerenkov photons at PeV energies in an EAS are in good agreement with the simulation predictions at lower energies (TeV). To consolidate the above-referred leads, better quality sheet-polarizers are being provided for the PE's and arrangements are being made for sampling the Cerenkov photon density at all of the 12 pro-MYST elements (and not only at TE # 2,5 and 8, as at present). The latter would provide independent information on the position of the shower-core through the conventional method of fitting the Cerenkov photon lateral distribution function. Simultaneously, recognizing the limitations of the present simulation studies viz., using monoenergetic TeV primaries with quantitatively different inter-shower fluctuation effects expected than for the PeV particle-beam sampled by the pro-MYST, the simulation studies are being repeated for experimental conditions as valid for the pro-MYST in order to have a more realistic comparison. In the event of these studies turning out to be positive, a promising independent method can become available for the characterization of the EAS primaries as also for locating their core, eventually leading to an independent estimate of their energies.

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