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Atmospheric Monitoring via Measurements of Scattered Light at the High Resolution Fly's Eye

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Abstract

The High Resolution Fly's Eye cosmic ray observatory measures scattered light from a remotely controlled steerable laser system to monitor the atmosphere in the detector aperture. This paper discusses these measurements that are made over a range of laser geometries, energies, and polarizations.

Introduction:

The High Resolution Fly's Eye detector (HiRes) monitors the atmosphere by measuring light scattered from columnated sources that are fired into the sky. A small number of sources on the ground can then probe a large volume of atmosphere. Extracting atmospheric parameters from detector measurements depends on transmission of light from the source to the scattering point, the scattering, and the transmission to the detector. We first discuss measurements of light scattered from our steerable laser system in terms of Rayleigh scattering theory and show the importance of the laser polarization. We then show that the current system probes the atmosphere to a distance of at least 25km.

Rayleigh Scattering:

The differential scattering cross-section for light scattered by the atmosphere can be calculated analytically by assuming the constituents are dielectric spheres. Rayleigh, or molecular scattering, is calculated in the limit that the sphere is so small that the electric field vector is constant throughout its volume. Light is then emitted through the mechanism of dipole radiation.

In Jackson's Classical Electrodynamics (1975) the scattered electric field due to an induced dipole is derived. Assuming the magnetic moment to be insignificant the scattered field is :

1. $$\mathbf{E}_{sc} = -k^2 \mathbf{p} \frac{e^{ikr}}{r}$$

k is the wave number of the radiation, r is the distance from the scatterer and **p** is the dipole moment of the scatterer. The power radiated from the scattered field in some direction, per unit solid angle per incident intensity is the differential scattering cross section. Since the intensity is the electric field squared, the differential scattering cross section becomes:

2. $$\frac{\partial\sigma}{\partial\Omega} = r^2 \frac{|\epsilon_{scat} \cdot \mathbf{E}_{sc}|^2}{|\mathbf{E}_{inc}|^2} = \frac{k^4}{E_o^2} |\epsilon_{scat} \cdot \mathbf{p}|^2$$

Here ϵ is the sum of two unit vectors. One is perpendicular to the scattering plane and the other is parallel to the scattering plane and perpendicular to the direction of propagation of scattered light. The area of the solid angle at a distance r has been multiplied by the outgoing intensity to give us power. The dipole moment of a dielectric sphere in a constant electric field is $\mathbf{p}=a^3\mathbf{E}_{inc}(\mu-1)/(\mu+2)$ where a is the radius of the sphere and μ is the dielectric constant of the sphere. Substituting this into **(2)** we get:

$$3.\ \frac{\partial\sigma}{\partial\Omega}=k^4a^6\left(\frac{\mu-1}{\mu+2}\right)^2|\epsilon_{inc}\cdot\epsilon_{scat}|^2$$

Now define a coordinate system where θ is the scattering angle and ϕ is the angle from the vector perpendicular to the scattering plane to the direction of incident polarization. We will use these angles to carry out the dot product of the polarization direction of the incident and scattered radiation. Finally, the differential scattering cross-section for a small dielectric sphere is:

$$5.\ \frac{\partial\sigma}{\partial\Omega}=k^4a^6\frac{(\mu-1)^2}{(\mu+2)^2}(\sin^2(\phi)\cos^2(\theta)+\cos^2(\phi))$$

Polarized Laser Tracks:

We now consider measurements of the hires steerable laser system (Mumford 1999) by the HiRes1 detector. For circularly and unpolarized light, the observed differential cross section is found by averaging over all possible polarizations, i.e. over ϕ. Since the average of $\cos^2(\phi)$ and $\sin^2(\phi)$ are both 1/2 the differential scattering cross section for molecular scattering becomes proportional to $\frac{1}{2}(1+\cos^2(\theta))$. However, if the laser light is linearly polarized such that the direction is perpendicular or parallel to the scattering plane it is possible to minimize or maximize the angular dependence of the differential cross section. The perpendicular polarization $(\phi=0)$ should have no angular dependence except for that which is inherent in the geometry of the detector. The scattering of parallel polarized light $(\phi=\pi/2)$ should approach zero at 90° scattering angle. The ratio should be $\cos^2(\theta)$.

To measure the effects of polarization the laser was fired across the HiRes1 detector so that a wide range of scattering angles could be measured. The beam was pointed at 0.6° in elevation and 2° from the line between the laser and the detector. The calibrated signal from the 1° PMT's viewing the laser track were summed over 4° bins of detector azimuth angle. Each bin includes detector elevation angles from 3.5° to 16°. A scattering angle is calculated for each bin. It should be noted that the polarization of the laser with respect to the scattering plane viewed by an individual PMT changes with the

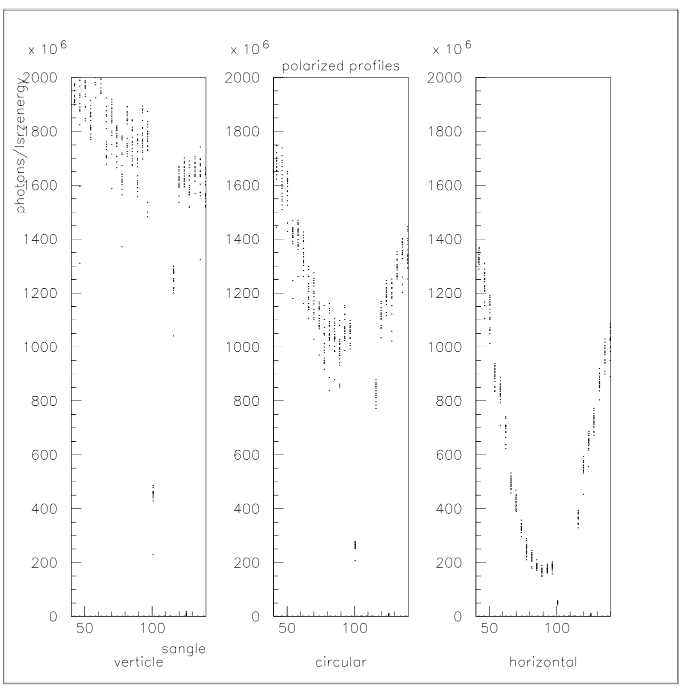

Figure 1: shows detector signal normalized by laser energy for vertical, circular, and horizontal polarizations.

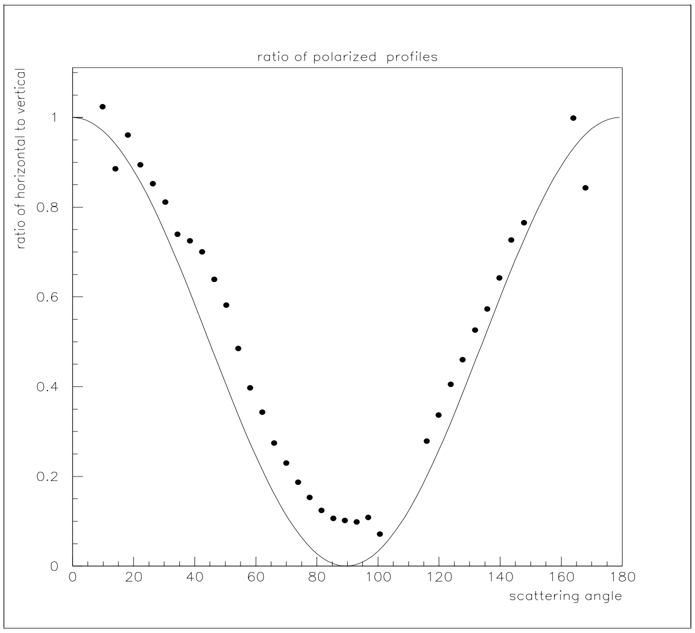

Figure 2: shows the ratio of the average profile of horizontal polarization to the average profile of the vertical polarization. The averages are done over 300 shots for each polarization. The predicted ratio from Rayleigh scattering of $\cos^2(\theta)$ is superimposed. Data is from April 10, 1999

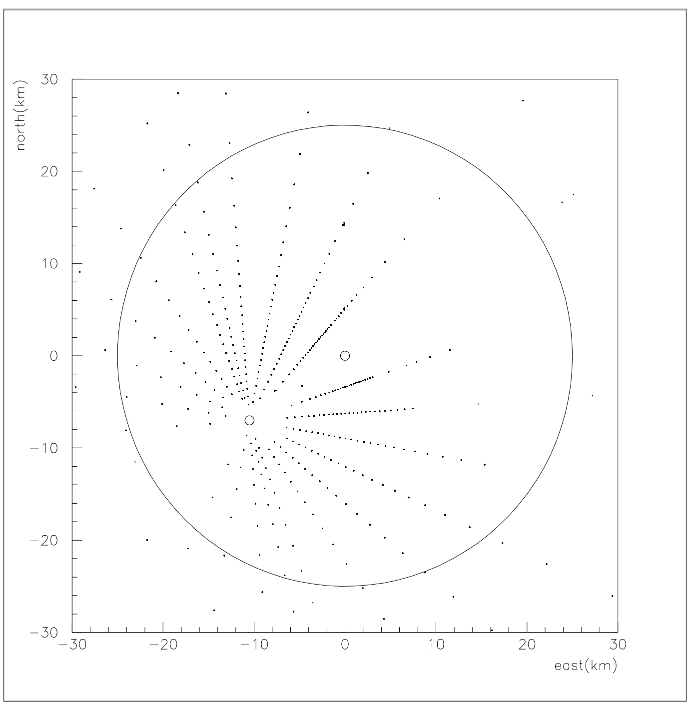

Figure 3. Points in the path of the laser where photons were seen. The position of the laser and detector are marked by small circles.

PMT's elevation angle. However the difference in the cross section between given tubes in a bin should be less than five percent for the geometries used in the measurement. The data shows the striking effect of changing the laser polarization.

A simple test of the scattering model is to compare the ratio of the distributions for perpendicular and parallel polarizations to the predicted $\cos^2(\theta)$. This ratio is shown in figure 2. Superimposed is the predicted curve. The data and the prediction are in good agreement. The most noticeable deviation is that the data does not reach zero at 90° scattering angles. This is true of both the ratio of profiles and the profile of the horizontal polarization. This effect is greater than that expected from errors in setting the beam polarization or from choice of data bins. A possible explanation is depolarization of the laser beam by multiple scattering off non spherical molecules (Liou 1980). We note, for example, that nitrogen is diatomic and more closely resembles an elongated ellipsoid than a sphere.

Probing the Atmosphere:

The range over which the detector can detect light scattered from the this laser system is shown in Fig. 3. The plot shows a pattern of laser shots that were fired at 15 degrees elevation and 15° apart in azimuth. The points on this plot lie along the laser trajectory that was observed by the detector. The laser beam was circularly polarized. Monte-carlo simulations predict that the mean distance of closest approach to reconstructed air showers at 10^{20} eV will be 25 km. A circle centered on the detector with a 25km radius has been superimposed to show that the range of this laser extends to this important region.

Profiles of the light detected as a function of the total distance traveled from the laser to

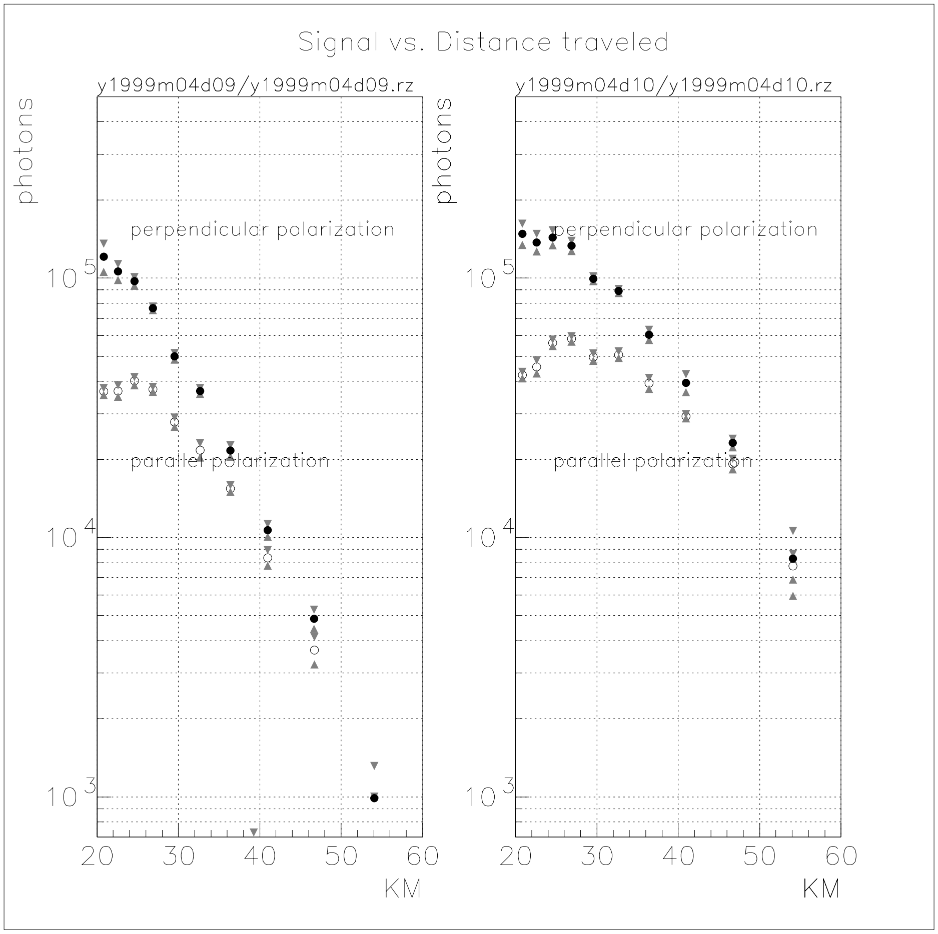

Figure 4 Profiles of Laser shots recorded on April 9th and April 10th 1999. The laser was aimed at 15 degrees in elevation and perpendicular to the line between the detector and the laser. The data has been normalized for shot to shot variations in the laser energy. The X axis is the total distance the light travels. A value of 46 km corresponds to a distance of 25km from the beam to the detector

the detector is shown in Fig 4 for perpendicular and parallel polarized light. The two panels correspond to two different nights. The change in these distributions suggest that the aerosol component of the atmosphere decreased from the first night (left panel) to the to the second night (right panel). The increase in the amount of light is seen at greater distances is consistent with an increase in the atmospheric extinction length.

Conclusion:

The HiRes Steerable laser system probes the atmosphere to distances where the HiRes detector can be expected to observe showers above the GZK cutoff. Polarization effects as predicted by Rayleigh Scattering theory have been observed. Night to night changes in the measured signal consistent with a changing aerosol component have been observed. Methods to extract atmospheric parameters directly from the data and by comparison with simulations are being evaluated.

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