1975ICRC....8.3059B

THE FLY'S EYE --- A NOVEL TECHNIQUE FOR SENSING EXTENSIVE AIR SHOWERS.

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We present here a description of a proposed new device (called the Fly's Eye) designed to detect the passage of extensive air showers through the atmosphere by their nitrogen fluorescence light. Experimental goals include the measurement of the total proton-air cross section in the energy range 10^{16}-10^{19} eV, a search for anisotropies, the separation of components in the primary cosmic ray beam, a detailed study of high energy pp interaction models, the observation of possible neutrino induced showers near 10^{20} eV, a measurement of the rate of gamma bursts, a precise measurement of the primary cosmic ray spectrum up to 10^{21} eV and a possible location of its high energy cutoff. The design parameters of the apparatus and the results of a computer simulation of its performance will be presented. Event rates for energies greater than 10^{16} eV are expected to be of the order of 10^6/yr.

1. Introduction. Studies of the physics of extensive air showers (EAS) using conventional counter techniques suffer from many difficulties, for example: (1) problems of normalization (2) uncertainties as well as possible systematic errors in shower energy determination (3) fluctuations in shower development primarily due to lack of knowledge of a given shower's starting point. These difficulties all stem from one essential shortcoming of existing air shower counter arrays; they all lack the ability to visualize the longitudinal profile of a single shower. The validity of this statement will certainly not induce any palpitations among those familiar with EAS. It is a widely-known and a well-known fact. Furthermore, it is also rather widely known that there may be a solution to the difficulty, namely the use of air fluorescence to monitor the development of an EAS as it progresses through the earth's atmosphere. Although the efficiency of the air as a scintillator is poor ($\approx .01\%$) its large sensitive mass ($\approx 10^{10}$ tons) coupled with the tremendous numbers of electrons ($10^6 < N < 10^{12}$) present in a large shower liberating such prodigious energies ($10^{15} \leq E \leq 10^{21}$ eV) make it an enticing alternative as a tool for visualizing EAS development. Several pioneering groups in the past (Greisen, 1965; Chudakov, 1962; Suga, 1962; Tanahashi, 1969) have proposed and attempted to examine the air shower fluorescence signal. Although the attempts were successful in that a signal was seen, they were unsuccessful in that the signal was too weak to obtain a significant event yield. However, a successful attempt at seeing the air fluorescence signal would be so rewarding that the Utah group has decided to fully commit itself towards the pursuit of this elusive Holy Grail.

In this communication (and in papers EA5-16 and T5-13) we present what is essentially a progress report concerning our current experimental program at Utah. We are in the process of building and instrumenting a detector system similar to that of Greisen *et al*. (Greisen *et al*., 1967) designed to see the air fluorescence light given off by an EAS as it passes through the atmosphere. Being fully aware that the signal is likely to be weak we have stretched both

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the optical design and electronics data handling parameters literally to their bursting point in order to optimize signal to noise ratios. Indeed, even in view of weak signal strengths we expect to achieve event rates on the order of 10^5-10^6/year. We present here both the details of the experimental goals as well as the experimental design parameters.

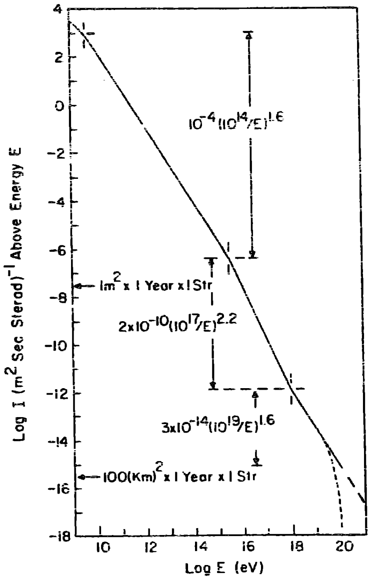

Figure 1.

2. General Description of the Apparatus. The detector system (called the Fly's Eye) will consist of an array of specially fabricated UV sensitive photomultiplier tubes clustered in the focal plane of a large number of 1.5 meter mirrors. The mirrors and associated phototubes will be mounted on a geodesic-like structure and will be exposed to the night sky on clear moonless nights. Further details of the optics will be presented in the next paper (EA 5-16).

The data acquisition will be performed on-line with all detector functions monitored and controlled by a number of on-site DEC LSI-11 computers. In addition, a telephone link will connect to a receiving and analysis center at the University itself. An electronic data processing and storage system will be directly attached to the outputs of each photomultiplier tube. An event trigger will be generated by a fast electronic package attached in parallel to the photomultiplier signal processing and storage electronics. Each lens unit (mirror plus 12 photomultipliers) will be capable of generating a system trigger. Upon the occurrence of a trigger, the acquired data from all photomultipliers containing a stored signal will be fed into the local computer network for further storage, processing, and transmission to the central University receiving computer for subsequent data analysis. (These details will be further covered in paper T 5-13.)

3. How the Fly's Eye Works. A limit on event rates for any EAS detector is set quite effectively by the rapidly-falling cosmic ray spectrum. This effect can be demonstrated from Figure 1. Note that a 1 m^2-sr detector is limited to showers of $E \lesssim 10^{16}$ eV while it requires a detector of enormous size ($\approx$several times 10^3 km^2-sr) to see showers with energies as high as 10^{21} eV. The beauty of the Fly's Eye technique lies in its ability to see the "brighter" showers at increasingly greater distances. Thus, the effective aperture of the Fly's Eye actually expands with increasing shower energy and to a large extent counteracts the rapidly-falling cosmic ray spectrum. This effect is illustrated in Figure 2 where we show how large a conventional air shower array would have to be in order to match the Fly's Eye expected event rate.

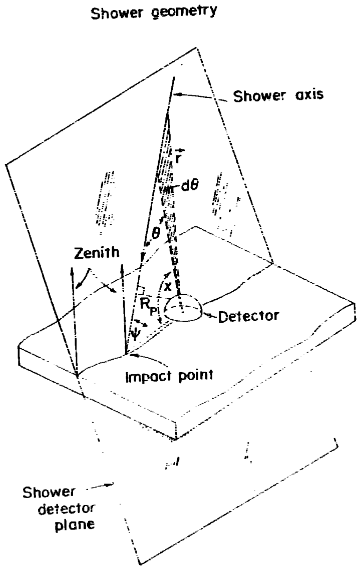

Figure 2.

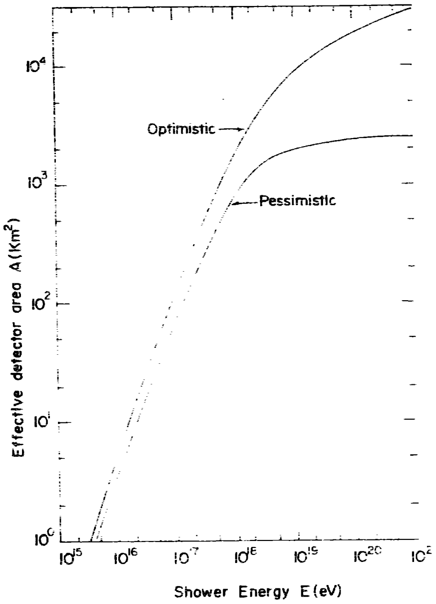

Figure 3.

The crucial parameters of interest here are the energy deposition of the shower and the number of shower electrons as a function of distance along the shower trajectory. A measurement of these parameters necessitates first a measurement of the shower's trajectory. Its location in space can be uniquely determined from the geometrical pattern of those phototubes which see the shower along with the accompanying sequential timing information. The projection of the shower axis onto the Fly's Eye geodesic is a great circle which determines the shower-detector plane in space. The sequential timing information determines the orientation of the shower axis in that plane as well as its distance from the detector. This latter statement is easily understood upon consideration of the kinematics and geometry of an EAS. Its lateral extent is of the order of tens to hundreds of meters, thus, from a distance it looks like a point source of light moving across the sky at the speed of light, c. (Its appearance is not unlike that of a blue relativistic, several watt bulb.) Since the shower travels at the same speed as the light it generates, the light reaching the observer from some point on the shower lags behind the passing shower front by a time

$$t(\theta) = R_p/(c \sin \theta) - R_p/(c \tan \theta) = R_p/(c \tan \theta/2)$$

where θ is the angle between the line of sight and the shower axis. From Figure 3, we see that $\theta + \chi + \psi \doteq \pi$ where ψ is the ground impact angle and χ is the observation angle for a particular phototube. Hence, the timing as a function of observation angle is given by

$$t_i = \frac{R_p}{c} \cot\left(\frac{\psi+\chi_i}{2}\right) \quad \text{or} \quad \chi_i = 2 \cot^{-1}(ct_i/R_p)-\psi.$$

And consequently, the shower impact parameter R_p and its impact angle ψ can be determined simply from a two parameter curve fit of the observation angles and pulse arrival times to the above equation.

Having determined the shower's trajectory, the intrinsic brightness of the shower at each stage of its development can then be determined from the pulse integral value profile of all those phototubes which saw the shower. Of course, the effects of light attenuation by the atmosphere must be taken into consideration.

4. Signal to Noise. Night sky light provides a background (more literally a "foreground") against which faint sources must be detected. In the relevant spectral region (300-500 nm) the night sky brightness B is about 8×10^5 photons/ster/m^2/μsec (Allen, 1955). Thus, a phototube looking at the night sky will suffer a continuous photocathode current of about $I_k \approx B\varepsilon A\Delta\Omega_i \approx 2000$ photoelectrons /μsec. The fluctuation in this number during a given integration time Δt_i is the noise figure ($N \approx \sqrt{2000\ \Delta t_i}$; 45 photoelectrons in 1 μsec) above which the signal

must appear. For example, a signal of 1 μsec duration must generate about 200-250 photoelectrons in order to be "visible".

To estimate how large a shower must be to generate a strong enough signal to be visible, from Figure 3 we see that in a time Δt (as seen by the detector) the source moves a distance

$$\Delta S = -\Delta(R_p/\tan\theta) = c\left(\frac{1+\cos\theta}{\sin^2\theta}\right)\Delta t$$

and the light reaching the detector from that element of path length is

$$L = N_i y\, \Delta S \frac{A}{4\pi r^2}\, e^{-r/\Lambda}$$

photons where N is the number of electrons in the shower, y is the fluorescence yield (≃4 photons/m/electron), A is the area of a mirror, and Λ is the attenuation length of light (Λ≃15 km @ 360 nm) in air. The photoelectron signal is then

$$S = N_i y \frac{c(1+\cos\theta)}{4\pi R_p^2}\, e^{-r/\Lambda}\, A\, \varepsilon\, \Delta t$$

The signal to noise ratio is then

$$\sigma = S/N \simeq N_i y \frac{c(1+\cos\theta)}{4\pi R_p^2 \sqrt{B}}\, e^{-r/\Lambda} \left(\frac{\varepsilon\, A\, \Delta t}{\Delta\Omega}\right)^{1/2}$$

Clearly, it is desirable to maximize ε, A, Δt and to minimize $\Delta\Omega$ to obtain an optimum signal to noise value. We have chosen a super S-11 phototube with extended UV response to obtain an ε≃0.24. The mirror is 1.5 m, as large as we can fabricate economically and $\Delta\Omega$≃0.006 sr. A value smaller than that would require too many phototubes to image the sky. The optimum value for Δt in the triggering system is the actual time that a real signal is present. These times will vary between 50 nsec and about 10-20 μsec depending upon whether or not the shower is either near to or far from the detector. So a priori one does not know what value to choose for Δt. Fortunately, the advent of cheap MSI and LSI electronics allows us to build a multiple parallel triggering system with different integration time constants in order to fully optimize Δt (see paper T5-13).

5. Conclusion. Finally, with our design we estimate that we should be able to see close by showers with energies as low as about several times 10^{15} eV with typical pulse widths of about 50-100 nsec. Showers as distant as 50 km should be visible if their energies are as great as about 5×10^{20} eV. Typical pulse widths here would be about 10-20 μsec.

We have developed a Monte-Carlo program to completely simulate the response of our proposed detector. The rate estimates from the results of that simulation study are given in the following paper. Here we note that we have designed our apparatus with such overkill, even if our signal to noise estimates were an order of magnitude too large (indeed, even if the fluorescence signal were nonexistant scattered Cherenkov light would produce only an order of magnitude lower signal to noise ratio) we should still see several thousand events per year with energies in the range 10^{17}-10^{19} eV! Thus far we have experimentally verified our noise figure estimates by exposing one of our phototubes to the night sky.

By early autumn of this year we hope to have operational a single lens unit to verify our signal strength estimates. If the single lens unit is successful in seeing signals from air showers, we will then proceed with the full-scale implementation. Indeed, to provide a self-checking mechanism for the attenuation of light by the atmosphere as well as to provide redundancy for the geometry determination. We would probably instrument two Fly's Eyes several km apart as in Figure 4.

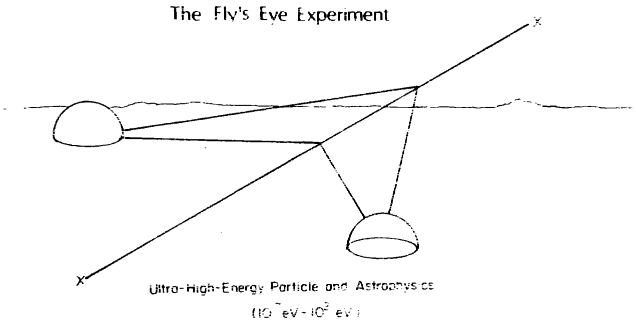

Figure 4.

Acknowledgements. We would like to acknowledge Ken Greisen for his advice, assistance and encouragement in this effort and we would especially like to acknowledge Jack Keuffel whose leadership and wisdom proved invaluable both in this research effort as well as all past efforts. His untimely death was a great blow to us and we dedicate our future success to him.

REFERENCES

Allen, C. W. 1955, Astrophysical Quantities (Athone Press, London), 2nd ed., p. 256.
Chudakov, A. 1962, 5th Inter-American Seminar on Cosmic Rays (Bolivia).
Greisen, K. 1965, Proc. Int. Conf. Cosmic Rays (London) p. 609.
Suga, K. 1962, 5th Inter-American Seminar on Cosmic Rays (Bolivia).
Tanahashi, G. *et al*. 1969, Proc. Int. Conf. Cosmic Rays (Budapest) EAS 4/2 p. 24.