ASTROPHYSICAL APPLICATIONS OF HIGH ANGULAR RESOLUTION ARRAY-TELESCOPES

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ABSTRACT

The air shower array-telescopes which are currently being used to search for and study point sources of UHE γ-rays have angular resolution ∿ 1°, limited by either the small total area of particle detectors or poor timing resolution. As the signal to noise ratio depends sensitively on the angular resolution, it seems certain that this figure will quickly be surpassed when second generation instruments come into operation. Since the trajectories of galactic cosmic rays with $E > 10^5$ GeV are practically straight lines on scales of 1 A.U. or less, these new instruments will be able to observe a shadow cast by the moon (angular diameter 0.5°). Although the angular diameter of the sun is practically the same, its 'shadow' will be more complex because of its magnetic field. Thus, high angular resolution observations of the sun afford a means of investigating the solar magnetic field, and also the charge composition of cosmic rays, including the ratio of antiprotons to protons.

1. Introduction. The first search for point sources of air shower primaries using fast timing to measure the individual arrival directions was made by Clark, using an array of four 0.13 m^2 scintillators located on the roof of the physics building at MIT. In reporting the results of this search he commented, "The sun and moon must cast a 'shadow' in the flux of high energy primary cosmic rays, and observations of this shadow effect might give new information about the magnetic fields of these bodies." (Clark 1957) With detectors of this size, and the best available electronics, the angular resolution (resolution in zenith angle, θ) was 4°; with a sample of 2660 events no statistically significant evidence of point sources was found. Studies made in the past 3 decades have shown that the sun's large scale magnetic field is weaker than it was thought to be in 1957, and have shown that it is not a simple dipole field. Nevertheless, there is no doubt that the shadow of the sun will show effects of the kind that Clark anticipated. It is known now that the moon has no magnetic field. Therefore the shadow of the moon predicted by Clark will be simply a geometrical shadow.

Regarding the sun, it is still not possible to predict quantitatively, with certainty, what effects will be observed. On the one hand, there is uncertainty about the magnetic field of the sun. "At the present time, very little is known about the actual magnetic field configuration and its changes", according to Zirker, writing in 1981. On the other hand, there is uncertainty about the charge composition of the cosmic rays that produce air showers. One would prefer to address these uncertainties one at a time, but having to deal simultaneously with two interlocking problems is common enough in cosmic ray studies. Despite the complexity some preliminary estimates will be made.

2. The method. The essential variables are:

1) The deficit in counting rate, which determines the statistical errors. This depends on the area A of the array-telescope and the energy E of the cosmic rays. (This is in a regime where E and cp are indistinguishable.)

2) The angular resolution of the array-telescope, and

3) The magnetic deflection.

Regardless of magnetic effects, the counting rate deficit due to particles intercepted by the sun or moon will equal $JA\Omega$, where J is the intensity and $\Omega = 5 \cdot 10^{-7}$ steradian is the solid angle subtended by either of these bodies (Liouville's theorem). I will assume $A = 10^4\ m^2$ for second generation array-telescopes. Then using the observed all particle cosmic ray energy spectrum, for primary energy 10^4, 10^5, 10^6 GeV the rate in question amounts to 80,000, 1,500, and 30 counts per year, respectively.

From an analysis of the statistical limitations on the angular resolution of array-telescopes it seems that an accuracy of 5 mrad at 10^6 GeV will be attained in the next few years by second generation instruments. The corresponding practical limits at 10^4 and 10^5 GeV are estimated to be 20 and 10 mrad, respectively. Achieving further improvement will have to await development of large area detectors capable of a much faster response than scintillators (conference paper OG9.6-5). For comparison, the accuracy of direction measurements in a proposed space station magnetic spectrometer facility will be 0.02 mrad (Müller 1985). Thus one can be fairly certain of detecting the shadow of the moon at 10^5 and 10^6 GeV with second generation resolution, but detection at 10^4 GeV seems doubtful, even with the more favorable counting rate.

The arrival direction of cosmic rays affected by the solar magnetic field will also be affected by the interplanetary magnetic field and the geomagnetic field. The latter fields will modify the arrival direction of cosmic rays grazing the moon. To estimate these effects I will use the relation

$$\theta = \frac{300Z}{E} \int B_\perp d\ell \ , \qquad (1)$$

where θ is the angular deflection (radian) in a given plane, produced by the perpendicular magnetic field $B_\perp$ (gauss) in a region covered by the integration, acting on a cosmic ray with charge number Z and energy E (eV). This holds when θ is not too large. In case of the earth one can use Störmer theory. Here I will use a Störmer-theory calculation of equatorial-plane orbits for illustrating approximately how cosmic ray orbits will be affected by the large-scale solar magnetic field. The illustration is valid to the extent that the heliomagnetic field varies as $1/R^3$ over a sufficient range of distances from the sun.

3. The geomagnetic effect. In this case the field integral is approximately $6 \cdot 10^7$ gauss cm (= 0.1 gauss x $R_\oplus$). It is noteworthy that this is nearly 2 orders of magnitude greater than for the spectrometer mentioned above. Substituting in (1), one finds that the deflection will be undetectable using array-telescopes except possibly for Fe nuclei at 10^4 GeV.

4. The effect of the interplanetary magnetic field. Assuming $B_\perp = 5 \cdot 10^{-6}$ gauss (Ness 1965), one finds that in case of travel from the moon the

effect will be completely negligible. For travel from the sun, the magnetic field integral will be $\sim 10^8$ gauss cm, so as in the geomagnetic case, the effect will be negligible except for 10^4 GeV Fe nuclei.

<u>5. The heliomagnetic effect.</u> The heliomagnetic field consists of a hierarchy of structures, the largest of which are called active regions. Typical data, given in Table 1, imply values of the magnetic field integral of order $1\text{-}2\cdot10^{11}$ gauss cm over regions with a size of order $R_\odot$, so by a simple scaling argument, comparing the sun with the earth, one expects sizable effects up to proton energies of 10^5-10^6 GeV, and correspondingly higher energies for Fe nuclei. Table 1 shows that above large active regions the field strength decreases with increasing distance about as $1/R^3$, so to at least a crude approximation the field can be modeled as a dipole. Fig. 1 shows trajectories of 20 GeV protons in the equatorial plane of the earth (Hillas 1972). The apparent location of the occulting object for an observer at infinity using protons or antiprotons is also shown. According to Störmer theory the same picture applies to the sun, when its field is approximated by a dipole, provided that the particle energy is scaled upward by a factor $(M_\odot/M_\oplus)^{1/2}$, where M denotes magnetic dipole moment. Choosing $M_\odot = 3\cdot10^{32}$ gauss cm, so that the equatorial surface field will be about 1 gauss, the scale factor comes out 2000. Hence Fig. 1 also illustrates the behavior of $4\cdot10^4$ GeV protons, or 10^6 GeV Fe nuclei, in the vicinity of the sun. Again using Störmer theory, the same picture can be applied to higher energy particles by drawing larger circles to represent the limb of the occulting sphere, the radius being proportional to $\sqrt{E}$. It appears by inspection of the figure that the proton and antiproton images will be separated adequately up to about 10^5 GeV.

Table 1. Magnetic field strength (gauss) vs height (solar radii) above active regions (Dulk and McLean 1978).

height	B
1.02	300
1.1	10
2	0.5
5	0.05

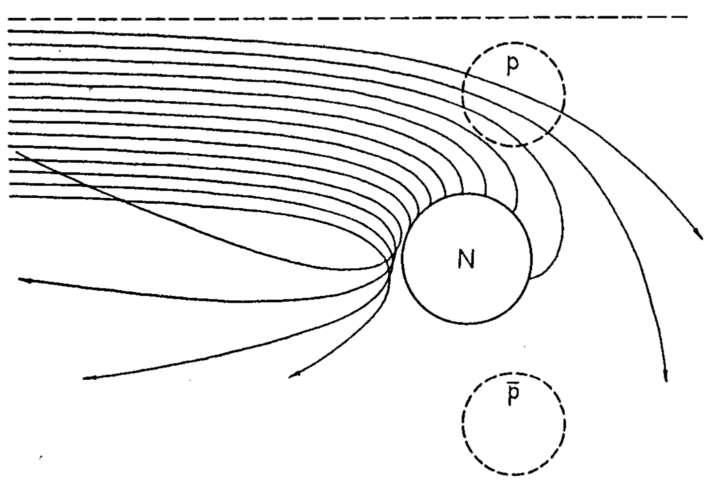

Fig. 1. Trajectories of charged particles in the equatorial plane of the earth's field, with asymptotic direction indicated by the dashed line, and equally spaced impact parameters (Hillas 1972). The solid circle represents the real location of the equator; the dashed circles, the apparent location of the occulting object for protons (p) and antiprotons ($\bar{p}$) at infinity.

6. Conclusions. Using second generation array-telescopes which I assume will have resolving power of 10 mrad at 10^5 GeV and 5 mrad at 10^6 GeV, it appears that the following can be done:

1) Detect the cosmic ray shadow of the moon. This will be a simple geometrical shadow, undisplaced and undistorted. The detailed character of the shadow will provide an independent test of the instrumental resolution of whatever array is used.

2) Detect the cosmic ray shadow of the sun. This shadow will be complex, made up of partial shadows corresponding to primary charges $Z = 1, 2, \ldots$ The partial shadows will be displaced from the true direction of the sun through angles proportional to Z/E. The larger the angular displacement, the more these partial shadows will be enlarged and distorted. Hence, partial shadows will only be discernable when they are near the true sun; otherwise they will blend into the background.

3) *identify the partial shadows belonging to primary protons, alpha particles, and principal charge groups through Fe, and thus measure the cosmic ray charge spectrum for a fixed rigidity of about 10^5 GeV/c.* The identification can be done in an empirical manner, with only crude information about the strength and character of the heliomagnetic field. At an energy a factor 2-3 lower than pictured in Fig. 1 (and all still lower energies) there will be no discernable shadow, because even the proton shadow will blend with the background. As one goes to higher energies, *the first shadow to appear will be the proton shadow.* As E is increased further, the proton shadow will move inward until it lies in the direction of the true sun. As this happens the shadows belonging to Z = 2 and more will successively, for the appropriate value of E, occupy the position where the proton shadow lies in Fig. 2.

4) measure the antiproton abundance up to $\sim 10^6$, where according to some models the fraction of antiprotons is nearly 0.5 (Stecker and Wolfendale 1984).

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References.

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