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ON THE POSSIBILITY OF DETERMINING THE AVERAGE MASS COMPOSITION NEAR 10^{14} eV THROUGH THE SOLAR MAGNETIC FIELD

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ABSTRACT

The discovery of primary U.H.E. gamma-rays has spawned plans for a new generation of air shower experiments with unprecedented directional resolution ($\lesssim 1^0$). Such accuracy permits observation of a cosmic ray "shadow" due to the solar (and lunar) disc. Particle trajectory simulations through models of the large scale solar magnetic field have been performed. The shadow is apparent above 10^{15} eV for all cosmic ray charges $|Z| < 26$; whereas, at lower energies, trajectories close to the Sun are bent sufficiently for this shadow to be lost. The onset of the shadow is rigidity dependent, and occurs at an energy per nucleus of $\sim Z \times 10^{13}$ eV. The possibility of determining the average mass composition near 10^{14} eV from 1 year's observation at a mountain altitude array is investigated.

1. Introduction. A challenge, proposed as a comment by Clark [1], to observe a narrow angle shadow in the cosmic ray flux due to solar and lunar absorption has not been taken up by air shower experiments. The reason is clear; for a statistically significant ($\geq 3\sigma$) deficit from the Sun or Moon, the whole-sky event number to be registered (assuming 1 sr exposure) is $\sim 3.10^6 \times d\theta^2/f$ ($d\theta$ = semi angle of directional resolution (degs); $f \simeq 0.1$, is the duty cycle for observing the Sun or Moon). Thus, with current resolution (typically $d\theta \sim 2°$) $\sim 10^8$ events are required. However, the discovery of primary U.H.E. γ-rays has spawned plans for a new generation of air shower arrays with unprecedented directional resolution [2,3]. It may be possible [3] to obtain $d\theta \sim 0.5°$, so that with a reasonable trigger rate of ~ 0.2 sec^{-1}, observation of cosmic ray shadows would be possible in 1 year's integration time.

The Moon acts as a 'passive absorber' at all air shower rigidities ($\geq 10^{13}$ eV/nucleus) since the effect of geomagnetic fields are insignificant above TeV energies. The directional resolution of air shower arrays is notoriously difficult to estimate; the lack of calibration point sources has resulted in reliance on calculations of the cumulative effects of numerous experimental limitations. Consequently, observation of the Moon's shadow will greatly aid the search for potential U.H.E. sources.

That the Sun is an 'active absorber' (i.e., the shadow is rigidity dependent) in the air shower regime can be seen simply. Above an energy where the particles' gyroradii are comparable to the solar radius, a narrow angle shadow cannot be observed. Putting $B \sim 1G$, $r_g \sim$

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7×10^{10} cm and adopting the high energy limit (rigidity α total energy/z) the loss of a shadow is expected for energies of order z x 2.10^{13} eV. If the rigidity dependence can be modelled accurately, we have the possibility of using the large scale solar magnetic field as a crude magnetic spectrometer [4].

Here, we consider a simple model for the field within 1 A.U. and calculate trajectories of particles with arrival directions within 1° of the Sun. The discriminating power of the technique for charge resolution near 10^{14} eV is estimated, and limitations due to field approximations are discussed.

2. Method. Application of the potential source surface technique [5], and the 'garden-hose' field topology [6] have been very successful in interpreting the measured ecliptic field topology near 1 A.U. [7]. We consider a simple potential source surface at 2 r_0, and extend the field to 1 A.U. using Parker's equations [6] with $\Omega = 2.7 \times 10^{-6}$ and V = 400 Km s^{-1}. Fluctuations are imposed by adding a component of equal magnitude at an angle of $|d\theta|$r.m.s. = 20° over a scale length of 1 r_0. A 4 sector structure is also imposed, with the field direction reversing across the sector boundary.

Particle trajectories are computed by step-wise numerical integration of the equations of motion, with the particle's constant velocity as a constraint. The calculations have been checked by examining the circular orbits of particles fired perpendicular to uniform fields. The step-length is the smaller of (a) 10^{-2} x gyro-radius or (b) 10^{-2} r_0. A step-length 10 x smaller results in negligible trajectory differences. Negatively charged particles are fired back from the Earth within a ~ 1° cone centered on the Sun. Trajectories are followed until they either intercept or miss the solar surface. Two thousand five hundred trajectories are computed over the acceptance cone for each field configuration and rigidity.

In Figure 1, the proportion of events within the cone which intercept the Sun is shown as a function of particle total energy for proton and Fe primaries (Model II). For comparison, the results for a simple dipole field, with no fluctuations, are also shown (Model I).

3. Discussion. It must be emphasized that: (1) the 'saturation obscuration' (in this case 18%) and zero obscuration are model independent, depending solely on the air shower array's field of view (in this case dθ = 0.6°); (2) the separation of nuclear species is model independent, being α Z; (3) as indicated in Figure 1, the energy at which the shadow appears is very model dependent. In particular, the magnitude and scale length of the field within ~ 5r_0 are of paramount importance. Model II may considerably underestimate the field magnitude within 2r_0, but overestimates the scale length. We believe there is a factor of ~ 5 uncertainty in the energy at which the shadow appears, and that Model II is a reasonable lower limit to the transition energy.

In Figure 1 the rise-energy (over which the obscuration rises from 10 to 50%), $E_{50\%}$, is ~ Z x 5 TeV, and $E_{90\%}$ ~ Z x 18 TeV (or, as a

fraction of E_{50}: ΔE_{50} ~ 0.49, ΔE_{90} ~ 1.9). These two parameters would

be severely underestimated (and hence the power to discriminate between composition models curtailed) if (a) the field of view was
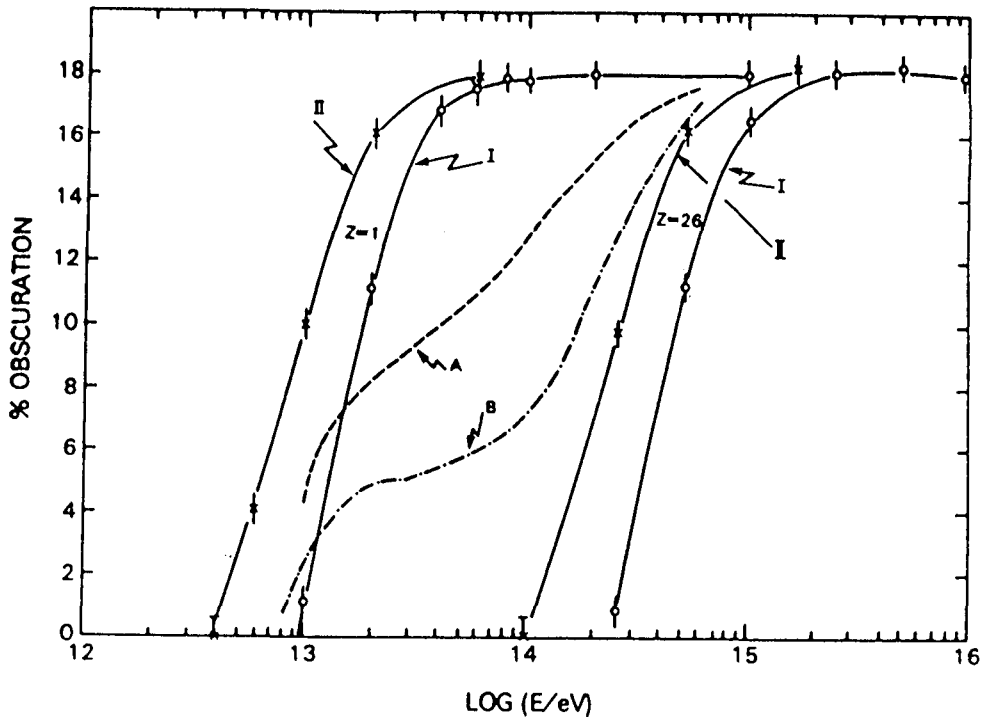
Fig. 1. The appearance of a solar shadow within a 1.2° acceptance cone for protons and Fe nuclei for field representations I, II (see text). The dotted curves show the resulting transition for two simple composition models (see text).

underestimated or (b) large, unknown, variations in the average magnetic field strength occurred over a 1 year timescale. Possibility (a) is removed by normalizing the saturation obscuration to that for the Moon (see Section 1). The global magnetic field varies by ~ x 3 near the photosphere through the solar cycle and by 20-40% at 1 A.U [8]. Thus, long term monitoring of the photospheric fields, currently undertaken, is required to minimize the effects of (b).

The values ΔE_{50}, ΔE_{90} can be compared to those calculated by a simple impact parameter approach [9]. Averaging over all impact parameters within the field of view which penetrate the solar surface, we obtain $\Delta E_{50} \simeq 0.45$, $\Delta E_{90} \simeq 1.5$, in close agreement with those determined above.

To investigate the mass resolution of the technique, we show the predicted transition for two models of the mass composition in the 10^{13} eV to 10^{15} eV decades in Figure 1. Curve (B) has an energy dependent, fractional composition (p: α: CNO: 10 < Z < 20: Fe) of (40-15 log (E/TeV): 15: 15: 15: 15 + 15 log(E/TeV) %), and curve (A) of (45-2.5 log(E/TeV): 15: 15: 15: 10 + 2.5 log(E/TeV) %). These models, though simple, are chosen to represent extreme bounds on the contro-versial variation in compositon (see, for example refs. [10], [11]). The energy window for composition discrimination lies near 10^{14} eV, and a statistical precision of <3% is required to choose between models. We conclude that this technique only becomes attractive if the transition energy has been underestimated by ≳x 5; then a high

statistics experiment ($\sim$ 1 sr^{-1} s^{-1} for 1 year) could explore the less well known 10^{14}-10^{15} decade.

Future work will incorporate more reasonable field topologies within $5r_0$ to obtain the transition energy with greater precision.

4. Conclusions. The planned U.H.E γ-ray arrays can calibrate their directional resolution from observation of a cosmic ray shadow centered on the Moon. A solar shadow will also exist above $\sim 10^{15}$ eV/nucleus. Trajectory simulations within a first order approximation to the solar magnetic field indicate that this shadow is rapidly lost below $\sim$ Z x 10^{13} eV. Unless the directional resolution of arrays can be improved still further, or a substantial underestimate has been made in the transition energy, the possibility of distinguishing between composition models in the 10^{14}-10^{15} eV decade is remote.

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