Simulation of the Sun Shadow by Cosmic-Ray Particles Traveling through the Solar, Interplanetary and Geomagnetic Fields

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Abstract

A simulation of intensity deficit of galactic cosmic rays which arrive from the direction around the Moon and the Sun is performed in the TeV region to reproduce the observed results at Yangbajing in Tibet. Test particles are emitted from the earth through the dipole geomagnetic field and the interplanetary magnetic field (IMF) with Archimedes spirals and dipole solar magnetic field. Displacements of the observed shadow center at 3 TeV and 10 TeV in the quiet sun phase in 1996-1998 are well reproduced. But, the observed large displacement in the active sun phase in 1991-1993 has not been reproduced yet.

1 Introduction:

By the small air shower array constructed at Yangbajing (90.52° E, 30.11° N, 4300 m a.s.l, 606 gcm^{-2}) in Tibet in China in 1989, the intensity deficits of galactic cosmic rays at the direction of the Moon and the Sun, so called the moon and sun shadows, were observed in the energy region around 10 TeV. The sun shadow center is largely displaced by $\sim 0.7^\circ$ south-west from the apparent sun's center in 1990 $\sim$ 1992, although the moon shadow center is observed at $0.14^\circ \pm 0.01^\circ$ westwards just as expected by the geomagnetic effect.(Amenomori et al, 1993-1)

When the datasets are divided into the terms of away and toward sectors of the interplanetary magnetic fields (IMF), the sun shadows are splitted into two centers with a mutual distance of 0.34° along the direction from north-west to south-east. (Amenomori et al, 1993-2, 1996)

To understand these phenomena in terms of the effect of the global magnetic field of the Sun, IMF and geomagnetic field, we attempted to simulate the trajectories of cosmic-ray protons and helium nuclei by assuming some simplified conditions and to reproduce the moon and sun shadows.

2 Assumptions:

Magnetic fields concerned in this simulation are somewhat simplified and treated as follows.

First, the earth's magnetic field is represented by a dipole moment of $M_{\mathrm{E}} = 8.1 \times 10^{25}$ Gauss·cm^3. The site of the Tibet air shower array, Yangbajing, is located at the magnetic latitude of 22.11° and the magnetic declination is negligibly small there. The strength is 0.31 Gauss at the geomagnetic equator. Deformation of the geomagnetic field by the effect of solar wind, i.e., by IMF is neglected. The dipole field has a strength about 20 μGauss at a distance of 25 earth's radius on the equatorial plane. Of course, the Moon has no magnetic field.

Second, the solar magnetic field is also simply assumed to be a dipole field with the magnetic dipole moment of $M_{\mathrm{S}} = 1.7 \times 10^{32}$ Gauss·cm^3 in a range within about 10 solar radius. Then, the strengths are 1.0 Gauss at the polar surface and 0.50 Gauss at the equatorial surface of the Sun. The dipole axis is assumed same as the rotation axis of the Sun, i.e., perpendicular to the plane of the ecliptic.

Third, the IMF is assumed to be generated and stationarily maintained by the steady solar wind with a constant velocity of 450 km/s. The solar wind is assumed to spread two-dimensionally on the plane of the

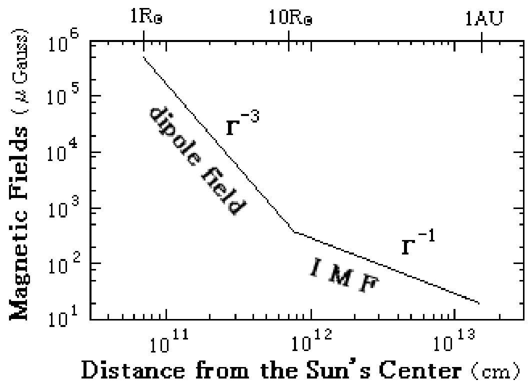

Figure 1: Strengths of the solar dipole magnetic field and IMF of Archimedes spirals as a function of distance from the sun's center. Their absolute values are assumed 0.50 Gauss at the solar equatorial surface and 20μGauss at the Earth's orbit.

ecliptic. Then its strength decreases proportionally to r^{-1} from the Sun and we choose a magnitude of 20 μGauss at the distance crossing the earth's orbit with crossing angle about 45°. Both the magnitude of solar dipole field and IMF is 400 μGauss at $r \simeq 10.8R_{\odot} \equiv 0.05$ AU as shown in Fig. 1, at which the magnetic field is switched from from the solar dipole one to the IMF, though the direction of line of force makes a jump.

On the other hand, the geomagnetic field has a strength of 20 μGauss at $r = 25R_{\rm E}$, which is the switching point of the magnetic field between the geomagnetic field and the IMF for the calculation of the sun shadow. For the simulation of the moon shadow only the geomagnetic field is taken into account, i.e., the IMF is neglected, because its effect is 10^{-2} times smaller than the geomagnetic effect for charged particles with energy larger than 1 TeV.

The IMF is assumed to have four sectors, two away and two toward sectors, which are axial symmetric on the plane of the ecliptic and they make Archimedes spirals as shown in Fig. 2 due to the rotation of the Sun.

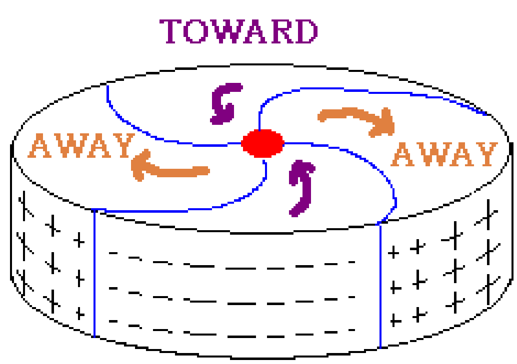

Figure 2: Two dimensional model of four sector IMF. The size of + or – implies strength of magnetic fields in the away and toward sectors, which are along the neutral sheets of Archimedes spirals.

The strength of IMF varies with azimuth angle ϕ as $B(r)$ sinϕ, where the amplitude $B(r)$ is π/2 times of the mean field strength. The maximum strength of the IMF, which is along the central curve between neighboring neutral sheets, is assumed to be, for example, $B(r) = 10\pi$ μGauss at r=1 AU. In this paper the three dimensional structure of the IMF such as waving of the neutral sheets is not taken into account.

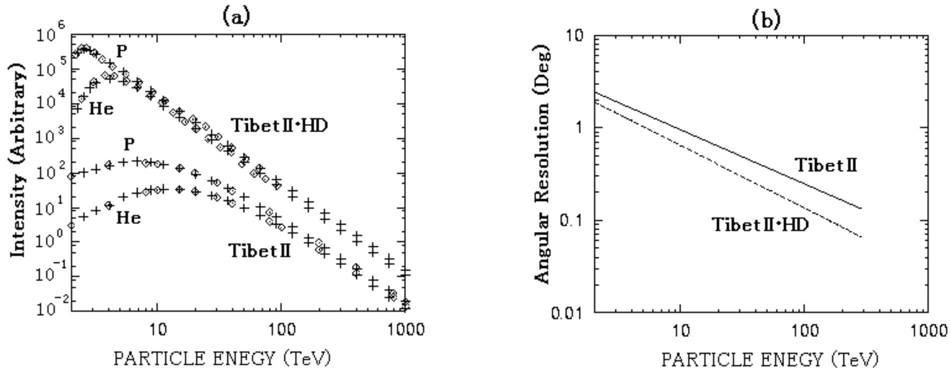

Figure 3: Used energy spectra of primary protons and heliums whose air showers are triggered by the Tibet II and Tibet II · HD arrays (a) and the used angular resolution for these arrays (b).

Trajectories of charged particles are calculated by emitting anti-charged particles from the earth in the wide angular range of $25° \times 25°$ in real angle around the Moon and the Sun. The calculation is stopped if it collides with the Moon and the Sun or travels past these objects. The emitted particles are protons and helium nuclei with "*minus charge*". The energy spectra and the angular resolutions are employed those of the simulation results for the Tibet II array and for the Tibet II · HD array both for the protons and the heliums with the arrival zenith angles within 50°, as shown in Fig. 3. The spectral indices are used -2.70 in the differential energy spectra for both primary protons and heliums in the $10 \sim 100$ TeV region. The intensity ratio of protons and heliums is used a factor 1.5 in such high energy region.

3 Results:

Particles with energy spectra given in Fig. 3(a) are emitted from the site at Yangbajing ($\simeq$ 90° E, $\simeq$ 30° N) to the Moon assumed to be fixed at the meridian on the equatorial plane. For the Sun fixed at the meridian on the equatorial plane these particles are emitted from the Earth's equator. The emitting angles of particles not colliding with the Moon and the Sun are plotted on the celestial map, in which these objects are fixed at its center, with probability distribution of two dimensional Gaussian of 50 % for the angular resolution shown in Fig. 3(b). First, figure 4 shows the moon shadow (a) and the sun shadow (b) for the Tibet II array in the 10 TeV region. Second, figure 5 shows those for the Tibet II · HD array in the 3 TeV region. Third, figure 6 shows the sun shadows when the earth is in the away (a) and toward (b) sectors for the Tibet II · HD array.

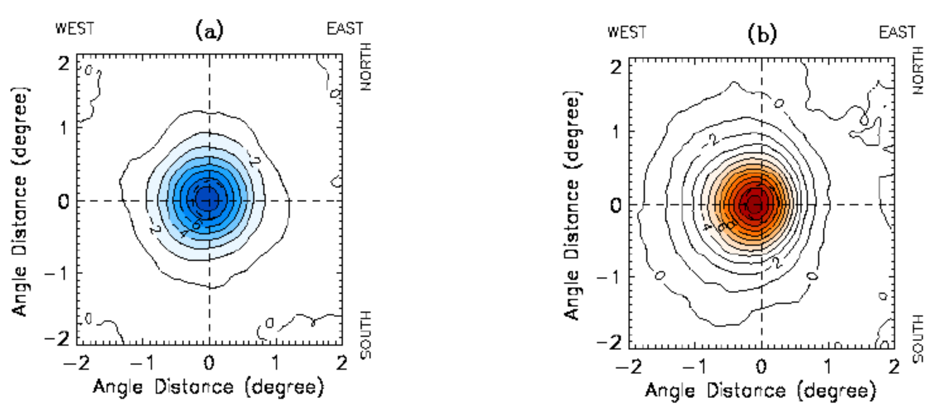

Figure 4: The moon (a) and the sun (b) shadows for the Tibet II array in the 10 TeV region.

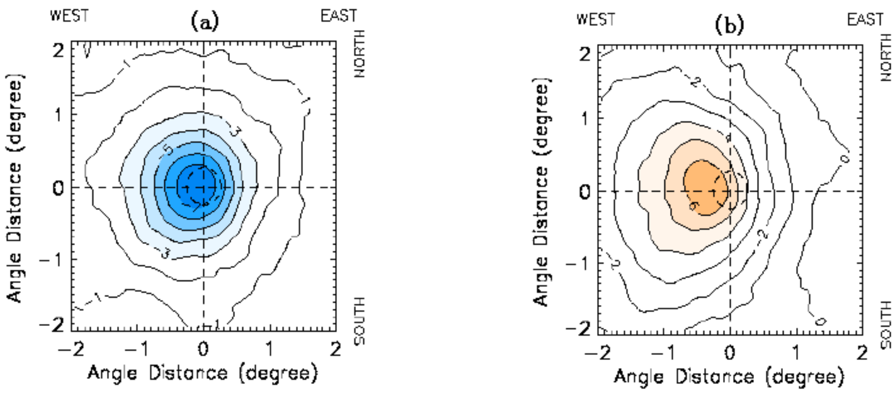

Figure 5: The moon (a) and the sun (b) shadows for the Tibet II · HD array in the 3 TeV region.

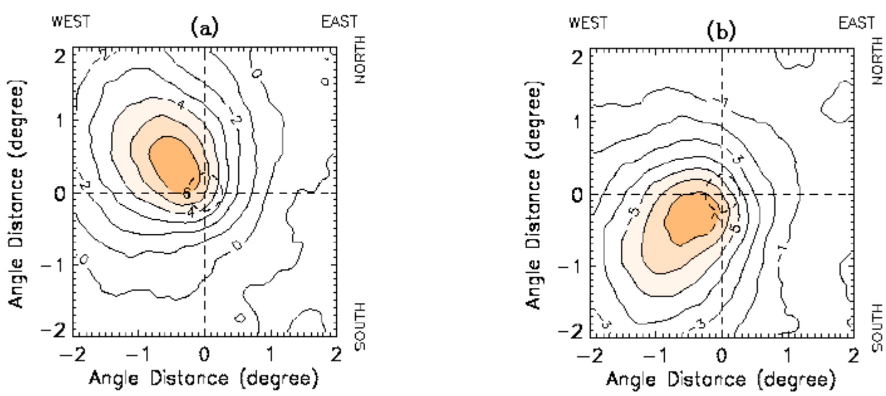

Figure 6: The sun shadows in the away (a) and the toward (b) sectors for the Tibet II · HD array.

The displacements of moon shadow's center are well consistent with the experimental results. The sun shadow's shift in the 10 TeV region is smaller than the experiment in active sun phase of 1990-1993 but consistent with the one in the quiet sun phase of 1996-1997.(Amenomori et al, 1997)

The sun shadows in the 3 TeV region are fitted by the maximum-likelihood method (Amenomori et al, 1993-1) with the angular resolutions given in Fig. 3(b). The displacement of $\sim 0.51^\circ$ westwards agrees with the expectation. Also the shifts of 0.69° and 0.68° along the north-south direction due to the away and toward fields are consistent with the expectation from the two dimensional solar wind assumed.

In order to compare with experiment in details the simulation should be done with three dimensional structure of the IMF and with different values of IMF strength and with air showers from the direction of the moving sun or moon in the sky.

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