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Solar magnetic field strength and the “Sun’s Shadow”

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The angular displacement of the center of the observed Sun's shadow from the center of the optical solar disc tells us the information of average solar magnetic field strength in the space between the Sun and the Earth. We analyze the displacement of the Sun's shadow observed in $5 \sim 240$ TeV cosmic-ray intensity with the Tibet-III air shower array during 10 years between 2000 and 2009, and compare with the MC simulations based on the coronal magnetic field model and Parker's spiral interplanetary magnetic field model. We find that the observed North-South displacement is significantly larger than the prediction of simulations. This result uniquely suggests the underestimation of the average field strength between the Sun and the Earth in our model. In this work, we will report the actual solar magnetic field strength evaluated from the observed Sun's shadow.

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1. Introduction

The Sun blocks cosmic rays arriving at the Earth from the direction of the Sun and casts a shadow called the Sun's shadow in the cosmic-ray intensity. Trajectories of cosmic rays which consisting of mostly protons and helium nuclei, are deflected by the magnetic field between the Sun and the Earth, depending on the magnetic field strength and the cosmic ray rigidity. The Tibet air shower (AS) experiment has successfully observed the Sun's shadow at 10 TeV energies and has confirmed, for the first time, the small but the measurable effect of the solar magnetic field on the shadow [1]. The observed intensity deficit in the Sun's shadow shows a clear 11-year variation decreasing with increasing solar activity. Our numerical simulations based on the coronal magnetic field model and the Parker's interplanetary magnetic field (IMF) model successfully reproduced the quantitative features of the observed shadow of the Sun. It is shown that, during the solar maximum period, cosmic rays passing near the solar limb are "scattered" by the strong and complicated coronal magnetic field and may appear from the direction of the optical disc reducing the intensity deficit of the Sun's shadow. On the other hands, the IMF between the Sun and the Earth also slightly deflects orbits of TeV cosmic rays. The ARGO-YBJ experiment reported that the observed North-South (N-S) displacement of the center of the Sun's shadow from the optical center of the Sun is consistent with the IMF strength observed at the Earth.[2] In this work, we analyze the angular displacement of the shadow's center observed by the Tibet AS array and quantitatively evaluate the IMF strength by comparing the observation with the detailed numerical simulations based on the potential field model (PFM) of the solar magnetic field.

2. experiment and MC simulation

We analyze the Sun's shadow observed in ten years between 2000 and 2009 by the Tibet-III AS array which has been operating at Yangbajing (4,300 m above sea level) in Tibet, China since late 1999 . The Tibet-III AS array consists of 789 scintillation detectors with a 7.5 m spacing, each with 0.5 m^2 detection area, covering a total detection area of 37,000 m^2 [3]. In this work, we divide the observed AS events into seven energy bins according to their shower size $\sum\rho_{FT}$ which is the sum of the number of particles per m^2 for each fast-timing (FT) detector, and is used as a measure of the energy of the primary cosmic rays. For $\sum\rho_{FT}$ we consider the intervals:$17.8 < \sum\rho_{FT} \leq 31.6$, $31.6 < \sum\rho_{FT} \leq 56.2$, $56.2 < \sum\rho_{FT} \leq 100$, $100 < \sum\rho_{FT} \leq 215$, $215 < \sum\rho_{FT} \leq 464$, $464 < \sum\rho_{FT} \leq 1000$, and $\sum\rho_{FT} > 1000$. The modal energies of primary cosmic rays corresponding to these energy bins are 4.9, 7.7, 13, 22, 43, 90 and 240 TeV, respectively, and the "window size" $\triangle d$, which is angular distance from ture direction including 68% events estimated by MC simulation and , are $2.0^\circ, 1.4^\circ, 0.9^\circ, 0.6^\circ, 0.4^\circ, 0.3^\circ$, and 0.2°, respectively. We select AS events to be analyzed under the following conditions; (i) any four-fold coincidence occurs in counters with each recording more than 1.25 particles in charge, (ii) the AS core position is located inside the array, (iii) the zenith angle of arrival direction is $\leq 40^\circ$.

For the analysis of the Sun's shadow, the number of on-source events (N_{on}) is defined as the number of AS events arriving from the direction within a circle of $\triangle d$ radius centered at a given point on the celestial sphere. The number of background or off-source events ($\langle N_{off} \rangle$) is calculated by averaging the number of events within each of the eight surrounding off-source windows which are located at the same zenith angle as the on-source window but apart in the azimuthal direction[3]. We then estimate the flux deficit relative to the number of background events as $D_{\rm obs} = (N_{\rm on} - \langle N_{\rm off}\rangle)/\langle N_{\rm off}\rangle$ at every 0.1° grid of the Geocentric Solar Ecliptic (GSE) longitude and latitude surrounding the optical center of the Sun. [1]

We assign the IMF sector polarity to each day referring to the daily mean GSE-x and GSE-y components of the IMF (B_x, B_y) observed by near the Earth satellites [4] and calculate the $D_{\rm obs}$ in "Away" and "Toward" sectors, separately. We assign "Away" ("Toward") sector polarity to a day when the IMF observed two days later satisfies $B_x < 0$ and $B_y > 0$ ($B_x > 0$ and $B_y < 0$). The sector polarity in the solar corona is carried out by the solar wind with an average velocity of $\sim$400 km/s and observed at the Earth about four days later. For our assignment of the IMF sector polarity to a day under consideration, therefore, we use the IMF data observed at the Earth two days later as an average along the Sun-Earth line on the day.

Figure 1 shows maps of $D_{\rm obs}$ at 13TeV in % in "Away" and "Toward" sectors, together with each projections on the vertical (North-South: N-S) and horizontal (East-West: E-W) axes. Using the method developed for our analyses of the Moon's shadow [3], we deduce the GSE latitude and longitude of the shadow's center, respectively from the best-fitting to the N-S and E-W projections. In Figure 1, the shadow's center clearly deviates from the optical center of the Sun at the origin of the map. It is also clearly seen that the shadow center deviates northward (southward) in the "Away" ("Toward") IMF sector, as expected from the deflection of cosmic-ray orbits in the average positive (negative) B_y along the Sun-Earth line.

For the comparison with the observed Sun's shadow, we have carried out detailed Monte Carlo (MC) simulations based on the solar magnetic field model, tracing orbits of anti-particles shot back from the Earth to the Sun in the model magnetic field between the Sun and the Earth [1]. In this work, we use the potential field model (PFM) for the coronal magnetic field called the current sheet source surface (CSSS) model [5], the simple Parker's model for the IMF [6] and a stable dipole field for the geomagnetic field. The CSSS model involves three free parameters, the radius $R_{\rm ss}$ of the spherical source surface (SS), the radius $R_{cp}(< R_{\rm ss})$ of the spherical surface where the magnetic cusp structure in the helmet streamers appears, and the length scale l_a of the horizontal electric currents in the corona. In our simulations, we set $R_{\rm ss}$, $R_{\rm cp}$ and l_a to 10.0, 1.7 and 1.0 solar radii ($10.0R_\odot$, $1.7R_\odot$ and $1.0R_\odot$), respectively. For more detail information of our MC simulation, readers can refer to Amenomori *et al* 2013.

3. result and discussion

In Figure2, we plot the observed and simulated N-S displacement angles as a function of the rigidity R. It is seen that the observed displacement angles displayed by black solid circles are reasonably well fitted by a function $\alpha/(R/10\rm TV)$ of R in TV with a fitting parameter α denoting the displacement angle at 10 TV. The magnitudes of the simulated displacement angles (green squares and green curve), however, are significantly smaller than the observations, indicating that our model underestimates the averaged IMF strength between the Sun and the Earth. In order to evaluate this underestimation quantitatively, we simply multiply the simulated solar magnetic field strength by a constant factor f everywhere in the space outside the geomagnetic field and carry out four simulations with f set to 0.7, 1.0, 1.5 and 3.0. From Figure2, we find that the averaged IMF strength between the Sun and the Earth estimated from the observed displacements of the Sun's shadow is about 1.5 times larger than the prediction by the PFM model in both of "Away" and "Toward" sectors. This is also confirmed by the comparison between the IMF strength observed near the Earth and the prediction by the PFM model.

4. conclusion

We find that the averaged IMF strength between the Sun and the Earth estimated from the observed displacements of the Sun's shadow are about 1.5 times larger than the prediction by the PFM model. The Sun's shadow observed by the Tibet AS array offers a powerful tool for the quantitative evaluation of the average solar magnetic field.

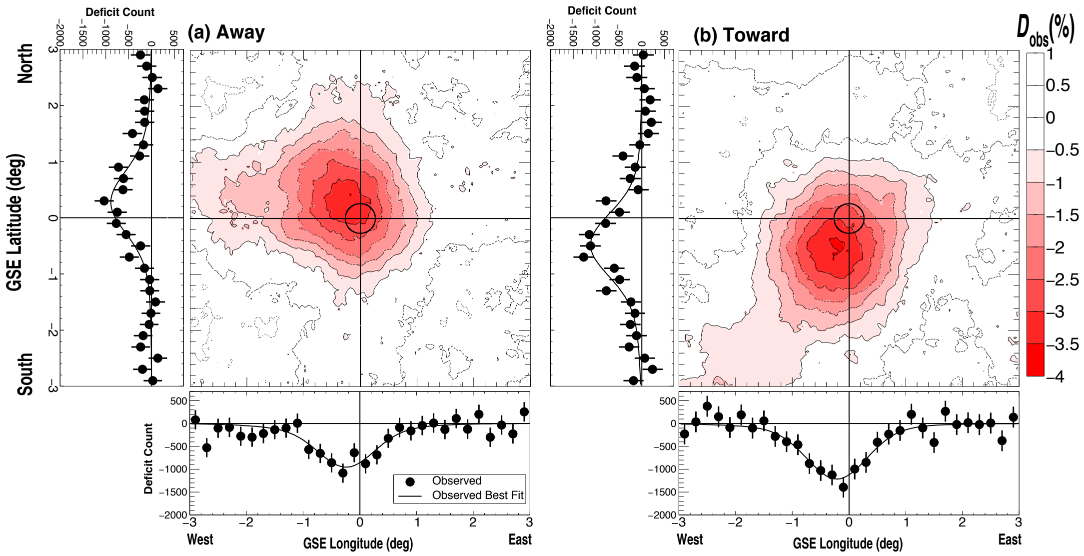

Figure 1: Two dimensional maps of D_{obs} in "Away" (left) and "Toward" (right) IMF sectors in 2000-2009 each as a function of the GSE-longitude and latitude. Each panel shows two dimensional contour of D_{obs} deduced from AS events with $56.2 < \sum \rho_{FT} \leq 100$ corresponding to the modal primary energy of 13 TeV. In this figure, we used the optimized smoothing window with a 0.9° radius. In each panel, a small circle centered on the origin shows the optical solar disc. The projections of D_{obs} on the horizontal and vertical axes are also attached to each panel.

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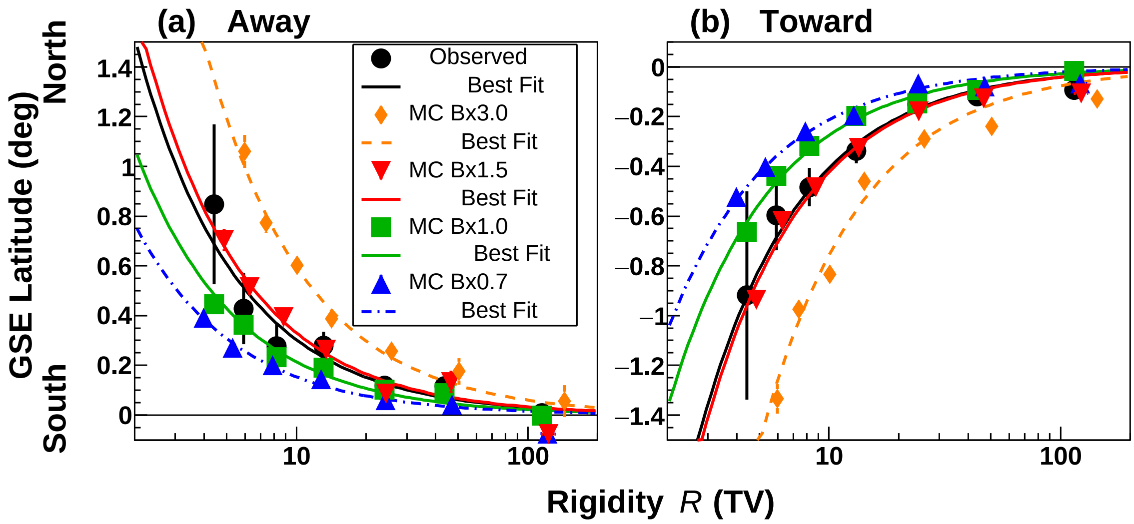

Figure 2: The rigidity dependence angles of the N-S displacements in "Away" (left) and "Toward" (right) IMF sectors. Black circles in each panel show the observed displacements as a function of the rigidity (R) on the horizontal axis, while blue triangles, green squares, red inverted triangles and orange diamonds show simulated displacements with the multiplication factors (f) of the simulated magnetic field strength, 0.7,1.0, 1.5 and 3.0, respectively (see text). The functions of $\alpha/(R/10\text{TV})$ best-fitting to black, blue, green, red and orange data points are also displayed by curves with the corresponding colors.

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