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Sun's Shadow in the Solar Cycle 23 Observed with the Tibet Air Shower Array and Comparison with Simulation Studies

THE TIBET ASγ COLLABORATION

Abstract: The solar activity in Cycle 23 gradually changes to the final minimum phase. The Sun's shadow generated by multi-TeV cosmic-ray particles has been continuously observed with the Tibet-II and Tibet-III air shower array since 1996 covering almost the whole period of Solar Cycle 23 from 1996 to 2005. We have shown that the Sun's shadow is strongly affected by the solar and interplanetary magnetic fields changing with the solar activity in the previous papers. In this paper, we present yearly variation of the Sun's shadow in association with the Solar Cycle 23. Additionally, we discuss comparison between observation result and simulation result of Sun's shadow using the Radial Field model.

Introduction

The Tibet air shower array for the first time observed the displacement of Sun's shadow in the 10-TeV cosmic ray flux obtained by a two-dimensional analysis method [1], using the 1991-1992 data. We have shown that the Sun's shadow is strongly affected by the solar and interplanetary magnetic fields changing with the solar activity [2, 3]. Furthermore, we have reported the result on the variation of the Sun's shadow in association with the Gnevyshev gap (GG)[4, 5] appeared in the maximum phase around 2001 of Solar Cycle 23. Solar Cycle 23 is gradually declining from peak state to predicted minimum phase around 2007 and shifting to the next cycle 24.

It is known that the interplanetary magnetic field (IMF) is formed as a result of the transport of the photospheric magnetic field(PMF) by the solar wind flowing continuously from the Sun (Parker 1963). The position and density of the Sun's shadow produced in charged cosmic-rays are affected by each magnetic field of PMF, coronal magnetic field (CMF) and IMF. The CMF is unable to make a direct measurement by ground-based observation. Therefore various methods have been developed to extrapolate the PMF for the construction of the three- dimensional structure of CMF. Hakamada [6] developed a simple method to compute spherical harmonic coefficient for the potential model of the CMF from a direct observation data of PMF. We use this Radial Field model (RF-model) to compute CMF within 1.0 to 2.5 solar radii. In this model, CMF has only radial component at Source Surface (2.5 solar radii). Therefore the Parker Spiral field model of IMF is smoothly connected to RF-model at Source Surface. Using these models, we simulate the Sun's shadow to compare them with the observation result from 1996 to 2005 during solar minimum to maximum and decreasing phase of Solar Cycle 23.

Observation with the Tibet air shower array

The effective area of the Tibet array has been gradually enlarged, by several steps, to larger and higher-density ones by adding the same-type plastic scintillation detectors to the preceding Tibet-I and II(HD) arrays. The Tibet-III array, as of late in 1999, is consisting of 533 detectors in a lattice pattern of 7.5 m spacing with the area of 22000 m^2. Furthermore, the full-scale Tibet-III with 761 fast timing (FT) detectors covering the effective area of 36900 m^2 has been operating since November 2003. This array detects air shower events in the energy region above a few TeV with frequency of

1.7 kHz, about 85 times higher than the Tibet-I array[7].

Hence, we can obtain a sufficient number of events to study the annual variations of the position of the Sun's shadow center against the apparent Sun's center on the cosmic-ray intensity map. In the analysis of the Sun's shadow we do not use the data obtained from September to February, because they correspond to higher primary cosmic-ray energy due to inclined showers in winter with much less event frequency and also with less displacement of the Sun's shadow center. So, those data are inadequate both in statistics and in energy for the purpose of this paper. The Sun's shadow analysis is possible in the 10 TeV region for all observation period after 1996, but available in the 3 TeV region only after 1997 using Tibet-IIHD and Tibet-III array.

Observation Results

Figure 1 shows the annual variations of the Sun's shadow in the 10 TeV region around the minimum phase (1996, 1997), increasing phase (1998, 1999) maximum phase (2000, 2001, 2002) and in the decreasing phase (2003, 2004, 2005) in Solar Cycle 23 observed with the Tibet-II and Tibet-III pixel skipping array with 15 m detector spacing. This figure shows that the solar activity close to the quiet phase in the 2005 data. In this figure, the Sun's shadow around the maximum phase can be seen in the 2001 data, but seen in neither of the 2000 and 2002 data. It is difficult to show a similar map in the 3 TeV region because of space limit of this paper. The tendency is prominent in the 3 TeV region. It is interesting that the influence of GG is appeared on the Sun's shadow remarkably in the 3 TeV region[8, 9].

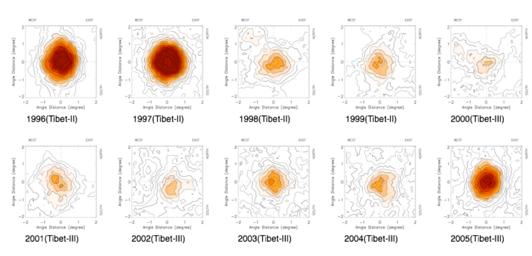

Figure 1: Annual variation of the Sun's shadow in the 10 TeV region observed with the Tibet array in 1996 - 2005.

Simulation

We have shown that both the solar magnetic field and the IMF influence on the Sun's shadow in the multi-TeV region, in addition to the geomagnetic field (GMF). And we have also shown that there is a strong correlation between solar activity and significance of the Sun's shadow[8]. It is difficult quantitatively analyze without a simulation study which takes into account the CMF, IMF and GMF components.

Simulation Condition

The CMF is estimated using RF-model by Hakamada[6] as described in the introduction. We calculate using up to 30 orders of spherical harmonic coefficients for the potential model of the CMF. We use these estimated CMF from 1.0 solar radius to 2.5 solar radii. The CMF is smoothly connected to Paker Spiral IMF at source surface (2.5 solar radius). The structure of IMF is calculated using the solar wind velocity based on an interplanetary scintillation observation by the Nagoya University group[10].

Other simulation conditions are summarized below.

- Air Showers are generated along the Sun's orbit. Their primary cosmic-ray composition is based on direct observation data.
- Anti-particles are shot back to the Sun.
- The track of the anti-particle is calculated in the magnetic fields. (CMF, IMF, GMF)
- The events hitting the Sun make the Sun's shadow.
- Air Showers generated by CORSIKA ver 6.200 (QGSJET) and detector simulation is made using Epics uv8.00
- Calculation is done for the period from March to August each year to match the observation condition.

Figure 2 demonstrates example of simulation results in 1996 (Solar Minimum) and 2000 (Solar

Maximum) with the observation results. Each simulation is consistent with the corresponding observation result.

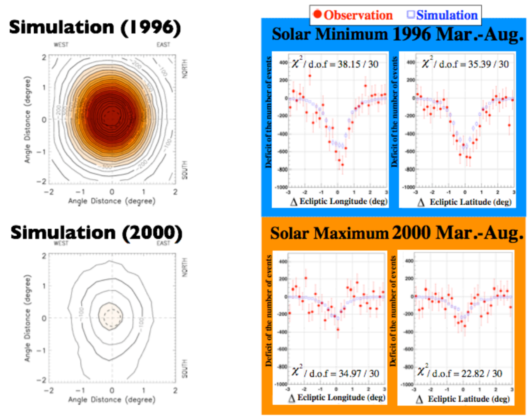

Figure 2: Simulation results for 1996 (Solar Minimum) and 2000 (Solar Maximum) with Observation results. Left side maps shows the event density around the apparent solar position. Right side figures show deficit in number of events along ecliptic longitude and ecliptic latitude.

Simulation Results

Figure 3 shows yearly sunspots number vs. deficit event number of events around the Sun's shadow within 3 degrees. This figure shows that the simulation results are in good agreement with the observation results.

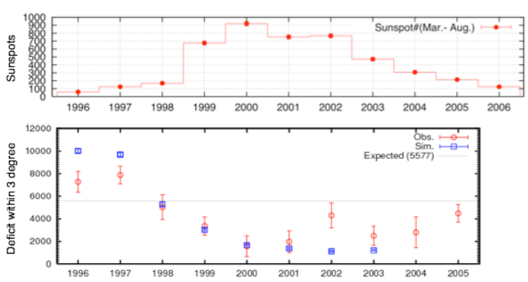

Figure 3: Yearly sunspots number vs. number of deficit events Sun's shadow within 3 degrees (10 TeV) for simulation results and observation results, respectively.

In order to separate the effect of the CMF component and that of the IMF component, we make a hypothetical simulation omitting CMF. Figure 4 shows the ratio of number of deficit events to the expected from the apparent solar solid angle (0.5° in diameter) assuming (1) simulation with CMF, IMF and GMF, (2) simulation with IMF and GMF and (3) observation results, respectively. These results imply that CMF has the dispersion effect on the deficit in the Sun's shadow. The dispersion effect is estimated to be about 45% in the quiet phase and 30% in the active phase. The quiet phase (1996, 1997) shows a different status from the active phase (1999 - 2003). In the quiet phase the deficit is larger than the expected. Furthermore, this result implies IMF has the conversion effect in the quiet phase. The conversion effect is estimated to be about 230% in quiet phase. IMF in active phase has the dispersion effect of about 55%.

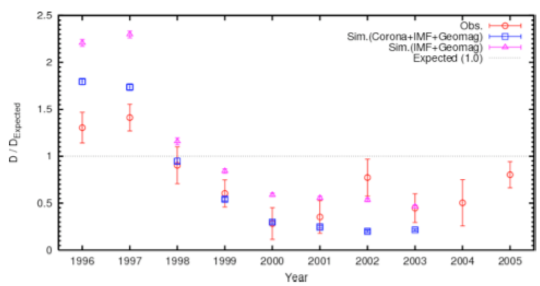

Figure 4: Ratio of the number of deficit events to expected from the apparent solar solid angle (~0.5° in diameter), assuming (1) simulation with CMF, IMF and GMF, (2) simulation with IMF and GMF and (3) observation results, respectively.

Conclusions

We update our observation result to 2005, together with a simulation result taking into account CME, IMF and GMF. The observed number of deficit events is in good agreement with the simulation. The simulation indicates the following results. A negative correlation is found between the Sun's shadow and the solar activity. In the quiet phase, the deficit is larger than the expected. In the active phase, the deficit is less than the expected. Therefor,the CMF has the dispersion effect. The magnitude is larger in the active phase than in the quiet phase. The IMF has the convergence effect in the active phase.

This is the first simulation trial taking into account detailed magnetic field structure. We plan to make a more detailed simulation study for comparing with observation results.

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