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X. R. Meng, K. Mizutani, J. Mu, H. Nanjo, M. Nishizawa,
M. Ohnishi, I. Ohta, T. Ouchi, J. R. Ren, To. Saito,
M. Sakata, Z. Z. Shi, M. Shibata, A. Shiomi, T. Shirai,
H. Sugimoto, K. Taira, Y. H. Tan, N. Tateyama, S. Torii,
H. Wang, Y. Yamamoto, G. C. Yu, P. Yuan, T. Yuda,
C. S. Zhang, H. M. Zhang, Zhasang, Zhaxiciren and
W. D. Zhou

(Tibet ASγ Collaboration)

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INSTITUTE FOR COSMIC RAY RESEARCH
UNIVERSITY OF TOKYO
3-2-1 Midori-cho, Tanashi, Tokyo 188, Japan

SHADOWING OF COSMIC RAYS BY THE SUN NEAR MAXIMUM OR AT THE DECLINING PHASE OF SOLAR ACTIVITY

M. Amenomori[1], B. Z. Dai [2], L. K. Ding[3], Z. Y. Feng [4], K. Hibino[5], N. Hotta[6], Q. Huang[4], A. X. Huo[3], H. Y. Jia[4], F. Kajino[7], K. Kasahara[5], Labaciren[8], S. M. Liu[3], D. M. Mei[8], L. Meng[3], X. R. Meng[8], K. Mizutani[9], J. Mu[2], H. Nanjo[1], M. Nishizawa[10], M. Ohnishi[11], I. Ohta[6], T. Ouchi[11], J. R. Ren[3], To. Saito[12], M. Sakata[7], Z. Z. Shi[3], M. Shibata[13], A. Shiomi[9], T. Shirai[5], H. Sugimoto[14], K. Taira[14], Y. H. Tan[3], N. Tateyama[5], S. Torii[5], H. Wang[3], Y. Yamamoto[7], G. C. Yu[4], P. Yuan[3], T. Yuda[11], C. S. Zhang[3,11], H. M. Zhang[3], Zhasang[8], Zhaxiciren[8], and W. D. Zhou[2]
(The Tibet ASγ Collaboration)

ABSTRACT

The shadows of the Sun and Moon have been detected in the 10 TeV cosmic ray flux by the Tibet air shower array at an altitude of 4300 m above sea level. The observation covers the period 1990 June to 1993 October, which almost coincides with a near maximum and decreasing phase of the latest solar activity

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[1] Department of Physics, Hirosaki University, Hirosaki 036, Japan

[2] Department of Physics, Yunnan University, Kunming 650091, China

[3] Institute of High Energy Physics, Academia Sinica, Beijing 100039, China

[4] Department of Physics, South West Jiaotong University, Chengdu 610031, China

[5] Faculty of Engineering, Kanagawa University, Yokohama 221, Japan

[6] Faculty of Education, Utsunomiya University, Utsunomiya 321, Japan

[7] Department of Physics, Konan University, Kobe 658, Japan

[8] Department of Mathematics and Physics, Tibet University, Lhasa 850000, China

[9] Department of Physics, Saitama University, Urawa 338, Japan

[10] National Center for Science Information Systems, Tokyo 112, Japan

[11] Institute for Cosmic Ray Research, University of Tokyo, Tanashi 188, Japan

[12] Tokyo Metropolitan College of Aeronautical Engineering, Tokyo 116, Japan

[13] Faculty of Education, Yokohama National University, Yokohama 240, Japan

[14] Shonan Institute of Technology, Fujisawa 251, Japan

cycle. Using the data obtained in this period, we examined a yearly variation of the Sun's shadow, and found for the first time that the position of the Sun's shadow considerably changed every year with the phase of the solar activity. A different variation of the Sun's shadow was also found between the "away" and "toward" sectors of the interplanetary magnetic field. These results seem to suggest a causal relation between the shadow's movement and the changing inclination of the heliospheric current sheet of the large-scale magnetic field. Further observation with higher statistics will provide a new clue to obtain direct information on the relation between a time variation of the large-scale structure of the solar and interplanetary magnetic fields and the phase of solar activity cycle.

Subject headings: cosmic rays – solar-terrestrial relations – solar wind – magnetic fields

1. INTRODUCTION

Almost all the cosmic rays are charged and propagate through interplanetary space while arriving to the Earth. Therefore, these particles will measurably bend under the influence of the magnetic fields in this space, if their energies are the order of 10 TeV or lower. It is known that the interplanetary magnetic field (IMF) is formed as a result of the transport of the photospheric magnetic field by the solar wind flowing continuously from the Sun. The IMF has a sector structure with the field direction reversing across the sector boundary (Wilcox & Ness 1965) so that the magnetic field points inward in some sectors and outward in others. This sector structure observed in the IMF may be interpreted in terms of an equatorial current sheet that is tilted with respect to the heliographic equator (Svalgaard & Wilcox 1978; Jokipii & Thomas 1981), and could equally well be accounted for if the basic north-south polarity of the solar magnetic field is maintained and, in addition, the neutral sheet separating the two regions is inclined to the plane of the ecliptic. The observed two-sector IMF pattern is interpreted as the result of a tilted solar magnetic dipole and the four-sector pattern as the result of a warp in the neutral sheet due to a quadrupole contribution to the solar magnetic field (Svalgaard & Wilcox 1978 ; Saito & Swinson 1986). This sector structure, however, would vary with the phase of the solar activity cycle. With increased solar activity, the number and the activity of solar active regions tend to increase and these active regions strongly disturb the configuration of the photospheric magnetic field, so that the sector structure of IMF may be highly modified. The IMF will exert an influence on incoming cosmic rays which will eventually be detected at the Earth. In particular, high energy cosmic rays will bring a direct information on the three dimensional structure of the IMF under the influence of the solar activity (Amenomori et al. 1994).

The Tibet air shower array (Amenomori et al. 1992 ; Amenomori et al. 1993), which has been successfully operated from January of 1990, has a good angular resolution, better than 1° at 10 TeV energies. The site is located at an altitude of 4300 m above sea level in Tibet (90°.53 E and 30°.11 N). Using the data taken by this array, we examined for the first time the effect of the IMF on the Sun's cosmic-ray shadow. We concluded that this field has a fairly strong influence on the displacement of the Sun's shadow (Amenomori et al. 1994). It is also interesting to note that the solar activity was in a transition state from near its maximum to a decreasing phase when our observation was continued. Therefore, the Sun's shadow should have varied every year according to a large-scale change of the solar and interplanetary magnetic fields in this period. We examine this effect in this paper.

2. EVENT SELECTION

The Tibet air shower array consists of 45 fast-timing (FT) scintillation detectors which are placed in a lattice with a spacing 15 m. This FT-array is also surrounded by 20 density detectors to obtain a good core location for each event. The system had operated at a rate of about 20 Hz under any four-fold coincidence in the FT-array from 1990 June to 1992 September, and then the trigger rate had been changed to about 40 Hz from 1992 October under any three-fold coincidence. This first phase experiment, however, was stopped in 1993 October to construct a new Tibet-II array. Thus, in this analysis, we used the data set recorded during the period from 1990 June through 1993 October.

The event selection was made as in our previous analysis (Amenomori et al. 1993 ; Amenomori et al. 1994). Among 4.5×10^8 events thus selected, used for the present analysis are the subsets of 2.07×10^6 events for the Moon and 2.77×10^6 events for the Sun around 8° and with the zenith angle less than 50°, respectively. A coordinate system was fixed on the object, putting the origin of coordinates on its center. The position of each event observed is then specified by the angular distance θ and the position angle ϕ, where θ and ϕ are measured from the center and from the north direction, respectively. In the following, we chose the equatorial coordinates for the Moon and the ecliptic coordinates for the Sun, respectively. The event distributions plotted in these coordinate systems are used to examine the shadowing of cosmic rays by these objects (Amenomori et al. 1993 ; Amenomori et al. 1994).

3. ARRAY PERFORMANCE AND GEOMAGNETIC EFFECT

The angular resolution of our array and the array performance are well examined by observing the Moon's shadow. Making the equidensity map of cosmic ray particles around the Moon (Amenomori et al. 1992 ; Amenomori et al. 1993), we estimated the angular resolution of our array to be $0^\circ.85^{+0^\circ.08}_{-0^\circ.07}$ with a significance of 8.9σ for all events. The maximum deficit position of the shadow profile is found at $0^\circ.12 \pm 0^\circ.07$ to the west and $0^\circ.00 \pm 0^\circ.07$ to the south when the angular resolution of the array is assumed to be $0^\circ.85$. The mean energy of primary cosmic rays responsible for generating air showers detected by our array is estimated to be about 11 TeV under the selection conditions described in Sec. 2. The deflection angle of a charged particle impinging on the Earth in the normal direction can be estimated by evaluating $< BL >= \int_a^\infty B dl$, where B is the geomagnetic field strength and a is the radius of the Earth. Under the dipole field approximation, the value $< BL >_{geomag}$ is calculated to be 100 T·m. Then, 11 TeV protons are bent to the west by about $0^\circ.15$ in the geomagnetic field, and so the observed displacement of the Moon's shadow is comparable to that expected from this effect. It should also be noted that there is no displacement in the north-south direction. Thus, the systematic error of our array is shown to be quite small, so that this result can be used as reference standards in the following analysis.

4. SUN'S SHADOW

We show the contour map of the deficit event densities around the Sun in Figure 1 for all events. The maximum likelihood analysis shows that the most probable position of the center of the deficit is at $0^\circ.61 \pm 0^\circ.10$ to the west and $0^\circ.32 \pm 0^\circ.17$ to the south, where the deficit events around the Sun's shadow are assumed to be distributed according to a Gaussian-type function giving the angular resolution of $1^\circ.1$. The logarithm of likelihood is calculated to be 16.2 at this position. The significance of the maximum event deficit is then calculated to be 5.7σ. A large displacement of the shadow from the apparent position of the Sun seen in Figure 1 could be explained by the effect of the solar and interplanetary magnetic fields (Amenomori et al. 1994). More direct information on the IMF may be obtained by examining changes of the Sun's shadow as a function of the phase of the solar activity, since this is strongly related to a change of the IMF structure. We study this in the following section.

5. YEARLY VARIATION OF THE SUN'S SHADOW

As is well known, the configuration of the solar and interplanetary magnetic fields changes considerably with solar cycle. In the latest solar cycle, the Sun was a high state (at or near maximum) during the period from 1989 through the middle of 1991 and then gradually turned to the declining phase. At that time, the solar magnetic field had large deviations from a pure dipole, i.e., a small dipole moment with large contributions from higher multi-poles, and the dipole field axis was almost sideways especially in the period from 1990 to 1991 just after the reversal of the polar fields (NOAA/USAF 1990-1993). The largest inclination (67°) of the neutral sheet, which separates the porality of the IMF, occurred around the middle of 1991, and also large solar flares were sometimes observed at that time. It is thus expected that large-scale changes of the solar and interplanetary magnetic fields may have occurred every year during this period, following the variation of solar activity.

It is very important that our array had operated almost continuously during the period between 1990 June and 1993 October just when the solar activity was near maximum or rather at the declining phase. As discussed in a previous paper (Amenomori et al. 1994), cosmic ray particles at energies of 10 TeV propagating through interplanetary space may give a direct information about the large-scale variation of the IMF. We then examined a yearly variation of the Sun's shadow based on our data set. For this, the data set was divided into four sub-data sets : 1990 June - 1990 October (4.9×10^5 events), 1991 April - 1991 October (7.3×10^5 events), 1992 March - 1992 July (7.3×10^5 events) and 1993 March - 1993 October (8.2×10^5 events). The shower data obtained in winter seasons are omitted because of their large zenith angles. Statistics of the data taken in 1990 are somewhat poor because full data taking started from the end of 1990 June ; thus the data should be used only for reference in the following.

Figure 2 shows the contour maps of the shadow profile of the Sun for every year. We can see that the Sun's shadow noticeably changed its position from one place to another in this period, while being always away from the apparent position of the Sun. That is, changes of the Sun's shadow seem to occur rather abruptly with the solar cycle. More interesting is the fact that the shadow considerably changed its position every year, especially in the north-south direction, while keeping away from the Sun to the west by about 0°.4 in the east-west direction (This is much larger than the geomagnetic deflection of about 0°.12). This suggests that the Sun's shadow is strongly affected by the IMF, which would vary with the solar activity as discussed above.

We examined separately a yearly variation of the shadow in the "away" and "toward" sectors. As discussed in Sec.1, the solar and interplanetary magnetic fields are highly modified near maximum or at the declining phase. During the declining phase, however, the IMF sector structure simplifies and becomes rather stable (Hoeksema 1986). Actually, according to the Solar Geophysical Data (NOAA/USAF 1990-1993), the IMF had almost the two-sector configuration in the period from 1990 through the beginning of 1992 and then gradually changed into the four-sector with mincing steps. The IMF kept almost four sectors between 1993 April and October. Figures 3 and 4 show yearly variations of the Sun's shadows by cosmic rays propagating through the "away" and "toward" sectors, respectively. Although the shadows observed are somewhat indistinct mainly because of poor statistics, different behavior can be seen in the movement of the shadow between the "away" and "toward" sectors, and the following features are remarkable :

1) During this period the Sun's shadows observed every year in both the "away" and "toward" sectors always kept away from the Sun to the west by about $0^\circ.2$-$0^\circ.3$ (after removing the geomagnetic displacement). This means that in every year from 1990 through 1993 there was a certain magnetic filed component directing toward the solar northern hemisphere to make the Sun's shadow shift to the west, almost independently of the polarity of the sector field. From this, we find that the value $< BL >_{solar}$ making the shadow shift to the west is 1.5-2.5 times as large as that for the geomagnetic field, where the effective path length L is essentially same as the distance between the Sun and the Earth, i.e., 1 AU $= 1.5 \times 10^{11}$ m.

2) A large variation of the shadow's position was observed in the "toward" sector every year, especially in the period from 1991 to 1992, while its variation was rather small and stable in the "away" sector. That is, the position of the shadow in the "toward" sector moved south-northward by about 1° in the period 1991-1992. It is interesting to note that this period was almost in the stage of transition of the solar activity from near maximum to a declining phase, while keeping the two sector configuration with a large inclination of the neutral sheet.

It is known that the IMF near the Earth is almost parallel to the ecliptic plane and has an Archimedian spiral configuration (Parker 1963). The azimuthal component of this Parker field becomes dominant at a large distance from the Sun (the field strength decreases inverse proportion to the distance and takes the value of about 2 nT near the orbit of the Earth.), and this field will make the shadow shift to the north in the "away" sector and to the south in the "toward" sector. It is also observed that the field strength near the Earth is rather stable even in an active phase of the solar cycle (Wilcox & Ness 1965). We can, however, expect that an abrupt change of the field configuration would occur in the vicinity of the Sun when the Sun is in an active phase. Major qualitative features of such field modulation, for example, can possibly be explained by the combination of the changing inclination of the neutral current sheet and the reversal in polarity of the large-scale magnetic field (Svalgaard & Wilcox 1978 ; Saito & Swinson 1986). Although we cannot go into details using the present data, a different movement of the shadow observed in the "away" and "toward" sectors could be attributed to the effect of a large-scale disordered field configuration produced by such a scenario. From this point of view, it is interesting and important to observe the Sun's shadow in a quiet phase of the solar cycle. The observation with higher statistics will be done with the new Tibet array in the very near future.

6. SUMMARY

Using the data obtained during the period from 1990 through 1993 with the Tibet air shower array, we examined a yearly variation of the cosmic ray Sun's shadow in this period. We observed a significant deviation of each shadow from its expected position every year, and concluded that the observed changes of the shadow during this period were possibly produced by a yearly variation of solar activity. In particular, a different movement of the shadow observed in the "away" and "toward" sectors would be caused by the effect of varying waviness of the current sheet of the large-scale magnetic field which divides the heliosphere into two hemispheres containing oppositely directed fields. In short, the results obtained suggest that a time variation of the Sun's shadow is directly sensitive to and is organized by the IMF and its neutral sheet. We expect that further observation with more statistics will provide a new clue to study a three-dimensional configuration of the solar and interplanetary magnetic fields under the influence of the solar activity.

The solar cycle is now in a quiet phase, but will go toward the next active phase starting from about the year 2000. The new Tibet II array has been fully operative since 1995 October, with the effective area being about 7 times as large as the old one, and this allows us to observe a variation of the Sun's shadow every 2-3 months. New information about how the solar and interplanetary magnetic field structure changes with the phase of the solar activity cycle may contribute considerably to the study of solar terrestrial physics.

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Figure Captions

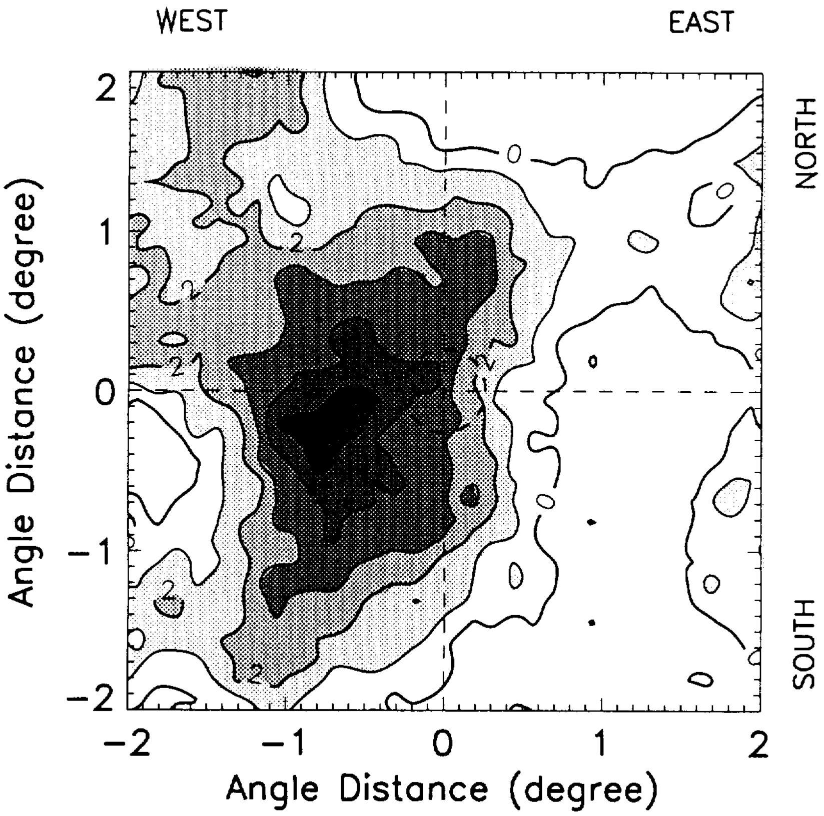
Fig. 1.— Contour map of the weights of deficit event densities around the Sun in the area of 4° × 4° centered on the Sun (*dotted circle*). The contour lines are drawn from a level of no deficit, 0σ, with a step of 1σ.

Fig. 2.— Yearly variation of the Sun's shadow in the period from 1990 through 1993.

Fig. 3.— Yearly variation of the Sun's shadow in the "away" sector between 1990 and 1993.

Fig. 4.— Yearly variation of the Sun's shadow in the "toward" sector between 1990 and 1993.

Fig. 1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EAST
NORTH
SOUTH
Angle Distance (degree)
Angle Distance (degree)
2
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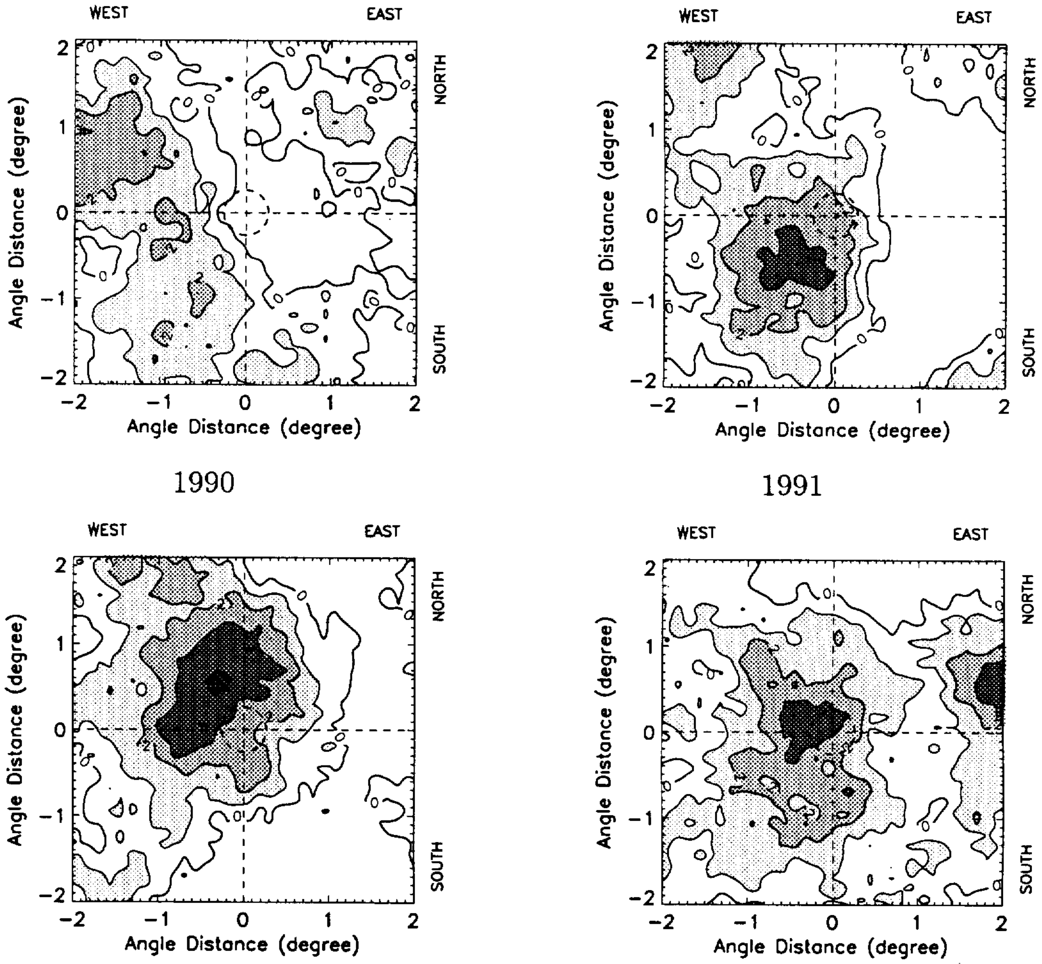
Fig. 2



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1991

1992

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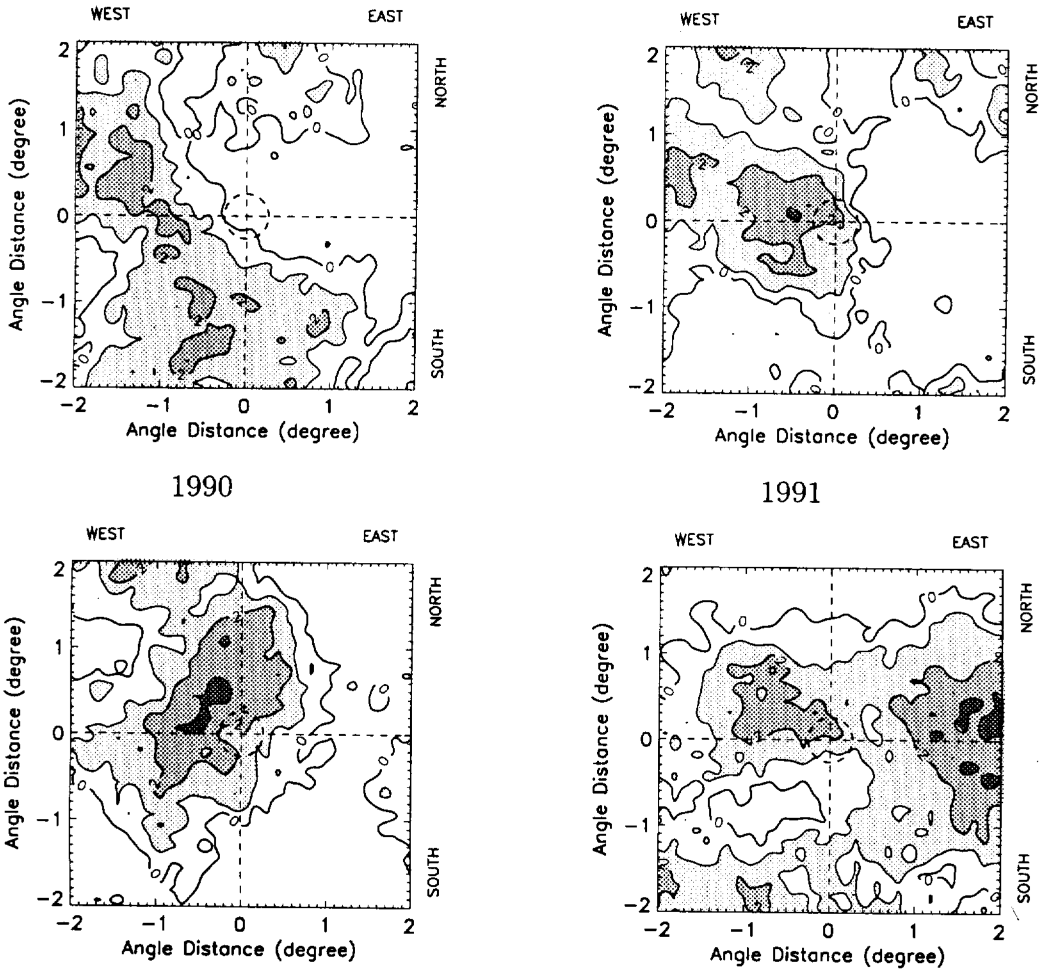
Fig. 3



1990

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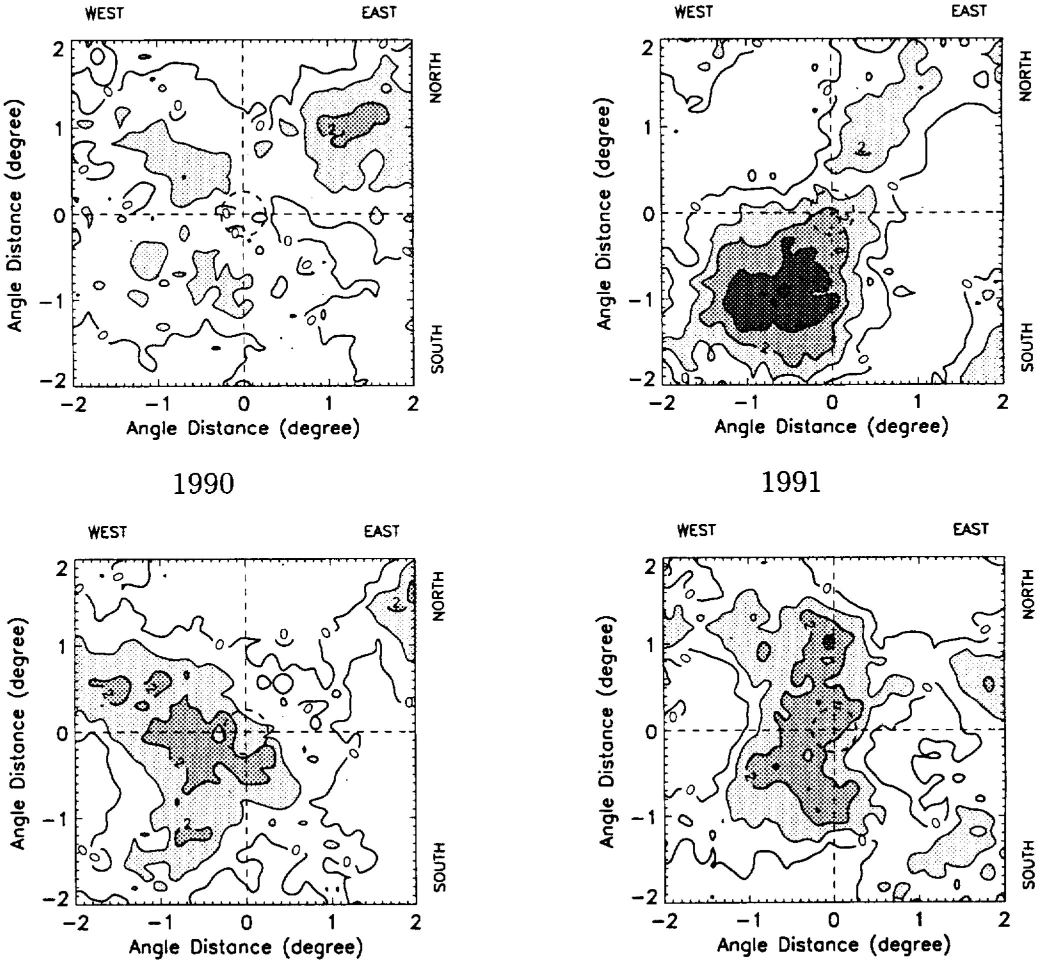
Fig. 4



1990

1991

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1993