CORONAL FARADAY ROTATION OF THE CRAB NEBULA, 1971–1975

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Abstract. We observed Faraday rotation of linearly polarized radio waves from the Crab Nebula (Tau A) at 4170 MHz during solar coronal occultations in June 1971–75. Mean amplitudes of the variations of position angle are larger in an active phase of the solar cycle than in a quiet phase. In occultations in 1971 and 1973, the position angle of the polarization varied oscillatory by 20–50 degrees due to local magnetic structures in the corona with a typical scale-length of about 0.5 $R_\odot$. In 1974, we observed a typical variation of position angle of polarization which is expected from a Y-shaped field configuration in coronal streamers.

The Faraday rotation is enhanced when the line of sight to Tau A passes through strong coronal magnetic fields computed from magnetograph observations, while the rotation is suppressed when the line of sight passes through large coronal holes observed in X-rays. Short-time oscillation of the rotation angle observed in 1971 and 1973 suggests that neutral sheets in coronal streamers oscillate at a period of 3 hours with an amplitude of $\sim 1\ R_\odot$ at a distance of $\sim 10\ R_\odot$ from the Sun.

1. Introduction

In June every year, the linearly polarized radio source, Tau A (Crab Nebula), is occulted by the outer corona of the Sun. The occultation gives opportunities to measure electron density and its inhomogeneities in the outer corona by observing a broadening of the image of the source at low radio frequencies (Dennison and Blesing, 1972). At microwave range, the occultation also gives opportunities to observe magnetic fields as well as electron density in the outer corona by measuring Faraday rotation of linear polarized radio waves from the source.

In 1971, we observed the occultation at 4170 MHz, and found that the position angle of linear polarization of Tau A varied oscillatorily by 20–50 degrees with a typical time scale of 3–5 hours (Sofue *et al.*, 1972; Kawajiri *et al.*, 1972). We have interpreted these variations as due to local structures of magnetic field with a typical scale of 0.5 solar radii. Reversals of sense of the Faraday rotation were observed in some local structures. The reversal suggests a reversal of field direction within the local structure probably associated with coronal streamers.

We further observed the occultations of Tau A in June from 1973 to 1975 using the similar methods to that used in 1971. In these years, it has become possible to compare the results with many other observations: coronal magnetic fields inferred from

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magnetogram observations (Newkirk *et al.*, 1975), OAO optical and X-ray observations (*Solar Geophysical Data*, 1971–75; Nolte *et al.*, 1976a, b). In this paper we report our observational results on Faraday effect obtained in 1971–75 occultations, and subject the results to detailed comparisons with the other observations.

2. Observations and Reductions

We observed position angle of linearly polarized radio waves from the Crab Nebula (Tau A) at 4170 MHz during the coronal occultations in June 1971, 1973, 1974 and 1975. Throughout the observations, we used a 26 m paraboloidal telescope at the Kashima Station of the Radio Research Laboratories. Table I summarizes positional relations of the Sun and Tau A in June of these years.

TABLE I

Positions of Tau A and the Sun (RA and Dec are for the epoch of 1950.0)

	1971		1973		1974		1975	
	RA	Dec	RA	Dec	RA	Dec	RA	Dec
Tau A	$5^{\rm h}32^{\rm m}48^{\rm s}$	21°59′.5	$5^{\rm h}32^{\rm m}55^{\rm s}$	22°00′.0	$5^{\rm h}32^{\rm m}58^{\rm s}$	22°00′.0	$5^{\rm h}33^{\rm m}02^{\rm s}$	22°00′.1
Sun at 0 h UT on								
June 13	$5^{\rm h}22^{\rm m}21^{\rm s}$	23°09′.5	$5^{\rm h}24^{\rm m}40^{\rm s}$	23°17′.3	$5^{\rm h}23^{\rm m}30^{\rm s}$	23°10′.4	$5^{\rm h}22^{\rm m}30^{\rm s}$	23°09′.4
15	30 39	43.5	32 48	17.5	31 48	17.0	30 49	16.2
17	38 58	21.2	41 06	22.2	40 07	21.5	39 07	21.1
Epoch of the closest approach	June 15 $12^{\rm h}00^{\rm m}$ UT		June 15 $00^{\rm h}58^{\rm m}$ UT		June 15 $06^{\rm h}57^{\rm m}$ UT		June 15 $12^{\rm h}12^{\rm m}$ UT	

As Tau A approaches very close to the Sun (5 $R_\odot$ at its closest approach), a difficulty of the polarization measurement has arisen, because of a confusion of the solar radio emission from side lobes of the antenna. In particular, strong local sources on the Sun would produce large errors on the polarization parameters of Tau A. To eliminate the confusion of the solar emission and to check the validity of the elimination, we took the following observational procedures (Figure 1; Kawajiri *et al.*, 1976).

Let Point A be the position of Tau A relative to the Sun, and Point B the relative position of Tau A a day after. The relative position of B at 00 h UT on June 17, for example, was the same as that of Point A at 00 h UT on June 18. The polarization parameters obtained for B on June 17 was used to evaluate and eliminate the side-lobe contribution to Tau A at Point A on June 18. Independent of this procedure, we could also evaluate the side-lobe confusion at A by an interpolation of the polarization parameters at $E_{\rm off}$ and $W_{\rm off}$, and similarly could check the evaluation for B by interpolating the parameters at $BE_{\rm off}$ and $BW_{\rm off}$. The 'off-positions', $E_{\rm off}$ and $W_{\rm off}$ ($BE_{\rm off}$

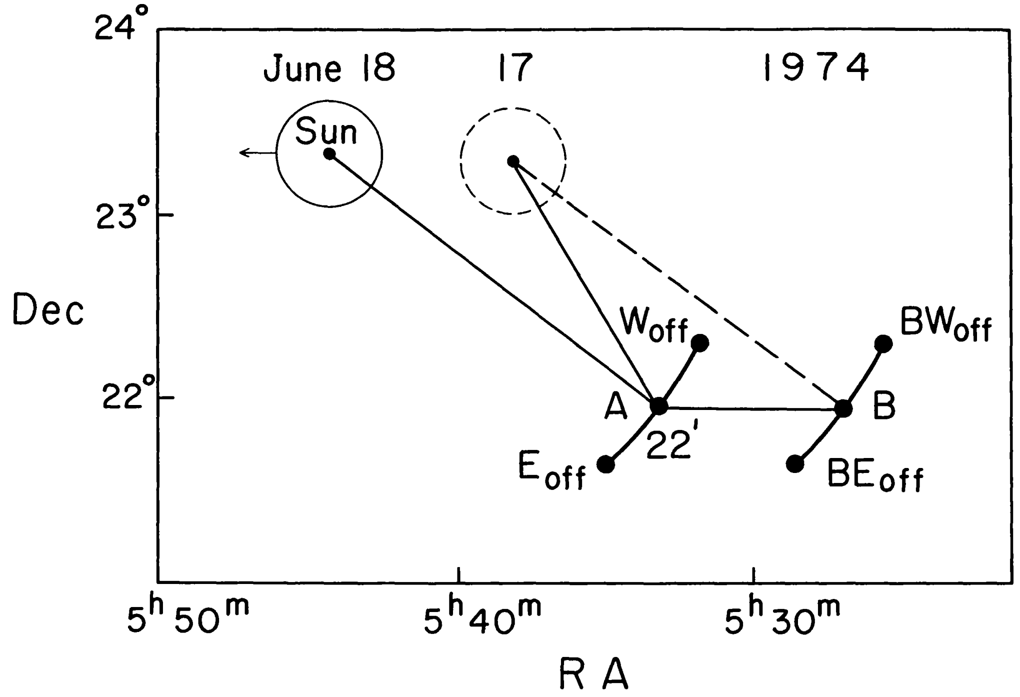

Fig. 1. Relative positions of Tau A (Point A) and the Sun on June 18 and 'off positions' (E_{off} and W_{off}), at each of which the polarization measurement was made. To evaluate and eliminate a confusion of solar emission from side lobes, we made the same set of measurements at points B, BE_{off} and BW_{off} one day before (June 17). The polarization measurement was made in the order of A (Tau A), E_{off}, B, A, W_{off}, B, A, . . . at every 3 minutes interval. In every 3 minutes, the polarizer of the telescope was rotated from 0° to 180° or vice versa.

and BW_{off}) were set at the same distances from the Sun as A(B), but 22′ apart from A(B) in the eastern and western sides, respectively. The interpolation enables us to estimate errors and to check the validity of the former procedure. All the data were recorded on magnetic tapes for convenience of the data processing. The position angle and degree of the polarization of Tau A were determined every 9 minutes (Kawajiri *et al.*, 1976). (The procedure used in 1971 and 1973 was a little simpler than the above: see Kawajiri *et al.* (1972).)

3. Results, 1971–75

Figure 2 shows position angle χ of the Crab Nebula (Tau A) during the coronal occultations in June 1971, 1973, 1974, and 1975. When Tau A was remote enough from the Sun, or in days before June 13 and after June 17, the coronal Faraday effect was so small that no significant rotation of the position angle took place. Figure 3 shows mean values of the position angle and polarization degree in these 'quiet' days. In the figure, we can also compare our results with some other observations made at different wavelengths. At our 4170 MHz, the intrinsic position angle of polarization is determined as $142° \pm 7°$, and the polarization degree is $4.7 \pm 0.7\,\%$, both values of which are in agreement with other observations.

As the source approached the Sun, its polarization plane was rotated by the Faraday effect in the corona. On June 14, 15, and 16, on which days Tau A approached the Sun

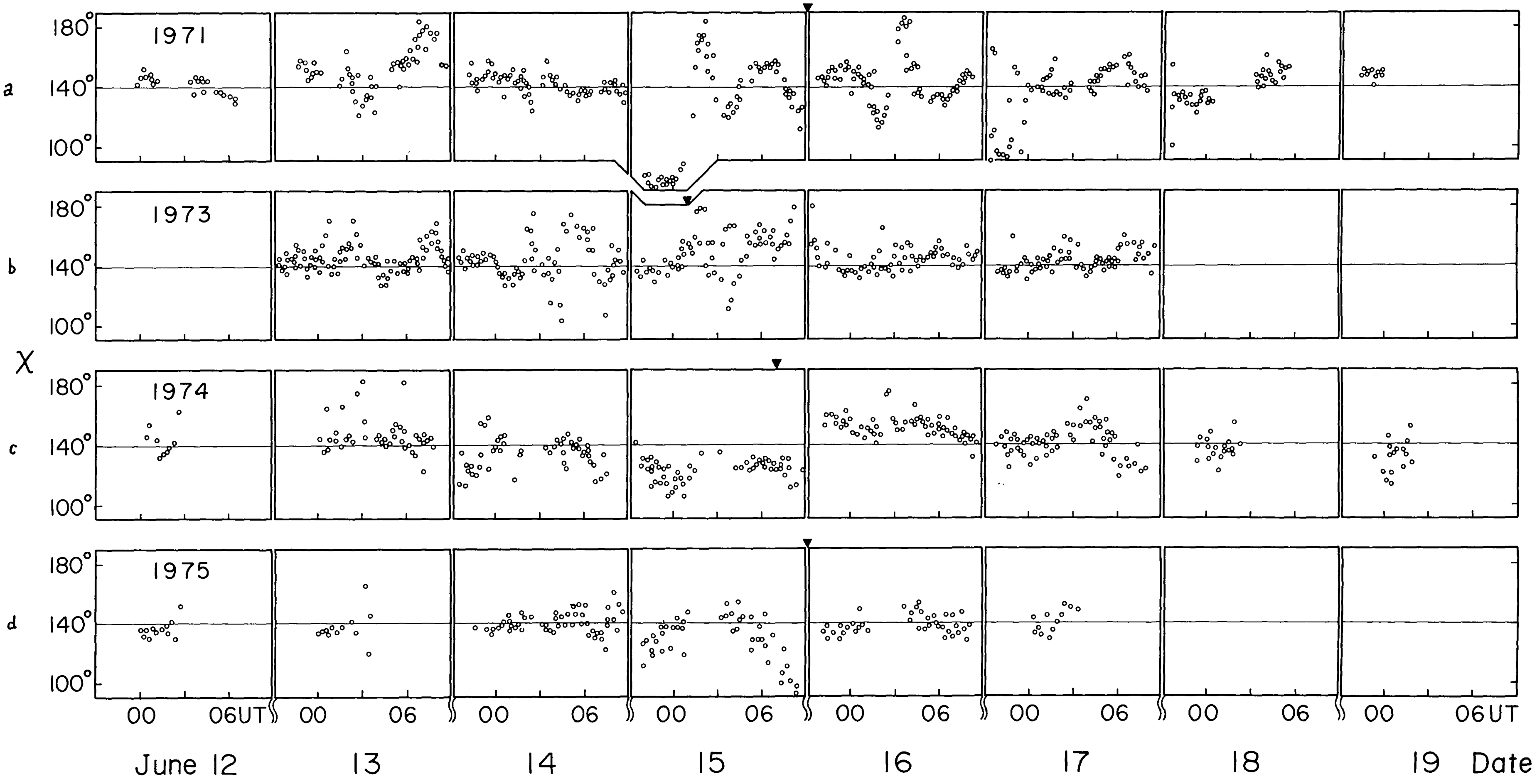

Fig. 2. (a) Observed position angle χ of Tau A during an occultation by the solar corona on June 12–19, 1971. The position angle varied violently as the source approached the Sun. (b) The same as Figure 2a but on June 13–17, 1973. (c) The same as Figure 2a but on June 12–19, 1974. (d) The same as Figure 2a but on June 12–17, 1975.

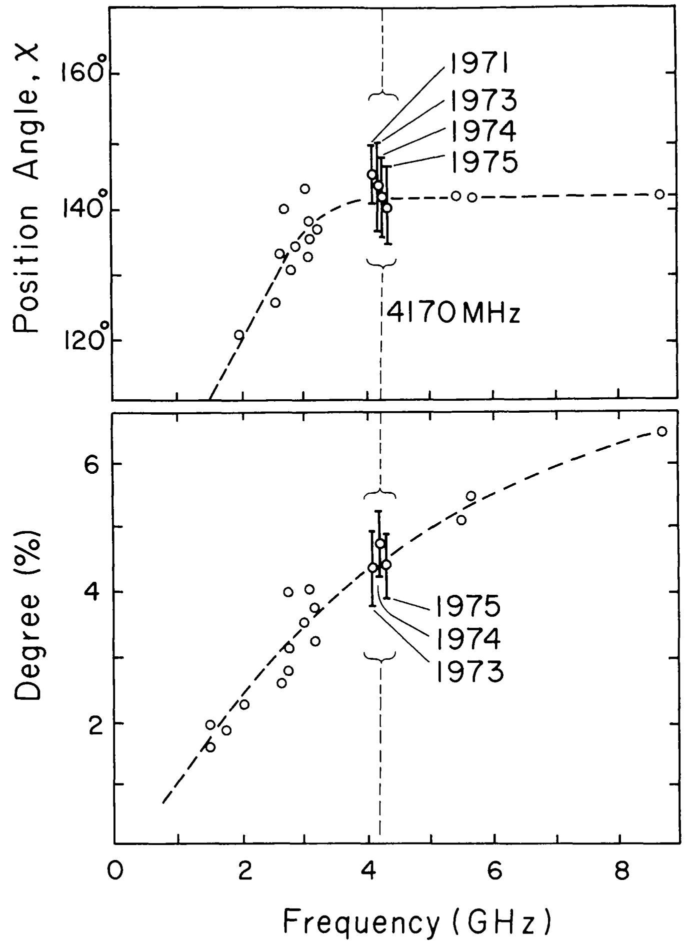

Fig. 3. Mean value of the position angle and degree of polarization of Tau A when the source was remote enough from the Sun. For a comparison, results from other observations at different wavelengths (see, e.g., Satoh *et al.*, 1967) are also plotted.

most closely (a minimum separation of 5 $R_{\odot}$ on June 15), the position angle varied around its intrinsic value by 20–50 degrees. In 1971 and 1973, the variations were in an oscillatory way with a typical time scale of 3–5 hours. In 1974, however, the variation was rather systematic, that is, the position angle gradually decreased down to ~130° until June 15, then it increased suddenly up to ~160°, and again gradually decreased returning to its intrinsic value, 142°. In 1975, no significant variation was observed exceeding 10°, except for a sudden decrease at around 0700 UT, June 15.

Figure 2 shows that the variation of the position angle becomes smaller as the year proceeds. This suggests that the Faraday effect on Tau A depends on the phase of the solar cycle. In Figure 4, we plot both standard deviation of the position angle and its maximum deviation from the intrinsic value on days of the closest approach as a function of year. For a comparison, we also plot monthly means of sunspot numbers taken from Dodson and Hedeman (1975). The figure shows that the magnitude of Faraday rotation in the corona depends on the phase of the solar cycle.

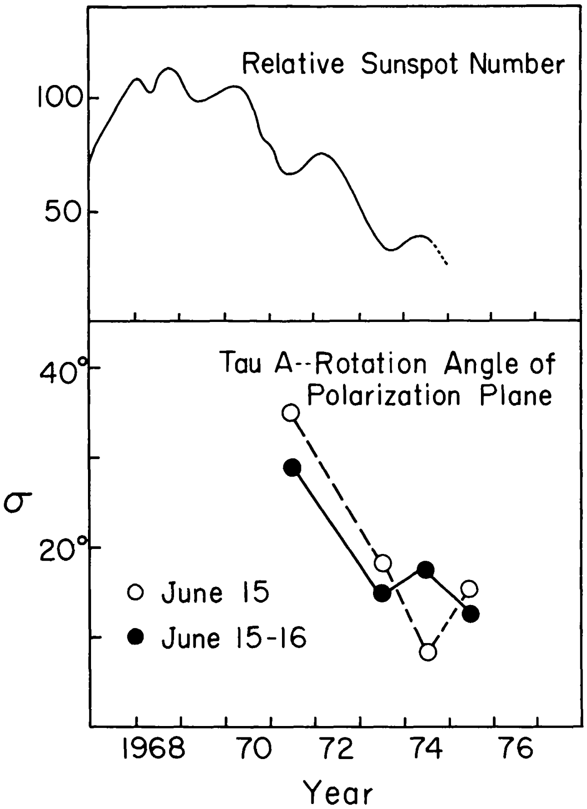

Fig. 4. Standard deviation σ of the rotation angle of Tau A's polarization plane on June 15–16 and that on June 15 alone, as a function of the year. Monthly means of Zürich sunspot number (Dodson and Hedeman, 1975) are shown for a comparison.

To see a spatial relation of the line of sight to Tau A to an overall distribution of solar magnetic fields and active regions, we project the line of sight radially onto the solar surface. Figure 5, where the Sun is fixed nonrotating, shows the projected lines of sight at 0000 UT on days of close approach in June 1971–75. In the figure, boundaries of magnetic polarities inferred from magnetogram observations (*Solar Geophysical Data*, 1971–75) and positions of Hα filaments as well as prominent active regions are also indicated. In 1971 and 1973, there were many active regions and then it is not easy to find a one-to-one correspondence between the observed variations in the position angles of the polarization and local magnetic structures on the Sun. However, as is shown in the next section, observed fluctuations in the position angles on 13 and 16 June, 1971 appear to be related to magnetic structures associated with Hα filament at around $L \approx 70°$, $B \approx -30°$ and $L \approx 140°$, $B \approx -30°$ respectively. Observed fluctuation of the position angle of the polarization on 15 June, 1971 may be related to magnetic structures in the region of the negative field at around $L \approx 110°$. Fluctuations on 13–15 June, 1973 may be related to a magnetic structure associated with Hα filament at $L \approx 90°$–$160°$ and connected to the magnetic field in the south polar region.

In 1974 and 1975, the Sun was relatively quiet, and the observed variations of Tau A's position angle of polarization can be attributed to some particular active regions and polarity changes on the Sun: In 1974, the direction of Faraday rotation of Tau A reversed from negative to positive on June 15–16. This reversal took place when the line of sight passed across a large Hα filament located $L \approx 210°$, $B \approx -10°$ to $20°$ (Figure 5c). Before and after the passage, the field polarities were positive and negative, respectively. Before the passage, the line of sight component of the field away from us dominated, while after the passage the field was toward us. This is in agreement with the fact that the rotation measure is observed to change suddenly from negative to positive at the passage.

A sudden decrease of position angle was observed around 0700 UT on June 15, 1975. This sudden variation can be attributed to a large Hα filament at $L \approx 70°$ to $80°$, $B \approx -10°$ to $30°$ (Figure 5d). After the passage of the line of sight across this filament, the field polarity is changed from negative to positive, and this would be the cause of the sudden increase in the negative rotation measure, and therefore a sudden decrease in the position angle.

4. Comparison with Other Observations

In this Section we discuss the observed results of the coronal occultations of Tau A in 1971 and 1973 in more detail in comparison with coronal magnetic fields and X-ray coronal holes.

(i) 1971

Newkirk *et al.* (1975) have provided daily maps of lines of force of magnetic fields in the solar corona calculated on the basis of magnetogram observations from August 1959 to January 1974. To compare our results with the field configuration in the corona, we reproduce their maps on 12–18 June, 1971 in Figures 6a and b. In these maps, we indicate the positions of Tau A relative to the solar disk center and superpose the observed variations of position angle of polarization on each day.

The rotation angle appears to have a correlation with the field configurations: In the region where the field lines are concentrated in the maps of 'strong fields' (Figure 6b), the position angle varies more amply compared to regions of weak fields. The most violent variations observed on June 15 are associated with very strong field lines of open configuration emanated from an active region on the photosphere.

On the other hand, on June 14, when the Faraday rotation was observed to be quiet, the line of sight to Tau A passed through a quiet coronal region radially associated with a quiet photospheric region.

(ii) 1973

(a) *Magnetic fields.* Figures 7a and b show coronal magnetic fields on June 13–17, 1973 reproduced from Newkirk *et al.* (1975). We again superpose our data of Faraday rotation on these maps. The overall field is stronger in the eastern half of the Sun than in the western half (Figure 7b). There appears a large magnetic region with an arch-like structure of field lines in the SW limb (Figure 7a). The Faraday rotation angle varied

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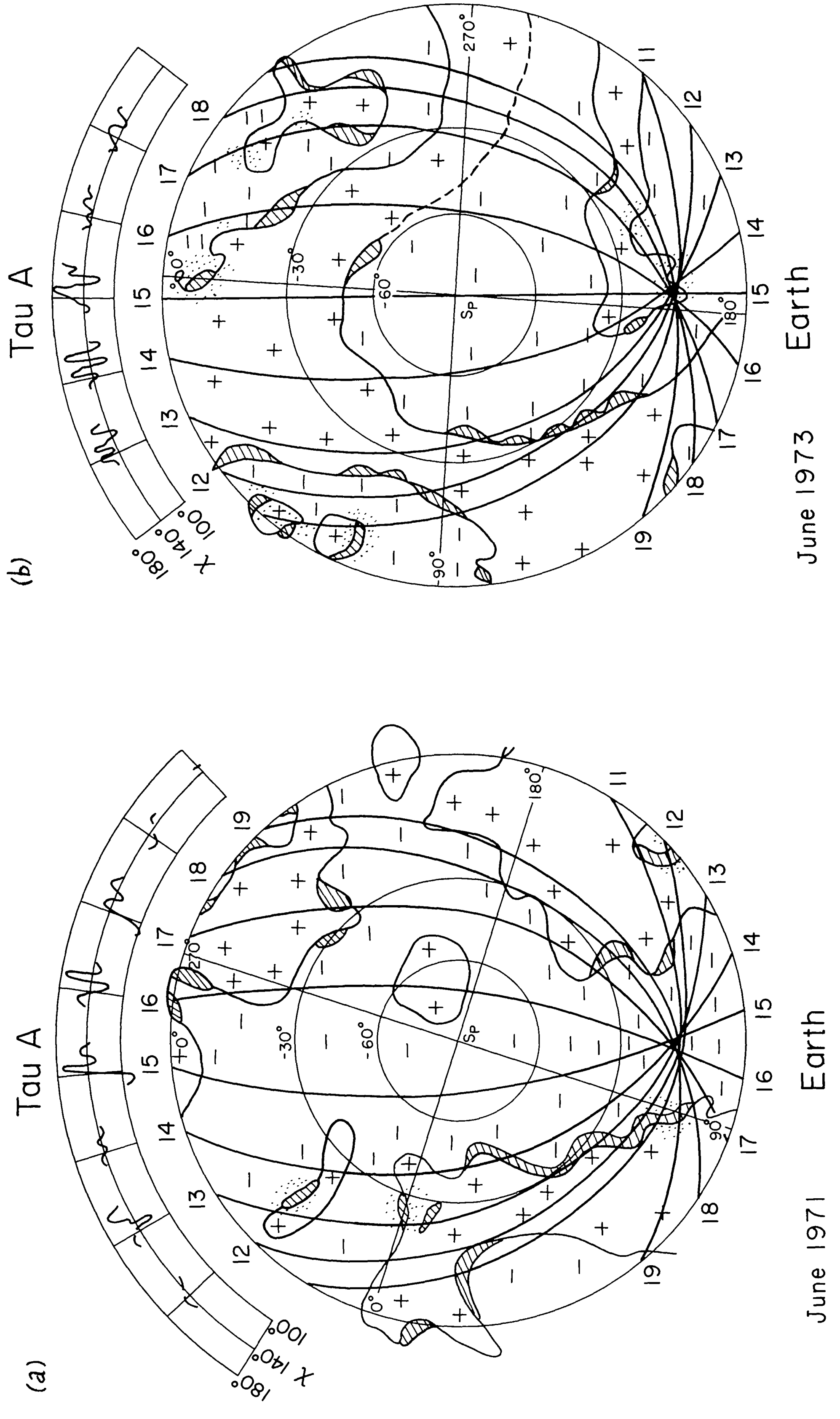

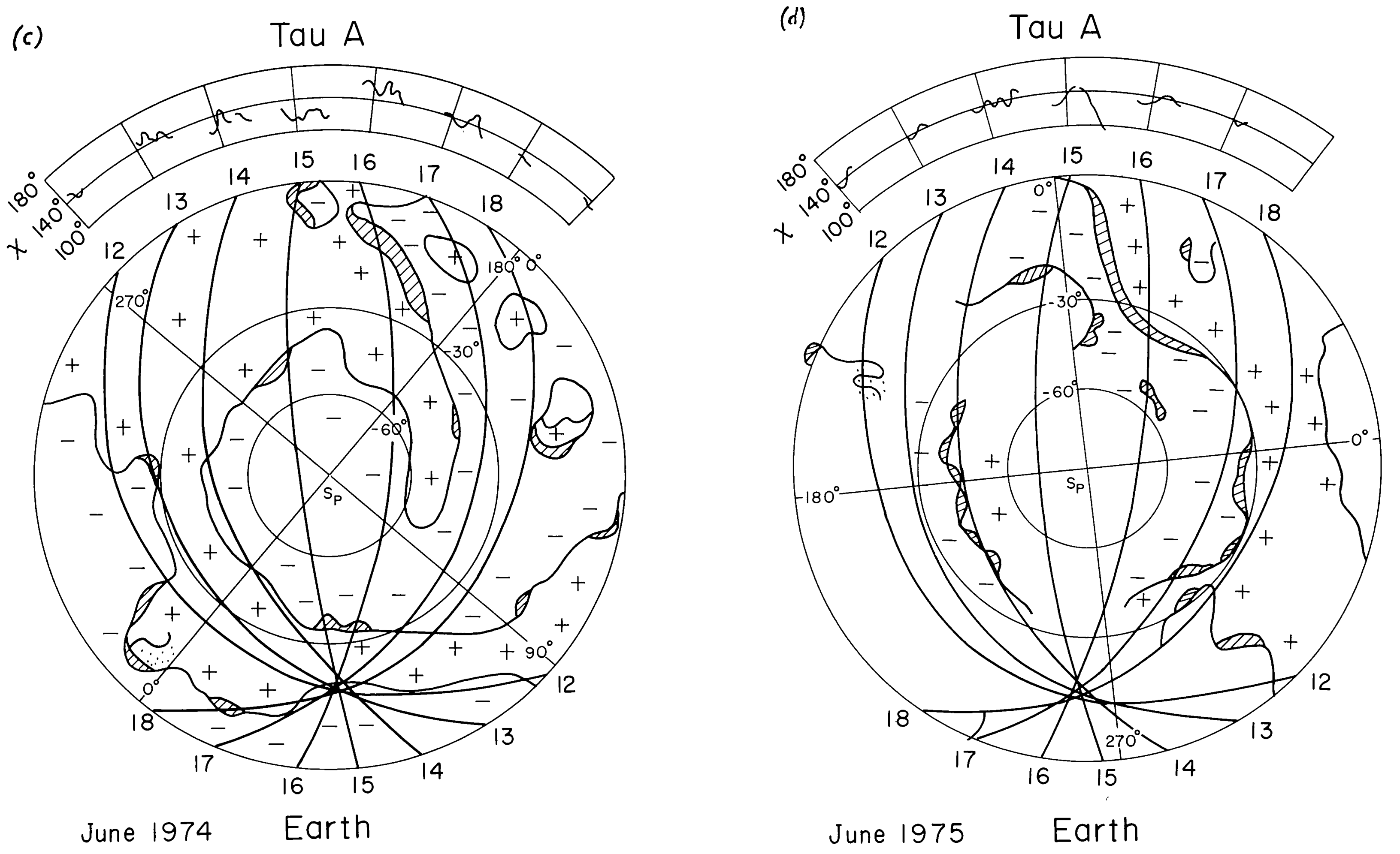

Fig. 5. Radial projections of boundaries of magnetic polarities on the southern hemisphere of the Sun onto a plane swept by the line of sight to Tau A in June of (a) 1971, (b) 1973, (c) 1974, and (d) 1975. Hα filaments are indicated with hatched areas. Thin lines show the lines of sight to Tau A at 00 h UT on 11–18 June. The Sun is fixed non-rotating, and the heliographic longitude and latitude are indicated. The magnetic and Hα data are from *Solar Geophysical Data* (1971–1975). Observed position angles of polarization plane of Tau A are drawn schematically at the top of the figures.

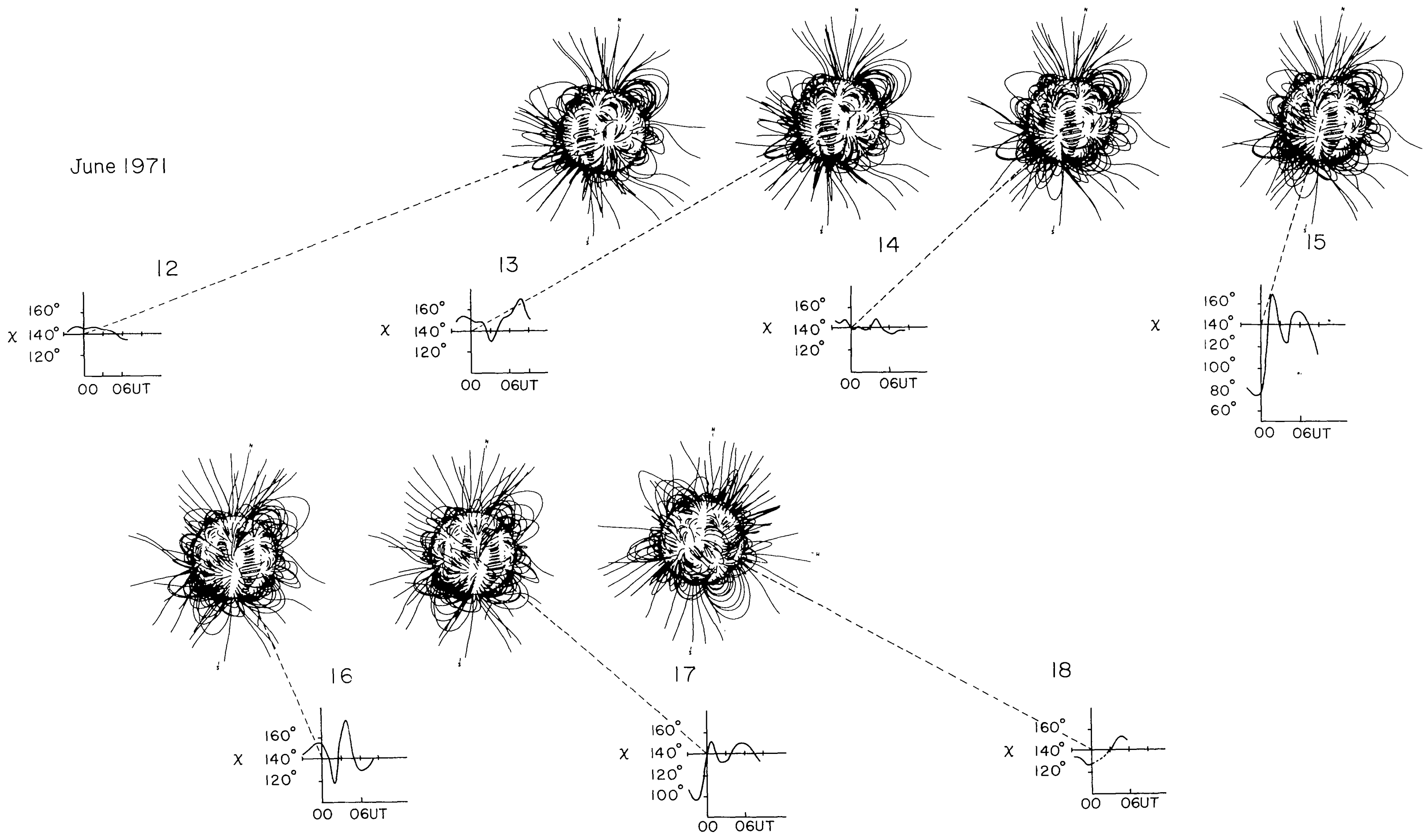

Fig. 6a. Smoothed variation of polarization angle superposed on maps of magnetic fields of the solar corona for the period of June 12–18, 1971 (reproduced, with authors' permission, from Newkirk *et al.* (1975)). The scale of the abscissa in the diagram of the polarization angle is adjusted so that the position of Tau A relative to the Sun is represented by a point on the abscissa at a corresponding time.

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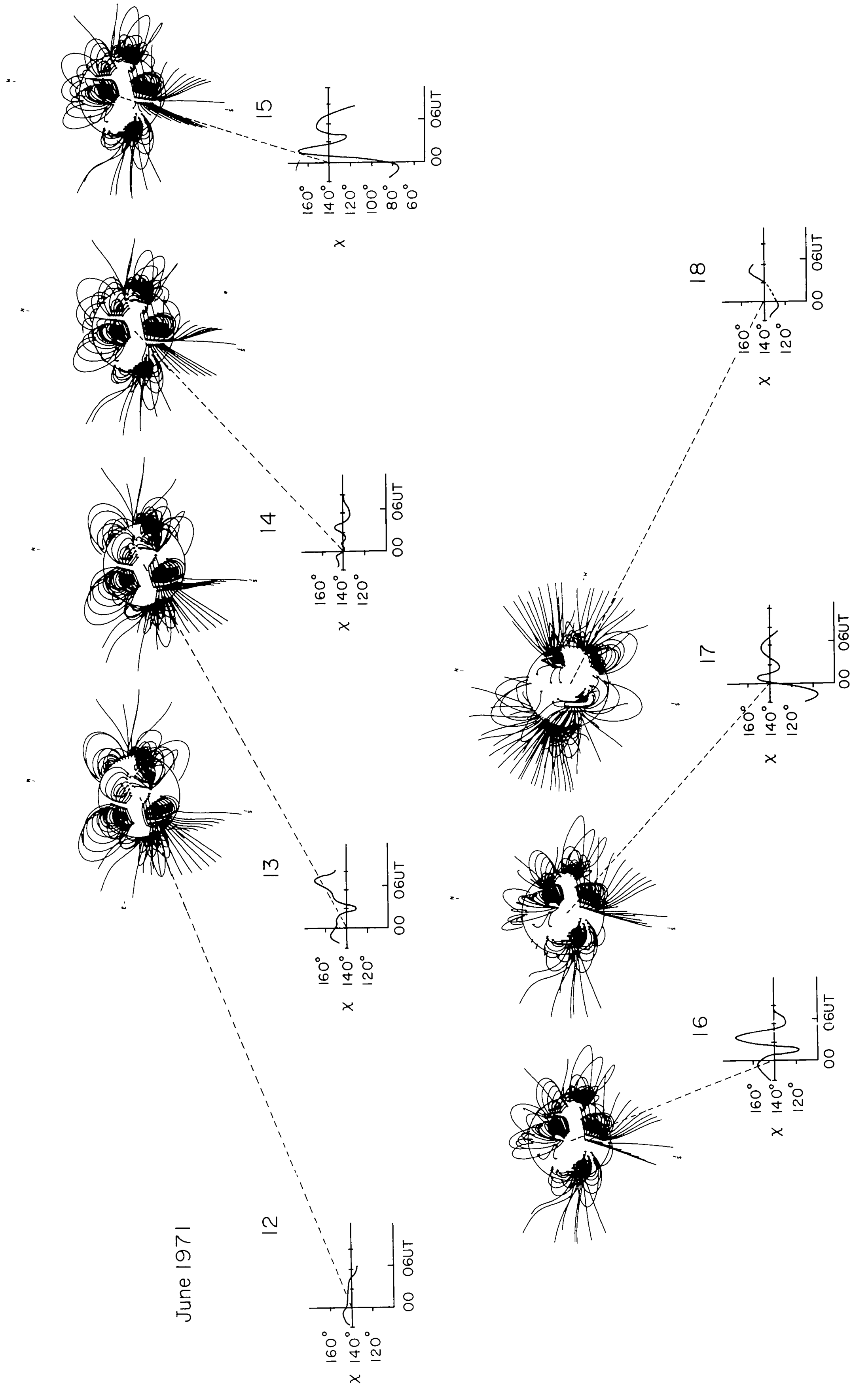

Fig. 6b. The same as Figure 6a, but for maps of strong fields.

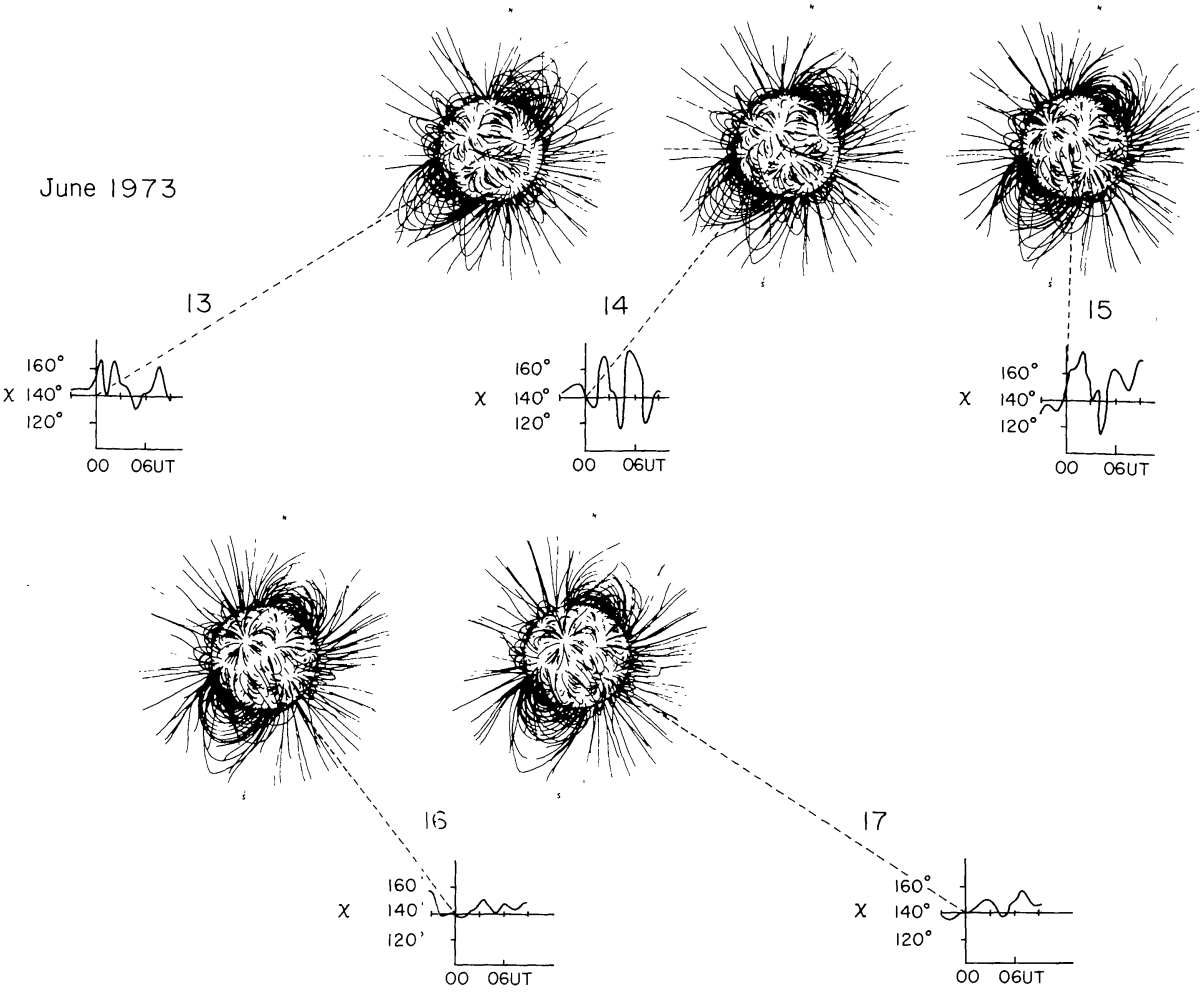

Fig. 7a. The same as Figure 6a, but for the period of 13–17 June, 1973.

violently on 13–15, on which days, the line of sight to Tau A passed through or closely to radial extension of this magnetic region.

On the other hand, no significant variation of the position angle was observed on 16–17. On these days, the line of sight was already out of this magnetic region, and was in a quiet coronal region without any strong emanation of field lines (Figure 7b). This quiet region is shown to be partly covered by a large coronal hole located around the south pole as shown below.

(b) *Coronal holes.* Recent extensive observations on satellite have made it possible to get maps of the Sun in X-rays with a high spatial resolution. Nolte *et al.* (1976a) have presented maps of X-ray coronas and coronal holes observed on Skylab for the solar rotation periods from 1601 to 1608 including June 1973. They (1975b) have shown that the coronal holes are sources of high-speed solar wind and the holes have sharp boundaries against surrounding coronal regions. If the coronal holes and their sharp boundaries radially extend from the solar surface to the outer corona, the line of sight to Tau A during our observational period would cross them.

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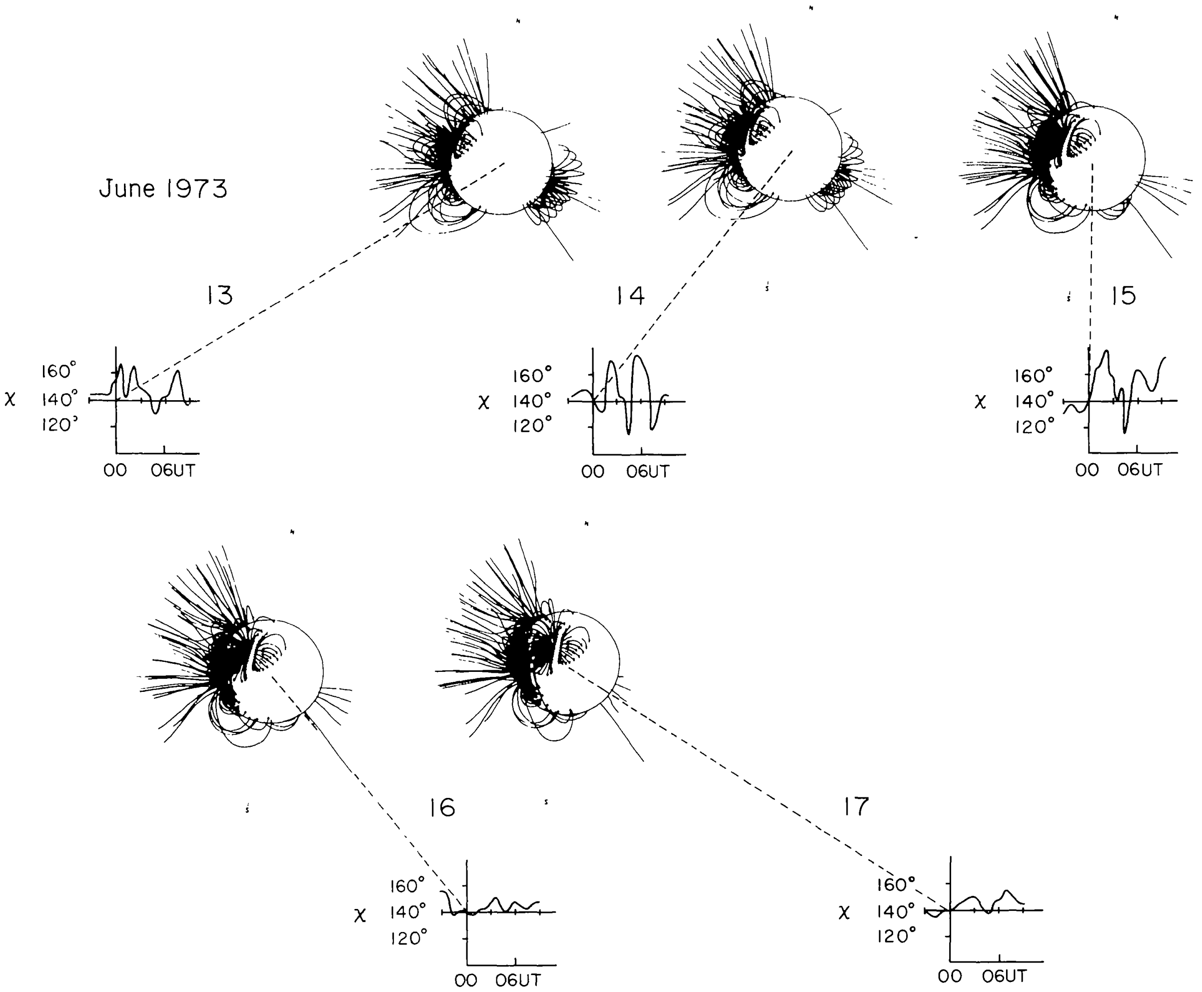

Fig. 7b. The same as Figure 7a, but for maps of strong fields.

To see how the line of sight crossed the coronal holes, we project the coronal-hole boundaries radially from the Sun onto a plane swept by the line of sight to Tau A. Figure 8 shows the projected plane in a map made with the same method as Figure 6. We indicate the lines of sight to Tau A at 00 h UT on 13–17 and also superpose smoothed variations of the position angle of Tau A. Large-amplitude oscillations of the position angle take place when the line of sight passes across tangentially the boundaries of the coronal holes (June 14, 15). It is remarkable that the variation is suppressed as the line of sight passes through a large coronal hole (June 16, 17). The latter fact may be due to the weakness of the magnetic field and to the low electron density in the coronal hole. Another probable interpretation is that the magnetic field lines run nearly perpendicular to the line of sight in the coronal hole (Figure 7b).

5. Discussion

We have shown that the mean magnitude of the Faraday effect on the Crab Nebula (Tau A) during occultations by the outer corona is related to the solar activity cycle

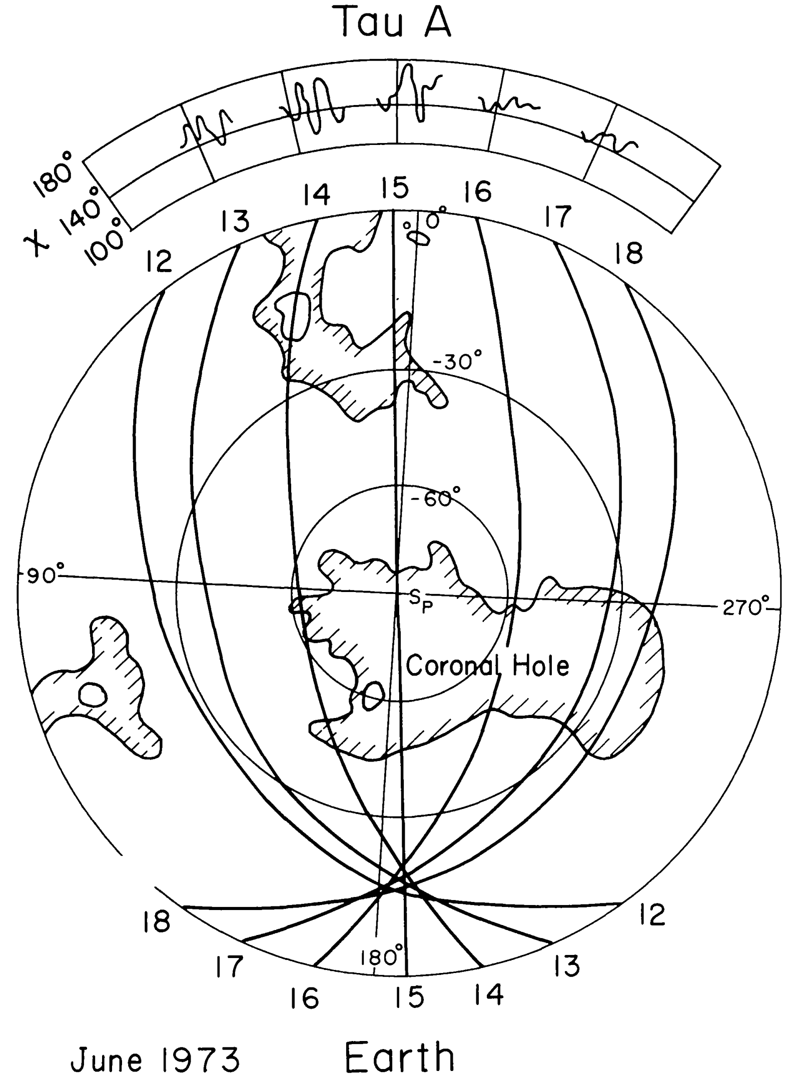

Fig. 8. Radial projection of boundaries of coronal holes in June 1973 onto a plane swept by the line of sight to Tau A. We made use of maps of coronal holes presented by Nolte *et al.* (1976a, b). The lines of sight to Tau A at 00 h UT on June 12–18 are indicated with thin lines. Smoothed position angle of polarization plane of Tau A on each day is superposed at the top of the figure. Compare with Figure 5b.

(Figure 3). The daily and short-lived variations of the position angle of Tau A's polarization plane have been subjected to detailed comparisons with configurations of coronal magnetic fields and X-ray coronal holes. The rotation of the polarization plane is enhanced when the line of sight to Tau A passes across radial extensions of strong magnetic fields that are associated with helmet-like streamers (Figures 6, 7). On the other hand, the rotation is suppressed when the line of sight passes through large coronal holes (Figure 8). Below, we make some order-of-magnitude estimates on the magnetic fields and electron densities in the outer corona on the basis of our observations.

Typical magnitude of absolute values of the rotation angle amounts to 30–50 degrees in the active phase of the solar cycle (1971–73), while it amounts only to 10–20 degrees in the quiet phase (1974–75). The rotation angle Ω from the intrinsic polarization plane is related to the rotation measure RM and a wavelength λ as $\Omega = \lambda^2$ RM. The observed rotation angles at our wavelength ($\lambda = 7.2$ cm) corresponds to 100–160 rad m^{-2} in 1971–73, and to 30–60 rad m^{-2} in 1974–75. The rotation measure is expressed by the electron density N_e (in cm^{-3}), the line-of-sight component of magnetic fields B (in gauss), and the pass length s along the line of sight as

$$\mathrm{RM} = 1.82 \times 10^{-2} \int N_e B \, \mathrm{d}s/R_\odot \simeq 1.8 \times 10^{-2} \, N_e B (s/R_\odot) \text{ rad m}^{-2}.$$

If we take $s \simeq 1 \, R_\odot$ as an effective pass length across a coronal streamer, we obtain $N_e B \simeq 5600$–8100 gauss cm^{-3} in 1971–73, and $N_e B \simeq 2100$–3500 gauss cm^{-3} in 1974–75.

The electron density for a quiet corona at $R > 5 \, R_\odot$ is given by $N_e = 2.5 \times 10^6 \, (R/R_\odot)^{-2.5}$ (Saito, 1970), where R is the distance from the Sun. If we assume a radial magnetic field expressed by $B = 1 \times (R/R_\odot)^{-2}$ gauss, we have $N_e B = 2.5 \times 10^6 \, (R/R_\odot)^{-4.5}$ gauss cm^{-3}. Insertion of $R \simeq 7 \, R_\odot$ into this equation as a typical value yields $N_e B \simeq 400$ gauss cm^{-3}. In order to fit the observed value of $N_e B$ we must take both N_e and B in a coronal streamer greater than those in the surrounding coronal region by a factor of 2–4.

The observations in 1971–73 show that the polarization plane oscillates at a short period of about 3 hours. This time scale corresponds to a linear scale of 0.5 $R_\odot$ at the solar distance, if the motion of Tau A relative to the Sun is taken into account. The oscillatory variation around the intrinsic polarization plane indicates a reversal of sign of the Faraday rotation measure, and therefore a reversal of the line-of-sight component of the field direction.

We can interpret such an oscillation as due to existence of a neutral sheet in a coronal streamer: As the line of sight to Tau A passes across the neutral sheet, the field direction reverses from one side to another and the reversal results in an oscillatory variation of the position angle. The oscillation continues repeatedly for more than half a day (for example, on June 13–15, 1973) and at a relatively regular period. It is unlikely that the field configuration spatially changes in such a regular fashion. Then the repeated oscillation may indicate that the neutral sheet itself oscillates back and forth around the line of sight with a time scale of ~ 3 hours. The amplitude of the oscillation should be larger than the size of Tau A (0.25 $R_\odot$).

The Alfvén velocity in the corona is estimated by the relation $V_A = [B^2/4\pi\rho]^{1/2} = V_0 \, (R/R_\odot)^{-0.75}$, where B and ρ are the field strength and gas density, respectively, and $V_0 = [B_0^2/4\pi\rho_0]^{1/2}$ is the Alfvén velocity close to the solar surface. If we take $B_0 \simeq 1$ gauss and $\rho_0 \simeq 2.5 \times 10^6$ cm^{-3}, then we have $V_A \simeq 1370 \, (R/R_\odot)^{-0.75}$ km s^{-1}, or $V_A \simeq 410$ km s^{-1} at $R \simeq 5 \, R_\odot$ and $V_A \simeq 240$ km s^{-1} at $R \simeq 10 \, R_\odot$. Because the Alfvén velocity decreases outward, the amplitude of the Alfvén wave will rapidly increase as the wave propagates outward along the streamer fields. The maximum amplitude a of the oscillation can be roughly estimated by $a \simeq V_A \tau/4$, if we put that the velocity of the oscillation becomes equal to the Alfvén velocity. Then we obtain $a \simeq 1\, R_{\odot}$ at $R = 5$–$10\, R_{\odot}$, if we put $\tau \simeq 3$ hours and $V_A \simeq 300$ km s^{-1}. This maximum amplitude is comparable to a typical radius of a coronal streamer at these distances.

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