Publ. Astron. Soc. Japan 24, 309-321 (1972)

Faraday Rotation of Linearly Polarized Radio Waves from the Crab Nebula by the Solar Corona

Yoshiaki SOFUE and Kin-aki KAWABATA
Department of Physics, Nagoya University, Chikusa, Nagoya
and
Nobuhiro KAWAJIRI and Nobuyuki KAWANO
Kashima Branch, The Radio Research Laboratories, Kashima, Ibaraki
(Received 1972 January 31; revised 1972 March 1)

Abstract

Position angles of linearly polarized rodio waves from the Crab Nebula (Tau A) were measured at wavelength λ=7.2 cm, in the middle of June 1971, at which time the source was occulted by the solar outer corona. The observed variation in the rotation measure suggests that there exist local structures in the magnetic field and electron density of the corona. The local structures have two typical scale lengths of the order of 0.1 and 1 $R_\odot$, respectively, at a distance of 5-10 $R_\odot$ from the sun. The field strength and electron density in the local structures are larger than the averaged values by a factor of 15 for the structures of scale length 0.1 $R_\odot$, and 4 for those of scale length 1 $R_\odot$.

Observed values of the electron density and scale length of the local structures are the same, in order of magnitude, as those for coronal streamers. The direction of the magnetic field reverses in the large scale local structure, which is identified with a radial extension of a helmet streamer.

Key words: Coronal streamer; Faraday rotation; Linear polarization of the Crab Nebula; Solar outer corona.

1. *Introduction*

The occultation of the radio source Tau A (Crab Nebula) by the solar corona provides an opportunity each year in June to investigate the coronal electron density at a distance of 5-30 $R_\odot$ from the sun. A considerable number of observations at metric wavelengths have been attempted, but few in the microwave range. In particular, the observational investigation of the structure of the magnetic field in the outer solar corona has not yet been performed satisfactorily. (See, for example, NEWKIRK's [1967] review article on coronal structures.)

GOL'NEV, PARIISKY, and SOBOLEVA (1964) have observed the polarization of the Crab Nebula at λ=6.3 cm during an occultation in a period of minimum solar activity. They have given only an upper limit of 0.8×10^{-2} G for the magnetic field in the solar outer corona due to the absence of a detectable Faraday rotation within their experimental accuracy.

On the other hand, STELZRIED, LEVY, SATO, RUSCH, OHLSON, SCHATTEN, and WILCOX (1970) have carried out an experiment to detect the Faraday rotation for linearly polarized radio waves at 2260 MHz (λ=14.4 cm) from Pioneer VI when the probe was occulted by the solar corona. They have formulated a model of the electron density distribution in the ecliptic plane assuming Parker's model with a spiral magnetic field.

The purpose of the observations reported here is to measure the Faraday rotation of linearly polarized radio waves from Tau A at $\lambda=7.2$ cm, with a view to investigating the coronal magnetic field and electron density at high heliographic latitudes and at a distance of 5–10 $R_{\odot}$ (in a period of maximum solar activity).

2. *Observations and Results*

Position angles of polarization of Tau A were measured from June 8 to June 19, 1971 inclusive. The sun-source distance scaled in solar radii varied from 20 $R_{\odot}$ on June 8 to 5 $R_{\odot}$ on June 15, the day of the closest approach, and 15 $R_{\odot}$ on June 19.

The 26 mϕ paraboloidal antenna at the Kashima Station of the Radio Research Laboratories was used for the observation. The frequency and band-width were 4170 MHz and 29 MHz, respectively. The half power beam-width was 10 minutes of arc. System noise temperature, including the parametric amplifier operating under room temperature, was about 145 K.

As the source approaches the sun, a difficulty arises in the observations due to the simultaneous reception of solar radio emission by side lobes of the antenna. In order to avoid errors due to the confusing solar radio emission, we use the following two observational procedures.

In the first procedure, we make observations at "off source" positions keeping

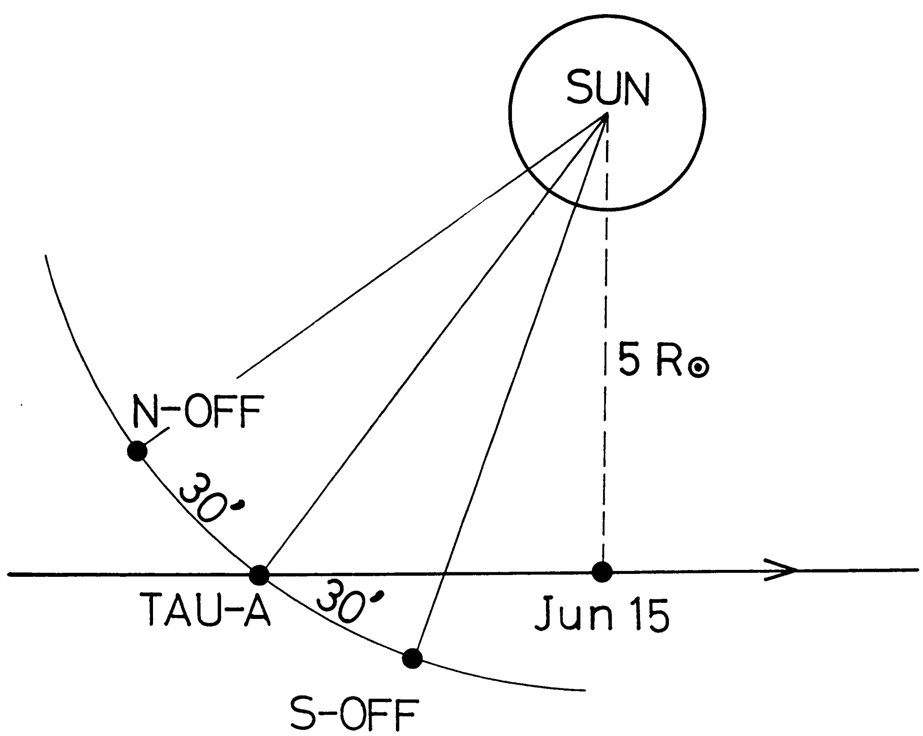

FIG. 1. Configurations of "on" and "off" positions relative to the sun. The observations are executed in the sequence N-off → Source → S-off → Source → N-off → ⋯. The average value of N-off and S-off positions is taken as a true value of the sky level at the source position.

the distances of "off source" positions from the solar center equal to those of the "on source" position, i.e., the position of Tau A (Figure 1). The "off" positions are set alternatively to the northern side (N-off) and to the southern side (S-off) of "on" positions. The distance between "on" and "off" positions is set to be 30 minutes of arc. We assume that the average value of the N-off and S-off observations at any time is the true value of the sky level at the position of Tau A.

In the second procedure used to eliminate the contributions from side lobes, the region near the orbit of Tau A referred to the sun is re-surveyed using the same method as before, after Tau A has gone far away from the sun. From this survey, flux densities and polarizations due to side lobes are estimated. This procedure, together with the first one, is used in the reduction of the data of June 14, 15, and 16, when the sun-source distance was smallest.

The polarization was measured by rotating a polarizer from 0 to 200 degrees

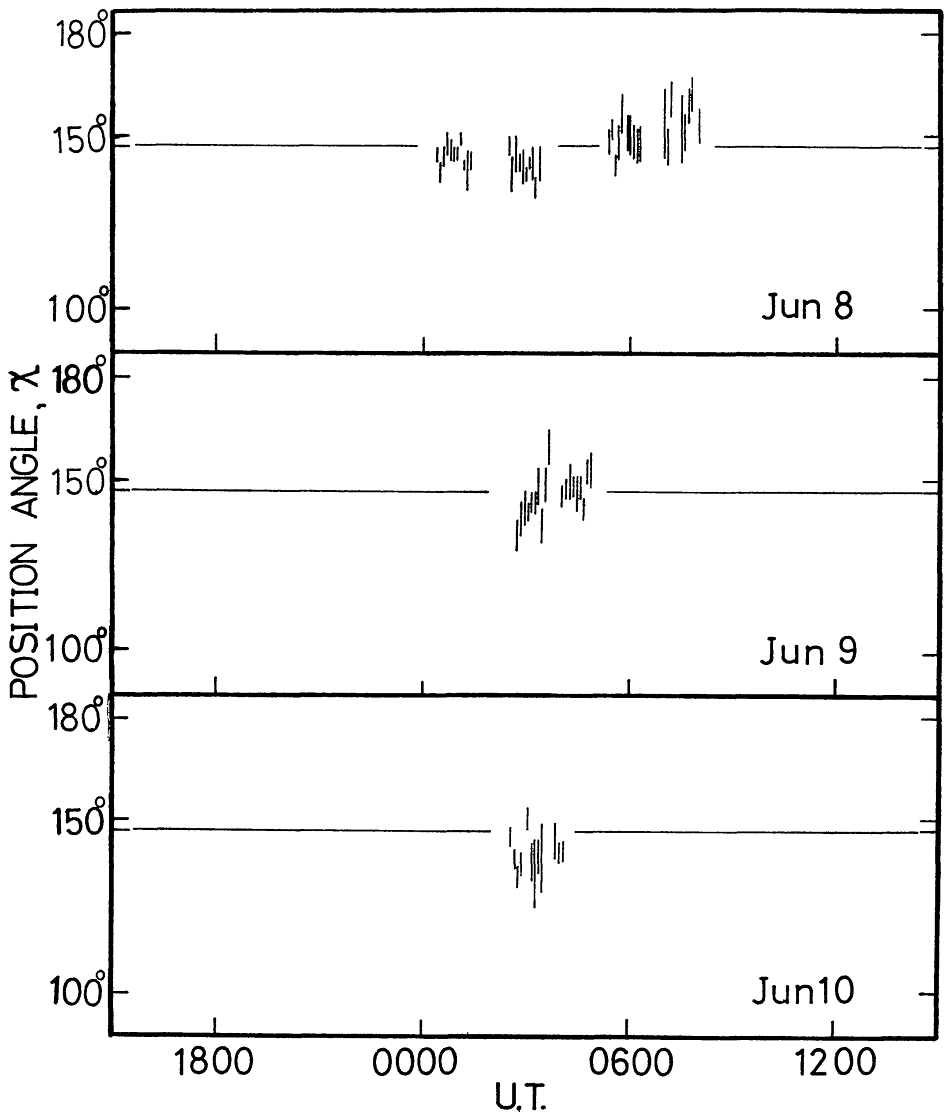

FIG. 2a. Observed position angles of polarization of Tau A on June 8, 9, and 10. Each point shows a value determined from one set of "on"-"off" observations. Lengths of the bars indicate probable errors.

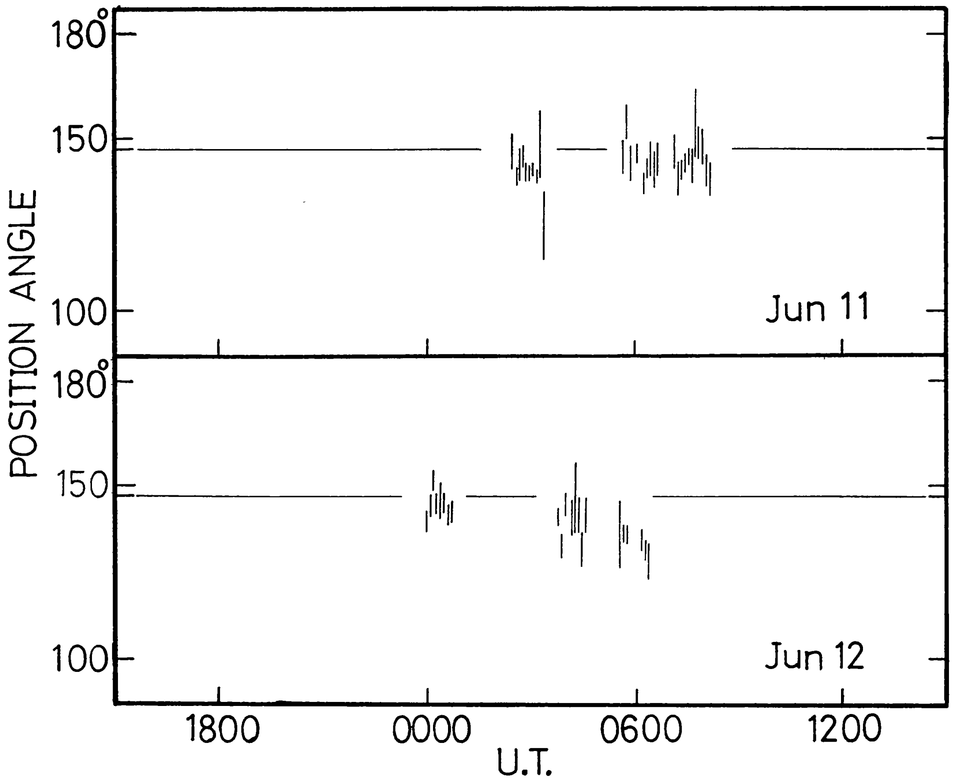

FIG. 2b. Same as Figure 2a, but for June 11 and 12.

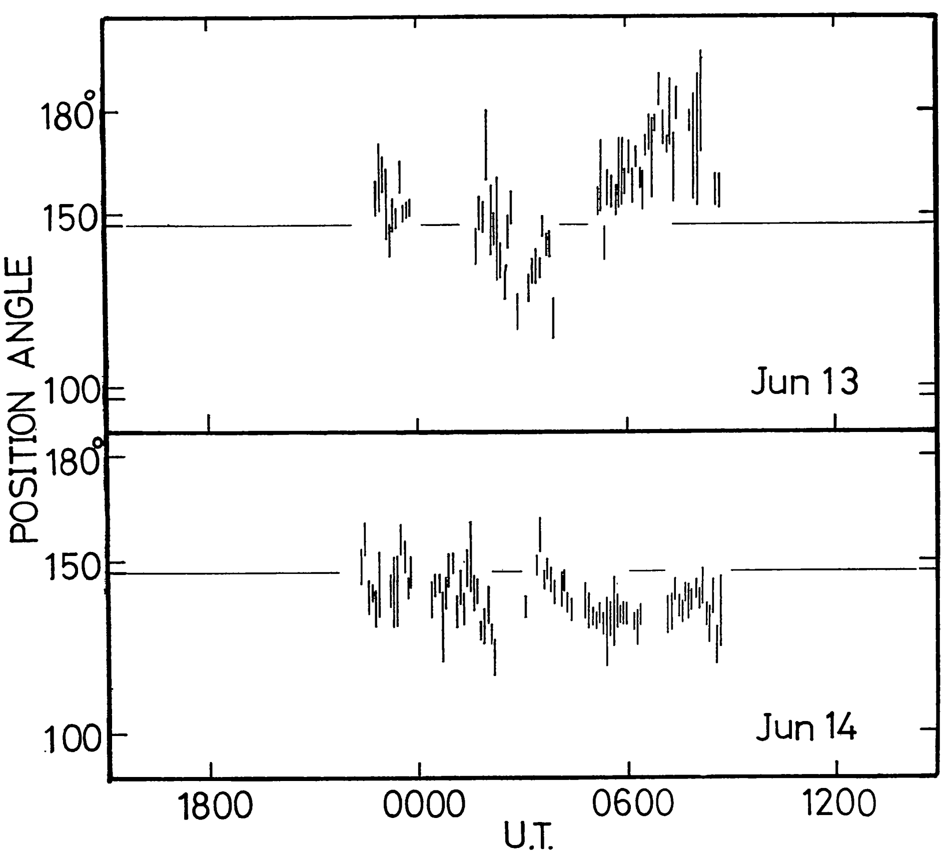

FIG. 2c. Same as Figure 2a, but for June 13 and 14.

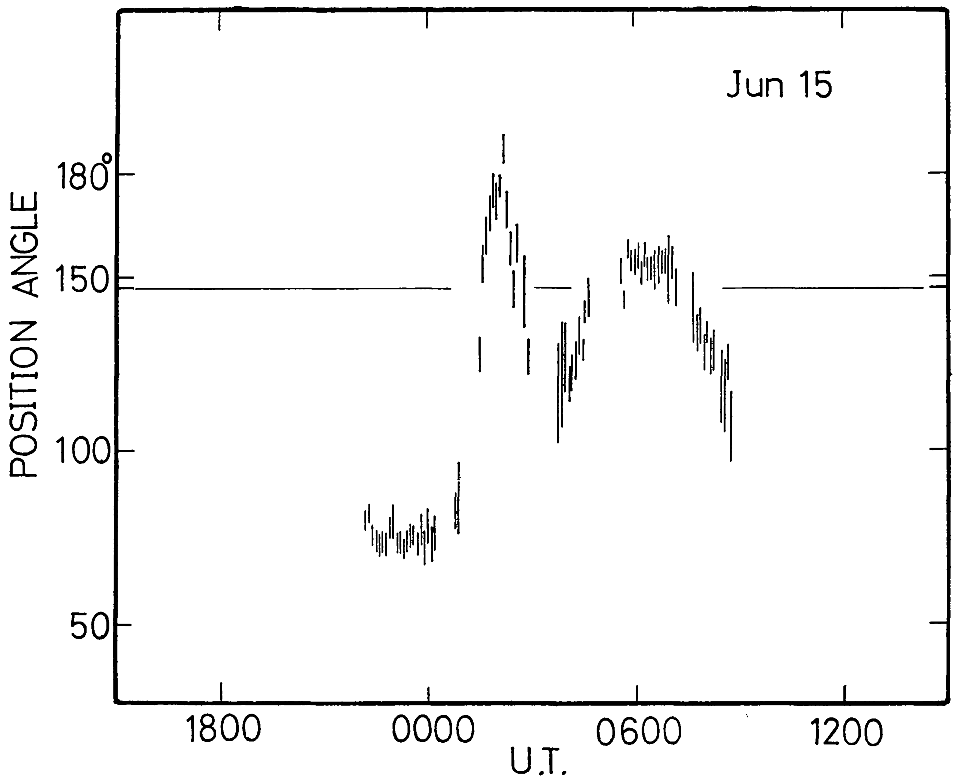

FIG. 2d. Same as Figure 2a, but for June 15.

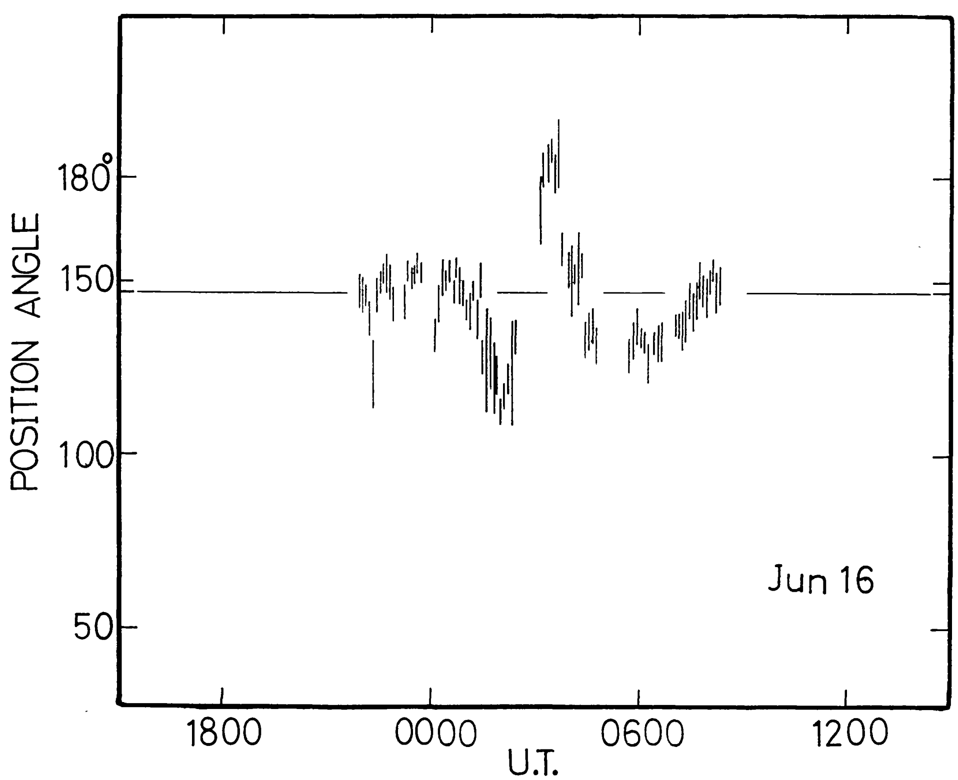

FIG. 2e. Same as Figure 2a, but for June 16.

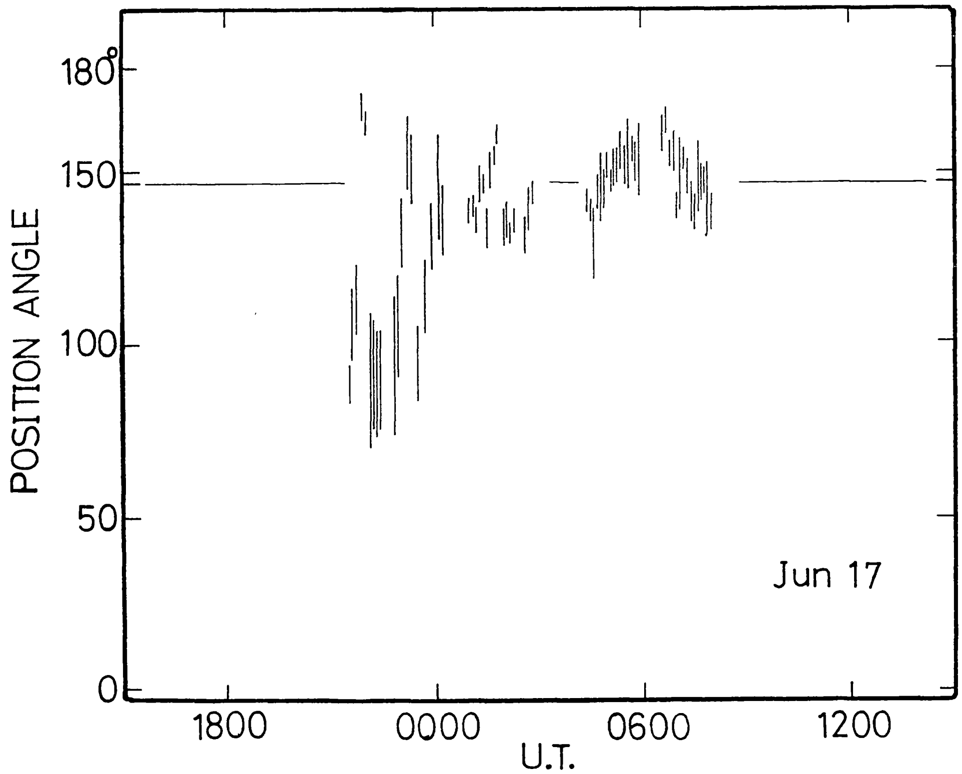

FIG. 2f. Same as Figure 2a, but for June 17.

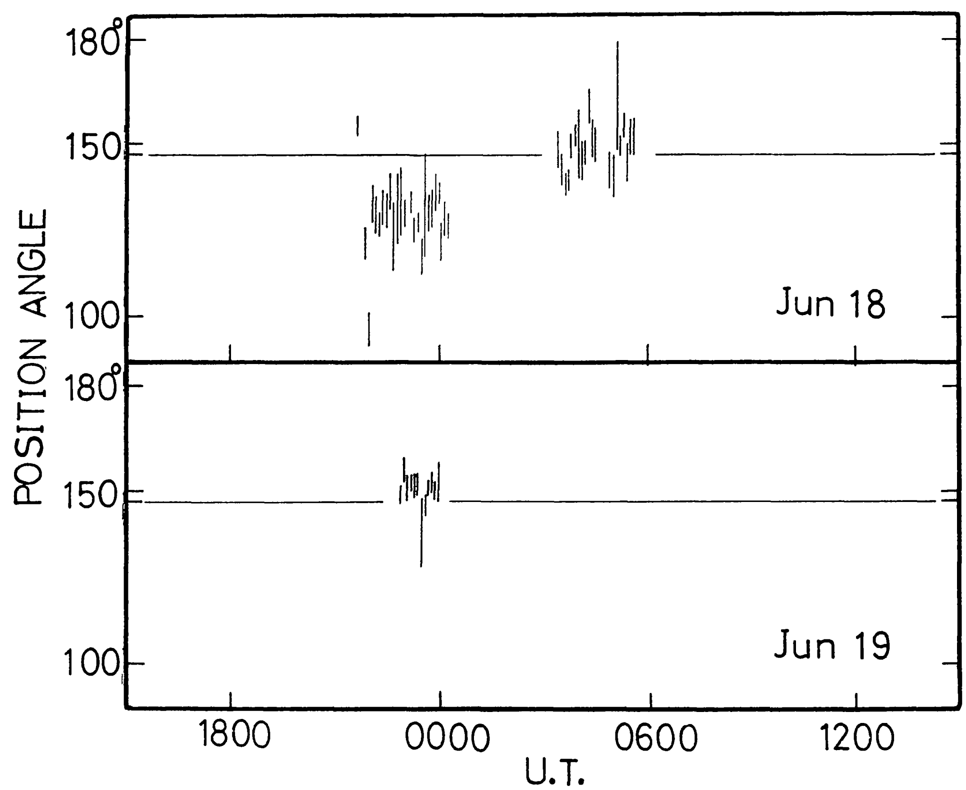

FIG. 2g. Same as Figure 2a, but for June 18 and 19.

referred to the antenna for "on" positions, and from 200 to 0 degrees for "off" positions. "On" and "off" positions were switched every 3 minutes, therefore we could determine a polarization angle every six minutes.

Instrumental polarization was corrected for by observing the non-polarized radio source Ori A, and the weakly polarized source Cas A. Fluxes were calibrated with reference to Ori A.

On June 14, 15, and 16, the two procedures for eliminating the solar emission gave identical results, and we think therefore that this error has been removed. Before June 13 and after June 17, the side lobe contribution from the sun is low, and therefore it is not necessary to pay particular attention to this point for these days. A detailed description of the observations and the data reduction, together with a comparison of results obtained by the two procedures, will be given elsewhere (KAWAJIRI, KAWANO, SOFUE, and KAWABATA 1972).

Figures 2a–2g show plots of position angles obtained using the first procedure. The intrinsic position angles undisturbed by the solar corona are determined to be $147^\circ \pm 3^\circ$, when Tau A is sufficiently far from the sun. At the closest approach of the source to the sun, on June 14, 15, 16, and 17, the position angle varies by some multiples of ten degrees around the undisturbed value.

The observed variation of position angle is rather irregular, and the average variation is small compared to the irregular variations. The irregular variations appear to have two distinct time scales of about 2 and 10 hours, respectively. Typical examples of such variations are seen in the results of June 15 (Figure 2d). Up till 01:00 UT, the position angle remains almost constant at about 80°. Then the position angle starts to increase rapidly, attaining a maximum value of about 180° at 02:00 UT. It then decreases until about 03:00 UT. A similar variation occurred also at about 03:00 UT on June 16 (see Figure 2e).

In addition to this rapid change, an oscillatory variation with a minimum just before 00:00 UT and a maximum at about 06:00 UT in the results of June 15 can be seen in Figure 2d. Oscillatory variations suggest that the direction of the magnetic field reverses in local structures.

The position angle from June 15 to 17 inclusive is systematically lower than the undisturbed value by about 15 degrees. The systematic shift of position angle is probably due to an overall magnetic field. However, as has been already mentioned, this average variation is small compared with irregular variations, which makes it difficult to construct a precise model for the overall distribution of the electron density and the overall structures of the magnetic field.

3. *Interpretation of the Results*

The total Faraday rotation for linearly polarized radio waves propagating through a magneto-ionic medium is given by

$$\Omega = \chi - \chi_0 = \frac{K}{f^2} \int N_e B_{\parallel} ds \,, \tag{1}$$

where

$$K = \frac{e^3}{2\pi m_e^2 c^2} \,. \tag{2}$$

Here χ is the rotated position angle, and χ_0 is the undisturbed position angle, which for Tau A is determined to be $147°\pm3°$ at the frequency $f=4170$ MHz. N_e, $B_{/\!/}$, and ds are the electron density, the line of sight component of the magnetic field and the line element along the line of sight, respectively. Other symbols have their usual meaning. If N_e, $B_{/\!/}$, ds, and Ω are measured in cm^{-3}, gauss, solar radii, and degrees, respectively, then the constant K is equal to 9.44×10^{16}. The rotation angle is then given by

$$\Omega=5.42\times10^{-3}\int N_e B_{/\!/} ds\ , \tag{3}$$

for the frequency $f=4170$ MHz.

(i) The overall structure of the magnetic field in the outer corona

We will make order-of-magnitude estimates for the Faraday rotation in the outer corona, assuming first a dipole and then a radial magnetic field with the electron density varying as $(R/R_\odot)^{-2.5}$. Now, we integrate N_eB along the line of sight from infinity to the point closest to the sun. The rotation angle is approximately given by

$$\Omega\approx5.4\times10^{-3}N_{e0}B_{/\!/0}\left(\frac{l}{R_\odot}\right)\mathrm{deg.}\ , \tag{4}$$

where l is a characteristic path length, and N_{e0} and $B_{/\!/0}$ are typical values of N_e and $B_{/\!/}$ respectively. The plane of polarization will rotate by an amount given by equation (4) when the wave travels from infinity to the point closest to the sun. If the axis of the dipole is perpendicular to the line of sight and the distribution of electron density is symmetric, it will rotate again by the same amount in the opposite sense in travelling from the point of closest approach to infinity. Therefore the amount of Faraday rotation in this case vanishes if the integration is carried out from the source to the earth. For a symmetric distribution of electron density the net Faraday rotation has non-vanishing value only due to the inclination of the dipole axis. The rotation angle is about a tenth of that obtained from equation (4), when the inclination is a few degrees as is the case for the sun. The distribution of the electron density in the corona, however, is strongly asymmetric, and this produces roughly the same amount of Faraday rotation as that given by equation (4).

We assume that the electron density is given by $N_e\approx2.5\times10^6(R/R_\odot)^{-2.5}\,cm^{-3}$ (the value given by SAITO [1970] for the quiet corona in the equatorial plane) and the dipole magnetic field is given by $B\approx1\times(R/R_\odot)^{-3}$ G. Then the magnetic field is nearly perpendicular to the line of sight at the point closest to the sun on the line of sight. The electron density and the magnetic field strength decrease at large distances. Then $N_eB_{/\!/}$ has the maximum value in the middle. Now we use $l\approx5\,R_\odot$, corresponding to the minimum elongation of Tau A, and $R\approx7.5\,R_\odot$, corresponding to a distance giving the maximum contribution to the Faraday rotation. Tnen we obtain $\Omega\approx1°$. The estimated value of the rotation angle is small compared with the observed overall rotation angle. Since neither the assumed values of the magnetic field at the solar surface nor the electron density in the outer corona can be increased by a factor of ten or more, the dipole field seems not to be a realistic model in the polar and high latitude regions at a distance of 5–10 $R_\odot$, at least during the period of maximum solar activity.

Next we consider the case of a radial magnetic field, given by $B\approx1\times(R/R_\odot)^{-2}$ G.

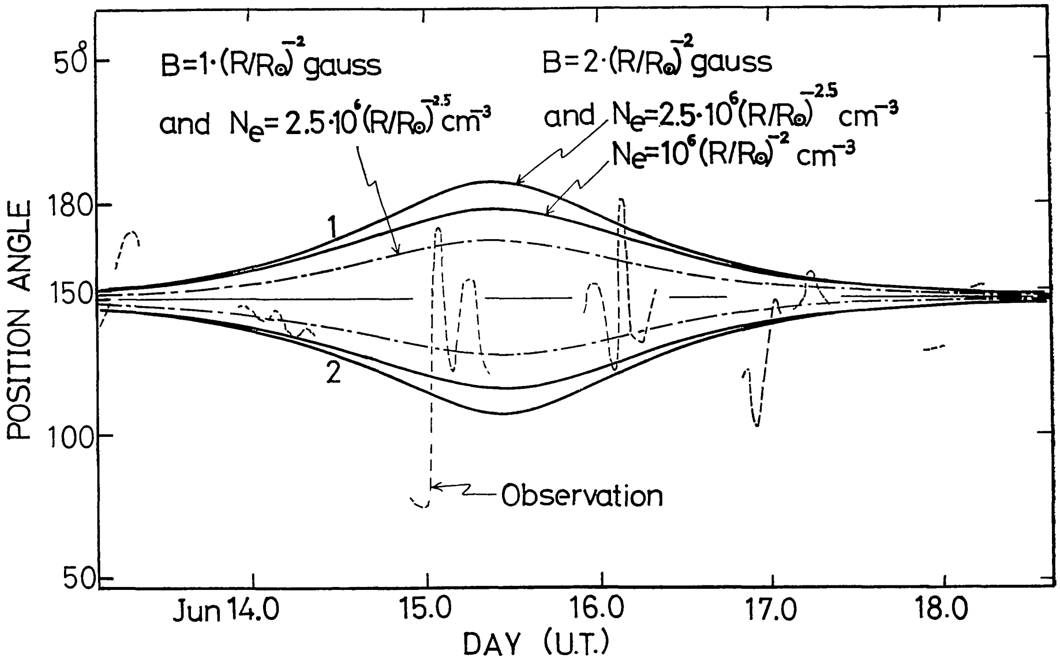

FIG. 3. Calculated position angles assuming a radial magnetic field. Curves 1 and 2 correspond to opposite field directions. Dotted curves show the smoothed variation of position angle from the observations. Compare the order of absolute magnitudes of the systematic variation in the observed values and those of the calculated values.

Values of χ estimated similarly to those for a dipole field are shown in Figure 3 as a function of the transit time of Tau A. This estimation gives $\Omega \approx 20°$ near the time of the closest approach of Tau A to the sun, and this value is approximately the same as the observed overall variation of position angle averaging out the irregularities. This suggests that the overall structure of the magnetic field in the maximum phase of solar activity is closer to a radial field than it is to a dipole field.

(ii) Local structure of the magnetic field and electron density in the outer corona

From June 14 to 17 inclusive, the observed position angle of Tau A has two distinct variations with time scales of 2 and 10 hours, respectively. Since no significant microwave outburst which will affect the side lobe contributions has been reported during the observations (Toyokawa Observatory 1971; Aeronomy and Space Data Center 1971), these variations presumably correspond to local structures in the magnetic field and electron density in the solar outer corona.

The observations of interplanetary scintillations by EKERS and LITTLE (1971) show that the velocity of irregularity at the distance of 6–40 $R_\odot$ is 200 km s^{-1}. If we assume the velocity of outflow is 200 km s^{-1}, then the observed time scale of 10 hours corresponds to a radial extension of 10 $R_\odot$ or more if we take into account the apparent motion of Tau A. This suggests that the structure responsible for the 10 hour variation of position angle is a stationary one such as a coronal streamer.

The observed time scale of 2 hours corresponds similarly to a radial extension of 2 $R_\odot$ or more. It cannot be decided whether the 2 hour variation is due to a narrow core streamer as described in (iii) or a sporadic outflow in the outer corona. However, the 2 hour variation seems to be located close to the center of the 10 hour oscillatory variation, as is seen in Figures 2d and 2e for June 15 and 16, and then the model of a core streamer will be preferred. Henceforth, we will assume the observed variations correspond to stationary structures such as coronal streamers.

The apparent velocity of Tau A relative to the sun, v, is 2.5 minutes of arc/hour. Let d and D be the characteristic sizes of a local structure and the apparent diameter of Tau A respectively, then the time scale of the variation of the Faraday rotation due to such a structure is related to these given variables by

$$\tau \approx \frac{d+D}{v}\,. \tag{5}$$

Inserting the values $D\approx 4$ minutes of arc, and $v=2.5$ minutes of arc/hour, we obtain a value of d equal to 0.1 and $1\,R_\odot$, corresponding to $\tau\approx 2$ and 10 hours respectively.

Assuming streamer-like structures are the cause of the observed variations, as illustrated in Figure 4, we can estimate the variation in electron density and magnetic field in the streamers.

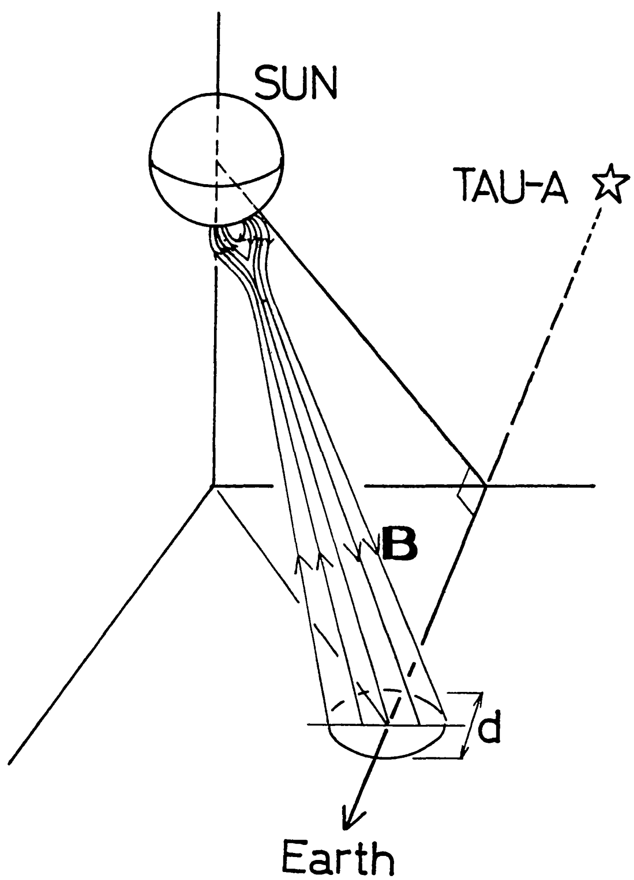

FIG. 4. Schematic configuration of the fluctuated structure in the outer corona. Direction of the magnetic field reverses in the local structure, which is identified to be an extension of a helmet streamer.

a) Small scale local structures: The rotation angle due to a local structure is given by

$$\tilde{\Omega} \approx 5\times 10^{-3} \tilde{N}_e \tilde{B} \left(\frac{d}{R_\odot}\right) \text{deg.}\,, \tag{6}$$

where the tilde over letters represents quantities in the local structure. Putting $\tilde{\Omega}\approx 50^\circ$ and $d\approx 0.1\,R_\odot$, we obtain

$$\tilde{N}_e \tilde{B} \approx 1\times 10^5\ \text{G cm}^{-3}\,. \tag{7}$$

If we assume that $N_e \propto B$ in a structure extending radially as a streamer, then the ratio of the product $N_e B$ in the local structure to the average of this product is given by

$$\frac{\tilde{N}_e \tilde{B}}{\bar{N}_e \bar{B}} \approx \left(\frac{\tilde{N}_e}{\bar{N}_e}\right)^2\,. \tag{8}$$

Here $\bar{N}_e$ and $\bar{B}$ are the average values of the electron density and magnetic field respectively. If we take $\bar{N}_e \approx 2\times 10^4\ \text{cm}^{-3}$ and $\bar{B}\approx 1\times (R/R_\odot)^{-2}$ G with $R\approx 7\,R_\odot$, then we obtain

$$\frac{\tilde{N}_e}{\bar{N}_e} \approx \frac{\tilde{B}}{\bar{B}} \approx 15\,. \tag{9}$$

Thus the electron density and magnetic field in the small scale structures are about a factor of 15 greater than the average value. These small scale structures we identify with streamers with small diameters.

b) Large scale local structures: Inserting $\tilde{\Omega}\approx 30^\circ$ and $d\approx 1\,R_\odot$, the relation for the Faraday rotation due to a local structure gives

$$\tilde{N}_e \tilde{B} \approx 0.6\times 10^4\ \text{G cm}^{-3}\,, \tag{10}$$

for the relatively large scale ones, leading to

$$\frac{\tilde{N}_e}{\bar{N}_e} \approx \frac{\tilde{B}}{\bar{B}} \approx 4\,. \tag{11}$$

As is seen in Figure 2, these local structures give an oscillatory variation in the rotation measure. If such structures correspond to coronal streamers, then the oscillation suggests that the direction of the magnetic lines of force reverses in a local structure, i.e., a streamer consists of two parts, with the direction of the magnetic field having the opposite sense in each part. This interpretation agrees with the picture of the magnetic field configuration in a helmet streamer as shown in Figure 4.

The scale length $1\,R_\odot$ deduced here agrees with the sizes of streamers derived from data of type III solar bursts by FAINBERG and STONE (1971). They have obtained scale lengths of 1 to 2 $R_\odot$ for streamer density inhomogeneities at a distance of $10\,R_\odot$ from the sun. The variations of the electron density estimated here are in agreement with those obtained by PNEUMAN and KOPP (1970) from theoretical considerations. They have obtained variations of a factor 3–4 above the background at 5–10 $R_\odot$.

(iii) The structure of a streamer with a core

As is seen in Figures 2d and 2e, for June 15 and 16, the rapid variation of position angle is superimposed on the slow oscillatory variation, and seems to be nearly at the center of the oscillatory variation. Assuming that these small scale structures are physically correlated with the large scale ones, we propose the following model for a streamer.

A streamer comprises two tubes with magnetic lines of force in opposite directions separated by a neutral sheet. Near the neutral sheet, the matter density and magnetic field are a factor of 4 greater than their ambient values. This highly condensed region (the "core streamer") has a diameter of 0.1 to $0.2\,R_\odot$, while the diameter of the main streamer is about $1\,R_\odot$, at a solar distance of 5–10 $R_\odot$. Steep gradients in the electron density and field strength, together with the reversal of the field direction at the neutral sheet, will cause a sharp variation in the observed rotation measure, as observed on June 15 and 16. Such a structure for the streamers has been suggested qualitatively by STURROCK and SMITH (1968).

4. *Summary*

The variation of the position angle of Tau A during an occultation by the solar corona was measured at $\lambda=7.2\,$cm. The observational results suggest that the overall structue of the magnetic field is radial rather than dipole (in a period of maximum solar activity).

The observed position angle has spiky variations with a short time scale and oscillatory variations with a long time scale, suggesting the existence of inhomogeneities in the magnetic field and electron density with characteristic scales of 0.1 and $1\,R_\odot$, respectively. The irregular variation of the magnetic field and electron density are about 15 and 4 times greater than the average value, for local structures of scales 0.1 and $1\,R_\odot$ respectively. The oscillatory variation in rotation measure suggests that the field direction reverses in a local structure, which is identified with the radial extension of a helmet streamer.

The data suggest that streamers are composed of two tubes with magnetic field in opposite senses separated by a neutral sheet. Around the neutral sheet there exists a core streamer with field strength and electron density about 4 times greater than the ambient values in the streamer. The diameter of the core streamer is about one tenth that of the main streamer.

The authors wish to thank Dr. T. Ishida, Chief of the Kashima Branch of the Radio Research Laboratories, for providing the opportunity to do the experiment. They are indebted to Messrs. T. Ojima and H. Ogawa for discussions and for their cooperation in the observations. They are also indebted to Mrs. Y. Minokawa, Messrs. M. Fukui, T. Omotaka, M. Inoue, K. Hamajima, T. Murai, and K. Kawamura for assistance in the observations and data reduction.

They also wish to thank Dr. M. Fujimoto and Dr. A. H. Nelson for a critical reading of the manuscript. A part of the data reduction was carried out on a FACOM 230-60 at the Computing Center of Nagoya University.

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