THREE-COMPONENT MAGNETIC FIELD OF SUNPOTS

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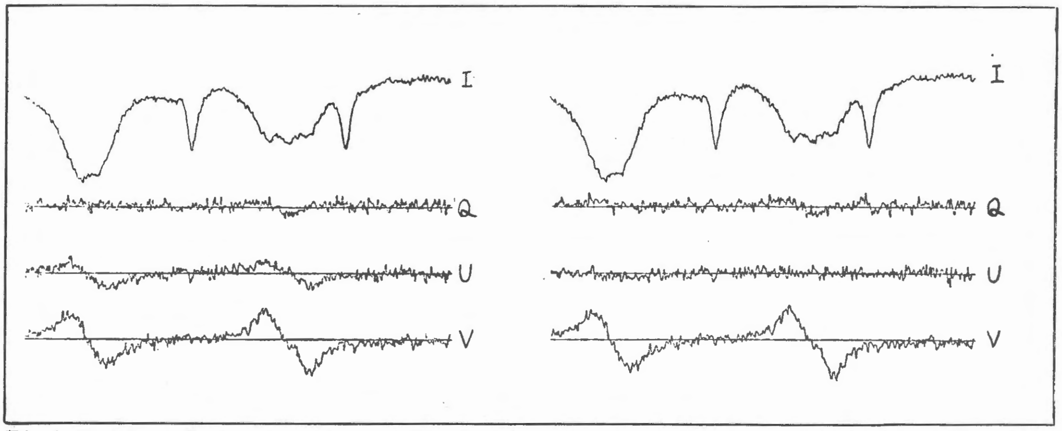
Four Stokes parameters of sunspots were observed with the photographic polarimeter fed to the Okayama 65cm solar coude telescope, and the three-component magnetic field was obtained. The Okayama solar coude telescope has two tilting mirrors (the coude mirror and the auxiliary mirror) which affect the polarization of the light from the sun. This instrumental effect should be corrected as shown in figure 1.



Figiure 1. Polarization effect of the tilting mirrors. Original Stokes parameters are on the left and the corrected ones on the right. Instrumental linear polarization (U) is removed in the right hand record.

The calibration of the instrumental polarization showed, wihtin the photometric accuracy, that the effect of the auxiliary mirror was negligible and the effect of the coude mirror was in good agreement with the calculated one from the alminium optical constants given by Shulz

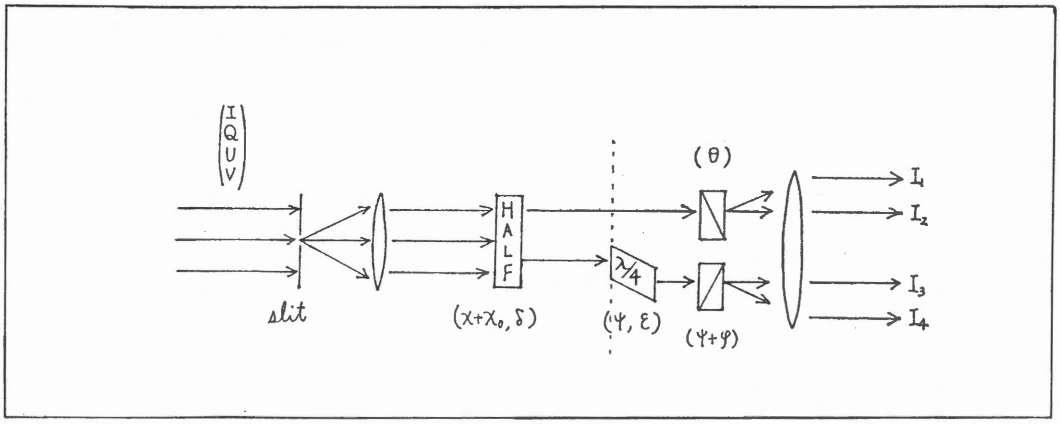


Figure 2. Schematic diagram of the polarimeter optics. A light beam is divided into four beams according to its polarization state. The symbols $(\chi+\chi_0)$, ψ, $(\psi+\varphi)$, θ show the direction of the crystal axis of a half wave plate, of a quarter wave retardar and of the Rochon analyzers respectively. And δ is the retardation of a half wave plate and ε is that of a quarter wave retardar. If the polarimeter is well constructed, $\theta=\psi+\varphi=\chi_0=45°$, $\psi=0°$, $\delta=180°$, $\varepsilon=90°$.

(1954) . Therefore, the instrumental effect was corrected by this calculation. Figure 2 shows the structure of the polarimeter, which is composed of a half wave plate, the Fresnel rohm as a quarter wave retardar, and the Rochon prism as an analyzer. The light entering the polarimeter is divided into four beams I1,I2,I3,I4 according to its polarization state. If the polarimeter is well constructed,

$$I1=(I-U)/2,\ I2=(I+U)/2,\ I3=(I-V)/2,\ I4=(I+V)/2 \quad (\text{for } X=0°)$$
$$I1=(I+Q)/2,\ I2=(I-Q)/2,\ I3=(I-V)/2,\ I4=(I+V)/2 \quad (\text{for } X=22°5)$$

where, X is rotational angle of the half wave plate, and the sign of V is defined after the convention of radio wave thory. The calibration of the polarimeter parameters (e.g.,actual retardation of the half wave plate, actual direction of the crystal axis etc.) was made within the photometric accuracy. As seen above, we need two exposures and eight strips of a spectrum, to have a complete set of Stokes parameters. As four beams have different paths, illumination and relative positions among the four strips are different. This difference was corrected with the use of the continuum level and the atmospheric lines.

A new method by Makita (1979) was taken in order to interpret the polarimetric spectra and determine the three-component magnetic field.

Makita's method assumes that:

(i) Magneto-optical effect is negligible.

(ii) The variation of any physical quantity is small along the layers of line formation.

(iii) The line profile can be divided into symmetry part and asymmetry part, the latter can be dealt with separately, following to E. Landi Degl'Innocenti and M. Landi Degl'Innocenti (1977) .

Assumption (i) is expected ,if the polarization degree is not so high. It implies U Should be zero at every wavelength, when a coordinate parallel to the azimuth of magnetic vector is taken. This transformation from the observing coordinate is performed as follows,

$$Q' = Q\cos 2\varphi + U\sin 2\varphi \quad (=\sqrt{Q^2+U^2}) \qquad (1\text{-}1)$$

$$U' = -Q\sin 2\varphi + U\cos 2\varphi \quad (=0 \qquad) \qquad (1\text{-}2)$$

The linear polarization in the new coordinate, Q', is obtained from the first equation (see in the parenthesis) , and the azimuth of the magnetic field vector, φ, is derived from the second equation, since U' should vanish. Hereafter we omitt the prime from Q' and U'. The analytic solutions of the polarization transfer equation, W1,W2,W3, have relations with the observing quantities,I,Q,V as follows.

$$W1 = I + (Q\sin\Psi + V\cos\Psi) \qquad (2\text{-}1)$$

$$W2 = I - (Q\sin\Psi + V\cos\Psi) \qquad (2\text{-}2)$$

$$W3 = Q\cos\Psi - V\sin\Psi = 0 \qquad (2\text{-}3)$$

where, Ψ is a known function of v,VD,a,VH,ψ, and v is the wavelength deviation from the line center normalized by Doppler width VD, a is a damping constant normalized by VD, VH is Zeeman split of -component normalized by VD, and ψ is the tilt of the magnetic field vector to the line of sight. As W3 is zero at every wavelength, $(Q\sin\Psi+V\cos\Psi)$ reduces to $\sqrt{Q^2+V^2}$. We can calculate W1 and W2 using only the observable quantities I,Q,V. As the analytic solutions, W1 and W2, have the same form except for the absorption coefficient (see Makita eq.(2.12)), the multiplet method is applied to W1 and W2.

$$\text{If } W1(v1)=W2(v2), \quad \text{then } \alpha 1(v1;VD,a,VH,\ )=\alpha 2(v2;VD,a,VH,\ ) \qquad (3)$$

where, $\alpha 1$ and $\alpha 2$ are the absorption coefficients of W1 and W2 respectively, and both are the known function of v,VD,a,VH,Ψ. The multiplet method is also applied to W2 of two lines belonging to the same multiplet number.

$$\text{If } W2(v2)=W2'(v2'), \quad \text{then } \alpha 2(v2;Vd,a,VH,\Psi)=\alpha 2'(v2';VD,a,VH,\Psi) \qquad (4)$$

where, the prime means the different line. The condition of eq.(4) enable to obtain VD,a for the case of a longitudinal magnetic field. Eq.(2-3) and (3) is applied to the line 6302.5 Fe which has Zeeman g-factor 2.5, and eq.(4) to this line and the same multiplet line 6301.5 Fe. Actually, we modify the eq.(3) and eq.(4) in order to treat every conditional equation eaqually and (O-C) of the observing quantities directly. Consequently, the parameters VD,a,VH,Ψ are determined by the least square method using the following conditional equations.

$$Q\cos\Psi - V\sin\Psi = 0 \qquad \text{for } \lambda 6302.5 \qquad (5\text{-}1)$$
$$(\partial W2/\partial v|_{v2^0})(v2-v2^0)=0 \qquad \text{for } \lambda 6302.5 \qquad (5\text{-}2)$$
$$(\partial W2'/\partial v|_{v2^{0\prime}})(v2'-v2^{0\prime})=0 \qquad \text{for } \lambda 6301.5 \text{ and } 6302.5 \qquad (5\text{-}3)$$

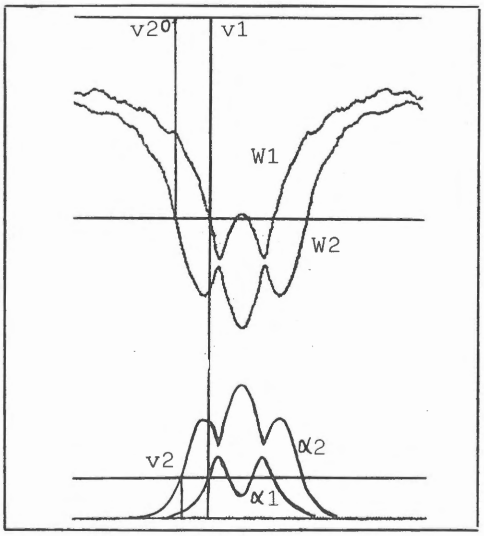


Figure 3. Application of the multiplet method. The upper is spectral line and the lower is absorption coefficient. We take v1 at first, then v2 and v2 are derived from the relations, $W1(v1)=W2(v2^0)$ and $\alpha 1(v1)=\alpha 2(v2)$. Parameters VD,a,VH,$\Psi$ are determined so as to minimize the difference between $v2^0$ and v2 for all the different v1.

The meaning of v2 and $v2^0$ are shown in figure 3. In the eq.(5-3), the ratio of the gf value of the two lines was assumed to be 3, which is given by LS coupling assumption.

The validity of Makita's method was investigated by the residual error of U and eq.(5-1), (5-2) and (5-3). In most case it is within the photometric accuracy. Following the above procedure, two sunspots were studied. One is an active sunspot in which several large flares occurred, and the other is a stable unipolar sunspot which lasted 7 rotations. We should note that there exists an ambiguity caused by the two branch of φ and $\varphi+\pi$. The selection of this branch is carefully done by considering the reasonable spatial distribution of the magnetic vector.

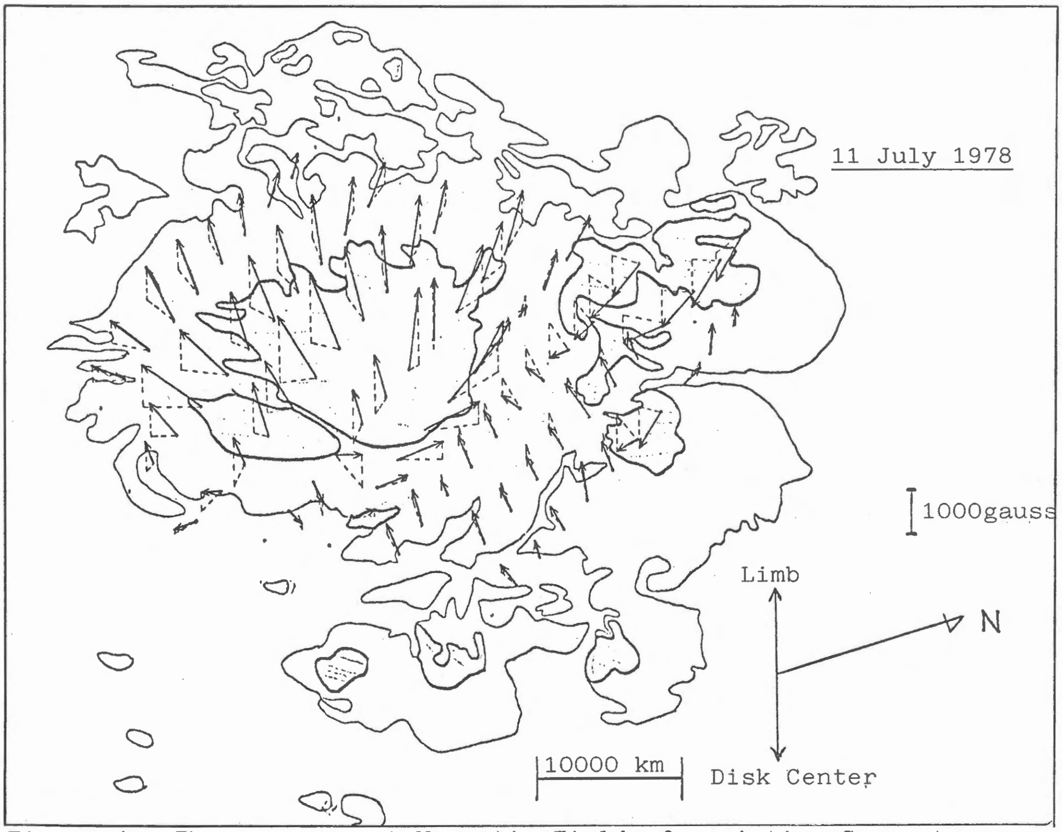


Figure 4. Three-component Magnetic Field of an Active Sunspot. solid lines represent the magnetic vector, and broken lines its vertical and parallel components to the solar surface,respectively. The lenght of the line shows the projection of the above three vectors to the line of sight. Vertical of the solar surface inclined by 45 .