WIDE BAND POLARIZATION OF SUNSPOTS

Mitsugu Makita
Tokyo Astronomical Observatory, University of Tokyo,
Mitaka, Tokyo, Japan

1. Observations

The wide band polarization of sunspots was first systematically observed by Leroy (1962). He measured the linear polarization and interpreted it as the differential saturation effect of π and σ Zeeman components. In 1974, Illing et al. (1974a, 1974b, 1975) measured all the polarization components, i.e., Stokes parameters, and found a net circular polarization. Our recent preliminary observation, made at the Okayama Astrophysical Observatory, almost confirms their result. The first two observations used a color or interference filter and put a polarimeter at the prime focus. Ours is made at the coude focus with the use of two polarization compensators (Makita 1970), and with a 10m-spectrograph. A summary is given in table 1.

Table 1. Observations of the Wide Band Polarization of Sunspots

observer & site	spectral range	spatial resolution	remarks
Leroy(1962), Meudon	4400A-4900A (filter)	5 arc sec.	only the linear polarization is measured.
Illing et al.(1974), Mt. Haleakala	5250A-5350A (filter)	4 arc sec.	
Ours, Okayama	5243A-5257A (spectrograph)	6 arc sec. x 3 arc sec.	

The Stokes parameter map of the sunspot thus obtained so far is listed in table 2. Our maps are shown in figure 1. They need some correction for a spatial distortion due to an indirect guiding of the

Figure 1. Stokes Parameter Maps Obtained at Okayama. From top to bottom, white light picture, circular polarization V(solid line shows a positive polarity), linear polarization L(dotted line shows a depression), and direction of the linear polarization, the bar length is equivalent to about 4 arc sec. Broken line is along V=0. Thick line shows the photosphere-penumbra boundary obtained from the intensity record. Comparison of this with the white light picture shows a image distortion of the scanning system. A step of the isopolarization curve is 5.10^{-4} and 2.5.10^{-4} for L and V, respectively. The outermost isopolarization curve also corresponds to this value. C shows the disk center direction.

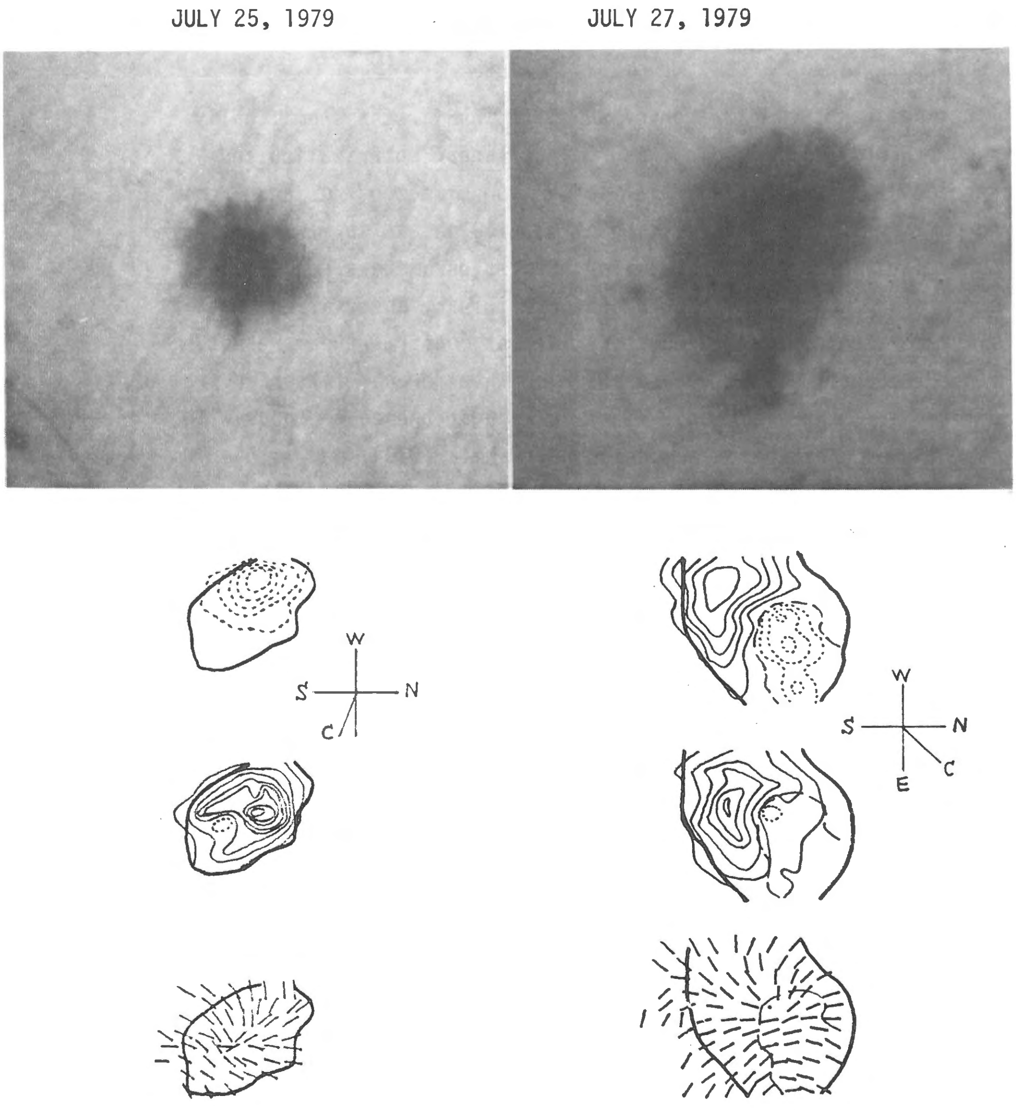
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Figure 1. Stokes Parameter Maps Obtained at Okayama. (continued)

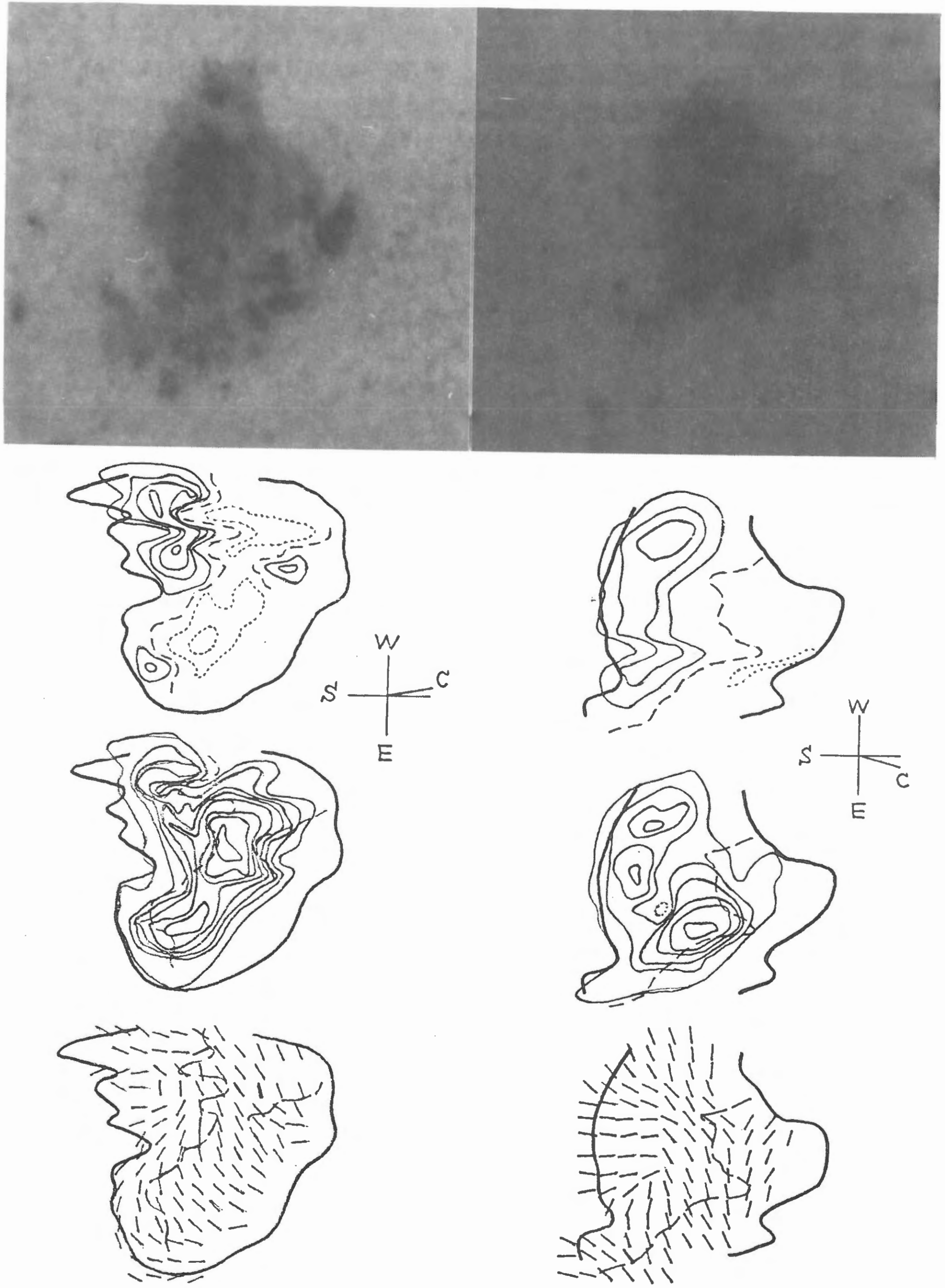

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Table 2. Stokes Parameter Map

date	spot no.*	sin θ**	cos θ**	remarks
1974 Feb.15 20h(UT)	26p,f	0.44	0.90	Illing et al.(1974b)
21h	21p	0.79	0.61	"
Feb.19 19h	27f	0.37	0.93	Illing et al.(1975)
				also observed in 5824A-5844A
Mar.26 2h	39p	0.31	0.95	Illing et al.(1974a)
27 2h	"	0.53	0.85	"
27 19h	"	0.67	0.74	"
28 20h	"	0.81	0.58	"
29 2h	"	0.85	0.53	"
29 21h	"	0.93	0.37	"
1979 Jul.25 6h	330	0.40	0.92	see figure 1
27 6h	342p	0.36	0.93	"
Nov.22 4h	562p	0.54	0.84	"
24 0h	"	0.45	0.89	"

* from "Solar Data"(Russian), p: preceding sunspot, f: following sunspot

** θ is heliocentric angle of the sunspot.

solar image by a side telescope, but this is not performed there. For the circular polarization, we adopt the sign convention in radio-wave theory, instead of in optics.

2. Origin of the Polarization

The observed polarization was assumed, by Leroy (1962), to be due to the Zeeman effect of the spectral line. Illing et al. (1974a, 1974b, 1975) also selected the same assumption. Figure 2 shows an example of our observation with and without a mask, put at the spectrograph exit and stopping the light at the strong spectral lines. (The mask should be carefully inserted, since the line wing left uncovered may fairly contribute to the net polarization) This clearly proves that the main polarization source is the strong spectral lines.

The interpretation of the linear polarization was beautifully done by Leroy (1962), therefore, we do not discuss it here. For the circular polarization, Illing et al. (1975) first proposed a joint effect of the

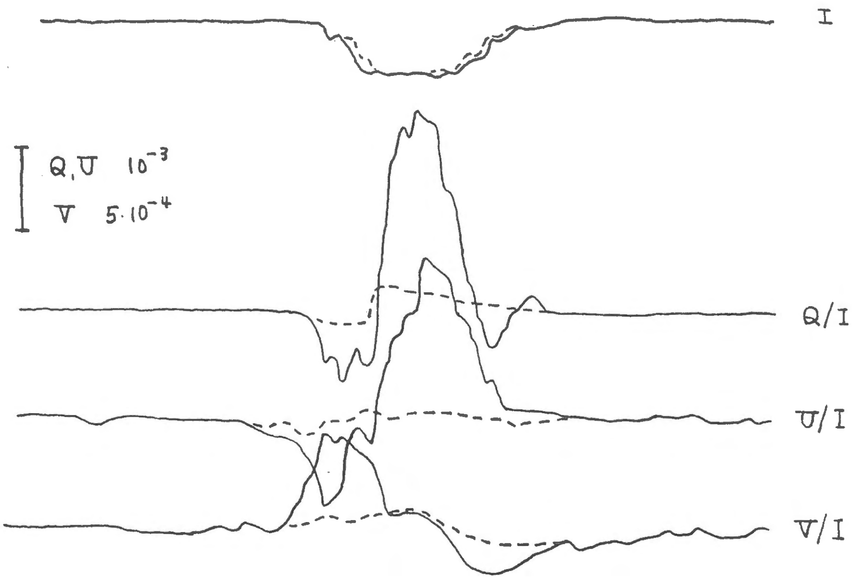
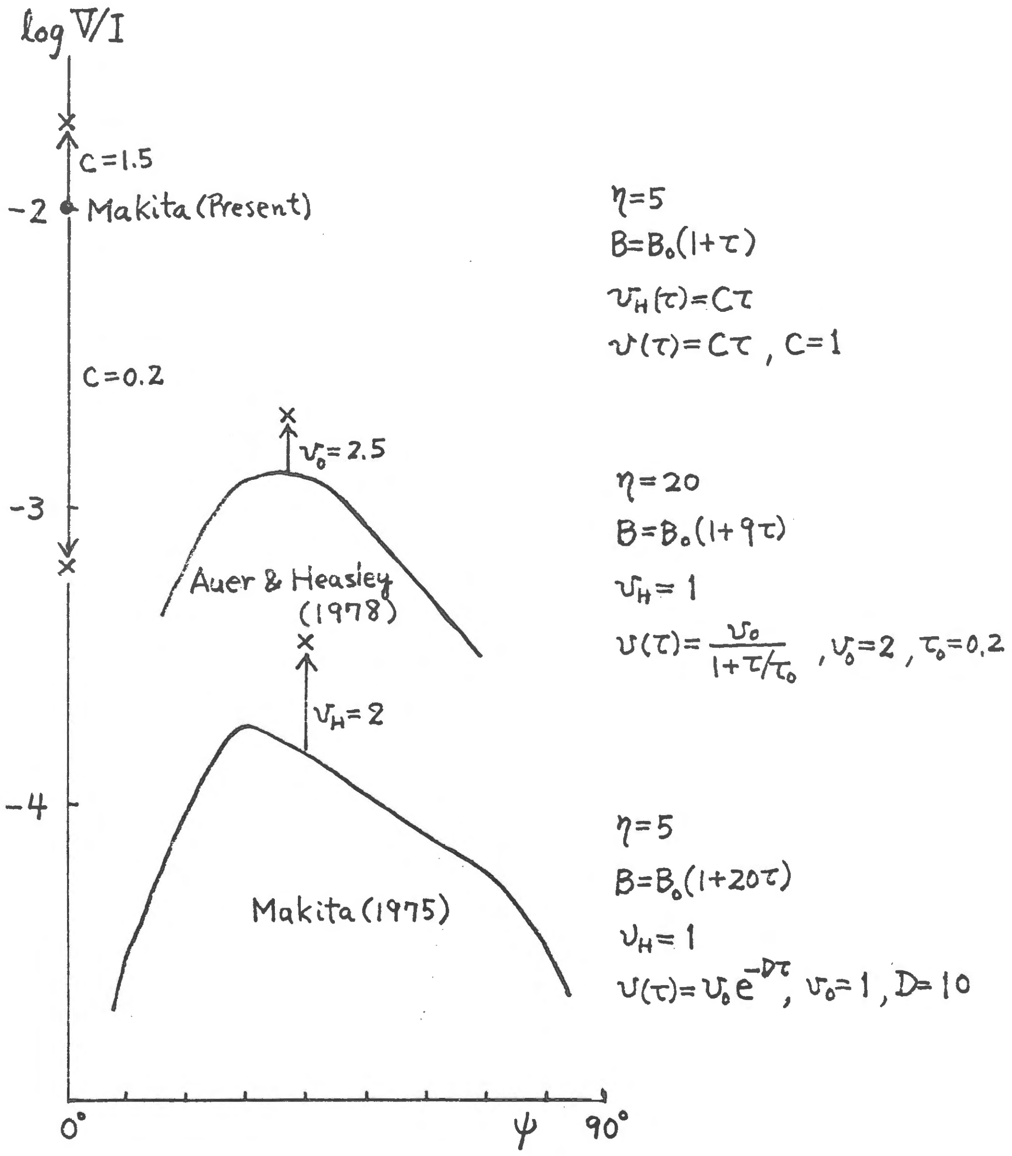


Figure 2. Observed Stokes Parameters of a Sunspot with and without Strong Lines. Broken curves show the observation without strong lines.

Nov. 24, 1979

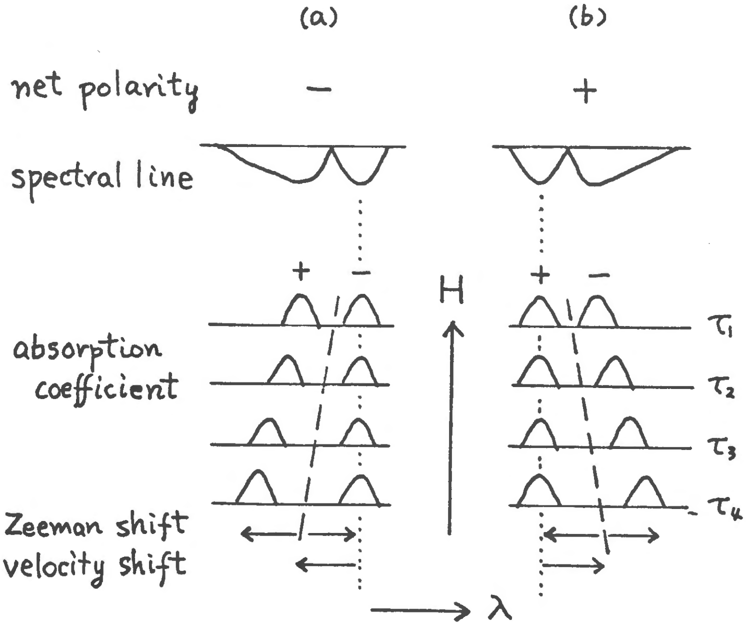
velocity and magnetic field gradients. Since the absorption coefficient of the σ component is symmetric against the line center, the observed net circular polarization implies some kind of asymmetrized effect in the line-forming layers. This is the velocity gradient. In the homogeneous magnetic field, it makes the coupling of the π and σ components asymmetric and causes a differential saturation effect. Under this assumption, the net circular polarization of a single line was estimated by Auer and Heasley (1978) and myself (1975, unpublished), for the atmosphere of the linear source function, $B=B_0(1+\beta\tau)$, and of the constant ratio of the line-to-continuum absorption coefficient, η . Figure 3 gives the result for the magnetic field at the disk center, having the various tilt, ψ , against the line of sight. At ψ =0° and 90°, there is no coupling of the π and σ components and no net circular polarization. The calculated value is at most 2.10^{-3}, just as much as the observed polarization. Accordingly, the strong saturated lines with η =20 must fully occupy the observed wavelength range.

Figure 3. Calculated Net Circular Polarization of a Single Line. The magnetic field is at the disk center and has a tilt ψ against the line of sight. An atmosphere with a linear source function B and a constant ratio η of the line-to-continuum absorption coefficient is assumed. Velocity $v(\tau)$ and Zeeman shift v_H, both normalized by the Doppler width, and the other parameters in the calculation are given in the right side. × shows the polarization when a different parameter, assigned by the arrow, is adopted.



This may not be probable and the other more powerful polarizing mechanism should be considered. Figure 4 shows such an another saturation mechanism, which is along the first proposal by Illing et al. (1975). Suppose the magnetic field is longitudinal and the velocity shift at every depth is equal to the Zeeman shift. Then, one σ component of the absorption coefficient is unshifted and suffers a greater saturation than the other component. A calculation for this case, under the same assumption of the atmosphere, gives the value of 10^{-2} as shown in figure 3. Consequently, it will be reasonable to conclude that both the velocity and magnetic field shifts have to vary within a unit optical depth by a few times of the Doppler width, in order to explain the observed net polarization of 10^{-3}.

Figure 4. Differential Saturation of the Zeeman σ Components. In the case of a longitudinal magnetic field, absorption coefficients at four atmosphere levels (τ_1 , τ_2 , τ_3 , τ_4) are schematically shown. Due to the combined effect of the Zeeman and velocity shifts, one σ component suffers a greater saturation than the other. The resultant spectral line has a non-vanishing net polarization.



3. Discussion on the Net Circular Polarization

The velocity field in the penumbra is known as the Evershed flow. By St. John's analysis (St. John 1913), it is an outward radial flow from the umbra and its speed increases in deeper layers. If we accept this and consider a sunspot with a positive magnetic polarity, N, the polarity of the wide band observation is expected from figure 4, following the conclusion in the preceding section. (Since the differential saturation effect of σ components is essential, the idea of figure 4 will be applicable to the case of non-longitudinal magnetic field) In the limb side penumbra, both the magnetic line of force and the flow go away from us. The figure 4b shows this, if we reverse the magnetic polarity. Accordingly, a net negative polarization is expected there. In the center side penumbra, with the approaching flow and the positive magnetic polarity, the figure 4a is the case, and the expected net polarity is also negative. Since the umbra is reported to have no measurable velocity (Beckers 1977), its net polarization will be negligible. Consequently, we expect that the net polarity is the same throughout the sunspot and the net polarization is weak in the umbra and at places with negligible longitudinal magnetic field.

The 13 circular polarization maps listed in table 2 are not consistent with the above expectation. They show a strong limb side polarization, and, in the center side, a weak or negligible reverse polarization (ours) or a 'speckle' with the reverse polarity (Illing et al. 1974a, 1974b, 1975). If the limb side polarity is assumed to be principal, the correspondence between the magnetic and net polarization polarities is as given by Illing et al. (1974b) and agrees with our expectation. However, the existence of the opposite polarity in the center side of the sunspot will either force to reconsider the conclusion in the previous section, or demand some complex velocity and magnetic structure, different from that given by St. John (1913).

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