# ON THE INTERPRETATION OF THE $\pi$-COMPONENT SPLITTING IN SUNSPOT SPECTRA

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**Abstract.** It is shown that in order to explain the observed splitting of the $\pi$-component in the sunspot umbra spectrum by the hypothesis of the coexistence in sunspots of weak- and strong-field regions with opposite polarities, one has to admit the additional assumption that in the weak-field regions the Doppler halfwidth ($\Delta\lambda_D$) and the ratio between line opacity and continuum opacity ($\eta_0$) are both less than those in the strong-field regions.

In recent works various authors discussed the problem of the splitting of the $\pi$-component in the Zeeman spectrum of sunspot umbrae (Severny, 1959; Deubner, 1967; Mogilevski *et al.*, 1968; Beckers and Schröter, 1968). In observations of the sunspot-umbra spectrum with polarization optics (for example, with a $\lambda/4$ plate and Wollaston prism) two polarized spectra are usually obtained, one of which has the intensity proportional to $I+V$, and the other to $I-V$. Here $I$ is the radiation intensity in the line, before passing the polarization optics, $V$ the intensity of the circularly polarized part of radiation. The effect of displacement of the $\pi$ component sub-components consists in splitting of the $\pi$ component of polarized spectra into two sub-components shifted relative to the line centre, this shift being oposite to the $\sigma$ component displacement. Thus, for a $\sigma$ component which is red-shifted, the corresponding $\pi$ sub-component is blue-shifted. This effect, as well as some other indirect considerations, were reasons to assume that the $\pi$ component in sunspot spectra (at least in the solar disk centre) cannot be explained by the presence of a transversal component of the field, but it is explained by the co-existence in the sunspot of regions with two different longitudinal fields: a strong field ($\approx 3000$ G) and a weaker field ($\approx 10$ times smaller) of opposite sign. These weak field regions are often identified with bright dots in sunspot umbra, although at present there are no direct observations confirming this identification.

In previous works it was supposed in fact that the hypothesis on the existence of regions with weak fields in the sunspot umbra should by itself be sufficient to explain the $\pi$ component splitting. However, as will be shown below, the problem is more complicated. We have calculated theoretical line profiles according to Unno's theory (1956) and attempted to adjust the parameters to bring them in agreement with the observations. In what follows, we shall briefly call the regions of strong and weak fields '$H_1$ and $H_2$ regions' respectively, and all physical parameters will have the suffixes 1 and 2 respectively.

Since the observations in the line centre are rather complicated because of the

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influence of diffuse light and the finite spatial and spectral resolution, and as spectral data of $H_2$ regions do not at all exist, we considered it unreasonable to undertake a precise fitting of the observed curves. We tried instead to obtain theoretical $I+V$ and $V$ curves with the same features as the observed curves, namely:

(1) In the $I+V$ parameter two maxima of different values are observed: a high maximum shifted from the line centre over a distance corresponding to 2000 to 3000 G field, and small maximum shifted to the opposite side over a $\approx 10$ times smaller distance, which corresponds to a field of 200–300 G.

(2) In the V parameter near the line centre a secondary maximum appears of opposite sign as compared with the sign of the primary maximum at this wing of the line. This phenomenon will be called the 'V reversion', while the corresponding secondary maxima are the 'reversal' maxima.

(3) The reversal maximum is 5–10 times nearer to the line centre than the primary maximum and approximately corresponds to a small maximum of $I+V$.

(4) The reversal $V$ maximum is 5–10 times smaller than the primary V maximum.

(5) The reversal maximum width is 5–6 times smaller than that of the primary maximum.

Hénoux (1968) suggested that $\pi$ component splitting may be explained by line saturation at large values of the transversal field. This effect really exists and becomes more pronounced for lines broadened by damping. However, saturation cannot explain the $V$ reversion. This fact was pointed out by Beckers and Schröter (1969) and is confirmed by our calculations.

Let us now consider whether the presence of a weak field could explain the above-listed features of the spectrum. At the beginning, the $I+V$ and $V$ curves were calculated for the radiation originated from one region. The calculations showed that

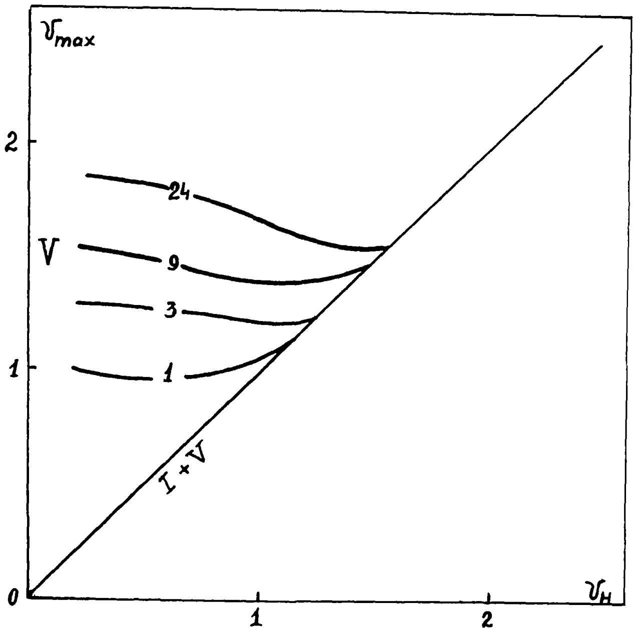

Fig. 1. Positions of maxima in $I+V$ and $V$ vs. $v_H$ at different $\eta_0$ values.

the positions of maxima in $I+V$ and in $V$ behave quite differently. While the $I+V$ maximum for longitudinal fields is always at a distance strictly equal to the Zeeman splitting value $\Delta\lambda_H$ (this law is valid for any weak field), the position of the $V$ maximum coincides with the $I+V$ maximum position and hence with $\Delta\lambda_H$ only for sufficiently large fields ($\gtrsim 1500$ G). For weaker fields the $V$ maximum position depends only on the form of the line contour, and therefore, for fields of $\approx 300$ G, the V maximum lies much further (5–7 times) from the line centre than $I+V$ maximum. Figure 1 plots the $I+V$ and $V$ maximum positions against the magnetic field strength for different values of the opacities ratio in the line and in the continuum $\eta_0$. The Zeeman splitting and wavelengths are expressed here in units of Doppler halfwidth of absorption coefficient $\Delta\lambda_D(v=\Delta\lambda/\Delta\lambda_D$, $v_H=\Delta\lambda_H/\Delta\lambda_D$; $\Delta\lambda_H=4.67\times 10^{-5}g^2H)$. To return to ordinary $\lambda$ and $H$ values it should be noted that for the line Fe I $\lambda$6302 Å $\Delta\lambda_D\approx 0.0375$ Å and that $v_H=1$ corresponds to $\approx 1000$ G. Thus, it follows from Figure 1 that for a weak field the $I+V$ maximum and $V$ maximum cannot coincide, whereas the secondary maxima coincide in the observations (feature 3).

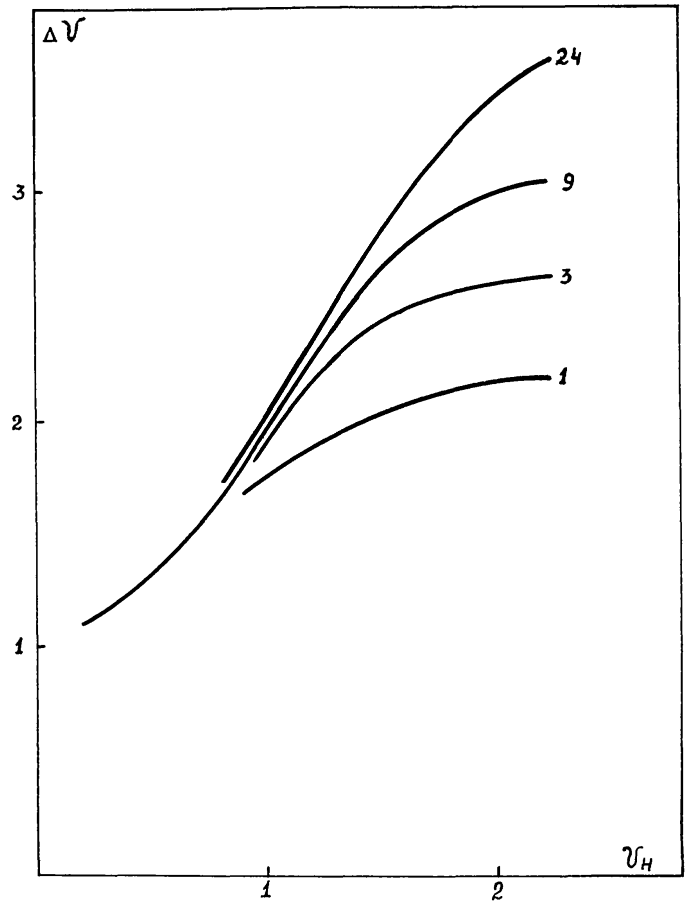

Fig. 2. $V$ maximum halfwidth vs $v_H$ at different $\eta_0$ values.

Figure 2 plots the $V$ maximum halfwidth against $v_H$ for different $\eta_0$ values. The halfwidth varies no more than by a factor 3–4, and this is not sufficient to explain the observed small width of the reversal maximum (features 4 and 5).

Finally, the resulting $V$ profile has been computed with the assumption that one part of the radiation originates from a $H_1$ region, and the other part from a $H_2$ region. Then $V = V_2 + (1-\alpha)V_1$, $\alpha$ being the part of radiation which originates from the $H_2$ region. Figure 3 shows the $V$ profile for $v_{H_2} = 0.3$; 0.6 and $\alpha = 0.2$, $\eta_0$ was choosen equal to 24, because it is the best value to fit the profile of the $\sigma$ component for large fields for the line Fe I 6302 Å. It is seen from Figure 3 that the only effect of the $H_2$ region is a slight distortion of the $V$ contour. With $\alpha$ increasing up to 0.5–0.6 a reversion may appear, but nevertheless, the reversal $V$ maximum is 20–50 times smaller than the primary $V$ maximum, which is in disagreement with feature 4, and the calculated reversal $V$ maximum is at least 2 times farther from the center of the line than the observed one.

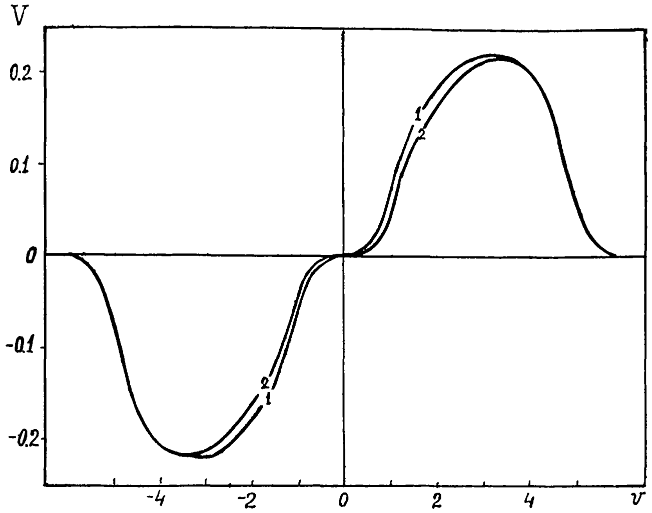

Fig. 3. Resulting $V$ contour for radiation from $H_1$ and $H_2$ regions with $v_{H_2} = 0.3$ (1) or $v_{H_2} = 0.6$ (2).

Thus, our calculations show that the hypothesis of the existence of regions with weak fields is insufficient by itself to explain the $\pi$ component splitting and $V$ reversion. However, we assumed throughout our calculations that the rest of the physical conditions in $H_2$ region are the same as in $H_1$ region. It is seen from Figure 1 that with $\eta_0$ decreasing, the coincidence of the $V$ and $(I+V)$ maxima occurs at smaller $v_H$ values. Therefore, one may hope that if $\eta_0$ is small in $H_2$ regions the situation will improve. Specific calculations, however, showed the $\eta_0$ influence to be insufficient. $V$ reversions appear only when $\eta_{01}/\eta_{02} \approx 30$, but even then the reversional maximum is 40 times smaller than the primary one.

If $\Delta\lambda_{D2} < \Delta\lambda_{D1}$, reversion appears at a smaller distance from the centre. The $V$ profile is represented in Figure 4 for the following values of parameters: $\Delta\lambda_{D1}/\Delta\lambda_{D2} = 5$, $H_1/H_2 = 10$, $\eta_{01} = \eta_{02} = 24$, $v_{H_1} = 3$, $\alpha = 0.20$; the wavelengths are expressed in units of $\Delta\lambda_{D1}$. A well-pronounced reversion is present, but with the difference between $\Delta\lambda_{D1}$ and $\Delta\lambda_{D2}$ decreasing this reversion disappears. We have also computed the $V$ contour for $H_1/H_2 = 5$ and $\Delta\lambda_{D1}/\Delta\lambda_{D2} = 3$. This contour is similar to that shown in Figure 4. Thus, a possible decrease of $\Delta\lambda_D$ in $H_2$ regions may cause a reversion, but then it would be necessary to assume a very great difference between $\Delta\lambda_D$ in $H_1$ and $H_2$-regions.

Finally, the combined effect of $\eta_0$ and $\Delta\lambda_D$ may be considered. Figure 5 represents the $(I+V)$ and $V$ contours computed for the following parameters: $H_1/H_2=10$, $\eta_{01}=24$, $\eta_{02}=3$, $\Delta\lambda_{D1}/\Delta\lambda_{D2}=2$, $v_{H_1}=3$, $\alpha=0.20$. The obtained contours have all above-mentioned features, indicated by the observations*.

Thus, in order to explain the observed $\pi$ component shifting and $V$ reversion by the existence of weak-field regions, it should at the same time be assumed that in these regions both $\eta_0$ and $\Delta\lambda_D$ are considerably smaller than in strong-field regions.

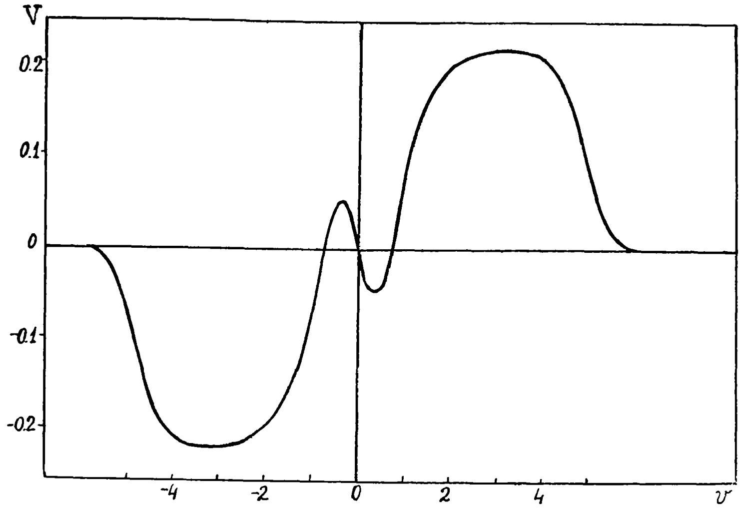

Fig. 4. Resulting $V$ contour for radiation from $H_1$ and $H_2$ regions with $\Delta\lambda_{D1}/\Delta\lambda_{D2}=5$, $H_1/H_2=10$; $\eta_0=24$, $\alpha=0{,}20$.

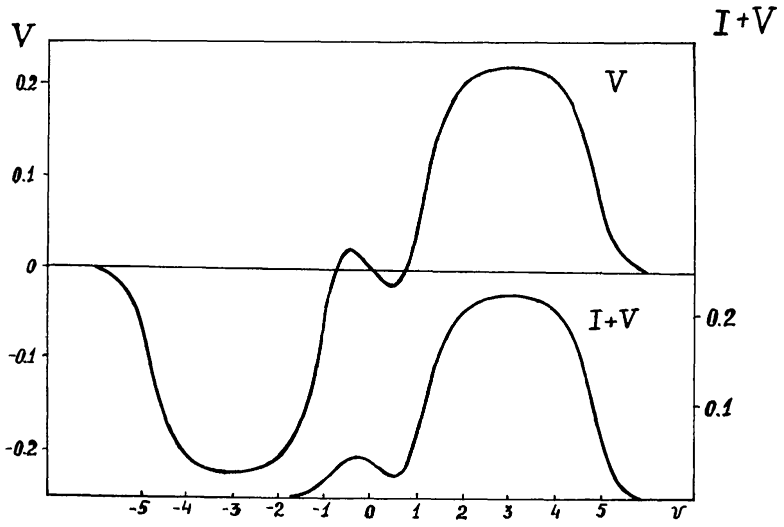

Fig. 5. Resulting $1-(I+V)$ contour and $V$ contour with $H_1/H_2=10$, $\eta_{01}=24$, $\eta_{02}=3$, $\Delta\lambda_{D1}/\Delta\lambda_{D2}=2$, $\alpha=0{,}2$.

* Contours shown on Figure 5 are expressed in units of continuous spectrum intensity. Besides that, instead of $I+V$ the parameter $1-(I+V)$ is shown.

The last question to discuss is whether such values of $\eta_0$ and $\Delta\lambda_D$ are reasonable. If the identification of $H_2$ regions with bright dots in sunspots is valid, it should be assumed that their $\eta_0$ and $\Delta\lambda_D$ values have to be closer to photospheric values than to the values in sunspots. As regards $\eta_0$, the obtained value is close to the photospheric value for the Fe I $\lambda$ 6302 Å-line. But the matter is more complicated with $\Delta\lambda_D$. In a number of investigations (Howard, 1955; Mattig, 1958; Zwaan, 1959) it is stated, on the basis of the analysis of curves of growth, that non-thermal velocities in sunspots are greater than in the photosphere. However, in several more recent works (Elste, 1963; Brückner, 1965) it has been shown on the basis of direct observations of non-magnetic line profiles that sunspot lines are at least not wider than the photospheric ones. If one accepts this latter result, then the assumption of the relative smallness of $\Delta\lambda_D$ in $H_2$ regions becomes questionable and the difficulties with the explanation of V reversion remain. It is possible, however, that the physical conditions in bright dots are more similar to conditions in faculae where velocities are somewhat smaller than in the photosphere. (Vojkhanskaya, 1967; Badalyan and Livshits; 1972.)

## References

Badalyan O. G. and Livshits M. A.: 1972, *Solar Phys.* **22**, 297.
Beckers, J. M. and Schröter, E. H.: 1968, *Solar. Phys.* **4**, 303.
Beckers, J. M. and Schröter, E. H.: 1969, *Solar. Phys.* **7**, 22.
Brückner, G.: 1965, in R. Lüst (ed.), 'Stellar and Solar Magnetic Fields', *IAU Symp.* **22**, 293.
Deubner, F. L.: 1967, *Mitt. Astron. Ges.* **22**, 33.
Elste, G. J.: 1963, *J. Quant. Spectr. Radiative Transfer* **3**, 185.
Hénoux, J. C.: 1968, *Solar. Phys.* **4**, 315.
Howard, R.: 1955, *Astrophys. J.* **127**, 108
Mattig, W.: 1958, *Z. Astrophys.* **44**, 280.
Mogilevsky, E. L., Demkina, L. B., Ioshpa, B. A., and Obridko, V. N.: 1968, in K. O. Kiepenheuer (ed.), 'Structure and Development of Solar Active Regions', *IAU Symp.* **35**, 215.
Severny, A. B.: 1959, *Sovjet Astron. J.* **3**, 214.
Unno, W.: 1956, *Publ. Astron. Soc. Japan* **8**, 108.
Vojkhanskaya, N. F.: 1967, *Astron. Zh.* **43**, 413.
Zwaan, C.: 1959, *Bull. Astron. Inst. Neth.* **14**, 288.