THE MAGNETO-OPTICAL FILTER

I: *Preliminary Observations in Na D Lines*

G. AGNELLI*, A. CACCIANI*, and M. FOFI*
Osservatorio Astronomico di Roma, Italy

(Received 2 April; in revised form 11 August, 1975)

Abstract. Transmission curves and theoretical calculi of the magneto-optical filter, designed and built by the authors, are shown together with some observed transmission spectra. At present the filter has a total halfwidth of ≈80 mÅ; and the maximum transmission is 25%. From the analysis of the theoretical curves and from the observed spectra, we deduced the possibility of making up a filter with a very narrow passband (less than 30 mÅ) and a very high transmission (up to nearly 100% apart from losses arising from the glass cell, lenses and polarizers).

The article concludes with a selection and discussion of photographs obtained with the filter.

1. Introduction

The working principle of the filter, depending on magneto-optical effects, has already been introduced in previous, so far only theoretical, publications (Cacciani, 1967; Cacciani *et al.*, 1968; Beckers, 1970; Cacciani *et al.*, 1970, 1971). It consists of Na vapours in a magnetic field H between two crossed polarizers. The latter cut off all of the spectrum except for those wave-lengths for which the vapours, due to magneto-optical effects, change the polarization (see Figure 1b).

The actual construction of the apparatus (see Figure 1a) has required the solution of a number of technical problems, which we will discuss elsewhere in a paper devoted exclusively to them.

In order to get the transmission profile of the filter, the relevant equations were numerically evaluated. In Figures 2a and 3a, Section 2, the results are shown for selected values of the parameter τ_0, i.e. the optical depth passed through by the light beam. A Voigt profile with a Doppler width $\Delta\lambda_D = 8.5$ mÅ was used. The hyperfine structure of the sodium D lines was also considered. Such a structure in fact broadens each Zeeman component considerably (≈ 16 mÅ totally): so this effect has to be taken into account. In comparison, the inhomogeneity of the magnetic field (at present $\Delta H/H \approx 5\%$) has a negligible effect.

The magneto-optical filter, we discovered, has a passband $HW \approx 80$ mÅ; and the theoretical maximum transmission is 25%. By varying the vapour Na density and the strength of the magnetic field, it is possible to have higher transmissions – up to nearly 100% – and a slightly larger passband (see Figure 4.) Moreover, better performances of the filter can be obtained by utilizing mainly the Faraday rotation instead of the Righi contribution to the transmission profile (See Section 2).

* Present address: Osservatorio Astrofisico di Arcetri, Firenze, where the whole of this research has been carried out.

Solar Physics **44** (1975) 509–518. *All Rights Reserved*

2. Theoretical Analysis

The optics of the magneto-optical filter (polarizers and vapours in a longitudinal magnetic field, see Figure 1b), can be mathematically expressed by the Jones' matricial calculus (Shurcliff, 1962). It leads to the following expression:

$$\frac{1}{2}\begin{vmatrix}1 & 0\\ 0 & 0\end{vmatrix}\begin{vmatrix}\cos\delta/2 & -\sin\delta/2\\ \sin\delta/2 & \cos\delta/2\end{vmatrix}\left\{e^{-\tau_{\sigma}\mathrm{R}}\begin{vmatrix}i\\ 1\end{vmatrix} + e^{-\tau_{\sigma}\mathrm{V}}\begin{vmatrix}-i\\ 1\end{vmatrix}\right\}, \tag{1}$$

in which $\{\ldots\}$ is the state vector representing the linearly polarized light L. In order to facilitate the calculus of our particular problem we designate such a vector as the interference (addition in the Jones' calculus) of two other vectors $\begin{vmatrix}i\\ 1\end{vmatrix}$ and $\begin{vmatrix}-i\\ 1\end{vmatrix}$, that is lefthanded and righthanded circular polarizations. The coefficients $e^{-\tau_{\sigma}\mathrm{R,V}}$ take into account the absorptions in the Zeeman effect. $\tau_{\sigma}^{\mathrm{R,V}}$ are the optical depths for the red and violet σ components. The matrix $\begin{vmatrix}\cos\delta/2 & -\sin\delta/2\\ \sin\delta/2 & \cos\delta/2\end{vmatrix}$ is the operator describing the Macaluso-Corbino effect, i.e. the Faraday rotation in the wings of the spectral line (Born, 1965). Because of this effect, the Na vapour, in a longitudinal magnetic field acts like a circular retarder which determines the phase-delay δ between the two vectors $\begin{vmatrix}i\\ 1\end{vmatrix}$ and $\begin{vmatrix}-i\\ 1\end{vmatrix}$. The matrix $\begin{vmatrix}1 & 0\\ 0 & 0\end{vmatrix}$ is the operator related to the exit polarizer P_2. Finally the coefficient $\frac{1}{2}$ is the normalization factor for intensity of the linearly polarized light L.

Following Jones' calculus the transmitted light is obtained by making the square modulus of the expression (1)

$$I_{TR} = \tfrac{1}{4}\left[e^{-2\tau_{\sigma}\mathrm{R}} + e^{-2\tau_{\sigma}\mathrm{V}} - 2e^{-\tau}\right] + e^{-\tau}\sin^2\delta/2, \tag{2}$$

where $\tau = \tau_{\mathrm{R}}^{\sigma} + \tau_{\mathrm{V}}^{\sigma}$.

In Equation (2) the transmitted light consists of two terms. The first one $\frac{1}{4}[e^{-2\tau_{\sigma}\mathrm{R}} + e^{-2\tau_{\sigma}\mathrm{V}} - 2e^{-\tau}]$ results from the so-called Righi effect. It is related to the Zeeman effect in that the σ components can only *absorb* circular polarized light, transmitting the other circular polarized component. The exit polarizer P_2 transmits half of this residual circular polarized light. The transmission due to the Righi effect can be as much as 25% if either $\tau_{\sigma}^{\mathrm{R}}$ or $\tau_{\sigma}^{\mathrm{V}}$ are very large (see flat regions in Figures 2a, 3a and 4). If, on the other hand, both $\tau_{\sigma}^{\mathrm{R}}$ and $\tau_{\sigma}^{\mathrm{V}}$ are large at the same time, the Righi effect transmission will be small (see central depression in Figure 3a).

The second term of Equation (2) results from the so-called Macaluso-Corbino effect, with amplitude smoothed by a factor $e^{-\tau}$. It is related to the refractive behavior of the Zeeman effect: For the wings of very strong lines δ can be large even where τ is small; so that the Equation (2) can approach $I_{TR} = 100\%$. This situation occurs in the very narrow region between the σ components shown in Figure 4.

The transmitted intensity I_{TR} was computed by using a Voigt profile with a Doppler width $\Delta\lambda_{\mathrm{D}} = 8.5$ mÅ and the hyperfine structure of the Na D lines. The Voigt profile

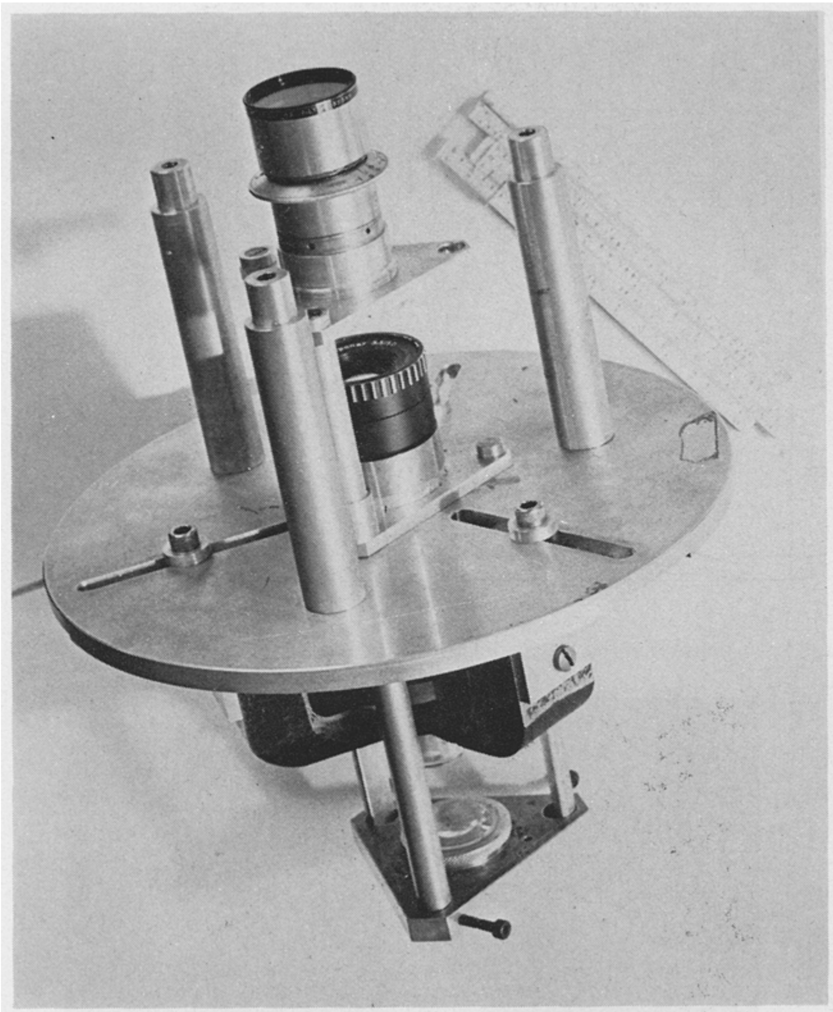

Fig. 1a. The magneto-optical filter with its own secondary optics.

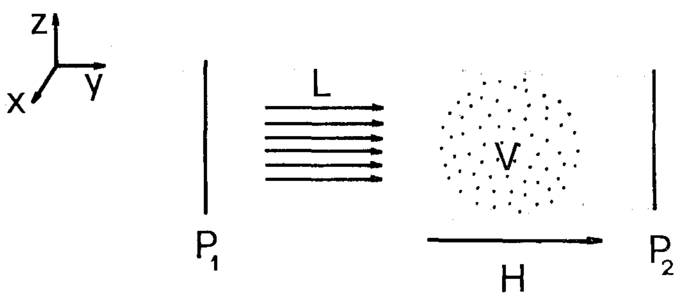

Fig. 1b. The optical scheme of the magneto-optical filter. P_1 and P_2 are two crossed polarizers with their axes in the x, z plane. L is the incoming light linearly polarized by P_1. The magnetic field H lies along the y-axis, V is the Na vapour.

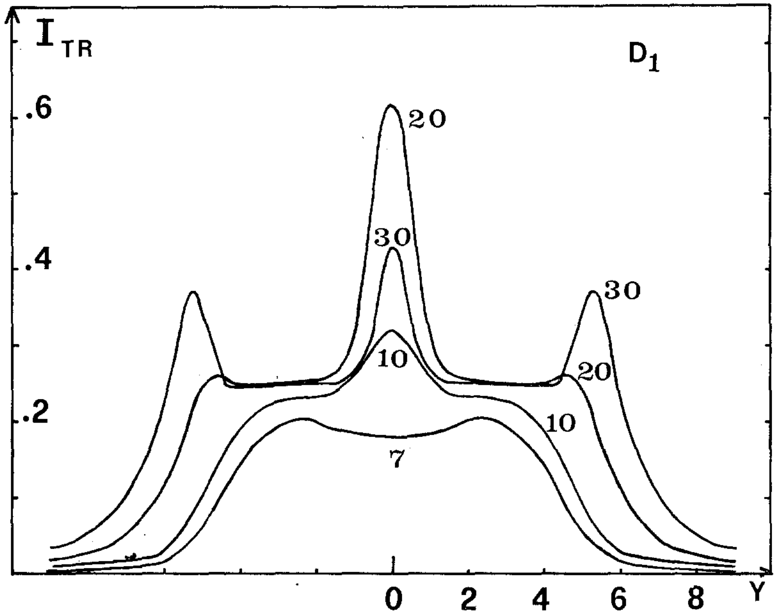

Fig. 2a. Na D_1 transmission profiles for different values of τ_0. $H = 1500$ G, $y = \Delta\lambda/\Delta\lambda_D$, $\Delta\lambda_D = 8.5$ mÅ.

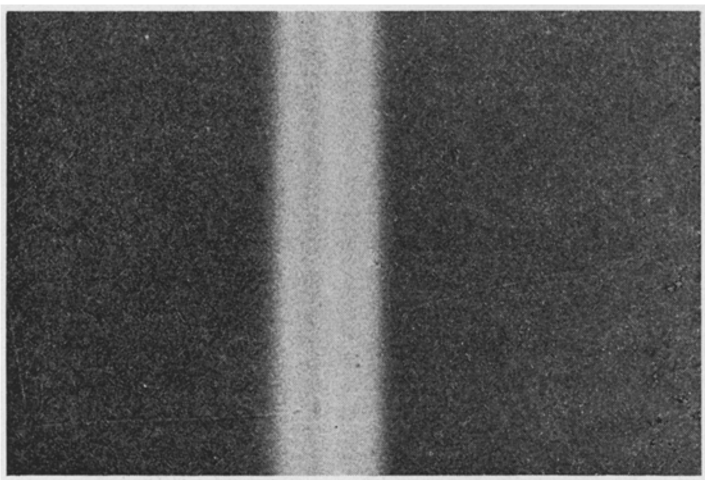

Fig. 2b. Na D_1 transmission spectrum, observed in the laboratory, with a total width of 75 mÅ. 19.5 mm = 100 mÅ.

gives the following formulae for the optical depths:

$$\tau_\sigma^R = \frac{\tau_0}{2} H_R(a, y)/H(a, 0),$$

$$\tau_\sigma^V = \frac{\tau_0}{2} H_V(a, y)/H(a, 0), \tag{3}$$

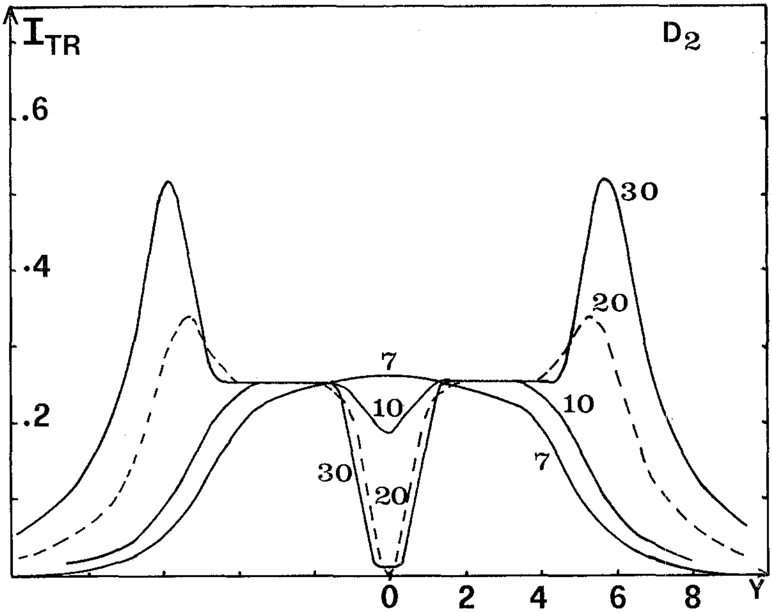

Fig. 3a. Na D2 transmission profiles with the same parameters as in Figure 2a.

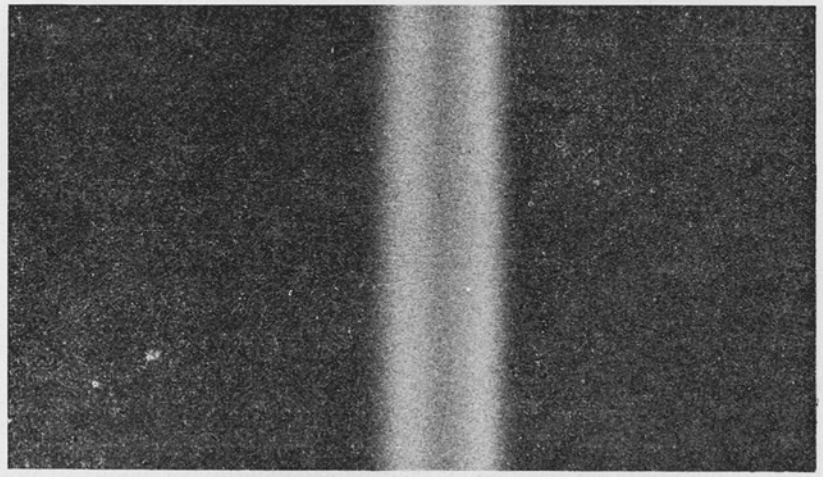

Fig. 3b. Na D2 transmission spectrum as in Figure 2b. Same size.

where $y = \Delta\lambda/\Delta\lambda_D$, $1/a = \Delta\lambda_D/(\gamma/2)$ ($\gamma = 1.18 \times 10^{-4}$ Å is the natural half-width). In our case $1/a = 150$. $H_R(a, y)$ and $H_V(a, y)$ are the Voigt functions relative to the red and to the violet σ components (Aller, 1963). τ_0 takes into account the Na vapour density. The phase angle δ, obtained from the Rachkowsky functions $\psi(a, y)$ (Rachkowsky, 1962; Beckers, 1969), is

$$\delta = \varphi_\sigma^R - \varphi_\sigma^V = \frac{\tau_0}{2}\left(\frac{\psi_R(a, y)}{H(a, y)} - \frac{\psi_V(a, y)}{H(a, 0)}\right), \quad (4)$$

where φ_σ^R and φ_σ^V are the phase angles, referred to the vacuum, introduced by the red and the violet σ components.

Figures 2a and 3a show typical transmission profiles for $H=1500$ G and for some representative values of τ_0.

For the same τ_0 the behavior of the D_1 and D_2 lines are different because of different Zeeman patterns.

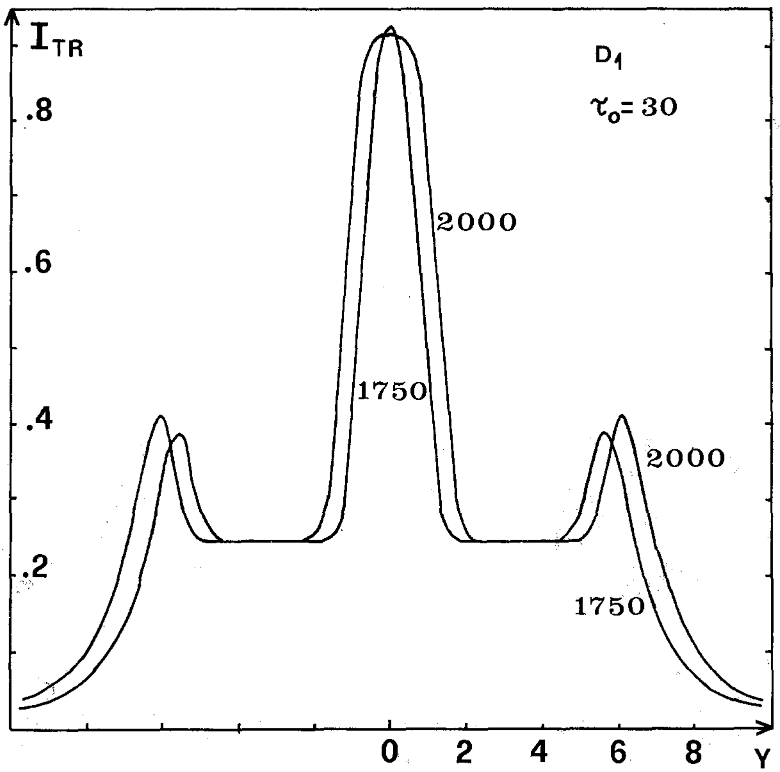

Fig. 4. Theoretical transmission profiles of Na D_1 with $\tau_0=30$ and $H=1750$ and 2000 G.

For lower values of τ_0 the passband is bell-shaped, determined mainly by the Righi effect, with a total halfwidth $\approx 9\Delta\lambda_D$, i.e. 80 mÅ (as we have also observed through a Fabry-Perot spectroscope.) For higher values of τ_0 the transmission profile becomes more and more complex. Spectral peaks, resulting from the Macaluso-Corbino effect, now combine with the flat transmission regions caused by the Righi effect.

Figures 2b and 3b show the observed spectra of D_1 and D_2 lines. They are in agreement with the theoretical curves.

The calculations shown in Figure 4 exhibit a central peak which can reach nearly 100%, while staying very narrow. In this central region (violet wing of the σ_R and red wing of the σ_V), the phase angle δ reaches a high value, since φ_R^σ and φ_V^σ have opposite signs. This fact suggests that a very narrow passband filter with a halfwidth <30 mÅ could be achieved by suppressing the flat regions and the external peaks. One could do this by using another absorption cell put in a magnetic field transverse to the line of sight and with its direction perpendicular to the axis of the exit polarizer P_2. Such a filter would absorb only the σ components and would transmit a very narrow central region near the π components.

3. Light Scattered by the Filter

Equation (2) does not represent the total light emerging from the filter. In fact the total output consists of two parts. The first one is the light directly transmitted by the effects discussed above (Equation (2)); the second one is the light scattered by the vapour itself. The last contribution comes from the light absorbed by the σ components and immediately re-emitted in all directions. Following the Zeeman effect, the scattered light is circularly polarized along the direction of the magnetic field, and is linearly polarized in the perpendicular directions. Several authors (Gonzi and Roddier, 1969; Fossat and Ricort, 1973; Snider *et al.*, 1974) have utilized the scattered light to investigate the velocity fields and the Einstein effect on the Sun. The main advantage of their resonance spectroscopy and of our magneto-optical filter is the true zero-shift level given by the adopted laboratory line. In a next paper we will show how it is possible to realize a Video-Doppler-Magnetograph by using magneto-optical effects. In our filter the scattered light does not contribute to the formation of the Sun's image; but it does provide a uniform background which can be made small by limiting the solid angle under which the vapour is seen by the optics.

4. Results

Figure 5a shows the first photograph of the Sun we obtained with the filter on 11 May 1974 – 1140 UT. Faculae, coarse mottling and supergranuli are well visible. By tuning the filter on the wings of the solar D lines – both wings are simultaneously accepted by the filter and the tuning is possible, in a limited range, by varying the temperature of the filter – we reached a situation in which the facular contrast vanished. Further out in the wings, faculae appeared slightly darker than the surroundings before becoming definitely invisible. We have not as yet studied this behavior quantitatively. Nevertheless we observed it many times visually and our rough impression is that the Na faculae are bright within 100 mÅ of the line core and that they are dark beyond 100 mÅ from the line center. Then they disappear before all the Sun becomes covered by a regular photospheric-like granulation.

It is beyond the object of this article to give a careful analysis of the observations carried out with the magneto-optical filter: so we now restrict our attention to a few examples, with the aim of showing the close relation between Na facular regions in our filtergrams and the magnetic structure obtained with the Mount Wilson (see Figure 5b) and Kitt-Peak (see Figure 6b) magnetograms.

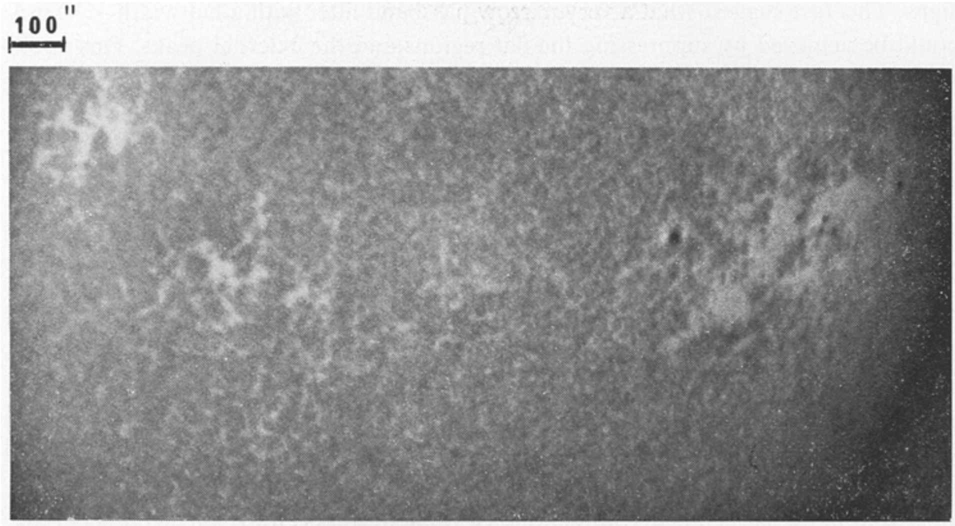

Fig. 5a. The Sun seen through the magneto-optical filter, 11 May 1974 – 1140 UT. North is up, west is to the right.

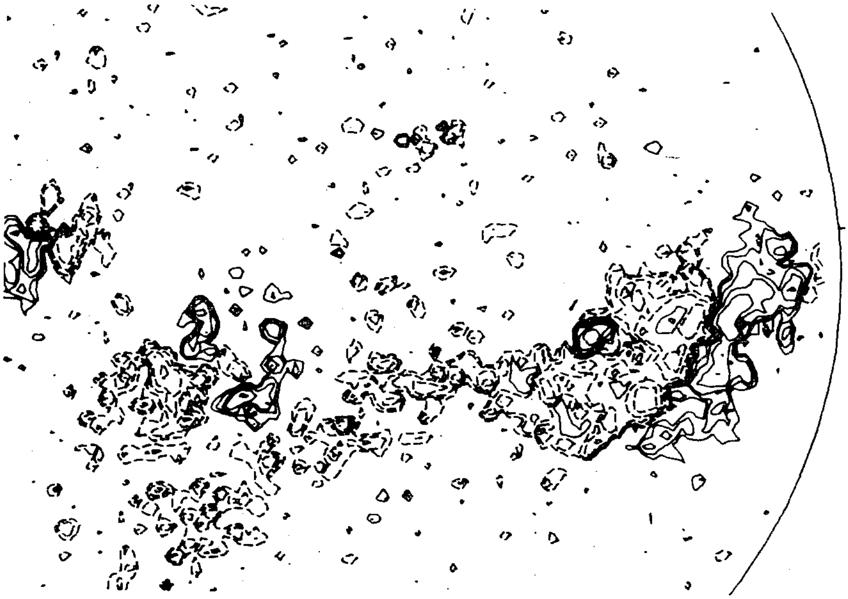

Fig. 5b. The Mount Wilson magnetogram of the same region as Figure 5a.

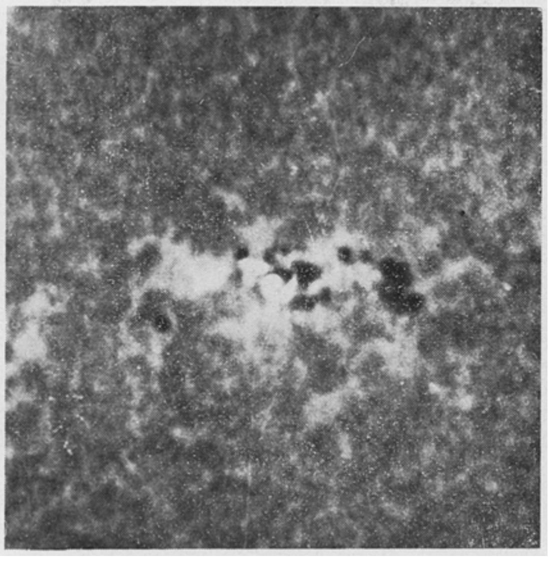

Fig. 6a. Filtergram of the flaring region of 4 July 1974 – 1400 UT
13.5 nm = 100 arc sec.

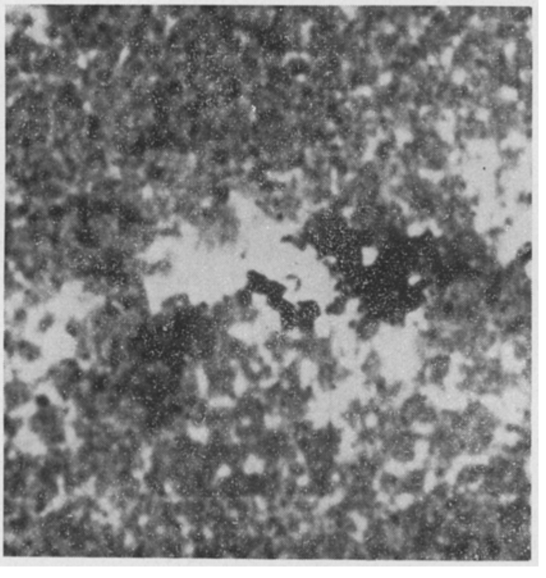

Fig. 6b. The Kitt Peak magnetogram of the same region as Figure 6a. Same size.

Figure 6a is a filtergram of 4 July 1974 – 1400 UT. The magnetic fields are coincident with the Na faculae and the spots group and a flare in its final phase are well visible. In Figure 7 the supergranular network in an active region is well outlined.

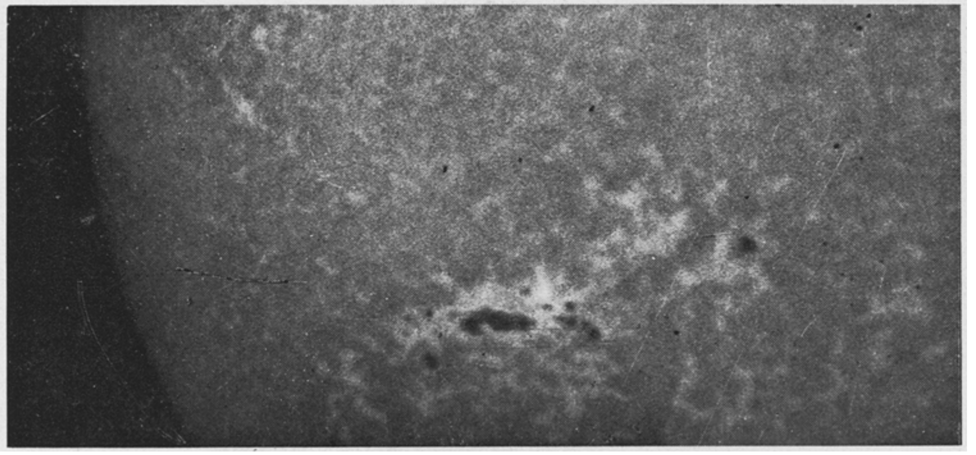

Fig. 7. The same region as in Figure 6a, 1 July 1974.
11.5 mm=100 arc sec.

Acknowledgements

Only because of the Arcetri Observatory facilities placed at our disposal by the Director, Prof. G. Righini, and to the generous cooperation by Drs G .Barletti, G. Ceppatelli and A. Righini were we able to carry out the present work. The authors are grateful to Mr S. Viligiardi and to Dr R. Habel (CNEN Lab. Frascati) for making the absorption cell a practical reality. We want to thank Dr T. Fortini (Rome Observatory) for her helpful discussion and encouragements. The computer utilized was UNIVAC 9400 of the ELDA Center (Rome).

References

Aller, H. L.: 1963, *The Atmosphere of the Sun and Stars*, Ronald Press, New York, p. 235.
Beckers, J. M.: 1969, *Solar Phys.* **9**, 372.
Beckers, J. M.: 1970, *App. Opt.* **9**, 595.
Born, M.: 1965, *Optik*, Springer-Verlag, Berlin, p. 515.
Cacciani, A.: 1967, Atti XI, Convegno Soc. Astron. Italiana, Padova.
Cacciani, A., Cimino, M., and Sopranzi, N.: 1968, *Solar Phys.* **3**, 628.
Cacciani, A., Cimino, M., and Fofi, M.: 1970, *Solar Phys.* **11**, 319.
Cacciani, A., Cimino, M., and Fofi, M.: 1971, in R. Howard (ed.), 'Solar Magnetic Fields', *IAU Symp.* **43**, 94.
Fossat, E. and Ricort, G.: 1973, *Solar Phys.* **28**, 311.
Gonzi, G. and Roddier, F.: 1969, *Solar Phys.* **8**, 255.
Rachkowsky, D. N.: 1962, *Izv. Krymsk. Astrofiz. Obs.* **27**, 148.
Shurcliff, W. A.: 1962, *Polarized Light*, Harvard University Press, Cambridge, Mass.
Snider, J. L., Eisenstein, J. P., and Otten, G. R.: 1974, *Solar Phys.* **36**, 303.