OBSERVATIONS OF VECTOR MAGNETIC FIELDS WITH A MAGNETO-OPTIC FILTER *

ALESSANDRO CACCIANI

*Jet Propulsion Laboratory and University of Rome, Italy***

JOHN VARSIK and HAROLD ZIRIN

Big Bear Solar Observatory, California Inst. of Technology, Pasadena, CA 91125, U.S.A.

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Abstract. We describe the use of the magneto-optic filter (MOF) to observe solar magnetic fields in the potassium line at 7699 Å. The filter has been used in the Big Bear video-magnetograph since 23 October. It gives a high sensitivity and dynamic range for longitudinal magnetic fields and enables us to measure transverse magnetic fields using the sigma component. Examples of the observations are presented.

The Big Bear video-magnetograph was developed by Leighton and Smithson; its recent evolution has been described by Zirin (1986). The digital image subtraction system permits observations of magnetic fields or velocities with any good monochromator. The system has been used regularly for years with a $\frac{1}{4}$ Å Zeiss birefringent filter. This filter has the advantage that it is readily tunable between 6000 and 7000 Å, has a fairly good optical throughput and gives excellent measurements of longitudinal fields. However, the bandpass is somewhat broad for measurements of transverse fields, and the system has limited field angle and some sensitivity to non-uniformities in the calcite.

The MOF (magneto-optic filter) was first described by Cacciani *et al.* (1966) and Cacciani (1967). Applications and observations were described by Agnelli, Cacciani and Fofi (1976) and by Cacciani and Fofi (1978). It has been used by Rhodes *et al.* (1988) at Mt. Wilson for both helioseismology and full disk longitudinal magnetograms. Rhodes *et al.* (1988) give extensive data on the setup. Cacciani *et al.* (1988) give a better algorithm for removing instrumental polarization and apparent cross-talk between Doppler and magnetic signals. The filter had been used by Cacciani and Zirin at Big Bear for a few days in 1986, and given excellent results; for various reasons, the matter was not pursued. With the return of solar activity, measurements of the transverse fields became particularly important, so on October 22, 1988, we installed at Big Bear (BBSO) a pair of cells fabricated in the laboratory of Dr Ed Smith at JPL and filled with potassium. The telescope is our straight-through 25-cm refractor with no detectable instrumental polarization. The rest of the system is the standard BBSO VMG system

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** NRC Senior Res. Fellow.

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described by Zirin (1986). The system immediately gave excellent results for longitudinal and transverse fields.

A scheme of the cell layout used in this case is shown in Figure 1. The effective bandpass of the filter is about 0.03 Å and the magnetic field strength, about 2000 G. This gives a splitting of 150 mÅ, somewhat less than the half width of the line, about 200 mÅ.

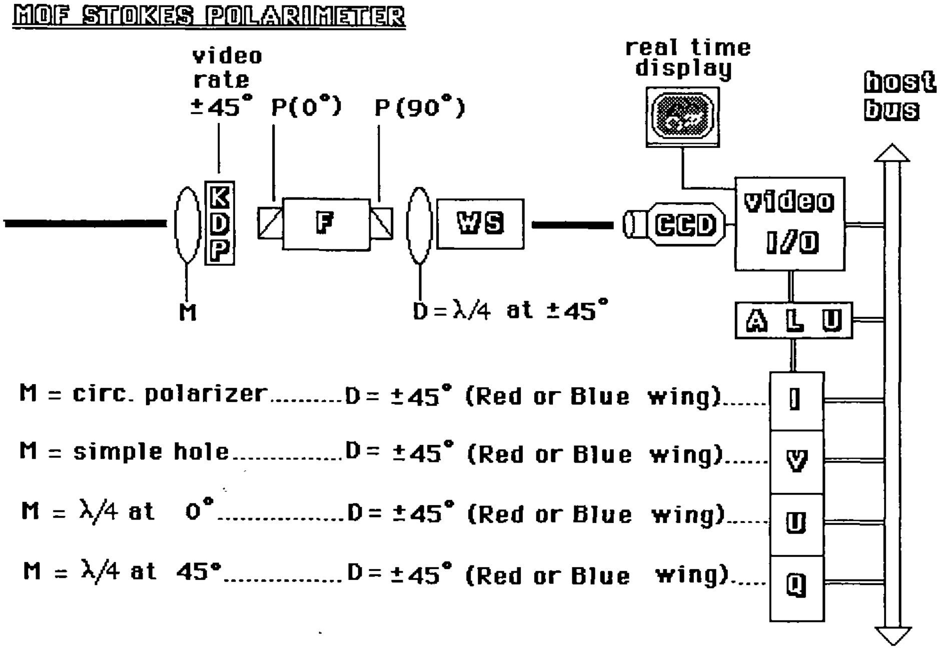


Fig. 1. A sketch of the arrangement of the MOF with the source of the Stokes parameters given.

The input beam is about $f/50$ with a 12 mm pupil, and the detector is a Cohu CCD camera. For magnetic field measurement it is simply necessary to place an electro-optic modulator (KDP crystal) ahead of the MOF. This alternately places the σ_1 and σ_2 components of the incoming light parallel to the axis of the entrance polaroid of the filter section F (see Figure 1). This section simply functions as a narrow-band filter in the pottasium line which permits both σ_1 and σ_2 components to pass through as they are transmitted by the KDP-polaroid combination ahead. The wing selector (WS) section coupled with a rotatable quarter wave plate produces absorption of one or the other components, permitting choice of either red or blue wing according to the relative velocity of the observer and the object on the Sun. Because the potassium wavelength is fixed, our only means of wavelength shifting is by making this choice. In principle one can shift the pass band by changing the heater current or field strength, but this was not provided for in our test setup.

For transverse field measurements, if the solar line profile is broad, the central π polarization is mixed with the orthogonal σ components from both sides. We found that mixing of the σ and π components could be avoided by observing in the line wing, even though the magnetic signal is reduced from its value at line center. One also finds less dependence on Doppler shifts from solar rotation. The direction of the polarization in the line wing is at right angles to the field. We are investigating other versions of the filter which may narrow the bandpass.

A combination of a quarter-wave plate and KDP crystal is used to modulate the incoming light, producing either the Q or U Stokes vector depending on the orientation of the quarter-wave plate. The degree of linear polarization P is given by

$$P = 0.5(Q^2 + U^2)/I \tag{1}$$

and due to the way the Stokes vectors are defined the position angle of the plane of polarization is given by

$$\omega = 0.5 \arctan(U/Q) . \tag{2}$$

Then for the σ component, the direction of the transverse field is given by θ_t where

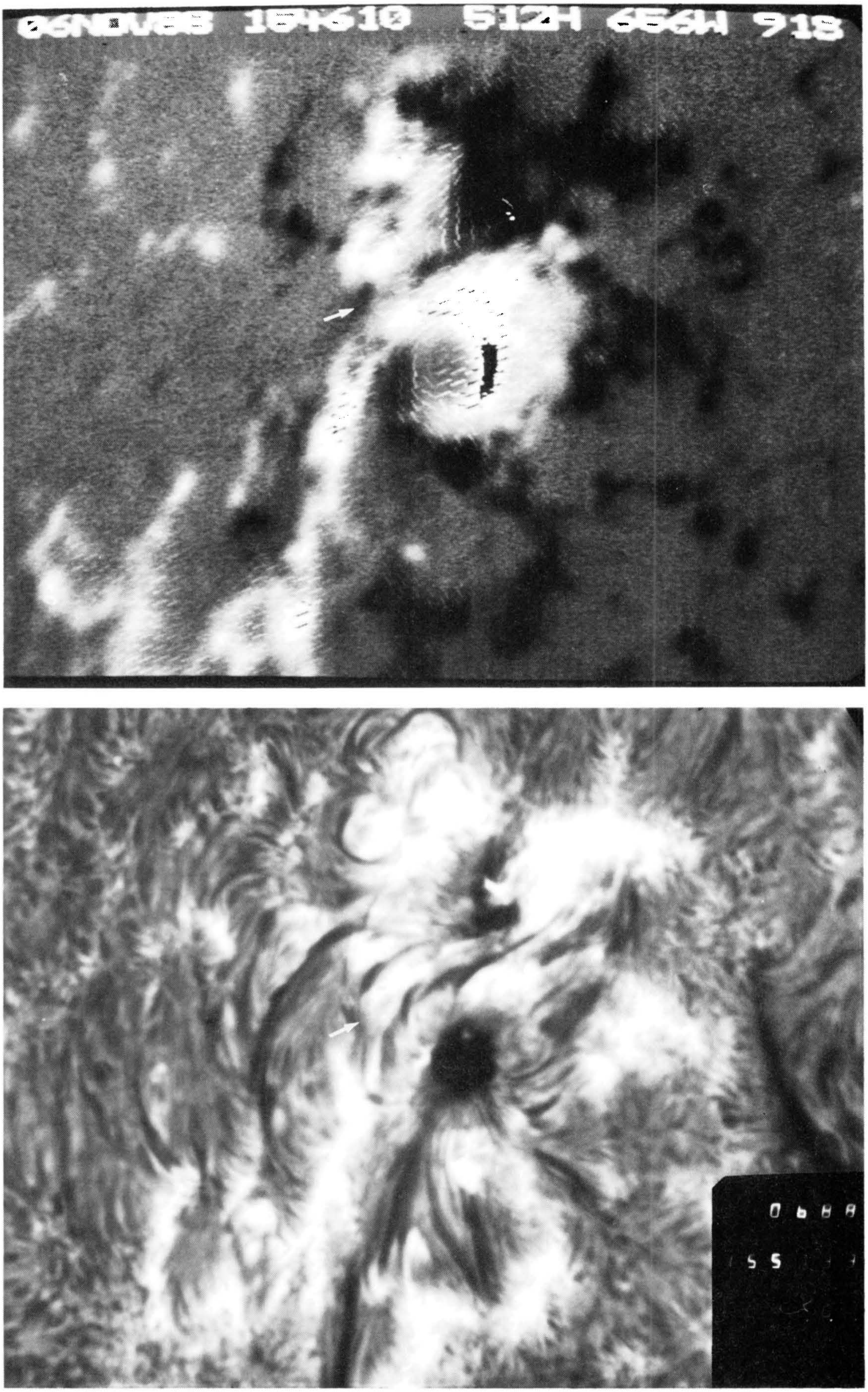
$$\theta = \omega + 90° . \tag{3}$$

After images of Q, U and I are obtained, images corresponding to the magnitude and direction of the degree of linear polarization are calculated using the above formulae for each pixel. Since each image is formed in an eight-bit image plane in our computer system, the magnitude is scaled from 0 to 255 and the direction is represented as an integral number of degrees from 0 to 179. Next, the image corresponding to the direction information is divided into 8×8 pixel sections. A new image is prepared consisting of one maximum intensity line for each 8×8 pixel section on a zero background with a direction corresponding to the average value of θ. The final transverse field line map consists of this direction map logically ANDed with the magnitude image. Thus the brightness of each line depends on the magnitude of linear polarization. In the limit of small amounts of Zeeman splitting, the magnitude of linear polarization depends on the square of the transverse magnetic field strength (Beckers, 1971).

For velocity measurements both the plate M and the KDP modulator in front of the first polarizer of the filter cell (Figure 1) are removed or disabled and the $\lambda/4$ plate in the WS cell is replaced by a modulator, which alternately chooses the red or blue wing of the line.

Figure 2 displays the longitudinal and transverse fields observed on 6 November, 1988 of Big Bear region 1312 compared with an Hα frame. Longitudinal field is expressed by brightness (positive field) or darkness, and the direction of the transverse field is indicated by white lines. Because the image in Figure 2 was obtained by adding the transverse field line map to a separate longitudinal image in an eight-bit image plane in our image processor, places where both transverse and positive longitudinal fields are strong show up as dark lines on a light background. The depth of the image plane also causes very strong longitudinal fields to 'wrap around' to the opposite shade.

The region is 656 arc sec W of the disk center, so most of the lines point toward the limb, giving the projection of the radial field on the plane of the sky. Aside from the penumbrae, four areas of transverse field appear, each of which is along a neutral line occupied by a filament. In symmetric sunspots at disk center a radial penumbral transverse field pattern is observed as expected. This and many other observations



a

b

confirm our belief that we are observing the transverse field accurately.

We have found that the MOF has the following advantages for this work:

(1) The MOF is free of the variable interference fringes we typically observe in long integrations with the Lyot filter, and provides a much more uniform field because of its wide acceptance angle. Because of the uniformity of the background, it is possible to make observations with much greater sensitivity than with the normal filter because the number of integrations that may be added are limited by buildup of fringes and other nonuniformities.

(2) We find a higher dynamic range for longitudinal fields than possible with the birefringent filter.

(3) The MOF provides good measurements of transverse fields, possibly superior to the Lyot filter. This probably is due to the spectral purity and narrow pass band.

(4) The low cost of the MOF compared to the Lyot filter makes it more accessible to observatories without access to the latter.

(5) The potassium wavelength probably offers better seeing than shorter wavelengths.

On the other hand, the MOF has some disadvantages:

(1) The bandpass is so narrow that direct images for reference are weak and focussing is difficult.

(2) The wavelengths are very difficult to shift, and only the red or blue wing selection is convenient. We hope to improve this by use of stronger magnets with variable field strength.

(3) With the Lyot filter all three functions (σ, π, and Doppler) may be controlled from the front of the system, while this version of the MOF requires two separate modulators.

(4) Buildup of a metal deposit on the windows can occur. In our case only a slight deposit, easily removed by heating the end plates, was found after three months of daily operation.

As can be seen in Figure 2, we need new software which displays the *tangential* and *radial*, rather than the transverse and longitudinal fields. This is already a problem with longitudinal VMG's, where observations at the extreme limb reflect the tangential field.

The sensitivity of these observations was limited by the weakness of the magnets, which limits us to the core of the line and the lack of longer integrations, which is somewhat limited by our current data storage system. A new system is being developed, with stronger magnets and devices to adjust the flux, which will make it possible to optimize the sensititivy.

We believe the success of the MOF makes it possible for observatories without access to the very expensive narrow passband Lyot filters to build magnetographs. The high

Fig. 2. (a) A magnetogram showing the transverse (white and dark bars) magnetogram supperposed on the longitudinal field (white = positive). Most bars point to the limb along the projection of the local radius vector. The transverse field is most marked along the filament separating the two spots (arrow). (b) An Hα frame of the same region showing how the horizontal field regions match neutral lines occupied by filaments.

quality of resulting magnetograms should further our study of the solar cycle substantially.

We are indebted to Dr Ed Smith, in whose laboratory at JPL the MOF cells were produced under Cacciani's guidance, and Prof. K. G. Libbrecht, who designed and build the MOF mounts and magnets. We are also indebted to Dr Alan Patterson and William Marquette, who carried out the setup at BBSO.

Our proposal to deploy this vector magnetograph was rejected by all funding agencies because the reviewers thought it would not work. The system was therefore assembled with Caltech support. However, the subsequent operation of the magnetograph and data reduction were supported by NASA under NGL 05-002-034, the NSF under ATM-8816007, and by the Office of Naval Research under ONR N00014-89-J-1069. A. Cacciani acknowledges the support of the National Research Council at JPL and the support of the original development of the MOF by the University of Rome, the Consiglio Nationale delle Richercha and the Ministero delle Pubblica Istruzione.

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