Mem. S.A.It. Vol. 78, 77

**Memorie** della

# Multi-wavelength analysis of the impact polarization of 2001 June 15th solar flare

Z. Xu[1] and J.C. Hénoux[2]

[1] Max Planck Institute for Solar System Research, Max-Planck-Str.2, 37191, Katlenburg-Lindau, Germany
[2] LEISIA, Meudon observatory, France

**Abstract.** We report here the impact polarization of the H$\alpha$, H$\beta$ and MgI (552.8 nm) lines during an M6.3 solar flare observed on 2001 June 15th with the THEMIS telescope in the multi-wavelength spectropolarimetric mode. Typical spectral intensity and polarization profiles are presented. All of these lines are linearly polarized and polarization degree vary 3% - 6% at line center. The directions of polarization are either parallel or perpendicular to the local transverse magnetic field, which are investigated by simultaneous observation of FeI (630.2 nm). The polarization islands are located at the edges of flare kernels. After eliminating scattering, Zeeman effect and intensity gradient, as possible origin of the observed polarization, this polarization is interpreted as due either to low energy proton beam or to the return current associated with electron beams.

**Key words.** Polarization — Sun: Flare

## 1. Introduction

During the rise or maximum phase of Soft X-ray emission, the chromospheric H$\alpha$ and H$\beta$ lines have been found to be linearly polarized in spectroscopic observations and filtergrams made during a few solar flares (Hénoux and Semel 1981; Vogt et al. 1996, 1999; Firstova et al. 1997; Vogt et al. 2001; Firstova and Kashapova 2002; Firstova et al. 2003; Hénoux and Karlický 2003; Xu et al. 2005). Recently the linear polarization of Mg I line at 552.8 nm (3p $^1P_1$ - 4d $^1D_2$ during a solar flare was firstly reported by Xu et al. (Xu et al. 2006).

This polarization has been interpreted as impact polarization due to collisional excitation of atoms by electrons or protons with anisotropic velocity distributions.

An anisotropic velocity distribution of fast charged particles gives rise, via impact excitation of atoms, ions or molecules, to an alignment of the angular momenta along the particle propagation direction, called self-alignment (Kazantsev and Hénoux 1995; Landi Degl'innocenti and Landolfi 2004). Then the excited atom or ions keeps information on the collision direction, and, in consequence, the radiation emitted could be linearly polarized. The highest polarization degree is observed at 90° from the beam direction. Depending on the energy of the incoming particle (Kleinpoppen 1969), the polarization direction may be either along the alignment axis, i.e. parallel to the beam propagation

*Send offprint requests to*: Z. Xu

direction, or perpendicular to it, since a $90^o$ rotation of the polarization direction takes place at a turnover energy $E_{tov}$ where the degree of polarization becomes null.

In the case of the H$\alpha$ line, for excitation by an mono-energetic mono-directional electron or proton beam and for observations made at 90° of this beam, the polarization degree reaches 30% at the 12 eV excitation threshold $E_{thr}$ with a polarization direction parallel to the particle beam velocity direction (Werner et al. 1996). Meanwhile the line radiation of MgI transitions at 552.8 nm has been estimated to be linearly polarized with a Stokes parameter Q almost equal to 60 % under the threshold excitation approximation (Kazantsev et al. 1998).

Here we will introduce the linear polarization observations as a whole during the 2001 June 15th solar flare, including H$\alpha$, H$\beta$, MgI and FeI lines, by use of a multi-wavelength spectropolarimetric mode of THEMIS. Spectropolarimetric observations and data analysis are presented respectively in sections 2 and 3. Several possibilities as polarization signal origins are discussed in section 4, finally we give the conclusion and perspective for the further research.

## 2. Spectropolarimetric Observations

On June 15th 2001, an M6.3 flare (GOES 8 soft X-ray class) beginning at 10:01 UT in the Active Region 9502, was observed from 10:07:20 UT to 10:30:56 UT by THEMIS in the MTR multi-line spectropolarimetric mode. Figure 1 locates the flare (S26 E41) and shows the orientations of the reference axis used to define the Q and U Stokes parameters. Figure 2 shows the temporal behavior of X-ray emission and our initial observation time. The flare region is repeatedly scanned 16 times by a 1″ width spectrograph entrance slit. For each scan position, two spectra formed by the extraordinary and ordinary beams carrying the $I+S$ and $I-S$ signals respectively, where S is alternately Q or U, are simultaneously recorded in a set of lines including H$\alpha$, H$\beta$, FeI (630.2 nm ), and MgI (552.8nm ).

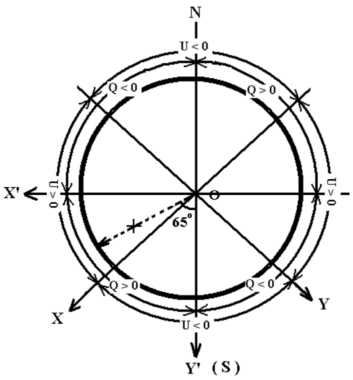


**Fig. 1.** Orientation reference axis, defining the Q and U Stokes parameters given by THEMIS. There exist a $45^o$ angle between the celestial north-south direction OS and the OX axis, that defines with OY the Stokes parameter Q ($Q = I_X - I_Y$, where $I_X$ and $I_Y$ are respectively the line intensities along OX and OY). The cross locates the flare of June 15th, 2001 and the dashed line points out the disk center-to-flare direction, which makes with the reference axis OS an angle close to $65^o$.

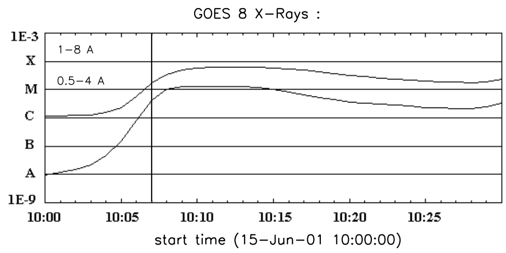


**Fig. 2.** Time evolution of soft X-ray emission (1-8 Å and 0.5-4 Å) for the 2001, June 15 flare. THEMIS observations began at 10:07 UT, as indicated by a vertical line.

It worth noting that this flare was associated with hard X-ray and radio flux impulsive emissions (Hénoux and Karlický 2003), which usually indicates that electron beams are bombarding the chromosphere. We focus here on the observations made from 10:07 to 10:15 UT when strong polarization signals were presents.

## 3. Linear Polarization Analysis

The data reduction, performed for Q and U observations, begin by flat field and dark current

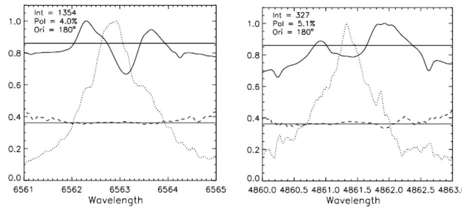


**Fig. 3.** $I$, $P$ and $\Theta$ spectral profiles of H$\alpha$ (left) and H$\beta$ (right), The units (Int, Pol, Ori) used for the intensity, polarization degree and orientation angle are given on the top left of each panel. The radial and tangential directions in unit of 180° are also plotted (full line).

normalization, that includes dark-current time variation corrections, spatial alignment of the two spectral frames carrying the $I \pm S$ signals, as well as correction for possible dilation or relative contractions of the profiles along both the slit and the spectrum directions.

After these preliminary data reduction, the Stokes parameter $S/I$ can be obtained by combinations of the $I + S$ and $I - S$ profiles as :

$$S/I = \frac{(I + S) - (I - S)}{(I + S) + (I - S)}. \quad (1)$$

Then, we can get the polarization degree $P$,

$$P = \sqrt{U^2 + Q^2}/I, \quad (2)$$

and the direction of polarization $\Theta$ (see the definition in paper of Xu et al. 2005) (Xu et al. 2005)

### 3.1. Typical intensity and polarization profiles of H$\alpha$ and H$\beta$

The majority of the H$\alpha$ and H$\beta$ intensity $I$ profiles show typical center-reversal emission where the polarization signal is also strong, as illustrated in Figure 3, which is usually regarded as the evidence of the non-thermal particles bombardment on the chromosphere. The linear polarization is concentrated at line center with a remarkably constant direction.

### 3.2. Linear polarization of MgI

In the case of MgI observation, we show one example of 2D spectra of $I$ and $Q/I$ in Figure 4.

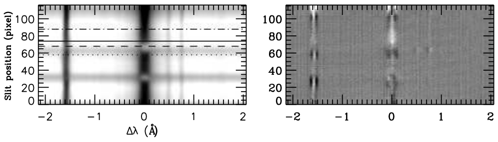


**Fig. 4.** An example of Stokes I (left) and Q/I (right) spectra of MgI (5528.4 Å) line. ScII line is also observed at about $\Delta\lambda = -1.6$ Å. Along the slit the spatial separation of two consecutive pixels is corresponding to 0.42 arc seconds on the solar image.

First of all, we find that there is no one-to-one relationship between intensity gradients and polarization signals, since no polarization is present in the continuum despite of the strong intensity gradient due to the sunspots. In addition, around the sunspot we can see some weak but characteristic signatures of the transverse Zeeman effect: almost symmetric profiles in $Q/I$. This is more conspicuous in ScII line nearby. Then, in the regions close to the upper flare kernel, rather than to the lower one, the $Q/I$ profiles exhibit a typical line-core impact polarization emission, which differs from Zeeman typical profile.

To illustrate this, we select 4 spatial locations along the slit and plot in Figure 5 their associated $Q/I$ and $U/I$ profiles. They are located respectively at the sunspot border ($y = 58$), at the flare intensity center ($y = 68$), at a location where the impact polarization is maximum ($y = 74$) and where polarization fades away ($y = 88$). In this figure, we can see in the $S/I$ profile the typical " W " shape due to the magnetic field and the line-core emission due to the impact polarization, which is limited to the Doppler line width and reaches almost 2% at line center.

### 3.3. The direction of polarization

As seen from the earth for charged particles moving along the magnetic field, the direction of impact polarization is either along the direction of the transverse field or perpendicular to it. Therefore, the impact polarization direction must be compared to the direction of the local transverse magnetic field, deduced from the Q and U profiles of the FeI (630.2 nm)

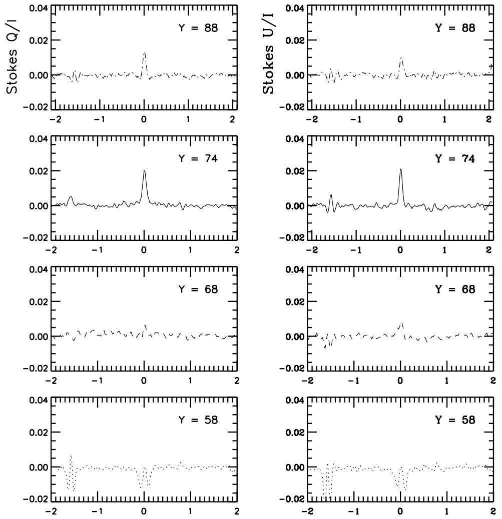


**Fig. 5.** Stokes $Q/I$ (left column) and $U/I$ (right column) profiles at the spatial positions pointed out in Figure 4. The correspondence is indicated by different line styles.

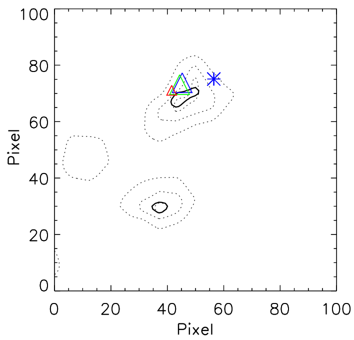


**Fig. 6.** Comparison of the two-dimensional distribution in pixels (0.42 square arc second per pixel) of the H$\alpha$ (blue), H$\beta$ (green) and MgI (red) lines linear polarization. $\triangle$ or $*$ symbols point out the position of the strongest radial or tangential polarization signal. H$\alpha$ (dotted line) and MgI (solid line) line-center intensity contours at 10:07 UT are also shown to locate the flare kernels. The contours of intensity in counts correspond, respectively, to 1300, 2200, 2800 in H$\alpha$ and to 1300 in MgI.

line. Comparison between the local transverse magnetic field and the polarization direction observed in H$\alpha$, H$\beta$ and MgI lines was analyzed in detail by Xu et al 2005, 2006. Here we just recall the main results that the local transverse magnetic field is close to the flare to disk-center direction with a small deviation and there is a significant tendency for the polarization directions observed to be parallel (*radial*) or perpendicular (*tangential*) to the transverse magnetic field within $20^o$. However, contrary to H$\alpha$, the H$\beta$ and MgI lines polarization direction are radial only. As shown in the following section, only radial polarization are cospatial. It worth also noting that the tangential polarization signal of H$\alpha$ is related to an associated mass flow.

### *3.4. Spatial distribution of linear polarization*

Two dimensional maps of the line-center intensity and polarization can been derived from combination of each scan. The H$\alpha$ (dotted line) and MgI (solid line) line-center intensity contours are plotted in Figure 6, superposed the maximum of polarization signal of these three lines. The polarization is found to be restricted to a relatively smaller area than the intensity signal, a few times $10^{17}$ cm$^2$. As we know, impact polarization is very sensitive to the particle propagation conditions like local density, coronal mass and particle nature and energy. Therefore, impact polarization is expected not being present all over the flaring region but rather at locations where kinetic particles have still anisotropic velocity distributions after crossing the corona and where the local hydrogen density is not too high in order to avoid strong depolarization effects.

In all three lines, the radial polarization comes nearly from the same location at the edges of one of the two flare kernels.

## 4. Discussion

It is necessary to discuss other kinds of possibility as linear polarization origin.

First, as shown above in section 3.2, one can eliminate the hypothesis of false polarization due to intensity gradients from Figure 4.

Secondly, scattering polarization can be ruled out since the flare is located at a place,

$S26^o\ E41^o$, where the heliocentric angle is not very large and. Furthermore, *The Second Solar Spectrum* (Gandorfer 2000) shows that the scattering polarization can not account for the polarization observed. For example the scattering polarization of the MgI line, expected to be maximum at the solar limb, is less than 0.05%.

Thirdly, the possibility of a Zeeman origin of the observed polarization are also to be discussed. Besides the rapid time evolution of such polarization signal (Xu et al. 2006), the multi-wavelength simultaneous observation can also give argument about this. Here we just show the comparison of the MgI, ScII and FeI line (630.2 nm and 630.1 nm ) profiles observed in Figure 7. Normally, if the magnetic field lead to a line-core emission profile by mixing of the $\pi$ and $\sigma$ components, the polarization resulted from such mixing will be lower than the one with a separated profile. However this is not observed in the MgI line. In additional, the decreasing amplitude, from the FeI to the ScII and MgI lines, of the Stokes profile $Q/I$ close to sunspots (y = 58) shown in Figure 7 indicates a decreasing sensitivity to the magnetic field, or a decrease of the longitudinal field since the field lines are expected to open up with height. Therefore, in case where the line-core emission polarization observed in the MgI line would be a $\pi$ component of the Zeeman effect, we expect a similar or even stronger signal to be present in the FeI and ScII lines. On the contrary, this is not found (see the bottom panels with y = 74).

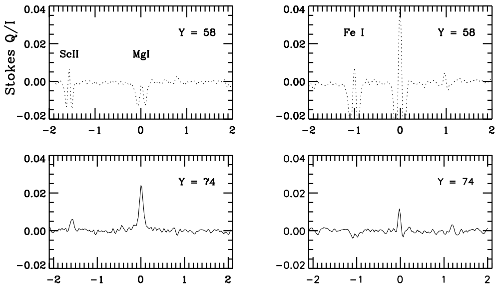


**Fig. 7.** Stokes profile $Q/I$ of ScII, MgI (left row) and FeI (right row) lines at a position close to the sunspot border ($y$ = 58) and at a place where MgI impact polarization is maximum ($y$ = 74). The obvious line-core emission in the Q/I profile of the MgI line, which is very weak in the FeI line.

## 5. Conclusions

From the discussion above, we arrive at the following conclusions:

1. The H$\alpha$, H$\beta$ and Mg line are linearly polarized, coming from the almost same location at the edge of one flare kernel.
2. The maximum value of polarization degree is about 3% - 6% and the polarization direction is related to the local transverse magnetic field. Furthermore, the polarization is limited in space and time.
3. This linear polarization signal can not be interpreted by scattering, Zeeman effect and the intensity gradient.
4. Since the impulsive hard X-ray and radio emission are present when such linear polarization is observed, we think such short-time linear polarization can be interpreted as due either to low energy proton beam or to the return current associated with electron beams.

Finally, we have to point out that we fully agree that it is still controversial about the impact polarization observation. Joint observation with other telescopes is needed to get ride the the effect of instrument and one of perspective is to include Na D1 lines observation, which is not sensitive to impact polarization.

*Acknowledgements.* The authors wish to acknowledge the support of V. BOMMIER to attend THEMIS user meeting.

## References

Firstova, N. M., Hénoux,J.C. and Kazantsev, S. A. et al., 1997, Sol.Phys., 171, 123-144.
Firstova, N. M. and Kashapova, L. K., 2002, A&A, 388, 17-19.
Firstova, N. M., Xu, Z. and Fang, C., 2003, ApJ, 595, 131-133.
Hénoux, J. -C. and Karlický, M., 2003,A&A, 407, 1103-1113.
Hénoux, J. -C. and Semel, M., 1981, Proceeding of Solar Maximum Year Workshop. eds. V.N.Obridko and E.V. Ivanov, Izmiran U.S.S.R., Vol. I, p.207.

Landi Degl'innocenti, E. and Landolfi, M., Polarization in spectral lines, Astrophysics and Space Science Librairy, Kluwer, 2004.
Kazantsev, S.A. and Hénoux, J. -C., Polarization Spectroscopy of ionized Gases, Kluwer 1995.
Kazantsev, S.A., Petrashen, A.G., et al., 1998,Opt.Spektrosk., Vol.85, No.2, 165.
Kleinpoppen, H. , "Physics of The One - and Two - Electron atoms". Editor: F.Bopp and H.Kleinpoppen, North-Holland., 1969, 612-631.
Vogt, E. and Hénoux, J. -C., 1996, SoPh, 164, 345-359.
Vogt, E. and Hénoux, J. -C., 1999, A&A, 349, 283-294.
Vogt, E., Sahal-Bréchot, S. and Bommier, V., 2001, A&A, 374, 1127-1134.
Werner, A. and Schartner, K-H., 1996, J.Phys.B:At.Mol.Opt.Phys., 29, 125.
Xu, Z., Hénoux, J. -C. and Chambe, G. et al., 2005 ,ApJ, 631, 618-627.
Xu, Z., Hénoux, J. -C. and Petrashen, A.G. et al., 2006 ,ApJ, 650, 1193.