Impact Polarization: A Diagnostic Test for Non-thermal Particles at Chromospheric Level During Solar Flares

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Abstract. By using the THEMIS telescope with the MTR mode, the Hydrogen Hα and Hβ lines have been observed to be linearly polarized by impact during the impulsive phase of two solar flares associated with high-frequency radio pulses. Two privileged directions of linear polarization are present, respectively radial (in the disk center to flare direction) and tangential (perpendicular to the radial direction). This polarization is due to non-thermal electron beams and to their associated return currents.
Figure 1. Direction of Hα linear polarization relative to the flare to disk-center direction for impact excitation by particles - electrons or protons - of energy $E$ either greater or lower than the turn over energy $E_0$.

1. Introduction

Measurements of the impact polarization of chromospheric lines provide information on the characteristics of the non-thermal particles, electrons or protons present in the chromosphere during solar flares. They could allow to identify the kind of particle, electrons or protons bombarding the solar chromosphere, and to precise the conditions of propagation of these particles together with the conditions of formation of their associated return currents.

2. Main characteristics of impact polarization

2.1. Usual definition of the impact degree of polarization

The anisotropy in the conditions of excitation by collisions may lead, depending of the transition, to the emission of polarized radiation. The polarization degree (Percival & Seaton 1959) of impact line radiation is usually defined as:

$$P(\beta, E) = (I_\parallel - I_\perp)/(I_\parallel + I_\perp),$$  \hspace{1cm} (1)

where $I_\parallel$ and $I_\perp$ are respectively the intensities of the vibrations parallel and perpendicular to the plane that contains the particle trajectory and the line of sight. The degree of polarization, $P(90^\circ, E)$, of the line radiation observed at $90^\circ$ of the beam depends on the transition and on the particle energy. For a singlet transition, $^1S - ^1P$, the line may be 100% polarized (Kleinpoppen 1969), with $P(90^\circ, E)$ varying from 100% near excitation threshold to $-100\%$ at infinite energy after changing of sign at a turn over energy $E_0$. The turn over energy depend on the nature of the impacting particle. Multiplet fine structure reduces the polarization degree value. The degree of polarization of the Hα line, close to 30% at threshold (in the case of excitation by electrons), changes from
positive to negative values at an energy $E_o$ equal to 200 eV for electrons (200 keV for protons) (Hénoux & Vogt 1998 and references therein).

2.2. Expected direction of impact polarization of flare chromospheric line radiation

As a consequence, the linear polarization of a line formed into the solar chromosphere by collisions with particles moving preferentially in the vertical polarization will be linearly polarized either in the radial (disk center to flare direction) or in the tangential direction (perpendicular to radial direction), depending of the particle energy as shown in Fig.1.

The chromosphere during solar flares may be bombarded by high energy electrons or by protons. Hecta KeV protons penetrating downwards will be accompanied by neutralizing electrons. In that case, both protons and neutralizing electrons will have energies below their turn over energies and would lead to radial linear polarization. High energy electrons, of initial energy exceeding ten to twenty keV, i.e. greater than $E_0$, propagating downwards will generate a neutralizing return current carried by local electrons.

For bombardment by mono-kinetic non-thermal electrons of energy $E^B$, the neutralizing condition:

$$ j_B = n^B_e V^B_e = j_R = n^R_e V^R_e, \tag{2} $$

gives for the return current energy $E^R$:

$$ E^R = \left( \frac{n^B_e}{n^R_e} \right)^2 E^B. \tag{3} $$

So, $E^R$ depends on the non-thermal electrons energy and on the return current electron number density $n^R_e$. Depending on the conditions for return current formation, this density could be lower than or equal to the local electron number density. Consequently, the return current energy can be lower to or higher than $E_0$ (Karlický & Hénoux 2002) and the direction of linear impact polarization can be either tangential or radial (Hénoux & Karlický 2003).

3. THEMIS impact polarization observations

Multi-lines spectropolarimetric observations of a few flares have been made with THEMIS using the MTR mode. We are just reporting here some linear polarization measurements made in H$\alpha$ and H$\beta$ at some times and at some locations during the impulsive phase of two solar flares. These flares were observed on 2001 June 15th and 2000 July 18th with very different instrumental settings.

3.1. 2001 June 15th flare

The June 2001 observations used the MTR mode with, per selected atomic line, a CCD camera on which both $I+S$ and $I-S$ spectra were focussed. The Stokes parameter $S$ could be either $U$ or $Q$ defined in a coordinate systems fixed by the instrumental setting. The field of view along the spectrograph entrance slit direction is close to one arc minute.
Figure 2. Hα (left) and Hβ (right) line intensity (full line), linear polarization degree (dotted line) and orientation profiles (dashed line) observed at 10:07:55 UT on June 15th 2001 at location a. The position along the spectrograph slit is indicated on the left part of each figure on one of the two superposed two I + S (up) and I − S (down) spectral images in the spectrograph dispersion plane for one of the two Stokes parameters U or Q.

Figure 3. Hα (left) and Hβ (right) line intensity (full line), linear polarization degree (dotted line) and orientation profiles (dashed line) observed at 10:07:44 UT on June 15th 2001 at location b.

Figure 4. Hα (left) and Hβ (right) line intensity (full line), linear polarization degree (dotted line) and orientation profiles (dashed line) observed at 10:07:35 UT on June 15th 2001 at location c.
Figure 5. Hα (left) and Hβ (right) line intensity, linear polarization degree and orientation profiles at five positions (seen on bottom left part of each figure) along the spectrograph slit. Superposed on the left are three couples of associated \(I + S\) (up) and \(I - S\) (down) spectral images. Observations made at 7:22:06 UT on July 18th 2000.

A 1N flare was observed on June 15, 2001. It was located at S26E41 in active region AR9502. The NOAA reported begin, maximum and end times are respectively 10:01, 10:13 and 10:20 UT. On radio waves in the 2.0-4.5 GHz range the measured polarization was accompanied by radio pulses, which indicate a bombardment of deep atmospheric layers by electron beams. HXRS instrument (Färnık, Garcia H. & Karlický, 2001) observed impulsive hard X-ray emission during the time of THEMIS observations.

THEMIS observations started at 10:07:20 UT. The scanning was made in twenty steps, separated by 3 arc second, with a scanning time for these twenty steps close to 90s. At each position, the Stokes parameters \(Q\) and \(U\) were successively recorded. Five lines were observed simultaneously. We report here on the Hα and Hβ lines observations. Intensity, linear polarization degree and orientation profiles in these lines, at three flare locations, called \(a\), \(b\) and \(c\), observed respectively at 10:07:55, 10:07:44 and 10:07:35 UT during the impulsive phase, are plotted in Figs. 2(a,b), 3(a,b) and 4(a,b). These profiles were obtained by integrating over about 2.5 arc second along the slit direction. The brightest intensity profiles and not the highest polarization signals have been selected. The polarization orientation angle takes for origin the celestial south-north direction. The disk center to flare direction was making with the reference axis an angle close, within ±5°, to 65° (0.36 in 180° unit, as in Figs. 2, 3 and 4).

At all locations, the Hα and Hβ lines are linearly polarized with a width for the polarization degree profile close to 10 and 20 nm respectively and a maximum varying between 1.6 and 3.4 % for Hα and between 2.8 and 3.4 % for Hβ. As shown in Fig.2(a,b) and 3(a,b), at locations \(a\) and \(b\) the polarization direction is close to tangential in both lines. Then at location \(c\), the polarization direction tangential in Hα becomes radial in Hβ.

### 3.2. 2000, July 18 flare

July 2000 observations used the MTR mode with a grid located just before the polarimeter. The grid allows to separate the images formed by the extraordinary and ordinary beams that carry the \(I + S\) and \(I - S\) signals without additional
optics, making the optical paths for the two beams as identical as possible (Semel 1980). The \( I + S \) images of the transparent strips are located between the \( I - S \) images of these strips. There are three sets of \( I + S, I - S \) couples.

A 1F flare was observed on 2000 July 18th. This flare was located at S13E16 in active region AR9087. NOAA reported the begin, maximum and end times to be respectively 07:08, 07:21 and 08:03 UT. Radio pulses, that indicate the bombardment of the deep atmospheric layers by electron beams, were observed by the Ondrejov radiospectrograph. THEMIS observations started at 07:22:02 UT just after the reported time of maximum emission. The scanning was made in twenty steps, separated by 4 arc second, giving a sampling time close to 50s. For each observing position, \( U \) and \( Q \) were measured successively.

On Figs.5(a,b), \( H\alpha \) and \( H\beta \) lines intensity, linear polarization degree and orientation profiles observed at five positions along the spectrograph slit at 7:22:06 UT are presented. Each profile is obtained by integrating over 2 arc second along the slit direction. On these figures, the polarization orientation angle, takes for origin the celestial south-north direction. The disk center to flare direction was making with this reference axis an angle close, within \( \pm 5^\circ \), to \( 55^\circ \). In \( H\alpha \), all along the bright location chosen, the linear polarization direction is very close to the tangential one, deviating by up to \( 20^\circ \) from this direction. On the other hand the \( H\beta \) line linear polarization is radial within \( \pm 20^\circ \). This deviation form radial or tangential direction may be due to the observed difference in sharpness of the \( U \) and \( Q \) images.

4. Conclusion

Two main directions of linear polarization, tangential and radial, are found in the \( H\alpha \) and \( H\beta \) solar flares observations. Only high energy electrons could explain the tangential direction of polarization observed in these lines. Since \( H\beta \) and \( H\alpha \) line polarization turn over energies \( E_{\text{tov}} \) are the same, the observed change of the polarization direction from tangential in \( H\alpha \) to radial in \( H\beta \) can be explained as due to the difference of formation depths of these two lines and to the contribution of the return current - associated with the electron beam - to chromospheric lines formation (Hénoux & Karlický 2003).

References

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Discussion

A. Gandorfer: What was the integration time?
Did you apply the beam-exchange method?
What was the spatial resolution scale?
J.C. Henoux: The integration time was 300 ms.
We did not use the beam-exchange method. Beam exchange method is most appropriate for observations where the signal is integrated all over the spectrograph entrance slit and less affected by solar structures and evolution. For flare observations the measurements will be affected by the time variation of the flare line intensity, introducing I cross-talk.
The profiles shown are spatially integrated over 2 to 2.5 arc second.

V. Zharkova: How would change the return current law in case of a power law energy distribution of electron beams. I am referring to our paper in A&A, 1995?
J.C. Henoux: For simplicity, I used here a mono kinetic beam. However, it is easy to rewrite the equation for current neutralization for the case of a power law distribution in energy of the particle number flux. Then the return current energy depends on the low energy cut-off and on the power index.

L. Kashapova: Did you use radiospectrum observations (I mean the drafts) for detecting beams of electrons?
J.C. Henoux: Yes. For both flares reported here Ondrejov radiospectrograph observations were available. They go up to 3 Ghz and show in both cases a drift in time to high frequency, signature of electrons propagating downwards.