CONDUCTIVE FLUX IN THE CHROMOSPHERE DERIVED FROM LINE
LINEAR POLARIZATION OBSERVATION

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ABSTRACT. Linear polarization in two chromospheric lines (Hα and
SI 1437 Å) was observed in the gradual phase of solar flares. The
polarized electric vector is directed towards disk center.

This polarization could be due to collisional excitation of hydro-
gen and SI by energetic electrons beamed in the vertical direction.
Direct excitation by a highly energetic beam of electrons of order
10–100 keV is doubtful. The heat flux in the region connecting the
transition zone to the high chromosphere during the gradual phase of a
flare could lead to an anisotropic excitation.

Selecting a function which represents the velocity distribution
of electrons carrying heat flux, the relationship between conductive
heat flux and linear line polarization has been computed. The applic-
ation of the relationship between linear polarization and heat flux
to the observed degree of polarization leads to the determination of
the conductive heat flux in the high chromosphere. This conductive flux
is of the order of magnitude of the total radiation loss in the chro-
mosphere and below, which is also of the order of magnitude of the
conductive flux in the transition zone.

INTRODUCTION

The aim of this paper is to show how the measurement of impact
line polarization can provide quantitative information on the mechanisms
of energy transport which take place in solar flares.

Chromospheric flares are usually interpreted as secondary pheno-
mena assuming that energy is supplied to the chromosphere, from the
flaring corona, via heat conduction, electron bombardment or X-ray
irradiation. The importance of these modes of energy transfer in the
energetic equilibrium of a flaring chromosphere is widely accepted
through theoretical considerations. In this paper an observational test
is presented which could give estimates of the relative importances of
the energy transport modes.

Heat conduction, electrons bombardment, and XUV irradiation are
associated with anisotropic velocity distribution functions of energetic
electrons:

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- Velocity distribution of electron beams are peaked in the magnetic field direction.
- Velocity distribution of electron transporting heat flux has a tail of energetic electrons in the heat flux direction.
- Photoelectrons produced by XUV irradiation are predominantly moving in the solar horizontal plane.

Therefore the determination of the main travelling direction of energetic electrons would allow discrimination between the different modes of energy transport.

The main characteristics of the velocity distribution anisotropy could be estimated by measuring line linear polarization for atomic species collisionally excited by these electrons:

Beams of electrons colliding with atoms could lead to the emission of linearly polarized lines. The maximum polarization is observed at 90° from the beam direction. This polarization is energy dependent and changes of sign when the energy increases. Therefore the degree of polarization gives information on the anisotropy of the colliding electrons and on the energy of these electrons.

Linear polarization observations made in two different chromospheric lines are reported in Section 1. The observed polarization is interpreted in Section 2 as impact polarization produced by electrons carrying heat flux. The conductive flux derived in Section 2 is compared in Section 3 to the conductive flux in the transition zone and to the total radiative losses in the chromosphere.

1. POLARIZATION OBSERVATIONS

Linear polarization was observed in two different chromospheric lines, Si 1437 Å and Hα, during the decay phase of two different events.

1.1. Si lines observations. We used the Ultraviolet Spectrometer and Polarimeter (UVSP) on the Solar Maximum Mission. This instrument is described by Woodgate et al. (1980) and by Calvert et al. (1979). The observational results briefly presented here are given in detail in Henoux et al. (1982).

When the instrument is used as polarimeter a magnesium fluoride waveplate is inserted behind the entrance slit of an Ebert Fastie Spectrometer and it is rotated in steps of 22.5°. The spectrometer grating serves as an analyser of polarization.

The rotation of the wave plate produced a modulation of the intensity if the incoming radiation is polarized. Fourier analysis is used to evaluate the Stokes parameters. The coefficients of the Fourier component modulated at four times the waveplate rotation frequency give the linear polarization.

Polargrams are obtained by rastering the solar image. They cover a field of view of 50" x 50" with a spatial resolution of 10" x 10". At each raster pixel the integrated line intensity was sampled at each of the 16 waveplate positions.

A flare of importance SB and class C4 was observed on July 15th 1980 from 22 48 UT to 23 07 UT. Line linear polarization was detected during the decay phase of soft X-ray emission in flaring pixels. Using a vectorial representation Figure 1 shows the degree of linear polarization and the orientation of the polarization for six flaring pixels.
FIG. 1 - Linear polarization in the Si 1437 Å line is represented by vectors of amplitude proportional to the degree of polarization and oriented in the direction of the electric vector. The maximum degree of polarization is 25%.

SI 1437 Å line emission is polarized at three of these six flaring points with a degree of polarization as high as 25%. The angle between the South-North direction and the electric vector varies from 109° to 117° and is therefore very close to the angle between South-North and disk-center-to-flare direction (116°). By adding the signal from the six bright pixels we found a mean polarization of 12% with an electric vector directed towards disk center to within 3°.

1.2. Hα line observations

We slightly modified an existing heliograph by inserting a rotating half-wave plate in front of a linear analyser in front of the Lyot Filter. This wave plate was rotated through 22.5° per step. Successive sets of 16 images were taken every minute on photographic film. A pass band of 0.75 Å centered at Hα center was used.

From each set of 16 images we derived seven determinations of the linear polarization. Four of these seven determinations are independant.

The decay phase of a 1B flare was observed on May 17, 1980. Four sets of 16 images were obtained in four minutes (from 0738 to 0741). Restricting the investigation to polarization signals of long duration (1 to 4 minutes), we integrated the signal over two and four minutes of observation, and we found polarization above Hα kernels and slightly outside these kernels. The direction of polarization was within 7° of the disk-center-to-flare direction (see Figure 2).
FIG. 2 - Linear polarization in the Hα line is represented by vectors of amplitude proportional to the degree of polarization and oriented in the direction of the electric vector. The maximum degree of polarization is 2%. The arrow on the bottom right corner represents the disk-center-to-flare direction.

The direction is stable in time above the kernels during the four minutes of observation. The degree of polarization is about 2%.

Si 1437 Å and Hα line observations lead to the same result: these two chromospheric lines are linearly polarized during the decay phase of the observed events. The polarized electric vector is directed towards disk center. Linear polarization may also be produced during the flare impulsive phase but the time resolution of the observations was not high enough to detect low duration polarization.

2. INTERPRETATION: IMPACT POLARIZATION PRODUCED BY ELECTRONS CARRYING HEAT FLUX

2.1. Impact polarization

Atoms collisionally excited by beams of electrons emit line radiation which may be linearly polarized. The theory was formulated by Percival and Seaton (1958). A review of the experimental and theoretical results on impact polarization was presented by Kleinpoppen (1969) and Heddle (1979).

The maximum polarization $P_{\theta}(v)$ is observed at $90^\circ$ from the beam direction ($P_{\theta}(v) = (I_\parallel - I_\perp)/(I_\parallel + I_\perp)$) where $I_\parallel$ and $I_\perp$ are respectively the intensities of the vibrations parallel and perpendicular to the beam; $v$ is the electron velocity. This polarization is energy dependant.

The linear polarization of photons emitted at an angle $\beta$ from the beam is given by $P(\beta,v) = P_{\theta}(v) \sin \beta/(1 - P_{\theta}(v) \cos \beta)$. (1) The linear polarization $P(\theta)$ produced by collisional excitation by electrons with a specific angular velocity distributions $dn(v)/d^3v$ can
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easily be computed.

We defined \( P(\theta) = (I_{/} - I_{\perp})/(I_{/} + I_{\perp}) \) where \( I_{/} \) and \( I_{\perp} \) are the intensities of the vibrations parallel and perpendicular to the plane defined by the line of sight and the solar vertical. \( \theta \) is the angle between the solar vertical and the line of sight.

For any velocity distribution with cylindrical symmetry

\[
P(\theta) = P(90^\circ) \sin \theta / (1 - P(90^\circ) \cos \theta).
\]

(2)

This equation is identical to Equation (1) when \( \beta \) and \( P_{90}(v) \) are replaced by \( \theta \) and \( P(90^\circ) \) where

\[
P(90^\circ) = \int_0^\infty \frac{2J_0 - P_{90}(v)(J_2 - J_0)}{3 - P_{90}(v)} \frac{v \sigma(v)}{d^3v} dv
\]

(3)

and

\[
J_n = \int_0^\pi \frac{d\eta(v,a)}{d^3v} \cos^n \alpha \sin \alpha \, d\alpha;
\]

\( \alpha \) is the angle between an electron travel direction and the solar vertical; \( \sigma(v) \) is the line excitation cross section.

2.2. Velocity distribution associated with heat flux

A typical electron velocity distribution which has a heat flux in the \( z \) direction but no net particle current was given by Manheimer (1977) as

\[
\frac{dn}{d^3v} = \frac{n_e}{(2\pi^{3/2})} \exp \left[-\frac{v^2}{2v_e^2}\right] \left[1 - 0.5 \frac{Q_s}{Q_s} \frac{v_z^2}{v_e^2} \right],
\]

(4)

where \( KT = m_e v_e^2 \) and \( Q_s = \frac{3}{2} n_e m_e v_e^3 \) is the saturated heat flux.

Negative values of \( \frac{dn}{d^3v} \) obtained for large negative \( v \) were replaced by zero. The first three moments suffer only minor \( z \) changes.

Then the effective heat flux \( Q^* \) (\( Q^* = \frac{1}{2} \int m_e \frac{v^3}{z} \frac{dn}{d^3v} \, d^3v \)) differs from \( Q \).

2.3. Polarization of the \text{Si} 1437 Å and \text{H}\alpha lines. Computation of the polarization and comparison with observations.

\( P(90^\circ) \) was computed using formula (3) and the modified version of Manhemier's distribution function for \text{H}\alpha and \text{SI} 1437 Å lines.

(1) \text{H}\alpha

The figure 3 shows \( P(90^\circ) \) as a function of \( Q/Q_s \) for three sets of known values of \( P_{90}(v) \) and \( \sigma(v) \) and, for two different temperatures of formation of \text{H}\alpha line center (\( T = 10^4 \) K and \( T = 2 \times 10^4 \) K).

Knowing the flare solar coordinates and using formula (2) \( P(90^\circ) \) was derived from the observed degree of polarization. \( P(90^\circ) = 6 \% \). For
such value of $P(90^\circ)$, the Figure 3 and the relation between $Q^* / Q_\text{V}$ and $Q/Q_\text{V}$ lead to the inequality $0.16 < Q^* / Q_\text{V} < 0.37$ where the two limits correspond to $T = 10^4$ and $T = 2 \times 10^4$ K.

FIG. 3 - Maximum linear polarization $P(90^\circ)$ of the H$\alpha$ line as a function of the heat flux. Calculations were made for two temperatures. Lower full line curve $\sigma(v)$ and $P_{90}(v)$ from Kleinpoppen and Kraiss (1968). Upper full line curves $P_{90}(v)$ from the DWPO approximation (Symes et al. 1975). In the last two cases $\sigma(v)$ is from Mahan et al. (1976).

(2) SI 1437 Å

The maximum polarization in the SI 1437 Å line is shown as a function of $Q/Q_\text{V}$ in Figure 4. $P(90^\circ)$ was computed for two sets of values of $P_{90}(v)$ derived from the polarization of resonance transition of alkali-metal atoms and from the polarization of the hydrogen Ly$\alpha$ line, and for $T = 10^4$ and $T = 2 \times 10^4$ K.

FIG. 4 - Maximum linear polarization $P(90^\circ)$ of the SI 1437 Å line as a function of the heat flux $\sigma(v)$ and $P_{90}(v)$ were obtained from data corresponding to either alkali transitions (full line curves) or H Ly$\alpha$ (dotted line curve).
From Equation 2 the maximum polarization P(90) corresponding to the mean degree of polarization observed (12%) is 31%. Finding this value on Figure 4 leads to the following inequality $0.13 < Q^* / Q_S < 10^8$ K and $T = 2 \times 10^4$ K and are close to the limits derived from Hα observations.

3. CONDUCTIVE FLUX IN THE HIGH CHROMOSPHERE - CONCLUSION

From the two preceding inequalities we derived $0.16 < Q^* / Q_S < 0.33$. Assuming $n_e = 10^{12}$ the extreme values of the saturated heat flux are $Q_S = 5.6 \times 10^7$ and $Q_S = 2.1 \times 10^8$ leading to $9 \times 10^6 < Q^* < 6 \times 10^7$ ergs cm$^{-2}$ s$^{-1}$.

This estimate of the heat flux can be compared to the conductive flux in the transition zone and to the radiative losses in the chromosphere. The conductive flux in the transition zone during flares was computed by Withbroe (1978) who found $F_c = 3.2 \times 10^8$ ergs cm$^{-2}$ s$^{-1}$ for a 2B flare. Machado and Emslie (1979) derived conductive flux values varying between $2 \times 10^6$ and $5 \times 10^7$ ergs cm$^2$ s$^{-1}$ for 7 subflares.

If we assume that no energy is lost between the middle of the transition zone and the Lyα–Hα center formation layer then the conductive flux in the high chromosphere, leading to a reasonable agreement with our estimates.

The measured conductive flux is of the order of magnitude of the total radiation losses in the chromosphere and below: Canfield et al. (1980) gave $4 \times 10^7$ ergs cm$^2$ s$^{-1}$ as the radiative output of a class (−N) flare.

The measurement of linear polarization makes possible the determination of the heat flux. This method is the only one which could give the conductive flux value in the high chromosphere. Its accuracy is still limited by the uncertainties in the atomic data and in the shape of the velocity distribution function. Nevertheless this first analysis of polarization observation clearly indicates that heat conduction plays an important role in chromospheric flare heating.
REFERENCES