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Electron Impact Polarization Expected in Solar EUV Lines from Flaring Chromospheres/Transition Regions

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Abstract

We have evaluated lower bounds on the degree of impact EUV/UV line polarization expected during solar flares. This polarization arises from collisional excitation by energetic electrons with non-Maxwellian velocity distributions. Linear polarization was observed in the S I 1437 Å line by the UVSP/SMM during a flare on 1980 July 15. An early interpretation suggested that impact excitation by electrons propagating through the steep temperature gradient of the flaring transition region/high chromosphere produced this polarization. Our calculations show that the observed polarization in this UV line cannot be due to this effect. We find instead that, in some flare models, the energetic electrons can produce an impact polarization of a few percent in EUV neutral helium lines (i.e., $\lambda\lambda$ 522, 537, and 584 Å).

I. Introduction

The aim of this paper is to find the amount of impact linear polarization expected to be present in atomic spectral lines formed in solar plasmas. This polarization arises because the steep temperature gradient of the transition region leads to non-Maxwellian velocity distributions of electrons carrying conductive heat flux.

The geometry of the adopted model is shown in Figure 1. The emitting upper chromosphere/transition region (hatched area, in Figure 1) of the loop is observed at the solar limb (where the polarization is largest). The curvature of that part of the loop is negligible, and the loop axis and the direction of the local magnetic field coincide with the solar vertical (Z axis). The pitch angle, θ, is measured from the loop axis. The temperature structure of these models is given by $T(s)$, where s is the distance to the loop apex along the magnetic field (or the loop axis). These models are described elsewhere (Ljepojevic and MacNeice, 1987; MacNeice, Fontenla, and Ljepojevic, 1990). The electron velocity distribution is

$$f = f\left(s, \mu, \frac{v}{v_T}\right) ,$$

where v_T is the electron thermal velocity and $\mu \equiv \cos\theta$. This distribution

- is *cylindrically symmetric* around the loop axis;
- follows the *Spitzer-Härm function* for $v < 2 \cdot v_T$ – this function is derived under the assumption of small deviations from Maxwellian, and can expressed as:

$$f\left(\mu, \frac{v}{v_T}\right) = \left[1 - \mu \cdot D\left(\frac{v}{v_T}\right)\right] \cdot M\left(\frac{v}{v_T}\right) , \qquad (1)$$

  where M is the Maxwellian function and D correspons to a perturbative expansion and we droped the variable s for simplicity;
- and is computed solving numerically the *high-velocity form of the Landau equation* (HVL) for $v \geq 2 \cdot v_T$ (Ljepojevic and MacNeice, 1989).

III. Emission-Line Polarization by Electron Impact

The impact polarization has been computed using a recent theoretical scheme based on the formalism of irreducible tensor operators (Fineschi and Landi Degl'Innocenti, 1989 and 1990a). In this scheme, the statistical equilibrium equations of a multi-level atomic system interacting with an electron beam are derived in full generality from the principles of Quantum Mechanics. The collisional excitation is calculated for electrons having arbitrary angular and velocity distributions. In this scheme, the effect of magnetic fields on the impact polarization can also be accounted for. This theory gives analytical expressions for the polarization cross sections of the electric multipole transitions due to atom-electron collisions, provided the Born approximation be assumed.

From the above-mentioned theory the presence of a magnetic field gives, for the emitted polarized radiation, a phenomenon similar to the well known Hanle-effect (i.e., impact

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The degree of linear polarization is given by

$$P = \langle S_1 \rangle / \langle S_0 \rangle \,, \tag{4}$$

where

$$\langle S_i \rangle = \int_{v_0}^{\infty} dv \int_{-1}^{+1} d\mu \cdot f\left(\mu, \frac{v}{v_T}\right) \cdot S_i(v, \mu)\,; \quad i = 0, 1. \tag{5}$$

Thus, for a given distribution f, the polarization, P, is a function of: the line wavelength λ; the electron temperature T; and the type of atomic transition, $J' \rightarrow J$. In the following, we restrict ourselves to lines where $J' \rightarrow J$ corresponds to $1 \rightarrow 0$. In this case there is no atomic depolarization, and the polarization is maximum, i.e., $W_{10} = 1$.

It is important to note that in the expression of $\langle S_1 \rangle$, the integral over μ corresponding to the part of f which follows the Spitzer-Härm function is

$$\langle S_1 \rangle \propto \int_{-1}^{+1} d\mu \cdot (1 - \mu \cdot D) \cdot (3\mu^2 - 1) = 0. \tag{6}$$

Therefore, no net polarization arises from the bulk of the distribution, and only the strongly anisotropic, high-velocity electrons in the tail are responsible for the polarization.

IV. Results

The results for the expected impact polarization can be expressed as $P = P(\lambda, T)$. For XUV/EUV/UV lines formed in the upper chromosphere/transition we show the "flare" case in Figure 2, and the "quiet Sun" case in Figure 3. In all cases, the direction of maximum polarization corresponds to the vertical. The results shown are for the transition $[J' = 1 \rightarrow J = 0]$.

The location of some lines which are observed in the Sun has been marked. For each of them the cross is drawn at the temperature where the emissivity (in $erg\, cm^{-3}\, s^{-1}$) peaks. The upper and lower ends of the bar correspond to the temperatures where the emissivity drops to about one third of the maximum. These temperature values were taken from the literature, where a Maxwellian electron distribution was assumed for the line-formation computations (Landini and Monsignori Fossi, 1990) and effects of the emitting ions diffusion are ignored. However, these diffusion effects may affect the actual ranges of temperature at which the lines are emitted, as shown by Avrett and Fontenla (1990).

The result plotted in Figure 2 shows that impact polarization by excitation of electrons carrying heat flux would be present in the EUV neutral helium lines 522, 537, and 584 Å.

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where Q is a function of the electron velocity and is proportional to the temperature gradient. Consequently, the line polarization resulting from electrons having the Manheimer distribution is zero:

$$S_1 \propto \int_{-1}^{+1} d\mu \, (3\mu^2 - 1) \cdot [1 + Q \cdot (\mu^3 - 3\mu)] = 0. \tag{8}$$

The original Manheimer function was modified by Hénoux *et al.* (1983b) replacing its negative values – physically meaningless – by zero in the range $1.5 v_T < v_z < 3 v_T$ ($v_z = v \cdot \mu$). This procedure was first suggested by Shvarts *et al.* (1981). We show in Figures 4 and 5 the distribution function we computed, and compare it with the Manheimer and the modified Manheimer functions. In Figure 6, we show the angular distributions which result from our calculation, and we compare it with the modified Manheimer values. The ordinate in this figure reflects the contribution of particular energy electrons to impact polarization. All these figures show that the modified Manheimer function is strongly anisotropic, and in fact *all the impact polarization in Hénoux et al. (1983b) calculations is due to such modification of the original Manheimer function.* For a line excitation energy (threshold energy) corresponding to a few times the thermal energy, the modified Manheimer distribution gives rise to high values of polarization, much larger than the ones obtained in our more accurate treatment. Moreover, for this modified Manheimer function the significant departure from an angular distribution which results in zero line polarization (cfr. eq. [8]) occurs at a lower range of electron velocities ($\sim 1.5 - 2 \, v_T$) compared to our treatment ($\sim 3 - 3.5 \, v_T$). Thus, by assuming the modified Manheimer function, UV lines with relatively low threshold energy (viz., long wavelengths) can be excited by electrons which already have strongly anisotropic velocity distribution, producing in this way large impact polarization in the line. On the contrary, if we consider the distribution we computed, the low threshold energy lines are mostly excited by electrons having almost isotropic distribution, and thus low impact polarization results (see Fig. 6). Therefore, the only spectral lines which are expected to show strong polarization are those with a threshold energy large enough so that line excitation is predominatly by highy suprathermal electrons ($v \geq 3 v_T$). The neutral helium lines ($\lambda\lambda$ 522, 537, and 584 Å), in the EUV wavelength regime, would fulfil this requirement.

As final remark, we point out that this result does not take into account the depolarizing effect due to radiative transfer in these resonance lines. This effect would be important for large optical thickness, τ, of the line emitting region. Optical thickness of EUV helium lines in solar flares depends on a variety of conditions of heating and irradiation of the and bombard the chromosphere. Proton beams have been proposed by Simnett (1986) to be important in some flares.

In order to assess the relative role played in solar flares by high or low energy electron beams and by proton or neutral beams, further Hα measurements as well as EUV observations with new imaging polarimeters (Fineschi *et al.*, 1990b; Hoover *et al.*, 1990) are highly needed.

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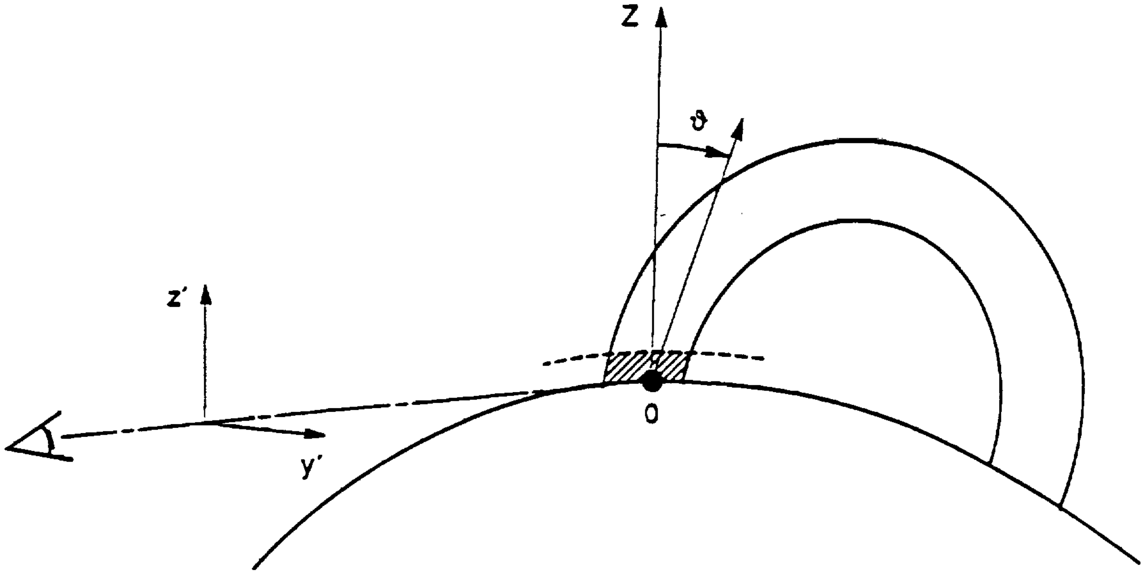

Figure 1. Geometry of the loop model and coordinate system for the calculation of the Impact linear Polarization. The emitting upper chromosphere-transition region (hatched area) of the loop is observed at solar limb. The curvature of that part of the loop is negligible, the loop axis and the direction of the local magnetic field coincide with the solar vertical, Z. The pitch angle, θ, of the electrons is measured from the loop axis.

EXPECTED POLARIZATION FOR THE QUIET SUN MODEL
(with Ambipolar Diffusion)

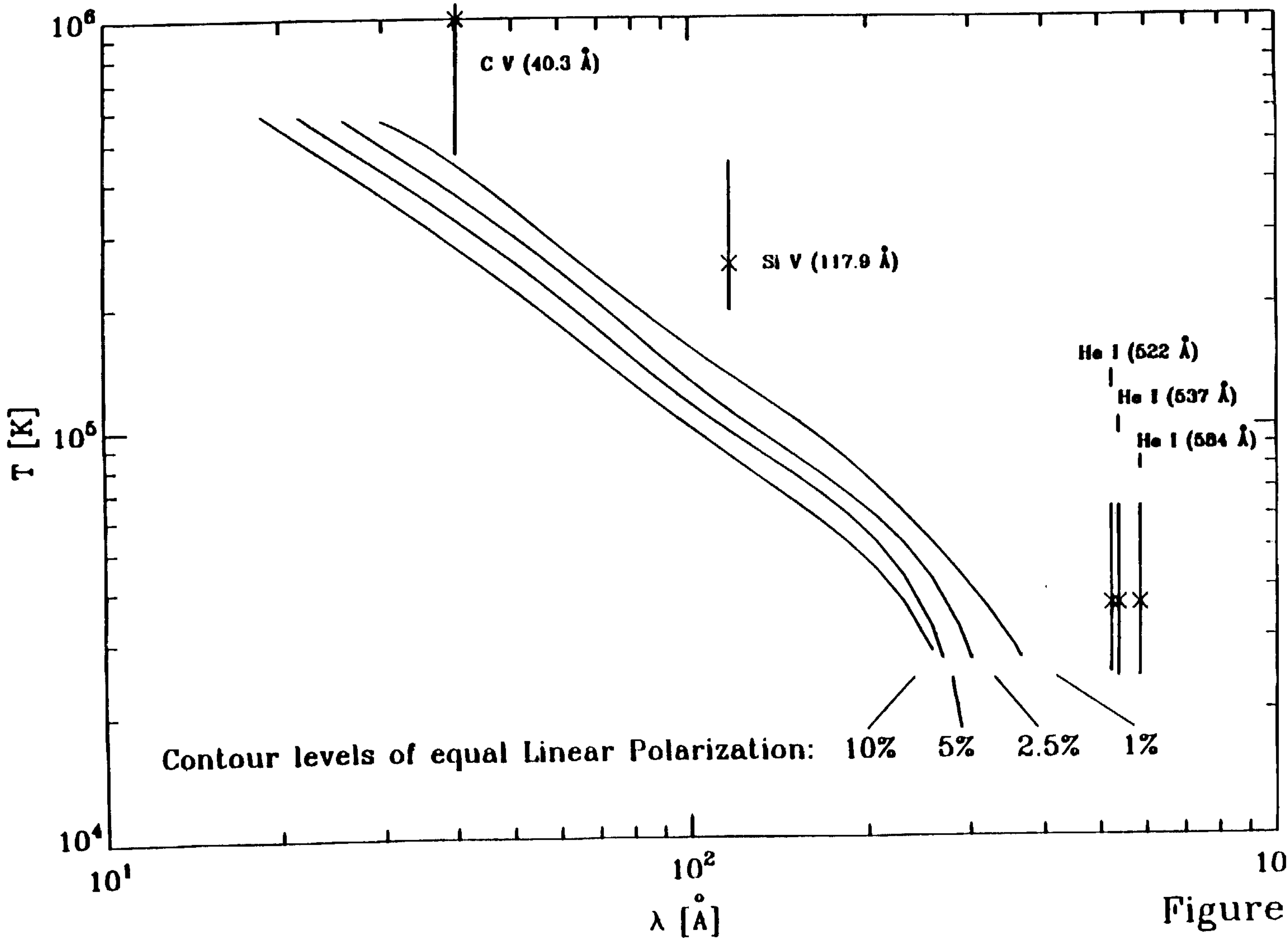

Figure 3.

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ANISOTROPY OF THE ELECTRON DISTRIBUTIONS

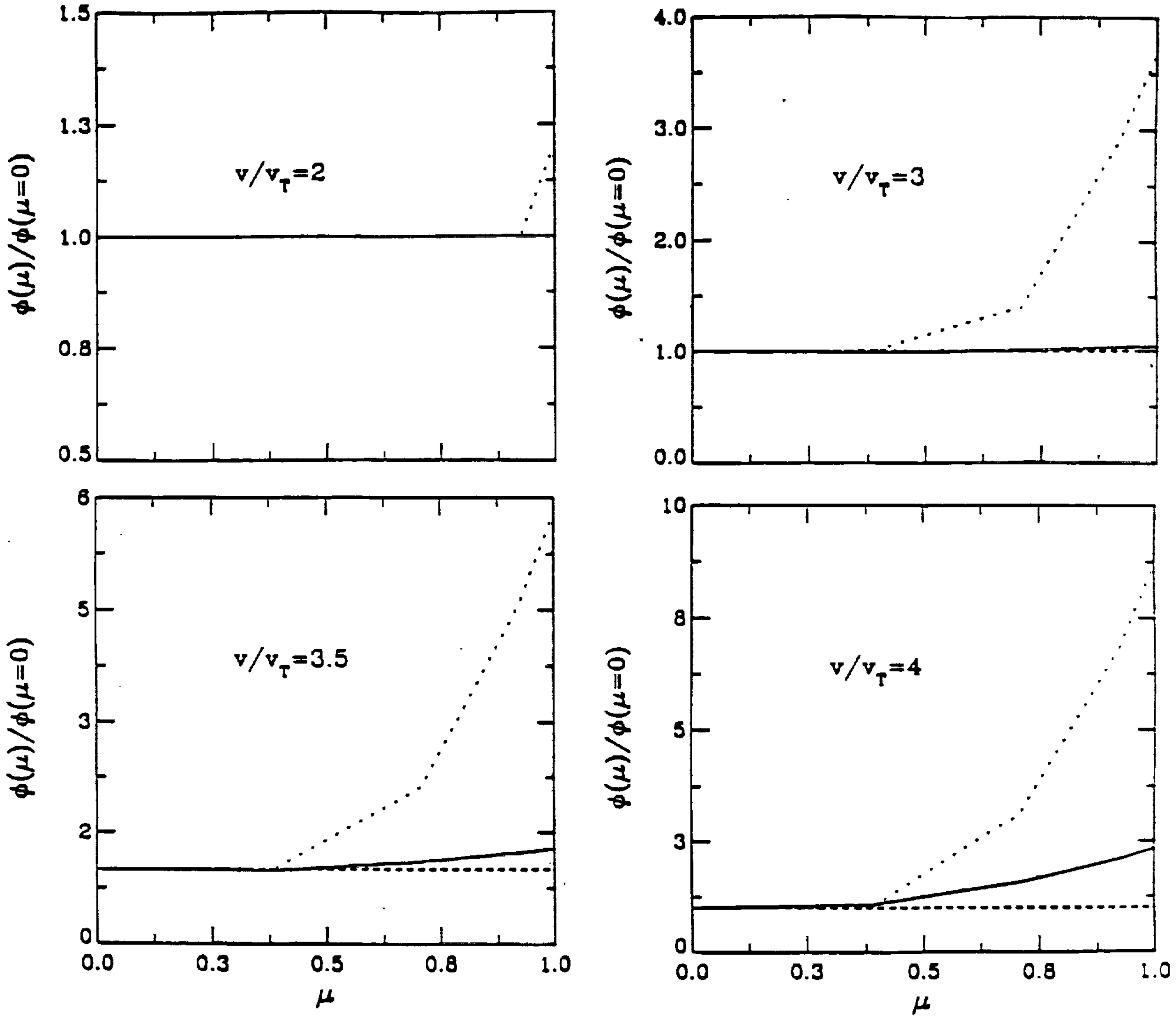

Figure 6. Plots of the symmetrical part,

$$\phi(\mu) \equiv \frac{1}{2}\cdot\left[f\left(+\mu,\frac{v}{v_T}\right)+f\left(-\mu,\frac{v}{v_T}\right)\right],$$

of the Spitzer-Härm+HVL (solid line) and of the modified Manheimer distribution (dotted line). (Dashed line: Maxwellian).