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The viewing angle effect on H_α-line impact polarisation in impulsive solar events

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Abstract. The effect of a viewing angle on the hydroden H_α-line impact polarisation is investigated in a plane vertical atmosphere arbitrary located on the solar disk. The impact polarisation is assumed to be caused by precipitating beam electrons with pitch-angular anisotropy steadily injected into the flaring atmosphere from its top. The polarisation is calculated for a 3 level plus continuum hydrogen atom affected by Zeeman splitting in a moderate magnetic field taking into account depolarising effects of diffusive radiation and collisions with thermal electrons. The H_α polarisation profiles are affected by electron beams only in the line cores whereas the wings are fully depolarized by the collisions with thermal electrons despite the extended wing emission, or "moustaches", caused by beam electrons. The full (integrated in wavelength) H_α-line linear polarisation, caused by moderate electron beams, is shown to be 2−20% and either negative or positive depending on the position of a flaring loop on the solar disk and the direction of an emitted photon from the local magnetic field. The polarisation plane is projected onto a viewing angle ψ, being a superposition of the flare location on a solar disk and the magnetic field deviation from vertical on the solar surface. For viewing angles less then 50° the H_α-line impact polarisation is negative increasing up to −10% towards smaller angles, meaning that the polarisation is mostly perpendicular to the plane $\boldsymbol{B}\times\boldsymbol{K}$ where $\boldsymbol{B}$ is the magnetic field induction and $\boldsymbol{K}$ is the photon momentum vector. For viewing angles greater than 60° the measured impact polarisation becomes positive, sharply increasing up to 20% towards the limb. In the range of 50−60° the observed impact polarisation goes through a zero point despite the actual presence of beam electrons in the flaring atmosphere. The theoretical predictions of the dependence of polarisation degree on viewing angle fit remarkably well the observations of H_α-line linear polarisation in small-scale flaring events such as moustaches or Ellerman bombs, located in different positions on a solar disk.

Key words. Sun: flares – plasmas – polarization – physical data and processes

1. Introduction

Observations of linear polarisation in spectral lines from solar flares provide unique information on the directions of energy transport from the corona to deeper layers during these highly dynamic events. The H_α-line is the most observable line in solar flares for ground-based instruments, and significant properties of energy transfer process can be derived from the measurements of its polarisation vector.

Linear H_α polarisation is not very often observed in large solar flares (Henoux 1991; Firstova & Bulatov 1996; Firstova & Kashapova 2002; Firstova et al. 2003) but more regularly in flaring events of much smaller scales called moustaches or Ellerman bombs (EB) with extended wings in the H_α line profile. These events have sizes from 5″ down to the diffraction limit of modern (1-m class) solar telescopes. Their resemblance in many spectral aspects to type II white-light flares (Hiei 1986) suggests the H_α line moustaches to be small-scale appearances of impulsive heating similar to larger solar flares caused by electron beam precipitation and non-thermal excitation of hydrogen atoms (Severny 1965; Bray & Loughhead 1974; Aboudarham & Henoux 1987; Zharkova & Kobylinsky 1989, 1993).

Polarisation observations in moustaches were not carried out as actively as the investigation of their structure and motion (Severny 1965; Bruzek 1972; Koval 1972; Kurokava et al. 1982; Nindos & Zirin 1998; Georgoulis et al. 2002). The observational results on polarisation in moustaches and flares by different authors often conflict with each other in terms of magnitude of polarisation and position of the polarisation plane. The degree of polarisation measured in the H_α line centre in flares ranges over 3−5%, in some rare cases exceeding 10% (Chambe & Henoux 1979; Henoux & Semel 1981; Henoux & Chambe 1990; Henoux 1991; Firstova & Bulatov 1996). In moustaches, considerable polarisation was also established the H_α line center seen to be about 7% (Firstova 1986) or in the range in 3–10% (Babin & Koval 1985–1988; Firstova et al. 1999; Kashapova 2002). Other observations of 32 moustaches by a different instrument reported that the polarisation, which does not exceed 8% (Rust & Keil 1992), with the bulk of them (about 87%) not exceeding 2%. A further spectro-polarimetric investigation of 164 Ellerman bombs has revealed their linear polarization in the Hα line to be less than 3% in 22 events (13.4% of the total number), less than 2% in 68% of the events and up to 12% in the remainder (~20%) of these events (Kashapova 2003). This ratio of the numbers of moustaches with high and low polarisation significantly exceeds those obtained by Rust & Keil (1992).

Confusion also occurs over the direction of the plane of polarisation measured by many observers. In the observations by Henoux et al. (1990) the direction of this plane is considered to coincide with the flare-to-disk centre direction leading to a positive polarisation, whereas some observations by Firstova & Bulatov (1996) show the plane is perpendicular to this direction resulting in negative polarisation. In different moustaches the polarisation planes can very often have opposite orientations or even not have a well defined direction on the solar disk centre (Firstova 1986; Firstova et al. 1999).

The first interpretation of H_α-line polarisation was made in an approximation of optically thin plasma, using the Born cross-sections for line excitation by charged particles or external radiation (Henoux & Semel 1981). The observed H_α line polarisation was assigned to impact polarisation by either electron beam or thermal electrons or to polarisation by high energy radiation (UV and EUV) depending on the position of the polarisation plane (Henoux & Semel 1981; Chambe & Henoux 1979). The plane of polarisation caused by suprathermal particles (electron or protons) or highly energetic UV and EUV radiation is expected to be mainly perpendicular to the solar centre direction, i.e. the polarisation is expected to be negative. A directed heat flux produces positive polarisation with the plane of polarisation being parallel to the solar centre due to the lower particle energies.

In order to explain the observed positive polarisation in the H_α-line, low energy proton beams ($E \leq 200$ keV) were referred to as the source of slow directed fluxes (Henoux et al. 1993; Vogt et al. 1997). The impact polarisation in H_α-line emission was computed for proton beams precipitating into a flaring atmosphere and causing a redistribution in population between the Zeeman split states using the density matrix formalism (Vogt et al. 1997). Collisional excitation of the hydrogen atoms by proton beams was taken into account as well as the radiative ones for incident and diffusive fields in H_α, L_α and L_β lines. The calculated H_α-line polarisation was found to be lower by up to an order of magnitude than that observed during a flare, fitting the observations only for the very weak emission at the very beginning of flare onset (Vogt et al. 1997). However, the authors did not take into account collective effects of proton beams on the ambient plasma, which can excite kinetic Alfven waves simultaneously with H_α-line emission (Voitenko 1998) that make questionable proton beam stability in such deep atmospheric levels. Therefore, in order to fit the observations, one must to consider other agents of H_α-line polarisation in flares.

These agents are likely to be electron beams propagating in the plasma of solar flares at H_α-line depths as suggested by Fletcher & Brown (1995). Their simulations used the stochastic kinetic solutions within a loss cone for electron beam precipitation that gave a reasonable polarisation degree of about 5–7%. However, this required electron beams with a initial energy fluxes greater than 10^{13} erg $\times$ cm^{-2} $\times$ s^{-1}, which are much higher than the typical energy fluxes deduced from the X-ray observations in solar flares (Hoyng et al. 1976).

More recent research has considered the effect of electron beams on H_α-line polarisation for a one dimensional atmosphere horizontally stratified with a moderate magnetic field (Zharkova & Syniavskii 2000). The beam is assumed to be stationary injected along the magnetic field direction with energy and pitch-angle diffusion causing non-thermal excitation and ionisation of hydrogen atoms. H_α photons were considered to be emitted with the photon momentum $\boldsymbol{K}$ towards the top of the atmosphere, which has a vertical axis along the direction of magnetic field $\boldsymbol{B}$. Then it was assumed that polarimetric observations are made from the atmopshere top, so a viewing angle coincides with the pitch angle.

For a solution of the steady state equation for a hydrogen atom with atomic super-fine structure caused by magnetic field splitting, the density matrix technique was applied that took into account collisions with thermal and beam electrons and excitation/de-excitation by external and diffusive radiation (Zharkova & Syniavskii 2000). The diffusive H_α radiation field for a 5 level hydrogen model atom without this super-fine structure was calculated in the full non-LTE approach as described by Zharkova & Kobylinsky (1991, 1993). The resulting H_α polarisation was found to appear near the line core only, positive near the red wing ($-0.25\ A^\circ$) and line centre but negative in the near blue wing ($+0.25\ A^\circ$) while the emission in the far wings is fully depolarised by collisions with thermal electrons. The full (integrated over a wavelength) H_α-line linear polarisation, caused by weak or moderate electron beams and observed along the direction of the magnetic field, was shown to be negative, increasing from −2% to −20% with an increase of viewing angle in a flaring loop, which in this geometry coincides with the pitch-angle.

The above results confirmed the conclusions by Henoux & Semel (1981) that electrons injected along magnetic field lines produce H_α-line emission polarized in the plane perpendicular to magnetic field, i.e. to the solar centre direction, if the flaring loop is vertical. However, these results do not explain the variety of H_α-line polarisation degrees and directions measured by different observers. Therefore, the motivation for the current paper is to refine our previous simulations of H_α line impact polarisation in a vertical magnetic loop to see the effect of an arbitrary viewing angle, i.e. with a projection of the polarisation plane from a spherical electro-magnetic wave emitted from the loop located arbitrarily on the solar surface and observed in the plane of a flat two-dimensional solar image. Theoretical models for simulated polarisation degrees and directions in terms of observables are presented in Sect. 2, a comparison with the available observations is discussed in Sect. 3 (with the observing recommendations in Sect. 3.1) and our conclusions are presented in Sect. 4.

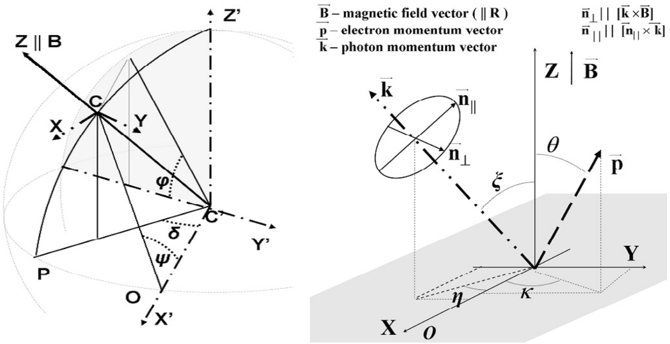

Fig. 1. A position of the polarisation plane of a photon emitted in the vertical magnetic loop at pitch angle of ξ and azimuthal angle η. A viewing angle ψ is the angle between the local Cartesian system XYZ and the system $X'Y'Z'$ associated with the solar sphere centre. The viewing angle along with the loop position on a solar disk define the projection of a polarisation plane in XYZ system onto the observational plane O$Y'Z'$ in the line of sight point O on the axis X' for an arbitrary electron momentum $\boldsymbol{P}$ and photon momentum $\boldsymbol{K}$ vectors (see the Sect. 2.1 about the orts, or unit vectors, of the polarisation plane).

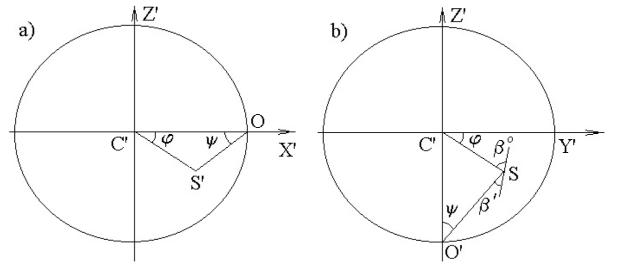

Fig. 2. The layout of a slit position during the observations in the line-of-sight (LOS) plane $Z'X'$ where the observer is located in the point O (see Fig. 1) and in the observation plane $Z'Y'$ where the flat solar disk image is obtained. Here β_0 is an angle between the slit and the object-to-disk center direction, β' is an angle between the slit and the object-to-LOS limb direction and ψ is the viewing angle.

2. Theoretical predictions

2.1. Geometry of the impact polarisation

For the calculations of H_α impact polarisation by electron beams we use an approach similar to those described by Zharkova & Syniavskii (2000) but with some changes in the polarisation plane orientation. It is assumed that a one dimensional flaring atmosphere is standing vertically on the solar surface with a magnetic field directed along the vertical axis Z in the local Cartesian coordinate system XYZ. The observer is located at the point O on the axis X' in the Cartesian coordinate system $X'Y'Z'$ centred on the solar centre with a viewing angle ψ (see Fig. 1) where the solar sphere is projected onto a flat solar disk (Fig. 2). Similarly to Zharkova & Syniavskii (2000), full non-LTE simulation for hydrogen emission is performed using the density matrix approach for a 3 levels plus continuum model atom with super-fine structure caused by Zeeman splitting in a moderate magnetic field. The ambient atmosphere is assumed to consist of the ambient hydrogen plasma with neutral atoms, ions and thermal electrons.

Beam electrons are steadily injected from the atmosphere top along the vertical axis Z with the energy power-law spectra and Gaussian pitch-angle dispersion $\Delta\mu$ (Zharkova et al. 1995; Zharkova 2000), so that the electron energy momenta have a direction $\boldsymbol{P}$, which have different pitch angles θ and azimuthal angles φ for different electrons in the beam. A beam electron is scattered on an ambient plasma particle and it emits a photon with momentum $\boldsymbol{K}$ at pitch angle ξ and azimuthal angle η, which is observed at viewing angle ψ on the flat two dimensional solar image obtained by the observer at point O on the axis X (Fig. 1). The resulting polarisation plane is defined by the orthogonal unit vectors, or orts thereafter, $n_{\|}$ and $n_{\perp}$ with the former being parallel to the vector $\boldsymbol{B} \times \boldsymbol{K}$, i.e. to the direction to the axis X, and the latter is perpendicular to $\boldsymbol{B} \times \boldsymbol{K}$, where $\boldsymbol{B}$ is the magnetic field vector and $\boldsymbol{K}$ is the direction of the emitted photon. This polarisation plane is projected onto a viewing plane at point O on the axis X perpendicular to the direction OX, i.e., a viewing angle ψ, which is a combination of flare location (heliolatitude and heliolongitude) on the solar sphere and the deviation of magnetic field from the local vertical.

2.2. The collisional tensor corrections

Electron beam kinetics was considered taking into account energy and pitch-angular diffusion in Coulomb and inelastic collisions with the ambient plasma ions, electrons and neutral atoms in the presence of the electric field induced by the precipitating beam and the vertical magnetic field confining the ambient plasma (Zharkova et al. 1995; Zharkova & Gordovskyy 2005). The electron beam distribution functions were used for calculation of the collisional tensor $\Phi_{ij}^{\rm coll}$ given by the formula (14) in Zharkova & Syniavskii (2000) that includes the scattering indicatrice $f_{ij}(\Omega)$ where Ω is the scattering solid angle for beam electrons with pitch angle θ (index i) and azimuthal angle φ (index j). Electron precipitation is computed at each depth point along the local vertical from the kinetic approach with axial symmetry in φ and uniformly a varying pitch angles in the assumption that in a single scattering process the angular changes are not very large, i.e. $\frac{\Delta\mu}{\mu} \ll 1$. The scattering process is assumed to be very anisotropic according to the pitch-angular diffusion (see Eq. (5) in Zharkova et al. 1995) while confined within the pitch-angles $\mu_{\rm min}$ and $\mu_{\rm max}$ at the ejection point with the limits increased to -1 and 1 during beam precipitation into the chromosphere and photopshere. The collision tensor for thermal electrons is assumed isotropic, similarly to Zharkova & Syniavskii (2000).

2.3. The radiative tensor corrections

The non-LTE problem for a 3 level plus continuum hydrogen model atom with levels split into superfine structure by Zeeman effect was solved for the considered geometry using the same approach as in the paper by Zharkova & Syniavskii (2000). However, in the current approach we introduce a viewing angle effect on the H_α emission by considering the Maxwell tension tensor of a spherical electromagnetic wave (Berestetsky et al. 1989) with an arbitary viewing angle ψ instead of the plane wave in the direction Z with a viewing angle $\psi = 0$ considered by Zharkova & Syniavskii (2000). This means that the momentum $\boldsymbol{K}$ of a photon emitted at the pitch angle ξ has the plane of polarisation inclined to direction $\boldsymbol{K}$ at angle ψ with the orthogonal orts, or unit vectors, $\boldsymbol{n}_{\|}$ and $\boldsymbol{n}_{\perp}$ definded by the vectors: $n_{\|} = B \times K$ and $n_{\perp} = n_{\|} \times K$ as presented in Fig. 1. The direction $n_{\|}$ is towards the observer located along the axis X and the angle between this direction and axis X is also the polarisation viewing angle. Therefore, the observer measures the projection onto these orts of an electromagnetic wave electric vector, whose components are defined by the formulae:

$$I_x^{ij} = I_0 \cdot (\sin(\psi)\sin(\eta) - \cos(\psi)\cos(\eta)\cos(\xi)),$$

$$I_y^{ij} = -I_0 \cdot (\sin(\psi)\cos(\eta) - \cos(\psi)\cos(\eta)\cos(\xi)), \quad (1)$$

$$I_z^{ij} = I_0 \cdot \cos(\psi) \cdot \cos(\xi)$$

where I_0 is the intensity emitted along the direction $\psi = 0$, i.e. along $\boldsymbol{K}$ and the indices i and j refer to the directions ξ or η, respectively. This formalisms is included into the diffusive radiative tensor Φ_{ij} described by the formula (8) in Zharkova & Syniavskii (2000). The Stokes parameters are calculated for the orts $\boldsymbol{n}_{\|}$ and $\boldsymbol{n}_{\perp}$ taking into account a viewing angle ψ as follows:

$$I(\psi) = \int\int\int [I_{\|}(\lambda,\xi,\eta,\psi) + I_{\perp}(\lambda,\xi,\eta,\psi)] \mathrm{d}\Omega \mathrm{d}\lambda, \quad (2)$$

$$Q(\psi) = \int\int\int [I_{\|}(\lambda,\xi,\eta,\psi) - I_{\perp}(\lambda,\xi,\eta,\psi)] \mathrm{d}\Omega \mathrm{d}\lambda \quad (3)$$

where the integration is over the solid angle Ω consisting of the angle ξ and η presented in Fig. 1 and the polarisation is calculated as:

$$P(\lambda, \psi) = \frac{Q(\psi)}{I(\psi)} \cdot \quad (4)$$

2.4. Viewing angle effect on the observed impact polarisation

As shown in our previous paper (Figs. 1–3 of Zharkova & Syniavskii 2000) the impact polarisation appears only near the line cores whereas the wings are fully depolarised by collisions with thermal electrons that is in agreement with the observations by Firstova (1986). The calculations also reveal that the simulated H_α-line profiles are rather asymmetric with the maximuma corresponding the main transitions for which $\Delta L = \Delta J$ ($3d_{5/2} - 2p_{3/2}$, $3d_{3/2} - 2p_{1/2}$ and $3p_{3/2} - 2s_{1/2}$). The full line polarisation is a sum of polarisation degrees in the transitions and it is dependent on a number of beam electrons. In this paper we do not present the effect of electron impact polarisation on H_α line profiles at various depths of electron beam precipitation, since it has been discussed in detail in the paper by Zharkova & Syniavskii (2000). Instead, we concentrate on the observable values such as full line polarisation and its sign, or the polarisation plane orientation.

As can be seen from Fig. 1, the polarisation plane in the system of coordinates XYZ of a flaring loop is always located in the plane perpendicular to those formed by the emitted photon direction $\boldsymbol{K}$ and magnetic field direction $\boldsymbol{B}$. The parallel ort $n_{\|}$ belongs to the plane $\boldsymbol{B} \times \boldsymbol{K}$ and $n_{\perp}$ is orthogonal to this.

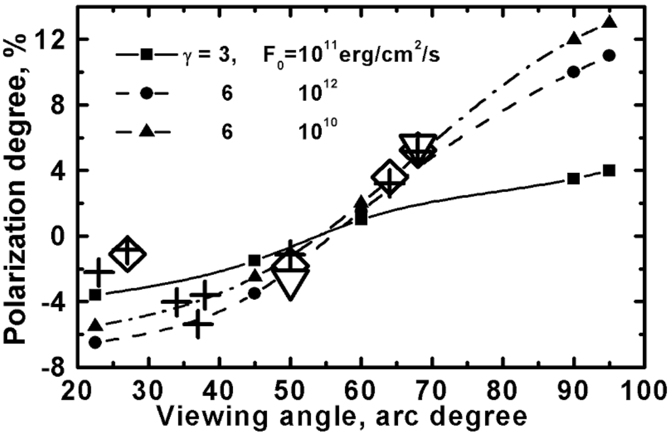

Fig. 3. The H_α linear polarisation as a function of a position angle ψ caused by electron beams with a spectral index $\gamma = 7$, $F_0 = 10^{10}$ erg/cm^2/s (dashed line with triangles), $\gamma = 7$, $F_0 = 10^{12}$ (dashed line with circles), $\gamma = 4$, $F_0 = 10^{11}$ erg/cm^2/s (solid line with squares). The crosses, diamonds and triangles are the observations for different moustaches, discussed in the text.

If the observer measures a photon from the top of a flaring atmosphere at angle ξ, the full line polarisation is negative varying from −3% to −25% as reported by Zharkova & Syniavskii (2000). Let us consider the more likely situation with the flaring atmosphere being located in the Cartesian coordinate system XYZ somewhere on the solar disk away from the disk centre and the observer being located at the point O of the Cartesian coordinate system $X'Y'Z'$ as described in Sect. 2.1. As mentioned before, in real observations the viewing angle is a combination of a loop location on the solar sphere and a magnetic field deviation from the local vertical, which can be separated only by supporting observations of the flare position on a flat solar disk image.

The integrated H_α-line linear impact polarisation caused by intense electron beams with soft ($\gamma = 6$) and hard ($\gamma = 3$) energy spectra calculated taking into account its projection onto the direction to the observer, or a viewing angle, is presented in Fig. 3 (the solid and dashed lines) for the times when the beam is on.

It is seen that the linear polarization observed from smaller to bigger viewing angles gradually changes from negative to positive magnitudes for all initial beam fluxes and spectral indices. For smaller (≤50°) viewing angles the full H_α polarization is negative and for bigger (≥60°) viewing angles it is positive being higher in absolute value than the negative ones. In the angle range of 50°−60° the polarization changes sign for all electron beams. The slope of the polarization curve versus viewing angle is smaller for lower initial energy fluxes (10^{10} erg/cm^2/s) and softer beams ($\gamma = 6$) and increases with beam intensity (or its initial flux) growth and spectral index decrease from 6 to 3 (compare the upper and lower curves).

Now let us see how these predictions comply with the observations. Apparently, comparing the theoretical polarisations with the measured ones can provide estimates for

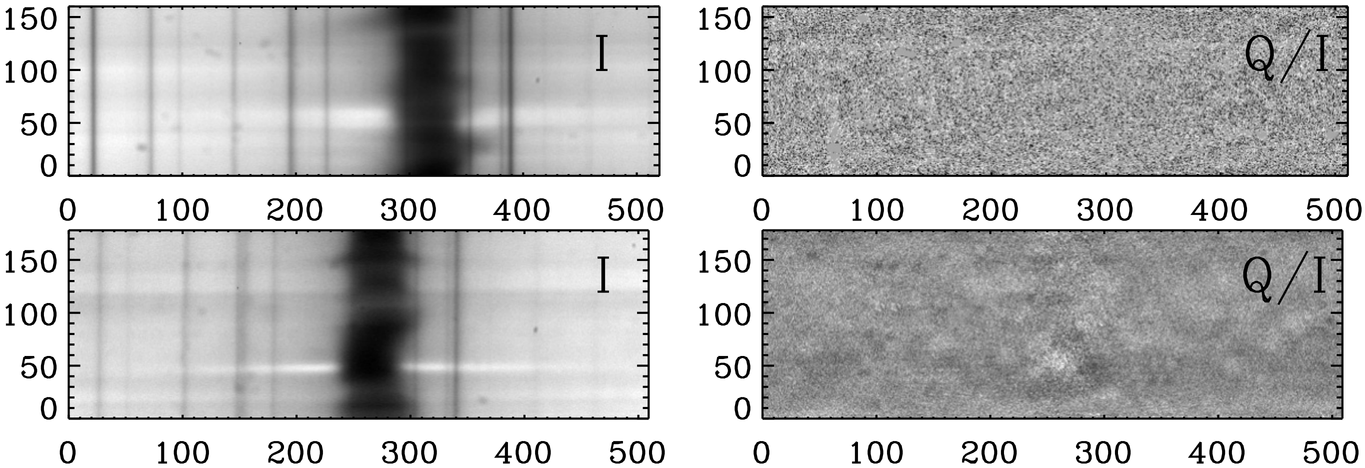

Fig. 4. The two examples of Stokes parameters I (intensity, the left panels) and Q/I (linear polarisation, the right panels) measured in moustaches with insignificant polarization (*the top panel*) and noticeable polarization (*the bottom panel*).

parameters of an electron beam causing this H_α impact polarisation. Their comparison with those derived from hard X-ray bremsstrahlung emission in the upper atmopsheric levels can provide important information about energy transport by electron beams from the very top to the deeper chromopsheric levels of a flaring atmosphere.

3. The results of observations

For comparison with the theoretical predicitions above, the profiles of Stokes parameters Q/I and U/I of moustaches in the H_α hydrogen line obtained from June to August 1999 from the Large Solar Vacuum Telescope are used (Somorovsky & Firstova 1996). The basic parameters of the instrument and the method of Stokes parameter observation and processing are described in detail by Kashapova (2002). Since moustaches are known to be very sensitive to seeing conditions and the image resolution varies from 0.5 to 1.2 arcsec, relatively short exposure times (0.05 and 0.1 s) are selected in order to minimize image tremor. In addition, normalization of the H_α line profiles to the continuum in each strip is carried out that helps to decrease the instrumental polarization (Firstova 1986). The sample Stokes parameters I and Q/I of moustaches are presented in Fig. 4 where the upper panel shows the moustache without polarisation and the bottom one demonstrates those with noticeable polarisation seen as a brighter source between 200 and 300 pixels (axis X) around 50th pixel (axis Y).

This data was previously analyzed by Kashapova (2003) without consideration of moustache locations on the solar disk. The Stokes parameters Q/I are converted from the slit coordinate system to the coordinate system related the object-to-observer direction according to the layout shown in Fig. 2.

It can be seen from plot b in Fig. 2 that the angles β_0 and β' are related to viewing angle ψ and latitude angle φ as:

$$\psi = \beta_0 + \beta' - (90^\circ - \varphi). \quad (5)$$

Here ψ' is the angle from the north-south vertical towards the slit on a flat solar image, under which the angle arc CS with length ψ is seen on the spherical solar surface. This is close to the viewing angle ψ presented in Fig. 1 within the applicability of flat disk coordinates instead of spherical ones, because of the triangles C′OS′ and C′O′S′ similarity in the planes ZX and ZY (compare plots a and b in Fig. 2). The angle φ is the polar angle on the solar disk that corresponds to a heliolatitude with its sign in the relevant hemispheres.

As stated above, in 68% of moustaches the H_α line linear polarization is found to be less than 2%, i.e., it is probably not caused by impacts but rather by chromospheric radiation (Zharkova & Syniavskii 2000), in 13% of them it ranges from 2−3% and in the remainder it reached 12% (Kashapova 2003). This high-to-low polarisation ratio obtained for different moustaches in various active regions and on different dates significantly exceeds the one reported by Rust & Keil (1992) for a single active region. In the present paper we count the number of moustaches with polarization exceeding and less than 2% in different zones of the solar disk centre. Each zone has a size of 20° centred on the viewing angle, i.e. the zone with a viewing angle of 50° includes the events located between 40 and 60°. The ratios of moustaches observed in a given zone that show low polarisation not exceeding 2% are presented in Table 1 and, naturally, the remaining moustaches have a linear polarisation of 2−12%.

From Table 1 one can see that the number of moustaches with a noticeable polarization degree varies significantly with distance from the solar disk centre, or with the moustache's position on the solar sphere. The number of moustaches with significant polarization (>2%) does not increase considerably towards the solar limb as suggested by Henoux et al. (1983). However, it does not drop to zero for viewing angles greater than 70° as predicted by the evaporative model (Fletcher & Brown 1998). Remarkably, the ratio of moustaches in the zone of 50° is very close to the results obtained by Rust & Keil (1992). This resemblance is rather surprising, keeping in mind that the observations by Rust & Keil (1992) were obtained in a single active region, while the Irkutsk's data was obtained at different dates in various active regions located in the southern and northern, eastern and western hemispheres of the Sun.

Table 1. Relative number of moustaches with the polarization less than 2%.

	Distance from the solar centre, present paper				Rust & Keil (1992)
	10° ± 10°	30° ± 10°	50° ± 10°	70° ± 10°	
Rate%	69	57	85	59	87

In Fig. 3 the measured degrees of polarisation are plotted versus the central zone angles on top of the theoretical curves with the crosses, diamonds and triangles presenting the results for different moustaches by Kashapova (2003). It can be seen that for the viewing angles less than 60°, the polarisation degrees are negative, approaching magnitudes −8−9% at angles smaller than 20°, although for some events located near 30° it does not exceed 2%. For viewing angles greater than 60° the degrees of polarisation are positive, approaching magnitudes 12−15% for angles of 90° (limb). In the zone between 50° and 60° the polarisation degree changes sign passing through zero magnitude.

These observations provide a very important property of the polarisation magnitude and its sign, or direction, which is dependent on the position of moustaches on the solar disk. Both the polarisation degree magnitude and its sign change in a very similar way for all the events considered. The higher degrees of polarisation are observed towards the centre or limb of the solar disk, being negative for the locations around the solar centre and changing to positive ones towards the solar limb. The agreement of the data with the simulations supports the proposed model of electron transport and suggests the beams as promising sources of impact polarisation in the chromopshere.

3.1. The observational recommendations

A comparison of the simulated polarisation degrees and signs with the observed ones presented in Fig. 3 by crosses, diamonds and triangles (see Sect. 3 for details) reveals for most observations a surprisingly good fit of the theoretical curves for the spectral index $\gamma > 4$ and any initial energy fluxes $F = 10^{10}$ or 10^{12} erg/cm^2/s presented in Sect. 2.4, keeping in mind the difference in the instruments and observing conditions. The absence of polarisation measurements for the beam with $F = 10^{11}$ erg/cm^2/s and $\gamma = 4$ is likely to be caused by additional Ohmic energy losses in the induced electric field that is much higher for harder beams as was concluded by Zharkova et al. (1995) and Zharkova & Gordovskyy (2005). This leads to a much bigger part of precipitating electrons returning to the coronal source on the top and only smaller part precipitating downwards to the chromosphere that obviously does not produce observable impact polarisation.

The only three observations near the solar disk centre have a degree of polarisation of −1−2% that is lower than the theoretical predictions for this viewing angle. However, these three observations may be of the inclined loops often reported by the observers. In order to fit them to the theory one can move the observational points towards the theoretical curves and deduce the angle of a magnetic field inclination from the local vertical, which for these observations can be about 25−30°.

Based on the comparison above, one can introduce observing constraints on observations for detectable H_α impact polarisation with future instruments with high spatial and spectral resolutions. The theoretical curves in Fig. 3 reveal that the softer and more intense beam, the higher is the degree of H_α polarisation produced by it. For viewing angles less then 50° the polarisation produced by beam electrons is negative and for angles higher than 60° it is positive. Hence, there is the zone at a viewing angle between 50 and 60° where the impact polarisation is about zero, since it is obscured by the viewing conditions of this radiation despite beam electrons being present in the flaring atmosphere.

This condition can be quantified from the formula (1) for the zero impact polarisation as the following inequality: $50° \leq \psi \leq 60°$. Thus, in order to observe impact polarisation, the latitude angle φ, the angle between the slit and slit-to-disk centre direction β_0 and the angle between the slit and slit-to-limb direction β' (see Sect. 3) are to be restricted as follows:

$$\beta_0 + \beta' + \varphi > 150°, \qquad \text{or} \qquad \beta_0 + \beta' + \varphi \leq 140°. \tag{6}$$

If the observer can comply with the limits above for slit positioning and latitude angles, this can ensure observation of measurable impact polarisation, if it is present in the event under investigation.

4. Conclusions

In this paper the effect of viewing angle is investigated for the hydroden H_α-line impact polarisation caused by precipitating beam electrons injected with energy power-law spectra into flaring atmospehers.

The H_α polarisation profiles are found to be affected by electron beams only near the line cores whereas the wings are fully depolarised by the collisions with thermal electrons that causes an appearance of extended wings in the H_α line like those observed in “moustaches”.

The full (integrated in wavelength) H_α-line linear polarisation, caused by moderate electron beams, varies in the range of 2−15% and can be either negative or positive depending on the position of the flaring loop on the solar disk, i.e. its heliolongitude and/or heliolatitude. For viewing angles less then 50° the H_α-line impact polarisation is negative increasing up to −10% towards angles of 20° or smaller.

For viewing angles greater than 60° the measured impact polarisation becomes positive sharply increasing up to 15% towards the limb and beyond. In the zone 50−60° the observed polarisation degree crosses a zero point despite the actual presence of beam electrons in a flaring atmosphere.

This imposes constraints on the slit and moustache locations that allow observations of the measurable impact polarisation signatures if they occur in these events, i.e. the slit positioning angles β_0 and β' are to be restricted to $\beta_0 + \beta' + \varphi > 150°$ or $\beta_0 + \beta' + \varphi \leq 140°$, where β_0 and β' are the slit angles towards the solar center and limb, respectively, and φ is the heliolatitude.

The theoretical predictions fit remarkably well the available observations of the H_α-line linear polarisation in moustaches, or Ellerman bombs, located in different positions on a solar disk. This fit allows observers to estimate the parameters of an electron beam causing this polarisation and to compare them with those derived from hard X-ray bremsstrahlung emission that can provide important information on the energy transport mechanisms in flaring events on the Sun.

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