Magnetic and Electric Field Diagnostics of Chromospheric Jets by Spectropolarimetric Observations of the H\textsubscript{i} Paschen Lines

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Abstract. In order to study the magnetic and electric fields of chromospheric jets, we observed the full Stokes spectra of the Paschen series of neutral hydrogen in active region jets that took place at the solar limb on May 5, 2012. For the observations, we used the spectropolarimeter of the Domeless Solar Telescope at Hida observatory, Japan. Inversion of the Stokes spectra taking into account the effect of magnetic field on the energy structure and polarization of the hydrogen levels (including the Hanle effect and level-crossing effects) elucidates the magnetic field approximately aligned with the visible structure of the jets. In addition to the magnetic field, the energy structure and the polarization of the hydrogen levels is sensitive to electric field through the Stark effect, electric Hanle effect (analogous effect with the Hanle effect by magnetic field), and the level-crossing effects. Since, we found no definitive evidence of the polarization produced by the effect of electric field in the observed Stokes profiles, we derived upper limits of electric field felt by neutral atom moving across the magnetic field, and conclude that the velocity of the neutral atom perpendicular to the magnetic field was below several percents of the velocity bulk plasma motion.

1. Introduction

Several processes can generate polarization in spectral lines in response to the presence of magnetic and electric fields in the radiation emitting plasma. The Zeeman and Stark effects are produced by the energy separation of the Zeeman sublevels due to the potential energy of the radiating atom in the external fields. As the splitted components have different polarization properties, this results in a wavelength dependent polarization across the spectral line. In the absence of velocity or field gradients in the emitting plasma, the broadband (i.e., wavelength integrated) polarization from the Zeeman and Stark effect vanishes. In contrast, in the presence of atomic polarization (i.e., population imbalances and quantum interferences among the magnetic sublevels; e.g., Landi Degl’Innocenti & Landolfi 2004 ), the emitted (scattered) radiation is typically characterized by a non-vanishing broadband polarization. The two dominant characteristics of atomic polarization are atomic alignment and orientation. Atomic alignment is a state of population imbalances between magnetic sublevels with different absolute values of their magnetic quantum numbers. Atomic orientation is characterized by population imbalances between sublevels with positive and negative magnetic quantum numbers. The effects of atomic alignment and orientation in the scattered radiation
are observed in the form of broadband linear and circular polarization, respectively. In the process of radiation scattering, the anisotropy of the incident radiation field produces atomic alignment, and the scattered light is therefore linearly polarized, with a magnitude depending on the scattering geometry. The presence of a magnetic field produces a decoherence of the quantum interferences between the magnetic sublevels resulting in a modification of the polarization (typically, depolarization and rotation) of the scattered radiation, known as the Hanle effect. Electric fields can have analogous effects on the atomic polarization and the emitted polarized radiation. Strong magnetic or electric fields also cause a conversion of atomic alignment into atomic orientation when the energy splitting of the sublevels induce atomic level crossings (A-O mechanism, Casini 2005). Collisions of the scattering atoms with free electrons and protons tend to reduce the atomic level polarization. For the typical density of the upper solar chromosphere, collisional transitions between the fine-structure levels pertaining to the same Bohr level of the neutral hydrogen may play a significant role in the depolarization process (Bommier et al. 1986; Sahal-Bréchot et al. 1996; Štěpán & Trujillo Bueno 2011).

Magnetic field governs the plasma dynamics in the outer layers of the solar atmosphere. Recent observations discovered the dynamical nature of the chromosphere where magnetic pressure is higher than gas pressure. Magnetic field structure in chromosphere is a key information to understand the heating and dynamical phenomena in the magnetic atmosphere.

It is believed that static electric fields are very weak in the highly conductive solar atmosphere, and electric fields generated in magnetic reconnection occur at spatial scales that are too small to be observed. On the other hand, the Stark effect that is produced by the Lorentz electric field, i.e., the electric field in the frame of neutral atoms moving across the magnetic field, can be large enough for detection with modern spectropolarimetric instrumentation, and involves plasma structures that can easily be resolved with existing solar telescopes. Beside the Stark effect, small electric fields have also an effect in terms of atomic polarization induced by the alignment-to-orientation conversion mechanism, which can occur in spectral lines of hydrogen that are formed in the scattering regime (Casini 2005). The observation of electric fields is of particular importance for understanding the dynamics of partially ionized plasma in the chromosphere, and also for the development of new spectropolarimetric diagnostic methods.

In this paper, we described measurements of magnetic and electric fields in a surge and in active region jets, and a first estimation of the upper limit to plasma velocities across the magnetic field lines.

2. Observations

Several jets in the active region NOAA 11476 were observed in several H\textsc{i} Paschen lines using the universal spectropolarimeter (Anan et al. 2012) of the Domeless Solar Telescope (Nakai & Hattori 1985) at Hida observatory, Japan. The polarimeter uses a continuously rotating achromatic waveplate as polarization modulator and provides the full Stokes vector of any spectral regions between 4000 Å and 11000 Å for all the spatial points along the spectrograph slit, with a spatial sampling of \( \sim 0.4 \) arcsec/px. The full Stokes spectra so obtained were calibrated for instrumental polarization using a predetermined Mueller matrix of the telescope.
The observation ran from 2:32 UT to 3:50 UT on 2012 May 5. Two beams with orthogonal polarizations are taken simultaneously with a CCD camera (Prosilica GE1650) with a spectral sampling of 70 mÅ/pix and an exposure time of 500 msec, and 99 frames are integrated in 49.5 sec, while the spin rate of the rotating waveplate is 0.1 rev./sec. Full Stokes spectra were observed in “sit-and-stare” mode for all $P_n$ lines of the Paschen series of H$_1$, for the values $n = 7, 9, 10, 11$ of the principal quantum number of the upper level. These lines were observed sequentially by rotating the spectrograph grating. The rms polarization sensitivity for the strongest lines $P_7$, $P_9$, $P_{10}$, and $P_{11}$ was estimated to be, respectively, $\sim 2 \times 10^{-3}$, $2 \times 10^{-3}$, $3 \times 10^{-3}$, and $3 \times 10^{-3}$. Because motion of the solar image on the slit caused by the seeing and telescope guiding error was approximately 1 arcsec in amplitude during the run of the observation, we averaged the Stokes spectra in the spatial direction over 2 arcsec.

The slit was placed outside the solar limb, approximately parallel to it, above active region NOAA 11476. The slit width and length were 1.28 arcsec and 128 arcsec, respectively. In our analysis, the slit identifies the reference direction of polarization, along which Stokes $Q$ is defined to be positive. During the observation, some jets and a surge took place across the slit. The jets were observed in $P_7$ between 2:32 UT and 2:47 UT, while the surge was observed in the $P_9$, $P_{10}$, and $P_{11}$ during the second half of the observation period. The distance of the slit to the visible limb for the observation of the jets and the surge was, respectively, $\sim 10$ arcsec and $\sim 15$ arcsec.

### 3. Diagnosis of Magnetic and Electric Fields

Figure 1 shows two examples of observed Stokes profiles of $P_7$ and $P_{10}$. It must be noted that the shape of the linear polarization signals resemble that of the intensity profile. This suggests the presence of atomic polarization in the upper levels of the transitions of neutral hydrogen in the studied jets and surge, and puts into question the assumption that was made in previous studies of electric field measurements by spectro-polarimetric observations, that the atomic polarization of highly excited levels should be negligible (e.g. Foukal & Hinata 1991; Casini & Foukal 1996), presuming that these levels are mostly populated by electron recombination. Our observations indicate instead that optically pumped atomic polarization must be significant, at least for the upper levels of the Paschen lines that we considered.

Casini (2005) derived a formalism for modeling the resonance scattering polarization of hydrogen lines in the presence of both magnetic and electric fields. In that work, he predicted that the simultaneous presence of magnetic and electric fields brings an enhancement of the A-O mechanism that is responsible for the appearance of net circular polarization (NCP). However, observed Stokes spectra do not show a significant amount of NCP. Since it is not possible to conclude from the data that electric fields may be producing any effect, we carried out the inversion of the Stokes spectra taking into account only the effect of magnetic fields according to the resonance scattering formalism. We then estimated an upper limit for the electric field in the plasma by calculating the polarization degree in the simultaneous presence of magnetic and electric fields, assuming for the magnetic field the configuration derived from the inversion.

#### 3.1. Magnetic Field

The observed Stokes spectra of the $P_7$, $P_9$, $P_{10}$, and $P_{11}$ lines were inverted by using PCA-based technique given in López Ariste & Casini (2002), which take into account
only the effect of magnetic fields according to the resonance scattering formalism. In our model we neglect collisional coupling among the atomic levels, which could play a role in depolarizing the scattered radiation. The Doppler velocity was derived from the shift of the center of gravity of the Stokes $I$ profiles, using the wavelengths of the Paschen lines as reported by Kramida (2010). Figure 2 shows the geometry and the parameters used in the line formation code.

Figure 1 shows two examples of inversion fit of the Stokes vector of P7 and P10 for a jet and for a surge, respectively. Linear polarization of the line (Stokes $Q$ and $U$) is produced by the resonance scattering and the Hanle effect. Particularly, the Hanle effect enable us to diagnose the azimuth of the magnetic field in the reference of the observer. As for the circular polarization, the Paschen-Back effect which depends on the longitudinal magnetic field strength produces antisymmetric Stokes $V$ profile about the line center and the A-O mechanism breaks the antisymmetry. Most of the observed Stokes profiles fit satisfactorily as shown in Figure 1.

The distributions of the inverted parameters along the slit are shown in Figure 3. The ranges of the physical parameters estimated from the inversion corresponding to the 90% confidence level are shown in the four bottom rows, respectively for the longitudinal component of the magnetic field, the magnetic field strength, the plasma temperature, and the plasma velocity along the LOS. In the top row, the direction of the lines indicates the direction of the magnetic field on the plane of the sky (POS, related to $\Phi_B$). The thin (thick) lines are the solutions which admit (do not admit) an alternative 90°-ambiguous configuration of the magnetic field. The magnetic field solutions that do not admit this azimuthal ambiguity indicate that the projected magnetic field on the POS is approximately aligned to the jets and the surge. Accordingly, 60% of the solutions
Figure 2. Geometric model for radiation scattering in the presence of a magnetic field. The cone of (photospheric) radiation irradiates the scattering atoms at the point $O$ of height $h$ above the solar surface. The direction of the magnetic field vector, $B$, is defined by the angles $\theta_B$ and $\phi_B$ in the reference frame of the local solar vertical $z'$ through the point $O$, and by $\Theta_B$ and $\Phi_B$ in the reference frame of the line-of-sight (LOS). The inclination angle of the LOS from the local solar vertical is $\theta$ and the direction of $y \equiv y'$, which corresponds to the reference direction of positive Stokes $Q$, is parallel to the solar limb.

marked with the thin lines were rotated by $90^\circ$ in order to align the projected magnetic field on the POS to the directions of the jets and the surge. After this operation, it is noticeable that the direction of the magnetic field on the POS appears to be systematically tilted away from the surge by about $25^\circ$ counterclockwise, which is larger than the estimated inversion error of $13^\circ$ of $\Phi_B$ corresponding to the 90% confidence level. We do not speculate on the physical origin of this tilt.

For the magnetic field strength of the three jets, using the observation at 2:47 UT, we found $60 \, G < B < 630 \, G$, $190 \, G < B < 960 \, G$, and $40 \, G < B < 200 \, G$. In the case of the surge, we found $10 \, G < B < 640 \, G$ for a 90% confidence level. The maximum Doppler velocity of the surge at 3:11 UT, 3:13 UT, and 3:16 UT was $7 \, \text{km s}^{-1}$, $4 \, \text{km s}^{-1}$, and $16 \, \text{km s}^{-1}$, respectively. The derived temperature must be regarded as an upper limit, because only thermal and natural broadening were considered for the inversion, while other broadening mechanisms such as pressure broadening, plasma turbulence, and collisional damping may also contribute to the effective line width.

The height of the scatterer $h$ determines the dilution and anisotropy factors of the incident radiation field, which in turn determine the state of atomic polarization in the zero-field case. However, for heights between 0.01 and 0.08 $R_\odot$ used in our model, the change in the polarization degree of the lines is small, and therefore the inverted values of $h$ are affected by large errors.

### 3.2. Upper Limit of the Electric Field

The time evolution of the surge can be seen in Figure 4, which shows a slit-jaw image at the line core of H$\alpha$ (left) and two time-distance diagrams showing the motion along two different sections of the surge, respectively parallel (top right) and perpendicular.
Figure 3. Inverted magnetic field, temperature, and Doppler velocity for the observed jets and surge at the position of the slit shown in the figure. The columns, from left to right, show the inversion results for the observed Stokes spectra of P7 (2:47 UT), P9 (3:11 UT), P10 (3:13 UT), and P11 (3:16 UT). The slit-jaw images in the top row show the direction of the magnetic field on the POS. The thin lines indicate inverted solutions affected by the 90° azimuthal ambiguity, while the thick lines correspond to the solutions with nonambiguous azimuth. The second to fifth rows show, respectively, the longitudinal component of the magnetic field, the magnetic field strength, the temperature, and the Doppler velocity. The abscissas indicate the position along the slit.

The observations taken at 3:11 UT, 3:13 UT, and 3:16 UT show the surge near its maximum extension. The observed Doppler shift indicates a significant component of plasma velocity along the LOS, which is also nearly perpendicular to the magnetic field, if we accept the inversion results that the magnetic field vector practically lies in the POS (Figure 3). Therefore, this event provides a good opportunity for testing the coupling between partially ionized plasma and magnetic fields, since neutral atoms that move across the magnetic field must experience a Lorentz electric field.

We used the inverted magnetic and velocity field configurations of the surge as the basis to calculate the emergent Stokes profiles in the additional presence of an electric field (Figure 5). The magnetic field, which is roughly aligned to the surge, is inclined about 45° from the local solar vertical, and on the POS (Figure 3). The velocity component is assumed to be along the LOS, because no significant apparent lateral motions were observed in the Hα slit-jaw images at the times of the observation, 3:11 UT, 3:13 UT, and 3:16 UT (Figure 4). Since the range of the magnetic field strength in the surge varies approximately between $10 \, G < B < 640 \, G$, we calculated the expected line po-
larizations in the presence of a Lorentz electric field for three magnetic-field strengths of 70, 200, and 600 G.

We calculated the theoretical net linear and circular polarizations of the Paschen H\textit{i} lines as functions of the strength of the Lorentz electric field, assumed to be perpendicular to both the magnetic field and the LOS, using the formalism of Casini (2005). Because of the particular field geometry (both fields lie on the POS), all configurations where the orientation of either of the two fields is inverted give rise to the same polarization.

Figure 6 shows the results for P9, P10, and P11 for the three selected values of the magnetic field strength. It is notable that the direction of the linear polarization does not change appreciably when the electric field is applied. This is in fact dominated by Stokes \textit{U} at all times, in agreement with the fact that the atom is in the saturated regime of the (magnetic) Hanle effect, and therefore the direction of linear polarization must be perpendicular to the magnetic field direction (135° in this calculation). This fact allows us to determine the azimuth angle of the magnetic field (\(\Phi_B\)) from the inversion independently of the effect of possible electric fields.

The upper limit of the electric field in the P9, P10, and P11 is estimated by comparing the observed polarization degree with the calculated values. In Figure 6, the horizontal dotted thin lines in each plot limit the range of polarization error due to both systematic and random sources. Additional polarization effects due to an undetected Lorentz electric field must then lie within this range.

In the P10 at 3:13 UT, we thus find an upper limit of 0.04, 0.3, and 0.8 V cm\(^{-1}\), respectively for the magnetic field strength of 70, 200, and 600 G. This implies that the upper limit of the velocity of neutral hydrogen moving across the magnetic field corresponds respectively to 0.6, 1.5, and 1.3 km s\(^{-1}\). Since the measured Doppler velocity in the P10 at 3:13 UT is 3.4 ± 1.6 km s\(^{-1}\), the velocity of neutral hydrogen moving across the magnetic field appears to be significantly smaller than the plasma’s bulk velocity.
Figure 5. Schematic picture of the magnetic, electric, and velocity vectors in the surge.

Figure 6. Broadband polarization of P9, P10, and P11 in Stokes $Q$ (top), $U$ (center), and $V$ (bottom), as a function of the electric field strength, in a 90° scattering event. Solid, dotted, and dashed lines correspond to magnetic field strengths of 70, 200, and 600 G, respectively. The thin horizontal lines in each plot limit the range of polarization error due to both random and systematic sources.

In the same way, we estimated the upper limit of the velocity of neutral hydrogen moving across the magnetic field at 3:11 UT from observations of the P9 line. We found in this case the values 0.8, 1.5, and 1.1 km s$^{-1}$ for the same magnetic field strengths, in very good agreement with the results found with P10. Using the P11 data (observed at
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3:16 UT) we found instead 1.1, 1.0, and 0.8 km s$^{-1}$, which also are in agreement with the results from P9 and P10. Since the measured Doppler velocity in the P9 at 3:11 UT, and in the P11 at 3:16 UT, are 3.3 $\pm$ 0.2 km s$^{-1}$ and 12.5 $\pm$ 1.4 km s$^{-1}$, respectively, all estimated upper limits of the velocity across the magnetic field are smaller than the measured Doppler velocities.

4. Discussion and Summary

We presented magnetic field measurements in a surge and in active region jets, and a first estimation of the upper limit of Lorentz electric fields, and the corresponding limit to plasma velocities across the magnetic field lines.

The direction of the magnetic field on the POS is found to approximately align to the jets and the surge. This confirms the common scenario of the chromospheric jet model, in which plasma is ejected along the magnetic field (e.g. Nakamura et al. 2012; Takasao et al. 2013). When we look carefully at the geometric relation between the magnetic field and the jet, we find that the direction of the magnetic field is slightly tilted counterclockwise from the direction of the surge. Further study with high-accuracy spectro-polarimetric data for a number of similar events is needed in order to clarify the details of the geometric relation between the magnetic field and jets.

The strength of the magnetic field in the three jets is found to be in the ranges $60 \, G < B < 630 \, G$, $190 \, G < B < 960 \, G$, and $40 \, G < B < 200 \, G$. In the case of the surge, we found $10 \, G < B < 640 \, G$ for a 90% confidence level.

The upper limit of the Lorentz electric field is estimated to be 0.04 V cm$^{-1}$ for a magnetic field strength of 70 G, based on the observed polarization degree in the P10 line. If we neglect the magnetic field and the atomic level polarization, as assumed in previous estimates of solar electric fields, the limit to the electric field that is derived from the observed polarization degree (using, e.g., the formalism of Fujimoto & Iwamae 2008, chap. 2) is $\sim 30$ V cm$^{-1}$, which is significantly larger than our estimates.

In our inversion model, we neglected collisional coupling among the atomic levels, which may reduce the effects of atomic polarization in the observed Stokes profiles.

From the upper limit of the Lorentz electric field, we also estimated the velocity of neutral hydrogen moving across the ambient magnetic field. At 3:16 UT, the surge reached its maximum height (Figure 4) and a large bulk velocity (i.e., Doppler shift) is observed (Figure 3). Therefore the velocity vector can be assumed to be along the LOS and perpendicular to the magnetic field (Figure 3). On the other hand, from our analysis of the polarization effects of Lorentz electric fields, the upper limit of the velocity of neutral hydrogen moving across the magnetic field is found to be 1.1 km s$^{-1}$ in this geometry. As this is much smaller than the measured bulk velocity of 12.5 $\pm$ 1.4 km s$^{-1}$, we conclude that neutrals must be in a highly frozen-in condition in the surge. The observed Doppler shift of the lines can be due to motion along the LOS of the whole plasma structure including the magnetic field within which the plasma is frozen. Then no macroscopic electric field would be generated in the reference frame of the neutrals.

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