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Kink Waves in Solar Flux Tubes and Polarized Line Profiles

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Abstract:
Waves are thought to play a fundamental role in the heating processes of the chromosphere and corona of the Sun and other cool stars. Of particular interest are periodic motions in so called flux tubes, elements of concentrated magnetic field. We investigate the influence of kink waves in flux tubes on polarized line profiles and demonstrate that they have a large effect. This should help us to set limits on the energy flux in such waves.

1. Introduction

MHD waves are prime candidates for transporting the energy needed to heat solar and stellar coronae from the convection zone through the photosphere (e.g., Herbold et al. 1985). Concentrated magnetic fields which form flux tubes allow for several wave modes that propagate and channel the energy into higher regions of the star (e.g., Choudhuri et al. 1993). Particularly promising are kink waves, which shake the flux tube back and forth in one horizontal direction, as is displayed in Figure 1 (left column). Magnetic fields are known to polarize the light of most spectral lines (Zeeman Effect). The subject of this study is the polarization signature caused by a propagating kink wave in photospheric flux tubes.

2. Overview of the Model

We give a brief summary of the most important model features:

1. The equilibrium flux tube satisfies hydrostatic equilibrium and horizontal pressure balance (thin flux tube approximation, Defouw 1976).
2. Analytically described kink waves (Spruit 1981) are overlaid on realistic atmospheric models describing the flux tube and its surroundings.
3. Stokes profiles are calculated numerically along a number of rays piercing the moving flux tube.

The velocity of the kink wave together with the flux tube's axis define the plane containing the considered lines of sight (Figure 1, left column). In this geometry the signals in Stokes V (a measure for circular polarization) and Stokes Q (a measure for linear polarization) are the strongest. V is sensitive to the line of sight magnetic component, Q to the transverse magnetic component.

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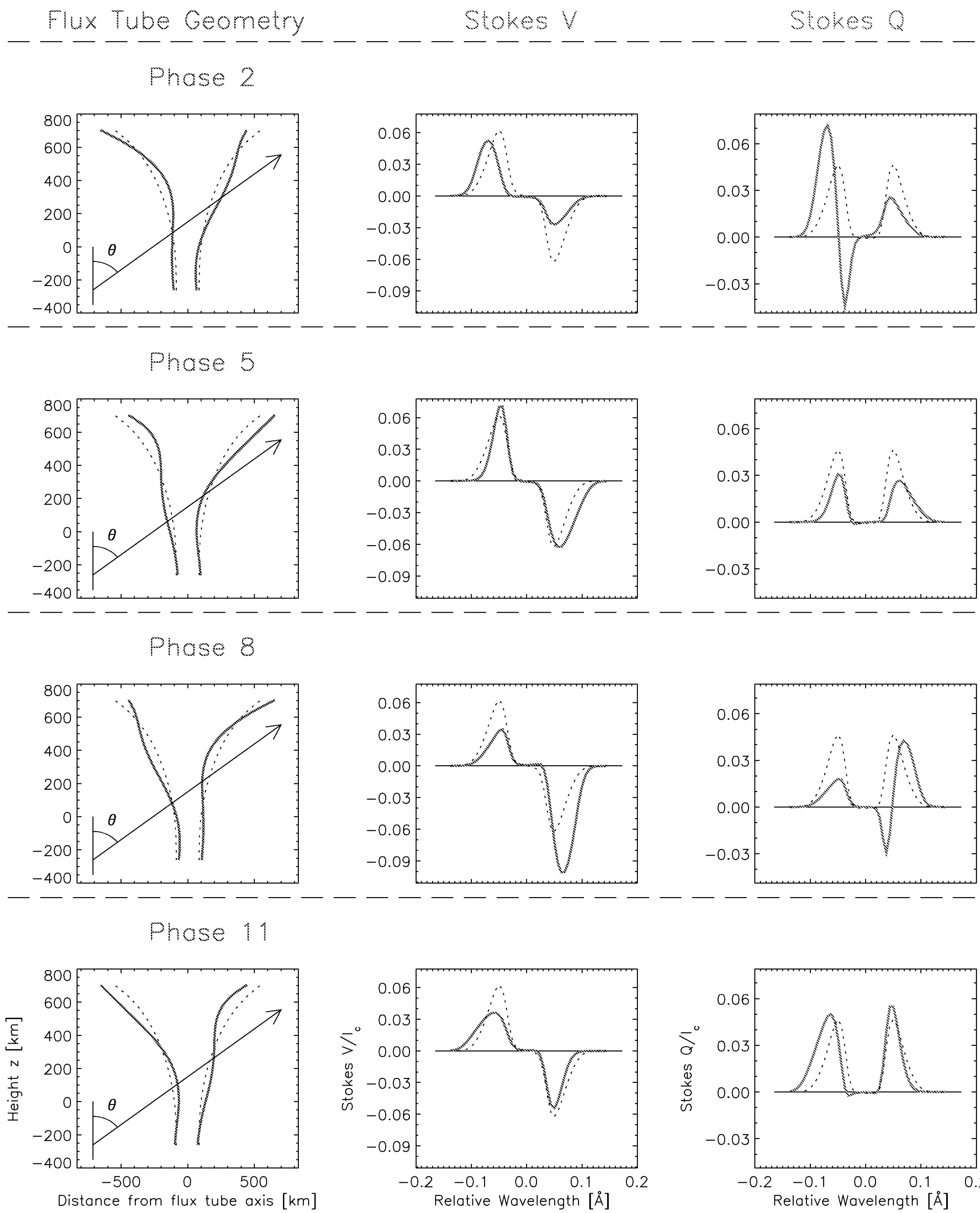

Figure 1. Influence of a kink wave on the flux-tube geometry (left panels) and on the polarization profiles of Stokes V (middle panels) and Q (right panels). Stokes V is net circular polarization, Stokes Q net linear polarization. Plotted are the boundaries of the flux tube (left panels) and the line profiles at 4 representative phases of the wave (middle and right panels). The arrow (left panels) stands for a typical line of sight, points towards the observer and forms a heliocentric angle for the plotted case of $\theta = 60°$. The dashed lines refer to the flux tube in the absence of the wave and the corresponding V and Q profiles.

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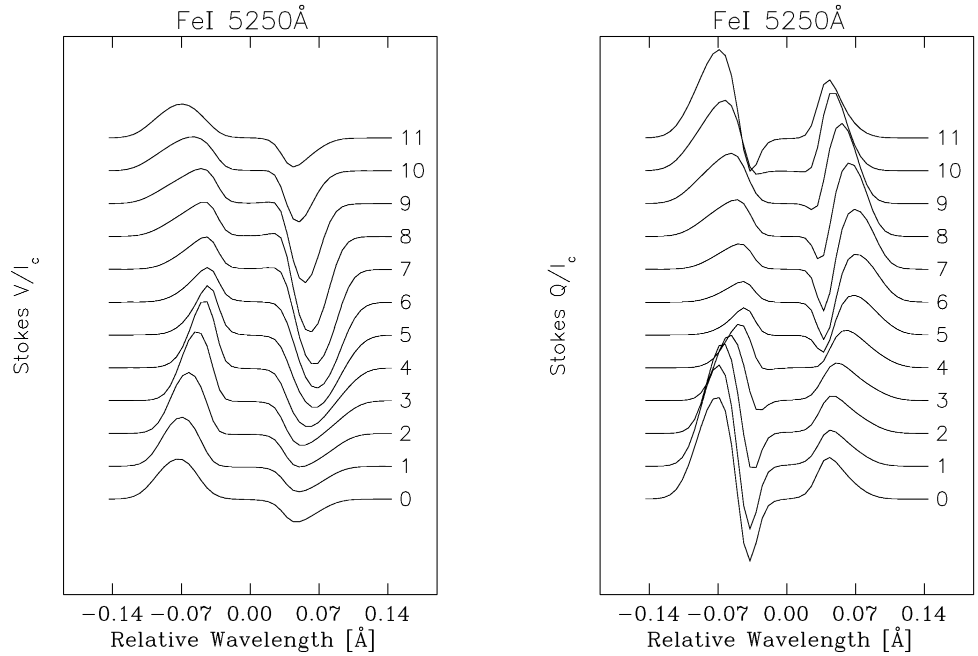

Figure 2. Stack plots of Stokes V (left frame) and Q (right frame) at different phases in the wave described in the text. The phases (or time steps) increase from 0 to 11 and cover a full wave period. Note the large changes in profile shape with time (i.e., blue-red asymmetry).

3. Results

This presentation focuses on the effect of a particular wave (with frequency 0.04 Hz, corresponding to a wave period of 2.6 min., and velocity $0.9\,\mathrm{km\,s^{-1}}$ at the lower end of the calculation domain) on the spectral line Fe I 5250.2 Å. A detailed parameter survey is presented and discussed by Ploner & Solanki (1997). Figure 2 displays Stokes V and Q at 12 successive phases (or time steps) covering a full wave period. The wave obviously shifts and broadens the profiles and changes the amplitudes as well as their relative ratios (blue-red asymmetries).

In order to separate the effects we introduce the line profile parameters (see Figure 3) and show in Figure 4 their temporal dependence. The line shift as well as the asymmetries (Figures 4a, b, g, h, i, and j) follow the wave motion and oscillate in phase between the different polarizations. The wave's velocities are better reflected in the line broadening (Figures 4c and d) than in line shift. The amplitudes respond non-linearly to the linear wave and oscillate in anti phase between the polarizations (Figures 4e and f).

In the remaining part of this paper we indicate the origin of this time dependence and demonstrate that kink waves also influence time averaged line profiles. The left hand panels of Figure 1 sketch the geometry of the flux tubes at the phases 2, 5, 8, and 11 (if one wave period is divided into 12 phases between 0 and 11). A typical line of sight is indicated by the arrow pointing towards the observer. Note that the spectral line is formed roughly between the height 100

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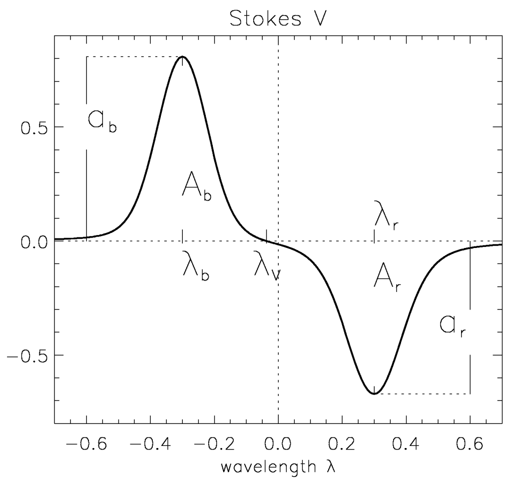

shift	λ_σ	$=$	$\frac{1}{2}(\lambda_r + \lambda_b)$
broadening	$\Delta\lambda_{cg}$	$=$	$\frac{1}{2}(\lambda_r - \lambda_b)$
amplitudes		$=$	$(a_r + a_b)$
amplitude asymmetry	δa	$=$	$\frac{a_b - a_r}{a_b + a_r}$
area asymmetry	δA	$=$	$\frac{A_b - A_r}{A_b + A_r}$

Figure 3. Definition of the line profile parameters of Stokes V. The definition for Stokes Q is analogous, using only the Zeeman split σ-components. Only the difference to the parameters calculated with no underlying wave is considered.

and 300 km. At that level the velocity and magnetic field inclination due to the wave are small at phases 5 and 11. Therefore the line profiles agree fairly well with the undistorted profiles and most line profile parameters are zero (Figure 4). At phases 2 and 8 the wave velocity, as well as the change of magnetic field inclination is largest and the corresponding line profiles are greatly modified. The line profile parameters possess maxima or minima near phases 2 and 8. Note again the anti phase between Stokes Q and V in the amplitudes, which reflects the different magnetic field directions.

We now consider time-averaged line profiles, which also correspond to a snapshot of a portion of the solar surface containing many flux tubes caught at random phases. The time averaged Stokes profiles resulting from the wave above are plotted in Figure 5. They are broadened, shifted and asymmetric. The asymmetries of Stokes Q and V have opposite signs, in contrast to the time-resolved line profiles.

This can be understood by noting that the time-resolved profiles contributing to the time-averaged profiles are weighted according to their amplitudes. Figures 4e and f clearly show that the Stokes V and Q amplitudes change in anti phase, whereas their asymmetries change in phase (Figures 4g to j). Hence in the case of Stokes V the negative asymmetry is more strongly weighted, giving the time averaged V profile a stronger red wing. For Stokes Q the positive asymmetry is most strongly weighted, leading to a stronger blue wing of the time averaged Q profile.

4. Summary

We used a simple MHD model to calculate propagating kink waves in solar magnetic flux tubes and computed the Stokes profiles of spectral lines formed in the presence of such waves (for more details see Ploner & Solanki 1997).

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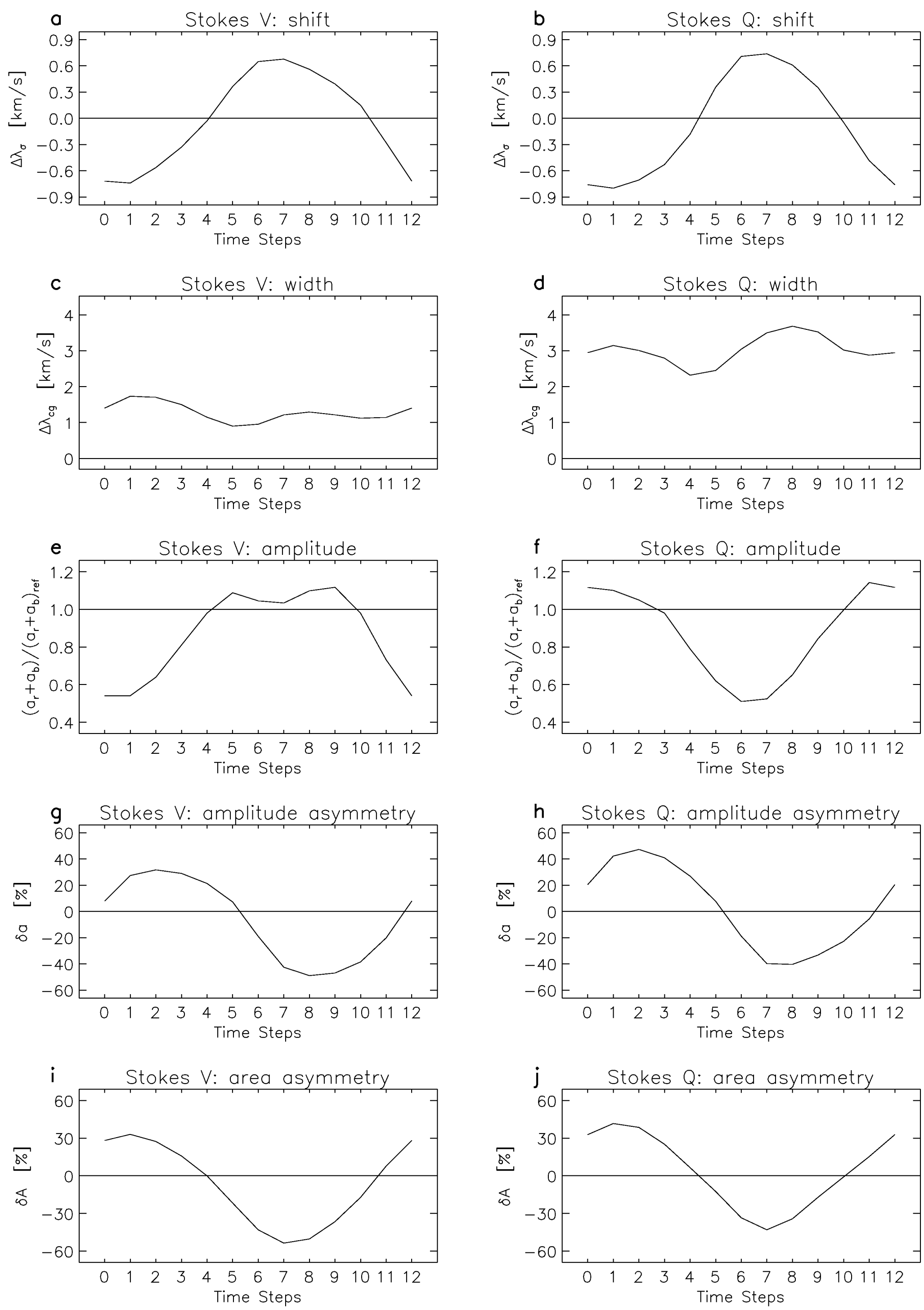

Figure 4. Plot of the line profile parameters defined in Fig. 3 versus time, for the wave shown in Fig. 1. The shifts (panels a and b) and asymmetries (panels g to j) oscillate in phase between the polarizations. The width is sensitive only to the magnitude of the velocity and oscillates with double the wave frequency. Note the anti phase of the amplitude oscillations between the two polarizations V and Q (panels e and f).

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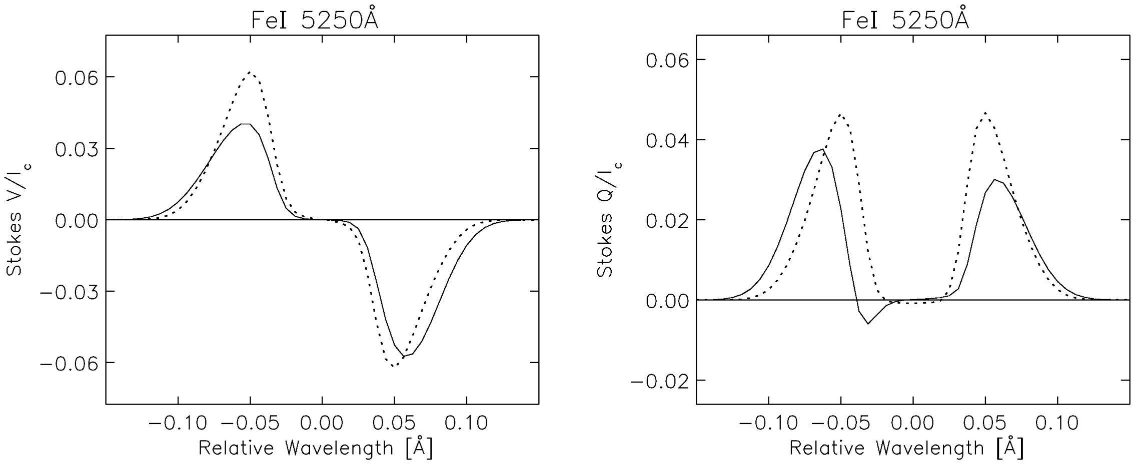

Figure 5. Time averaged line profiles (solid curves). Plotted are the averages over all profiles shown in Fig. 2. Also plotted are the equilibrium profiles resulting from the equilibrium flux tube (i.e., no wave, dotted curves).

Temporally resolved line profiles are highly asymmetric and broadened, but only slightly shifted. The various line parameters of Stokes V and Q oscillate in phase, with the exception of the line-profiles amplitudes which are in anti phase. In contrast to the time-resolved profiles time-averaged V and Q profiles have opposite signs of asymmetry and shift.

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