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Interpretation of coronal off-limb spectral line width measurements

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Abstract. Spectral line widths measured above the solar limb have been used to infer wave velocity amplitude height dependencies, supporting Alfven wave coronal heating and wave driven solar wind models. Comparison of the inferred amplitude/density dependence with a constant magnetic field strength, undamped wave propagation model have shown good agreement, providing the first strong support of Alfven wave heating models. We derive the density dependence for wave propagation in an expanding flux tube with decreasing field strength, and show that the resulting density dependence is identical to that of the constant field strength case. We use the expanding flux tube propagation model to infer the wave amplitude in the low photosphere, which is a factor of 9 lower than granulation velocities.

Key words. Sun: corona, solar wind, solar-terrestrial relations

1. Introduction

The central problem in coronal physics remains the heating and solar wind driving mechanisms. Alfven waves, generated at the photosphere and propagating into the corona, have been suggested as the source of energy and momentum flux required to heat and drive the coronal plasma. These waves are a possible source of heat and momentum flux, since they can propagate along magnetic field lines from the high density turbulent photosphere at high speed into the corona, where they might deposit energy and momentum. The presence of Alfven waves propagating off limb would be indicated through an increase in line width beyond thermal broadening, since wave motions are transverse to the direction of propagation and therefore one of the two components of wave motion is along the line of sight from Earth. Furthermore, since undamped outwardly propagating waves would travel through plasma of decreasing density, the wave amplitude is predicted to increase with height, which might be detected through spatially resolved line width measurements.

There have been several off-limb spectral line observations made to search for Alfven wave signatures. Measurements of ultraviolet Mg XI line widths made during a rocket flight showed an increase of width with height to a distance of 70 000 km, although the signal to noise was weak (Hassler et al. 1992). Ground-based observations of visible Fe X line spectra in a coronal hole made using the 40 cm coronagraph at Sacramento Peak Observatory showed an increase of line width with height in the hole, but strong sky-scattered light made interpretation of the results difficult (Hassler & Moran 1994). More recently, the SUMER ultraviolet telescope/spectrograph (Wilhelm et al. 1996) on board the Solar and Heliospheric Observatory (SOHO) (Domingo et al. 1996) has allowed further high resolution, spatially resolved measurements of ultraviolet coronal line widths which have been used to test for the presence of Alfven waves (Doyle et al. 1998; Banerjee et al. 1998). The SUMER instrument was used to record the off-limb, height-resolved spectra of a Si VIII density sensitive line pair, in an equatorial coronal region (Doyle et al. 1998), and a polar coronal hole (Banerjee et al. 1998). The measured variation of line width with density and radius supports undamped wave propagation in low coronal holes, since Si VIII line widths increase with higher radius and lower density. This is the first strong evidence of outwardly propagating undamped Alfven waves in coronal holes and may help explain coronal hole heating and high speed solar wind drive.

The relation between density and wave amplitude used to interpret the Si VIII observations assumes constant magnetic field strength. However, the field strength varies significantly over the region considered. We derive a relation between density and amplitude for varying field strength and show that if total wave energy flux is conserved along an expanding flux tube, the relation used for constant field strength is valid. Thus, the interpretation of the line width measurements of Doyle et al. (1998), and Banerjee et al. (1998), as signatures of undamped Alfven

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wave propagation is correct. We also derive the wave amplitude at lower heights in the solar atmosphere under the assumption of energy conservation.

2. Alfven wave energy flux

Alfven waves propagate along magnetic field lines, with wave dynamics determined by the balance between magnetic tension and fluid inertia. Pure Alfven waves are nondispersive, so the phase and group velocities are equal, and are given by:

$$V_{\mathrm{A}} = \frac{B}{\sqrt{4\pi\rho}}, \quad (1)$$

V_{A} is the phase/group velocity, B is the field strength and ρ is the mass density. The wave energy flux density Γ for vertical propagation in a stratified, plane parallel atmosphere is given by the products of the wave energy density and the Alfven velocity:

$$\Gamma = \rho\ \xi^2\ V_{\mathrm{A}}, \quad (2)$$

where ξ is the rms wave velocity. Combining Eqs. (1) and (2), the energy flux density may also be written:

$$\Gamma = \frac{1}{\sqrt{4\pi}}\ \sqrt{\rho}\ \xi^2\ B. \quad (3)$$

The total energy flux crossing a surface of area A is given by:

$$\Gamma_{\mathrm{t}} = \frac{1}{\sqrt{4\pi}}\ \sqrt{\rho}\ \xi^2\ BA. \quad (4)$$

If total wave energy flux is conserved as waves propagates outward, the wave amplitude has the following dependence on density, magnetic field strength and area:

$$\xi \propto \rho^{-1/4}(BA)^{-1/2}. \quad (5)$$

3. Interpretation of coronal hole line-width measurements

In studies of Si VIII line widths in the equatorial corona using the SUMER ultraviolet spectrograph on board the Solar and Heliospheric Observatory Spacecraft (SOHO), measurements showed a significant increase of line width with height above an equatorial region (Doyle et al. 1998) and polar coronal hole bases (Banerjee et al. 1998), indicating the presence of outwardly propagating Alfven waves. In testing the wave hypothesis, the authors assumed constant magnetic field strength and area, which results in the following relation between amplitude and density:

$$\xi \propto \rho^{-1/4}. \quad (6)$$

The local density was inferred from measurements of the ratio of a Si VIII line pair, and the more intense line was used to obtain the line width. Measured line widths were inversely proportional to the quadratic root of density between 1.0 R and 1.035 R, where R is the solar radius, above an equatorial region (Doyle et al. 1998) and between 1.0 R and 1.2 R above a coronal hole base (Banerjee et al. 1998), agreeing with the amplitude dependence predicted by Eq. (6).

However, since the magnetic field strength may vary significantly over the height range of the observations, we consider the effect of a variable magnetic field. Above the coronal hole base, the field strength will probably decrease with radius at least as strongly as r^{-2}, and possibly stronger due to super-spherical hole expansion. If we consider an inverse-squared field strength dependence and constant area, from Eq. (5), the relation between ξ and ρ is given by:

$$\xi \propto \rho^{-1/4}\ r. \quad (7)$$

The predicted amplitudes are then 12% higher at 1.15 R and 16% higher at 1.2 R. The measured linewidths between these distances would lie below the curve given by Eq. (6), with a difference of 1 σ or greater, and the evidence for undamped Alfven wave propagation is weakened at these heights. Below 1.15 R the difference in the measured amplitude and that predicted by Eq. (6) is less than one σ. Above an equatorial region, the field may be approximately constant over the observed height range and the field variation may be ignored.

The discrepancy between the prediction of the model with inverse-square field strength dependence and the line width measurements is resolved if the flux tube geometry is taken into account. If a tube carries an Alfven wave flux and magnetic field flux both evenly distributed over its cross sectional area A, BA is constant as the A increases and B decreases and Eq. (6) is valid. So, the constant field strength model and expanding flux tube models predict the same density dependence measured by Doyle et al. (1998) and Banerjee et al. (1998), supporting Alfven wave models of coronal heating and fast solar wind drive.

4. Alfven wave amplitudes in the low photosphere

In addition to using nonthermal Si VIII line-width measurements to test for the presence of coronal Alfven waves, observations were also used to infer wave amplitudes in the low photosphere under the assumption of energy conservation (Banerjee et al. 1998). The inferred amplitude was then compared with convective velocities in order to determine if fluid motions in the low photosphere might be driving the coronal Alfven waves. The cross sectional area filled with wave flux and the density were assumed constant between the low corona and photosphere. In this case, the wave amplitude has the following dependence on field strength (From Eq. (5)):

$$\xi \propto B^{-1/2}. \quad (8)$$

The magnetic field strength in the photosphere was taken to be 2000 G. This value is consistent with field strength measurements made in the low photosphere, which are associated with small flux tubes of 200 km diameter.

Given the measured velocity amplitude of 30 km s^{-1} at 1.04 R in a coronal hole and assuming coronal and photospheric field strengths of 5 G and 2000 G respectively, the wave amplitude is 1.5 km s^{-1} at the low photosphere, consistent with granulation velocities, suggesting that convective motions may drive the coronal Alfven waves indicated by the line width measurements.

We compute the low photospheric wave amplitude for the expanding flux tube model. In this case, the amplitude depends only on density (Eq. (6)). We estimate the flux tube density (atomic and proton) in the low photosphere by assuming equal magnetic and particle pressures and obtain a value of 10^{17} cm^{-3} for a field strength of 2000 G and a temperature of 6000 K. This is a factor of 10^9 higher than density at 1.04 R, implying factor of 178 increase in wave amplitude between the low photosphere and low corona. Given the measured velocity amplitude of 30 km s^{-1} at 1.04 R, the amplitude inferred in the low photosphere is 0.17 km s^{-1}, a factor of 9 lower than convective velocities.

5. Conclusion

The expanding magnetic flux tube and constant field strength/constant area undamped wave propagation models both predict an inverse quadratic dependence of Alfven wave amplitude on density. Thus, regardless of whether waves propagate in flux tubes of constant or expanding area, the line width measurements of Doyle et al. (1998) and Banerjee et al. (1998) indicate the presence of undamped Alfven waves in the corona. These measurements support Alfven wave coronal heating and solar wind drive models. We have inferred the wave amplitude in the low photosphere using the expanding flux tube model and have obtained a value a factor of 9 lower than convective velocities at that height. Thus, Alfven waves are probably not driven directly by the low photospheric convective motions, but possibly by fluid motions at a higher altitude.

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