Ionization diagnostics of solar magnetic structures?

Can observed waves tell us anything at all about spicules?

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Acknowledgements

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Dr. Jaume Terradas
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Prof. Robertus Erdélyi, Prof. Michael Ruderman

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Plasma density measurements from intensity

Traditionally using spectral line intensities. Assuming filling factor, background subtraction, etc. correct still forced to make many assumptions.

\[ I_\nu = S_\nu \kappa_\nu \rho \Delta x \]

- \( I_\nu \): Intensity
- \( S_\nu \): Source function
- \( \kappa_\nu \): Opacity
- \( \rho \): Plasma density
- \( \Delta x \): Geometric depth
Spicule filling factor?

Spicules very narrow features at spatial resolution limit of telescopes, e.g., SOT (approx. 200 km).

Unresolved expanding flux tube

De Forest (2007)
Spicule plasma density modelling

Density model from eclipse flash spectra (Makita 2003).

Assumptions

1) constant source function

2) intensity of metallic lines
   \[ \text{intensity of hydrogen density} \] (Zirker 1958)

3) Balmer line intensity
   \[ n_e n_p \] (isothermal plasma assumption)

4) Height dependent spicule filling factor 0.01-1.01
Spicule magnetic field measurement

From Centeno et al. (2010). S/N ratio poor for off-limb Zeeman and Hanle measurements. Integration time of 45 minutes at two different altitudes (2” and 3” above limb). Much longer than lifetime of individual spicules.
Can we use wave observations to say something about spicule structure?

Example of propagating kink wave observed in spicule with Hinode/SOT Ca II H filter from He et al. (2009). Relatively undynamic “Type I” spicule.

Flow speed (up and down) ≈ 10 km s\(^{-1}\)

Phase speed ≈100 km s\(^{-1}\)

→ Sub-Alfvenic flow (not always the case!)
Can measure the follow crucial wave parameters as a function of height (He et al. 2009)

1) Period

2) Phase travel time (→phase speed)

3) Velocity amplitude

Wave propagates along the spicule in about 150 s, well within the spicule lifetime.
Wave properties vs height

From He et al. (2009). See also earlier work by Zaqarashvili et al. (2007)
Using ideal MHD

Allow internal and external plasma density to be different

\[ \rho_i(s) \neq \rho_e(s) \]

Assume average \( R \) dependence for magnetic field, i.e.,

\[ B_s = B_s(s) \]

\[ B_R = -\frac{1}{2} R(s) \frac{dB_s}{ds} \]

\[ \Rightarrow \nabla \cdot \mathbf{B} = 0 \]
**Governing wave equations**

\( m = 0 \) (the “torsional Alfven wave”)

\[
\frac{d^2}{ds^2} \left( \frac{v_\varphi}{R} \right) + \frac{\omega^2}{v_A^2(s)} \left( \frac{v_\varphi}{R} \right) = 0
\]

\[ v_A^2(s) = \frac{B^2(s)}{\mu \rho(s)} \]

\[ \rho(s) = \rho_e(s) \quad \rho(s) = \rho_i(s) \]

See e.g. Hollweg (1981), Poedts et al. (1985).

\( m = 1 \) (the “kink wave”)

\[
\frac{d^2}{ds^2} \left( \frac{v_\perp}{R} \right) + \frac{\omega^2}{c_k^2(s)} \left( \frac{v_\perp}{R} \right) = 0
\]

\[ c_k^2(s) = \frac{B^2(s)}{\mu \langle \rho(s) \rangle} \]

\[ \langle \rho(s) \rangle = \frac{\rho_i(s) + \rho_e(s)}{2} \]

Verth & Erdélyi (2008), Ruderman et al. (2008), Andries & Cally (2011)

N.B. not the same as equation by Spruit (1981)!
Basic kink wave behaviour (no damping)

WKB solution for velocity amplitude is

\[ v_\perp(s) \propto R(s) \sqrt{c_k(s)} \]

1) \[ \langle \rho(s) \rangle = \text{constant}, \quad B(s) = \text{constant} \]
   \[ \Rightarrow \quad c_k(s) = \text{constant} \]

2) \[ \langle \rho(s) \rangle \propto B^2(s) \]
   \[ \Rightarrow \quad c_k(s) = \text{constant} \]

3) \[ B^2(s)/\langle \rho(s) \rangle \neq \text{constant} \]
   \[ \Rightarrow \quad c_k(s) \neq \text{constant} \]
Observational examples

In study by He et al. (2009) they use Hinode/SOT to measure amplitudes and wavelengths in spicules. Are there understandable trends here?
Effect of damping

Following on from Roberto’s talk. Ion-neutral damping is a frequency dependent effect.

To compete with damping due to resonant absorption need $\omega \approx \nu_{\text{in}}$.

Martinez-Sykora et al. (2012)  
Okamoto & De Pontieu (2011).
Effect of resonant absorption

In the TTTB approximation **damping length** due to RA was investigated by Terradas et al. (2010), Verth et al. (2010) and Soler et al. (2011)

<table>
<thead>
<tr>
<th>Equilibrium type</th>
<th>Damping relation</th>
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<tbody>
<tr>
<td>( \langle \rho(s) \rangle = \text{constant}, \quad B(s) = \text{constant} ) ( \Rightarrow ) ( c_k(s) = \text{constant} )</td>
<td>( L_D \propto \frac{c_k}{\omega} )</td>
</tr>
<tr>
<td>( B^2(s)/\langle \rho(s) \rangle \neq \text{constant} ) ( \Rightarrow ) ( c_k(s) \neq \text{constant} )</td>
<td>( v_\perp(s) \propto \exp \left( -\frac{s}{L_D} \right) )</td>
</tr>
<tr>
<td>( L_D(s) \propto \frac{c_k(s)}{\omega} )</td>
<td>( v_\perp(s) \propto R(s) \sqrt{c_k(s)} )</td>
</tr>
<tr>
<td>&amp; ( \times \exp \left( -\int_0^s \frac{ds}{L_D(s)} \right) )</td>
<td></td>
</tr>
</tbody>
</table>
Assume a straight tube (constant magnetic field), constant density

\[ \langle \rho(s) \rangle = \text{constant}, \quad B(s) = \text{constant} \]

\[ \Rightarrow \quad c_k(s) = \text{constant} \]

\[ v_\perp(s) \propto \exp \left( -\frac{s}{L_D} \right) \]

\[ L_D \propto \frac{c_k}{\omega} \]
Effect of RA: example 2

Assume a **expanding tube** (non-constant magnetic field) and **non-constant density** so that kink speed varies.

\[
\frac{B^2(s)}{\langle \rho(s) \rangle} \neq \text{constant} \\
\Rightarrow c_k(s) \neq \text{constant}
\]

\[
L_D(s) \propto \frac{c_k(s)}{\omega}
\]

\[
v_\perp(s) \propto R(s) \sqrt{c_k(s)} \times \exp \left( - \int_0^s \frac{ds}{L_D(s)} \right)
\]
Velocity amplitude: Coronal holes

The trend in non-thermal spectral line broadening (interpreted as velocity amplitude) has been claimed to be the source for both coronal heating and solar wind acceleration (Hahn et al. 2012, Bemporad & Abbo 2012).

McIntosh et al. (2011) used SDO/AIA to estimate phase speed with height.

Measured average velocity amplitude of 25 km s^{-1}
It is well known (Kneseer’s oscillation theorem) that the governing kink wave equation can have a cutoff if $c_k(s)$ is increasing linearly with height (or greater).

$$\frac{d^2}{ds^2} \left( \frac{v_\perp}{R} \right) + \frac{\omega^2}{c_k^2(s)} \left( \frac{v_\perp}{R} \right) = 0$$

$$\omega^2 > \frac{c_k^2(s)}{4s^2}$$

**Linear profile**

$$c_k(s) = As + B$$

$$\omega^2 > \frac{A^2}{4}$$

**Quadratic profile**

$$c_k(s) = As^2 + B$$

$$\omega^2 > \frac{A^2}{4}s^2 + \frac{AB}{2}$$
Spicule statistics

Okamoto & De Pontieu (2011) studied wave properties of large sample.

59% propagating up
21% propagating down
20% standing

1) High pass filtering due to longitudinal stratification (cutoff frequency)
2) Low pass filtering caused by transverse stratification (resonant absorption or ion-neutral damping)
Case study: Verth et al. (2011)

From observational case study of He et al. (2009), all wave variables, apart from \( R(s) \), can be estimated.

\[
\frac{d^2}{ds^2} \left( \frac{v_{\perp}}{R} \right) + \frac{\omega^2}{c_k^2(s)} \left( \frac{v_{\perp}}{R} \right) = 0
\]

\[
B(s) \propto \frac{1}{R^2(s)} \quad \rightarrow \quad \langle \rho(s) \rangle \propto \frac{B^2(s)}{c_k^2(s)}
\]

where

\[
\langle \rho(s) \rangle = \frac{\rho_i(s) + \rho_e(s)}{2}
\]
Least squares fit to data: Phase travel time

\[ t = t_0 \exp \left( \frac{s}{A_1} \right) \]

\[ c_k(s) = c_{k,0} \exp \left( -\frac{s}{A_1} \right) \]

\[
\frac{d^2}{ds^2} \left( \frac{v_\perp}{R} \right) + \frac{\omega^2}{c_k^2(s)} \left( \frac{v_\perp}{R} \right) = 0 \quad \rightarrow \quad v_\perp(s) = v_{\perp,0} \frac{R(s)}{R(0)} \exp \left( -\frac{s}{2A_1} \right)
\]
Least squares fit to data: Velocity amplitude

\[ v_\perp(s) = v_{\perp,0} \frac{R(s)}{R(0)} \exp \left( -\frac{s}{2A_1} \right) \]

\[ v_{\perp}(s) = v_{\perp,0} \exp \left( \frac{s}{A_2} \right) \]

\[ R(s) = R(0) \exp \left( \frac{s}{H_R} \right) \]

\[ H_R = \frac{2A_1 A_2}{2A_1 + A_2} \]
Spicule flux tube area vs height

Tsuneta et al. (2008) estimated upper limit area expansion of 345 between photosphere and corona (in Sun’s south polar region).
Spicule magnetic field strength vs height

Comparison with average unsigned magnetic field from 3D radiative MHD simulations of De Pontieu et al. (2007) (courtesy M. Carlsson).
Comparison of footpoint magnetic field

Comparison between wave study result and 3D radiative MHD simulation highly dubious!
A dipole structure at footpoint of spicule, c.f., simulation?
Spicule plasma density vs height

Electron density
Spectroscopic studies of Becker (1968), Makita (2003)

Plasma density
Spectroscopic study of Makita (2003)

Estimate using kink wave observation by Verth et al. (2011)

TEMPERATURE INCREASE WITH HEIGHT (De Pontieu et al. 2011)?
Spicule ionisation fraction vs height

By combining wave observation (plasma density scale gradient) and spectroscopy (electron density gradient) can estimate ionisation fraction.

\[ \langle \rho(s) \rangle \propto n_H(s) \]

Assuming plasma density is proportional to hydrogen number density and most free electrons are from hydrogen then ionisation fraction is

\[ x_H(s) = \frac{n_e(s)}{n_H(s)} \]

Conclusions

- Studying waves can give insight into the height dependence of both magnetic field and plasma mass density. Not without value in the chromosphere!

- Need good estimates of both height dependence of phase speed and velocity amplitude. One without the other not very useful. Although can say something about cutoff frequency with just phase speed.

- Can studying waves tell us anything about ionisation? Certainly can help with estimating height dependence of mass density in chromosphere. Not without value!

- Damping regime due to ion-neutral collisions interesting. High frequency effect. Would be difficult to disentangle from other damping effects, e.g. resonant absorption (also frequency dependent).