SPICULE FORMATION BY ION-NEUTRAL DAMPING

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ABSTRACT

The possible mechanism of generation of spicules by Alfvénic waves is studied in dissipative MHD where dissipation is mainly caused by ion-neutral collision damping, as suggested by Haerendel (1992). Ion-neutral damping becomes non-negligible at the high cyclic frequencies involved, typically greater than 0.1Hz, and the potential role played by this effect in both forming and supporting solar spicules is investigated. 

The propagation of high frequency Alfvén waves on vertically open solar magnetic flux tubes is considered by numerically solving a set of 1.5D MHD equations. Spicule-like structures with heights of around 4000–10000 km were formed. The formation was found to be primarily caused by the impact of a series of slow shocks generated by the continuous interaction between the upward propagating driven wave train and the downward propagating train of waves created by reflection off the transition region. At the lower end of frequencies considered the heating due to ion-neutral damping was found to provide only a small benefit due to the increased thermal pressure gradient. At higher frequencies, whilst the heating effect becomes stronger, the much reduced wave amplitude reaching the transition region hinders spicule formation. The adiabatic results suggest that ion-neutral damping may not support spicules as described by Haerendel (1992).

Key words: spicule; transition region; ion-neutral damping; Alfvén waves.

1. INTRODUCTION

Solar spicules are long, thin cylindrical jet-like structures seen above the solar limb and best observed in strong chromospheric emission lines. They appear to be guided along the intense magnetic flux tubes at supergranule boundaries. Widths are 300–1500 km (Nishikawa, 1988) which is similar to the spatial resolution of the observing instrumentation and, as a result, there is some disagreement on their properties in the literature. According to the general consensus (Beckers, 1972; De Pontieu, 1999; Sterling, 2000) matter of approximately chromospheric densities (3 \times 10^{12} \text{ g cm}^{-2}) and temperatures (5000–10000 K) ascends with speeds of 25 km s^{-1} to heights of 5000–15000 km above the photosphere. Typical lifetimes are 5–15 minutes after which the spicule is observed either to fall with velocity similar to the ascent velocity or occasionally to fade from view. Density and temperature are both fairly constant along the spicule length. Some spicules are believed to rotate rapidly. Ruždjak (1977) found that peripheral rotational velocities of 25 km s^{-1} gave theoretical line profiles similar to those observed.

It is unclear whether the spicule rise is ballistic or not (Nishikawa, 1988). The high initial velocities of about 80 km s^{-1} required to produce spicules of sufficient height have not been observed on the disk although it should be noted that this may be a consequence of the low resolution. There is evidence of signal propagation speeds of up to 300 km s^{-1} (Hasan & Keil, 1984). This is much larger than the local sound speed of around 20 km s^{-1} but similar to the local Alfvén speed, suggesting magnetic waves may play an important role in spicule formation. Because the ascent and descent velocities of spicules are similar to the Alfvén and sound speeds of the upper chromosphere, any realistic investigation of their evolution must be non-linear. For this reason, most previous studies have taken the form of 1D and 1.5D numerical simulations, both hydrodynamic and magnetohydrodynamic. A number of potential formation mechanisms have been considered, an excellent overview of which may be found in Sterling (2000). This work concentrates on ion-neutral damping of high frequency Alfvén waves as the driver for spicule formation, as originally proposed by Haerendel (1992). In the photosphere and chromosphere the solar plasma is only partially ionised. Changes in the magnetic and electric fields directly impact the ion fluid but the neutral fluid is indirectly affected, being collisionally coupled to the ions. At characteristic frequencies well below the neutral-ion collision frequency the slippage between the neutral and ion fluids is unimportant, but at sufficiently high frequencies Alfvén wave damping and dissipation can occur. Haerendel (1992) and De Pontieu & Haerendel (1998) showed, under the WKB approximation applied to plane-polarised linear Alfvén waves, that this effect produces a net waveperiod averaged force in the direction of wave propagation which, for realistic parameters of the solar atmosphere, can support a spicular structure against gravity. De Pontieu (1999) numerically investigated this effect by using an essen-


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tially 1D hydrodynamic model which incorporated the widening of a solar magnetic flux tube by looking at the evolution along a cylinder of flux lines and included the heating and coupling into vertical momentum due to wave damping by explicitly adding the approximate contributions derived in De Pontieu & Haerendel (1998). It was found that structures resembling solar spicules could indeed be generated and supported by this mechanism under these approximations, though for the parameters chosen, the heights of around 6000 km were toward the lower end of the typically quoted observational range. Whilst the WKB approximation was used in the linear limit, the velocities occurring in the simulation were in violation of this limit. It is therefore reasonable to believe that nonlinear effects may have a definite impact on the results. In addition, the WKB assumption breaks down in the transition region where the Alfvén speed increases by an order of magnitude in around 200 km. The intention here is to extend the model to 1.5D fully dissipative and nonlinear MHD simulations, enabling investigation of the effects of nonlinearity, wave reflections off the transition region and more accurate consideration of the small scale structure of the results.

2. DETAILS OF THE MODEL

Consider a rigid, vertical, axisymmetric and initially untwisted flux tube. We define a local orthogonal curvilinear coordinate system by \( z \), the distance along a field line, \( \theta \), the azimuthal angle about the axis of symmetry and \( \xi \), a coordinate measured in the \( z \times \hat{\xi} \) direction. We assume \( v_\xi = 0 \) and \( \partial / \partial \theta = 0 \). The heating due to wave damping is included but otherwise the problem is considered adiabatic. The basic MHD equations yield:

\[
\frac{\partial}{\partial t} \left( \frac{\rho v_z}{B_z} \right) + \frac{\partial}{\partial z} \left( \frac{\rho v_z v_z}{B_z} \right) = 0, \quad (1)
\]

\[
\frac{\partial}{\partial t} \left( \frac{\rho v_\xi}{B_z} \right) + \frac{\partial}{\partial z} \left( \frac{\rho v_\xi v_\xi}{B_z} \right) = 1 \frac{\partial}{\partial z} (r B_\theta), \quad (2)
\]

\[
\frac{\partial}{\partial t} \left( \frac{\rho v_z}{B_z} \right) + \frac{\partial}{\partial z} \left( \frac{\rho v_z v_z}{B_z} \right) = -\frac{1}{B_z} \left[ \frac{\partial \rho}{\partial z} + \rho g - \frac{v_z^2}{\tau} \frac{\partial}{\partial z} \left( \frac{\mu_0 \sigma r}{B_z} (r B_\theta) \right) \right], \quad (3)
\]

\[
\frac{\partial}{\partial t} \left( \frac{\rho v_\xi}{B_z} \right) + \frac{\partial}{\partial z} \left( \frac{\rho v_\xi v_\xi}{B_z} \right) = -\frac{\partial}{\partial z} \left( \frac{v_z}{\tau} \right) + \frac{s}{B_z \mu_0 \sigma r^2} \frac{\partial}{\partial z} (r B_\theta), \quad (4)
\]

\[
\frac{\partial}{\partial t} \left( \frac{\rho v_\xi}{B_z} \right) + \frac{\partial}{\partial z} \left( \frac{\rho v_\xi v_\xi}{B_z} \right) = -\frac{\partial}{\partial z} \left( \frac{\mu_0 \sigma r}{B_z} (r B_\theta) \right), \quad (5)
\]

where \( e = \frac{p}{\rho} + n_e k T \) is the internal energy, the sum of the thermal and ionisation energies, and \( s \) is the ion slip, a measure of the slippage between the ion and neutral fluids. Details of the method used in calculating the ionisation and ion slip can be found in De Pontieu (1996). The initial pressure and temperature profiles are taken from the VAL IIIc model atmosphere (Vernazza, 1981). The density profile is then calculated assuming a perfect gas law and initial hydrostatic equilibrium. The numerical grid is non-uniform with spatial resolution of at least 20 grid points per wavelength at all positions and times in the simulation. A flow-through boundary condition, \( \partial / \partial z = 0 \), is applied to all variables at both boundaries. The adiabatic constant is \( \gamma = 5/3 \). The \( B_z \) component of magnetic field is given by an analytic function as described by De Pontieu (1996), two parameters of which are the coronal and surface magnetic fields. In this work, the surface and coronal vertical magnetic field is taken to be 1600 G and 20 G respectively. Alfvén waves are launched by the addition of a localized artificial body force in the equation of angular momentum,

\[
F = A(z) \sin(\omega t),
\]

centered at \( z = 600 \) km in height. This force could represent the perturbations at the footpoint of the flux tube caused by granular buffeting. The numerical solution is obtained using the Versatile Advection Code developed by Tóth (1996). Flux corrected transport schemes are used, chosen for their ability to accurately and stably handle the strong shocks which arise in the simulations.

3. RESULTS

Fig. 1 shows the evolution of the density profile with time for a wave period of 4 s and initial amplitude 20% of the background Alfvén speed. Fig. 2 shows the velocity profile of the transition region, identified with the top of the structure and visible in Fig. 1 as the point at which the density becomes relatively constant. The wavefront reaches the transition region at about 50 s and starts to push it upwards. The plasma is then decelerated by gravity. There is a sharp increase in velocity with a period of about 20 s. Somewhat more than half of the Alfvén wave flux is reflected off the transition region resulting in a downward propagating train of reflected waves. This reflected wave train interacts with the upward propagating waves resulting in a series of shocks which propagate upward at the slow speed. The initial vari-
Figure 2. Transition region velocity for the simulation in Fig. 1.

Figure 3. Investigating the effect of damping. Transition region position against time for 4s wave period, 20% initial amplitude and 10G coronal magnetic field.

ation in shock strength, as measured by the increase in transition region velocity they cause, is unsurprising because the length of interaction which produces each subsequent shock increases as the reflected wave train propagates downwards. After around 100 s, the reflected wave train reaches the driving wave source. From this time on, the length of interaction for subsequent shocks is similar. Shocks formed after 100 s reach the transition region from around 200 s after which the shock strength becomes more uniform.

Fig. 3 shows the motion of the transition region for three runs with identical parameters with the damping term in the induction equation and the heating term in the energy equation turned on or off as appropriate. The inclusion of damping alone makes little difference whilst the inclusion of heating increases the height of the structure. Evolution of the structure is dominated by the shocks rather than the force from ion-neutral damping predicted by the linear WKB theory. However, the heating from damping has a definite effect, increasing the thermal pressure gradient and helping to support the plasma against gravity, resulting in greater heights. At longer wave periods, the three results converge as the damping and resultant heating become negligible. At shorter wave periods, the waves become too strongly damped in the upper corosphere and the reduction in wave amplitude reaching the transition region overcomes the positive benefit from increased heating resulting in smaller structures.

Table 1. The dependence of maximum height in Mm of wave period at 20% amplitude, 20G field.

<table>
<thead>
<tr>
<th>Period</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>20</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.5</td>
<td>3.8</td>
<td>4.5</td>
<td>4.6</td>
<td>5.1</td>
<td>5.7</td>
<td>6.1</td>
</tr>
</tbody>
</table>

From Table 1 it can be seen that height increases monotonically with increasing wave period. The initial velocities are largely determined by the amplitude of the wavefront. At 2 s time period, the damping is significant and the much reduced wave amplitudes reaching the transition region account for a much reduced initial velocity. At the longer wave periods, damping has a reduced effect and the initial velocities are more similar.

A study of the reflection of Alfvén waves off the transition region in our model shows that longer period waves are more strongly reflected. The increased strength of the reflected wave train leads to stronger shocks forming which would help to explain the increased velocities and heights. Counteracting this, the heating effect will decrease with increasing time period, reducing the ability of the thermal pressure gradient force to support the structure against gravity.

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
</tr>
</thead>
<tbody>
<tr>
<td>4s Period</td>
<td>3.3</td>
<td>3.8</td>
<td>4.2</td>
<td>4.9</td>
</tr>
<tr>
<td>40s Period</td>
<td>3.3</td>
<td>6.1</td>
<td>9.9</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Table 2. The dependence of maximum height on amplitude for 20G field.

Table 2 shows that height increases monotonically with amplitude. This is exactly as would be expected. As well as increased velocities, higher amplitudes lead to stronger non-linear steepening and increased reflection efficiency. The main point of interest is that structures of spicular heights and velocities can indeed be generated under the current regime for certain sets of parameters. Whether these parameters are realistic or not remains an open question due to the lack of observational constraints.

<table>
<thead>
<tr>
<th>Magnetic field</th>
<th>10</th>
<th>20</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>4s Period</td>
<td>3.4</td>
<td>3.8</td>
<td>5.1</td>
</tr>
<tr>
<td>40s Period</td>
<td>5.4</td>
<td>6.1</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Table 3. The dependence of maximum height on coronal field for 20% amplitude.

Table 3 shows the effect of coronal magnetic field on spicule height. The damping strength is proportional to the magnetic field which reduces the amplitude of waves reaching the transition region and tends to reduce height. In contrast, temperatures and therefore the supporting thermal pressure are higher for the same reason. Characteristic velocities
Figure 4. Temperature and density profiles at 4s period, 20% initial amplitude and 20G coronal magnetic field. The full lines show the profiles at 600 s whilst the dotted lines show the initial profiles.

(in the absence of damping) are also higher due to the increased Alfven speed. Once again though, it is reflections that dominate the picture. Increasing the coronal field also leads to two competing effects with regard to reflection strength. Firstly, the increased wavelength relative to the fixed transition region width makes reflections more efficient. On the other hand, all other things being equal, steepened waveforms are more strongly reflected. Increasing the coronal field leaves less distance relative to the wavelength for the waves to steepen before reaching the transition region which reduces reflection efficiency. This explains why the 4s period results show a monotonic increase as the 10G and 20G cases lead to only weak reflection whilst the results for 40s period show no clear trend.

Fig. 4 shows the temperature and density profiles at the end of one characteristic simulation with the initial profiles shown for reference. The density profile shows the stratification into high and low density regions caused by the interaction of the upward propagating and reflected wave trains. The profiles are similar in character for all parameters considered. It is interesting to note that the average temperatures along the spicule core of 10000 - 15000 K are largely independent of the wave period. This initially surprising result is due to the natural limit imposed on the heating mechanism; it is only effective whilst the plasma is only partially ionised. Thus the short wave periods reach their final temperatures quicker than the longer wave periods but all wave periods have similar temperature profiles by the end of the simulation. The peaks and troughs in the density profile become considerably more pronounced with increasing wave period, reaching more than a factor of 10 apart for 40s wave periods. Such fine structure may not be visible in observations so that the results are not necessarily in contradiction with the fairly flat profiles observed.

4. CONCLUSION

1.5D dissipative and fully nonlinear MHD numerical simulations were run to test the hypothesis of Haerendel (1992) that ion-neutral damping of Alfven waves, which becomes important in the solar atmosphere for cyclic frequencies greater than approx. 0.1 Hz, can provide a mechanism for the formation and support of solar spicules. Waves were launched by a continuous localised source in the photosphere. The initial impact of the wavefront was found to push the transition region upward. The subsequent evolution of the structure was found to be dominated by the slow shocks formed by the continuous interaction between the upward propagating wave train and the waves reflected off the moving transition region. The structures formed had density and temperature profiles broadly in agreement with observations. Heights and velocities could also be recreated but were more parameter sensitive. Alfven wave damping helped to heat the structure but the coupling into vertical momentum predicted by the WKB linear analysis was only a minor effect in the subsequent evolution. Since the effect depends on the presence of neutrals in the plasma, inclusion of thermal conduction and radiative losses may increase its importance by lowering the temperature and increasing the neutral density. As well as the WKB approximation initially being violated in the transition region, it is also violated everywhere once the interaction of upward propagating and reflected waves results in stratification into high and low density regions. It is perhaps not surprising then that the anticipated effects failed to materialise. This stratification is primarily the result of a partially standing wave. A more random source of Alvénic disturbances should reduce this effect and will also be studied in future work.

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