JETS AND BRIGHTENINGS GENERATED BY ENERGY DEPOSITION IN THE MIDDLE AND UPPER SOLAR CHROMOSPHERE

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Abstract. Numerical simulations of energy depositions in the middle and upper solar chromosphere result in ejection of chromospheric material into the corona and heating of the chromospheric gas. These simulations may be capable of describing some of the features seen by the soft X-ray telescope on board the Yohkoh satellite.

Key words: Sun – Chromosphere - Heating - Spicules

1. Introduction

Sterling et al. (1991, hereafter Paper 1) and Sterling et al. (1993, hereafter Paper 2) investigated the consequences of depositing thermal energy in the middle and upper solar chromosphere using 1-D numerical simulations. Those calculations have implications for Hα, UV, and X-ray microflares, and have resulted in a new spicule model. Here we summarize the methods and results of those two papers, and discuss new implications of that previous work in terms of recently acquired data from the soft X-ray telescope (SXT) on board Yohkoh.

2. The Numerical Models

The models assume rigid magnetic flux tubes of length ≈ 20,000 km, and solve the hydrodynamic equations for conservation of mass, momentum, and energy. Approximate forms for radiation losses and heat conduction are included. A source term in the energy equation represents energy deposition into the chromosphere. Different simulations are executed by varying the duration, location, and magnitude of that energy source term. The two

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papers explored an energy range for the input source ranging from $5 \times 10^{24}$ to $5 \times 10^{28}$ ergs.

Paper 1 limits the input energy source to a narrow region near the top of the chromosphere and assumes a semi-circular loop magnetic field geometry. Paper 2 allows for a broader range of source input regions and assumes a vertical open magnetic field. Other differences between the two models are of little consequence to the following discussion.

3. Results

Combining the results of Papers 1 and 2, we can make the following general statements. (We do not discuss less frequently occurring exceptions here.)

1. One of three different types of ejections of chromospheric matter into the corona results for a given set of input chromospheric energy source parameters:
   a) Pressure-Gradient Jets
      These are elongated, relatively iso-density and iso-thermal ejections resulting from the gradient in pressure between the ambient atmosphere and regions heated by the input energy. These types of jets generally form when the input energy source is distributed over the entire upper chromosphere.
   b) Two-Component Jets
      These jets are composed of a warm, denser pressure-gradient driven lower component and a cool, more rarefied shock-driven upper component. They generally form when only a localized region of the upper chromosphere is heated to sub-coronal temperatures.
   c) Gas Plugs
      These are regions of cool, dense (chromospheric) material surrounded by coronal gas, generally only a few thousand kms in extent. They form when a localized region of the chromosphere is heated to super-coronal temperatures. When the input heating is large enough, radiation and conduction at the boundary of the gas plug are not sufficient to maintain the cool gas plug for long, resulting in "evaporating gas plugs."

2. In some cases, pressure-gradient jets have properties similar to those of Hα spicules. This type of model spicule, which places the spicule driving force in the middle and upper chromosphere, differs fundamentally from model spicules resulting from earlier numerical studies by, e.g., Suematsu et al. (1982), Hollweg (1982), and Sterling & Mariska (1990), which placed the driving force near the base of the chromosphere. Several of the pressure-gradient and two-component jets have $\rho > 5 \times 10^{-13}$ g cm$^{-3}$, which is higher than typically quoted spicule densities. Thus we
do not include such features in our definition of model spicules. These jets may represent a category of surges (see Shibata et al. 1982).

3. Depositing energy in the chromosphere results in heating and expansion of the local chromospheric gas. When the input energy source heats the chromosphere to $> 10^5$ K, emissions in UV may result. These may, in fact, be the "UV microflares" observed by Porter et al. (1987). Similarly, heating the gas to $> 10^6$ K may produce UV and X-ray microflares. Assuming this to be the case, we find that some pressure-gradient jets, some two-component jets, and all gas plugs are associated with UV microflares. Only the gas plugs are associated with X-ray microflares. In addition, all three features would be associated with brightenings in H$\alpha$.

4. Solutions which produce jets with spicule-like features tend to not be associated with UV microflares, and are never associated with X-ray microflares.

4. Preliminary Comparisons with Yohkoh SXT Observations

Using data from the Yohkoh SXT, Shibata et al. (1992) have found that X-ray jets are a common feature of the solar atmosphere. The jets studied in that paper reached sizes of $5 \times 10^3 - 4 \times 10^5$ km with velocities of $30 - 300$ km s$^{-1}$. If the jets result from energy deposition in the chromosphere, then we would expect that they can be generated by the models discussed above. Shibata et al. (1992) suggest that a magnetic reconnection type of mechanism may be responsible for some jets. That view could be consistent with the models of Papers 1 and 2 if the reconnection is the source of the thermal energy deposition in the chromosphere.

In order for X-ray jets to be visible, the emission measure of the emitting gas in the regime observed by SXT would have to increase substantially over that of the background coronal plasma. This is what we find in the case of gas plug solutions: Paper 1 shows that the coronal gas below the plug is hotter and denser than the coronal gas above the plug. Thus the emission measure of the gas below is increased over the (nearly ambient) coronal gas above the plug. In a preliminary calculation for the gas plug in Fig. 6 of Paper 2, we have found that the emission measure of the gas from the region below the upward-moving gas plug is several orders of magnitude more intense than than that of the ambient corona. Here we define emission measure as $\int N_e^2 dV$, where $N_e$ is the electron number density and $dV$ is the volume of gas emitting in the temperature interval $1.2 - 2.5$ MK. This more-intense region evolves upward with velocity $\approx 50 - 100$ km s$^{-1}$, and may appear as one type of X-ray jet seen by SXT. Higher velocities may result in cases of more energetic and evaporating gas plugs.

Some simulation results in Paper 1 show that in some cases a gas plug
ejected from the chromosphere at one end of a coronal loop can traverse the loop and reflect off the chromosphere at the far end of the loop. We have yet to perform emission measure analyses for such a case, but we can speculate that such a feature may show up in SXT images as an X-ray loop filling from one end and extending to the other end. In some cases, the start and finish of the gas plug’s trajectory would be particularly bright in X-rays because the pressure built-up is larger along the “lower legs” of the loop (see Figs. 3c and 4c of Paper 1). An example of an SXT feature that such simulations may describe is the 7 December 1991 X-ray bright point flare and associated plasma jet discussed in Strong et al. 1992. The simulations may also be able to explain some features of active region transient brightenings seen by SXT (Shimizu et al. 1992).

5. Conclusions

Numerical simulations of thermal energy depositions in the middle and upper chromosphere show, subject to the assumptions of the models, that:

1. The chromospheric gas becomes heated, and ejections of chromospheric material into the corona result. The heated chromospheric material should be visible as intensity enhancements in Hα, UV when \( T_{\text{chrom}} > 10^5 \) K (where \( T_{\text{chrom}} \) is the temperature the chromospheric gas is heated to at the location of energy input), and X-rays when \( T_{\text{chrom}} > 10^6 \) K.

2. Chromospheric jets which resemble spicules sometimes result, but jets with densities higher than those reported for spicules can also result. The spicule-like solutions are rarely associated with UV microflares, and never associated with X-ray microflares.

3. Coronal material below evolving gas plugs can have emission measure several orders of magnitude higher than that of the ambient corona. This material may appear as X-ray jets seen by SXT, and/or as other features observable by SXT.

References