SOLAR CHROMOSPHERIC AND TRANSITION REGION RESPONSE TO ENERGY DEPOSITION IN THE MIDDLE AND UPPER CHROMOSPHERE

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ABSTRACT

We present results of a series of numerical simulations modeling chromosphere and transition region response to deposition of thermal energy ranging from $\sim 5 \times 10^{24}$ to $5 \times 10^{28}$ ergs in the middle or upper chromosphere. Assuming an initial model solar atmosphere on a rigid, vertical magnetic flux tube, we introduce a thermal energy source in the middle chromosphere and solve the resulting one-dimensional hydrodynamic equations. Our calculations include the dissipative effects of heat conduction, optically thin radiation losses in the corona, and an approximate expression for the radiation losses of lower temperature plasma. In response to the energy deposition, chromospheric material is ejected into the corona in the form of pressure gradient generated jets, jets with pressure-gradient, and shock-generated components, or high-speed gas plugs.

Which category of ejection occurs depends on the spatial and temporal distribution and on the magnitude of the input energy source. Heating of the chromosphere by the source may result in brightenings in Hz, UV, and/or X-rays, perhaps appearing as the observed brightenings sometimes referred to as "microflares." Some input energy source parameters generate jets with properties similar to those of Hz spicules. These spicule producing source parameters, however, only rarely result in UV-emitting temperatures in the chromosphere. We therefore conclude that spicules are not produced by UV microflares in general, if the microflares are of the nature described here.

Subject headings: radiative transfer — Sun: chromosphere — Sun: transition region

1. INTRODUCTION

Jetlike spicules and mottles are among the most prominent small-scale features of the quiet solar chromosphere. A number of suggestions have been presented in attempts to explain the mechanism which drives chromospheric material into the corona, generating these objects. To date, most numerical studies of this problem have placed the driving source in the low chromosphere or in the photosphere (e.g., Hollweg 1982; Suematsu et al. 1982; Sterling & Mariska 1990; Suematsu & Takeuchi 1991). Sterling & Mariska (1990) concluded that velocities similar to those of photospheric granules at the base of a flux tube might be able to drive spicules, provided that radiation losses are not too extreme, and the amount of magnetic flux tube area expansion between the photosphere and transition region is moderate.

By studying ultraviolet (UV) images of quiet regions, Porter et al. (1987) found that transient, localized brightenings, or UV microflares tend to occur in the chromospheric network. Since spicules visible in chromospheric lines also seem to emanate from the network, they suggest that the two features may be related. Fontenla et al. (1989) have also suggested that microflares may drive spicules and other jetlike features. If these UV microflares are a middle or upper chromospheric or transition region phenomena, this suggestion would imply that the source of spicules is at greater heights than assumed in previous numerical studies. Sterling et al. (1991); also see Sterling & Mariska (1991) made a preliminary numerical investigation of this possibility by assuming that the energy associated with microflares is deposited in a narrow region just below the transition region at one end of a coronal loop. Although that numerical study did indicate that brightenings in UV emission lines and chromospheric ejections could occur simultaneously in response to the energy deposition, the ejections had the form of compact cool, dense "gas plugs," which do not resemble spicules. In this paper, we continue that investigation into the relationship between brightenings and chromospheric ejections by varying the energy source's spatial and temporal distributions and by placing the source at different heights in the middle and upper chromosphere. This requires that we treat the conditions in the chromosphere more carefully than in the Sterling et al. (1991a) study, taking into account the radiation losses there. Also unlike that study, here we will assume that the energy deposition occurs at the base of an open flux tube, or at the base of a very long coronal loop where the other base plays no role in the dynamics of the system over the time scales of spicules.

Shibata et al. (1982) and Shibata (1982) also studied chromospheric response to energy deposition at varying heights in the chromosphere in the absence of radiation losses and heat conduction. They found that the physical properties of the resulting ejections can change markedly as a function of the source height. Our work here can be considered an extension...
of their work, with radiation losses and heat conduction included, and a more realistic form for the energy source. Despite these differences, we will find that some of the key results of the earlier work are reproduced here (see §4).

In addition to the Porter et al. (1987) work, and the related study by Porter & Moore (1988), there exists other evidence that chromospheric jets may be driven by energy deposition in the chromosphere. High-resolution photographs of dark mottles on the solar disk show brightenings at their bases in Hz (e.g., Foukal 1990). Almost all surges display Hz brightenings at their bases initially (e.g., Zirin 1988), while there may be at least one example of X-ray emission at the base of a surge (Harrington, Rompolt, & Garcynska 1988; Svestka, Farnik, & Tang 1990). Moore et al. (1977) found that Hz macrospicules are associated with X-ray bright points. Each of these observations is consistent with the suggestion that mass expulsions from the chromosphere are a response to energy releases in the chromosphere resulting in localized chromospheric heating and corresponding brightenings. (These observations may, however, also be consistent with the above noted models placing the driving source for spicules in or near the photosphere, since energy deposition at such heights may also result in Hz and/or white light brightenings in the lower atmosphere [see, e.g., Shibata et al. 1982; Suematsu et al. 1982; Suematsu & Takeuchi 1991].)

In the present paper, we will use the term “microflare” to mean a transient, enhanced brightening in the chromosphere in Hz, UV emission lines, or X-rays driven by an unknown source. We will comment on some possible sources in §4. For each set of source parameters, we will investigate the nature of the resulting ejections. We will also investigate the resulting temperatures in the chromosphere, and assume that temperatures above 10^5 K may result in UV microflares, and that disturbances heating chromospheric gas to temperatures in excess of 10^6 K may result in X-ray and UV microflares. Depositions resulting in temperatures less than 10^5 K may still appear as brightenings (microflares) in chromospheric lines such as Hz. In this way we can predict the nature of ejections associated with different types of microflares. Details of the model follow in §2, our results are presented in §3, and a discussion follows in §4.

2. THE MODEL

We perform our calculations assuming a rigid vertical magnetic flux tube of length 20,000 km, with one end located in the photosphere and the other end open. This setup could either represent a coronal hole, or an approximate model of a very long (＞20,000 km) quiet region coronal loop. A thermal energy perturbation in the chromosphere drives flows along the loop described by

\[ \frac{\partial}{\partial t} (\rho A) + \frac{\partial}{\partial z} (\rho v A) = 0, \]

(1)

\[ \frac{\partial}{\partial t} (\rho v A) + \frac{\partial}{\partial z} (\rho v^2 A) = -\rho g A - A \frac{\partial p}{\partial z}, \]

(2)

\[ \frac{\partial E}{\partial t} + \frac{1}{A} \frac{\partial}{\partial z} \left[ (E + p) v A - \kappa A \frac{\partial T}{\partial z} \right] = -\rho v g - L + S + E_0 h(z, t), \]

(3)

where

\[ E = \frac{1}{2} \rho v^2 + \frac{p}{\gamma - 1}, \]

(4)

which are, respectively, the hydrodynamic equations for conservation of mass, momentum, and energy. The coordinate z is height along the flux tube, t is the time coordinate, and the variables \( \rho \), \( v \), \( p \), \( T \), \( A \), \( S \), and \( L \) represent the density, velocity, gas pressure, temperature, area variation of the flux tube, the background heating, and the radiation losses, respectively. Since the flux tube is vertical, the gravitational acceleration, \( g = 2.7 \times 10^4 \), is constant. The base of the transition region (see below) in our coordinate system is set at \( z = 2200 \) km. This results in \( p \) and \( S \) values of \( 7.97 \times 10^{-7} \) g cm^-3 and \( 1.62 \times 10^5 \) dyn cm^-2, respectively, at \( z = 0 \) km. More typical photospheric values for \( p \) and \( S \) are \( 2.86 \times 10^{-7} \) g cm^-3 and \( 1.13 \times 10^5 \) dyn cm^-2, respectively, occur at \( z = 157 \) km; we adopt this height for the photosphere in our model.

Figure 1 shows the variation of flux tube area with height, normalized to the area at the photosphere. We select this geometry in an effort to mimic the expected expansion with height of the magnetic field in the solar atmosphere. In our model, the field strength varies by a factor of ~25 between the photosphere and transition region; thus 1500 G photospheric fields would be reduced to ~60 G at the transition region level, 2043 km above the photosphere in our model.

We assume an isothermal photosphere and chromosphere at \( T = 6230 \) K, and calculate the transition region and coronal properties by balancing radiation losses and heat conduction with the background heating in the initial model. This results in a transition region base pressure of 0.1 dynes cm^-2, and a coronal temperature of \( 7.7 \times 10^5 \) K at the top of the grid, with a background heating rate of \( 7.2 \times 10^{-5} \) ergs cm^-3 s^-1. We assume a perfect gas with \( \gamma = 5/3 \), and average atomic mass \( \mu = 1.3 \), obeying the equation of state

\[ p = N k_B T, \]

(5)

where \( N \) is the particle number density and \( k_B \) is Boltzmann's constant. These parameters yield a scale height of 150 km and are roughly appropriate for the chromosphere, where the gas is neutral or partially ionized. Since the corona is ionized, our assumptions do not hold there, and our quantitative results for the corona will therefore only be approximately correct. We expect our qualitative predictions for the corona to still be valid, however, since general properties of the corona compared to lower regions of the atmosphere, such as high temperature and low densities, are retained in our model.

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We use three different forms for the radiation losses, depending on the temperature. When $T > 10^5 \text{ K}$, we assume the gas is optically thin, with corresponding radiation losses of

$$L = N_e N_p \Phi(T),$$

where $\Phi(T)$ is the radiative loss function, and $N_e$ and $N_p$ are the electron and proton number densities, respectively, and

$$N_e = \frac{\rho Z}{\mu m_p (1 + Z)},$$

where $Z = 1.059$ is the mean ionic charge and $m_p$ is the proton mass. We use a form for $\Phi(T)$ similar to that given by Rosner, Tucker, & Vaiana (1978), but modified by Raymond (see Mariska et al. 1982). Between 40,000 K and $10^5$ K, we take $\Phi(T)$ to be

$$\Phi = 6.46 \times 10^{-35} T^3,$$

which attempts to account for some of the optical depth effects of the low transition region (McClymont & Canfield 1983). When $T < 40,000$ K, we assume the gas radiates like the chromosphere. A proper treatment of the losses in this regime requires solving the equations of radiative transfer. Instead we use an approximate method to treat the radiation losses in the chromosphere based on work by Anderson & Athay (1989). They calculate the amount of heat needed in their model chromosphere to match the temperature profile of the average Sun empirical VAL model (Vernazza, Avrett, & Loeser 1981). They find the interesting result that the heating rate per gram required is roughly constant, at $4.9 \times 10^9 \text{ ergs g}^{-1} \text{ s}^{-1}$, over a large part of the chromosphere. Converting this to a volumetric heating rate, and taking it to be the chromospheric radiation loss rate, we find

$$L = 4.9 \times 10^9 \rho(z, t).$$

We use this expression in regions of positive pressure fluctuations when $T < 40,000$ K. In regions of negative pressure fluctuations, we assume no radiation losses or heating; only the constant background heating acts in that case.

Anderson & Athay (1989) found their constant heating rate per gram result to hold approximately over the main chromosphere temperature plateau, extending from 6000 to 8000 K. The required heating rate per gram then jumps substantially in the lower transition region, implying larger radiation rates there than indicated by equation (9). Comparing our model temperatures with those quoted in Anderson & Athay (1989) is not straightforward, as we assume a constant $\mu$, whereas the $\mu$ in the VAL model they use varies with temperature. Moreover, the VAL model is much more complex than the simple isothermal chromosphere that we adopt. Therefore we can only guess at the most appropriate range of applicability of equation (9) in our model. If we consider only temperature values alone, then the Anderson & Athay results imply that we are underestimating the radiation losses in our model between $T \approx 8000$ and $T \approx 40,000$ K by using equation (9). On the other hand, Athay (1986) has suggested that the correction we use between $T = 40,000$ and $T = 10^5$ K (eq. [8]) may be too large (see the discussion in Mariska, Emslie, & Li 1989), implying that we may be overestimating the radiation losses at those temperatures. So, although our expressions for the radiation losses in the chromosphere and transition region are uncertain to some extent, we believe they are adequate for estimating the effects of radiation losses in chromospheric temperature material for our purposes in this study.

To represent the energy deposition in the chromosphere, we add an additional expression representing a thermal energy perturbation to the last term in equation (3). The amplitude of the perturbation is $E_0 \text{ ergs cm}^{-2} \text{ s}^{-1}$ (heating rate), and $h(z, t)$ contains the spatial and temporal variations. By integrating this term over space and time, we find the total energy deposited to be

$$E_{\text{tot}} \approx 2\pi^{-1/2} \omega A_0 E_0,$$

where we assume the input takes place with a sinusoidal time dependence for one-half of one sine cycle of period $2\pi$, and with a Gaussian spatial distribution $\exp \left[ -(z-z_0)^2/(w^2) \right]$, centered at height $z = z_0$, and $A_0 = A(z = z_0)$. Relation (10) is approximate since we take $A$ to be constant over the input region in estimating $E_{\text{tot}}$. We will explore dynamic and thermodynamic results for various values of $w$ and $\tau$ in what follows, but will restrict $E_{\text{tot}}$ to the range $8 \times 10^{24} < E_{\text{tot}} < 3 \times 10^{28}$ ergs; this covers the estimated energy range for microflares ($\lesssim 10^{27}$ ergs) given by Parker (1988). (Also see Porter & Moore 1988, who estimate a UV microflare energy of $10^{26}$ ergs.) We will also express the energy values in terms of the heating rate $E_0$. For our model parameters, our selected energy range corresponds to heating rates from $\sim 0.2$ to $2000 \text{ ergs cm}^{-2} \text{ s}^{-1}$ (Eq. [10] of Sterling et al. 1991 is misprinted. The exponent of $\pi$ should be $-\frac{1}{2}$ instead of $\frac{1}{2}$.)

We solve equations (1)-(7) using the NRL Dynamic Flux Tube model, which is based on a flux-corrected transport (FCT) algorithm. Convective terms in the equations are handled explicitly, while the optically thin and nearly optically thin radiation, as well as the heat conduction terms, are solved implicitly to maintain numerical stability. We subtract off the static momentum equation from the right-hand side of equation (2) in order to improve numerical stability at the boundaries during the explicit step. The treatment of shocks in FCT codes is similar to the treatment of shocks in finite difference schemes, in that both methods utilize an artificial diffusion term. One advantage of FCT over some other schemes, such as the Lax-Wendroff scheme (e.g., Richtmyer & Morton 1967), is that numerical oscillations resulting near shocks are much reduced in FCT codes. Such oscillations, however, are not always completely removed, so that some residual oscillations occur near shocks in some of our calculations. See Mariska et al. (1982) for more details on the NRL Dynamic Flux Tube model, and see Book, Boris, & Hain (1975), and Boris & Book (1976) for details of FCT codes.

Our computational grid contains 400 fixed cells, with a resolution varying exponentially in the lower atmosphere, with a coarsest value of one cell per 15 km at the lower boundary ($z = -300$ km), down to one cell per 10 km just below the transition region. Throughout the transition region, the resolution is constant at one cell per 10 km, and then it exponentially increases again in the corona, to a coarsest value of one cell per 280 km at the top of the grid ($z = 20,000$ km). (These are the standard parameters. In some cases, where the jets resulting in the calculations extend to above 20,000 km, we place the top of the grid at 40,000 km. In such cases the resolution at 30,000 km—the approximate height of the tallest features we find—is $\sim 600$ km. All the simulation results displayed in Figures 2–6 in this paper use the standard parameters.) Our 10 km grid spacing in the transition region is not sufficient to resolve the steep gradients which occur there. Moreover, our grid is fixed in time, so the resolution of the transition region, and similar structures resulting in our calcu-
lations at later times can have much poorer resolution than the initial transition region. Therefore we do not apply the results of our calculations in this study to detailed examinations of the structure and evolution of the transition region itself. We use flow-through boundary conditions, allowing for the free passage of material in and out of the system. We also use an absorbing layer (Sterling & Mariska 1990) in the first and last 10 grid cells to help insure that residual reflections at the boundaries and small flows generated at the boundaries do not enter into the main computation region. The resulting code generates background flows of less than 0.5 km s$^{-1}$ in the corona over the duration of our longest calculations (500 s).

3. RESULTS

By injecting an energy source, we drive gas flows and temperature and density variations along the flux tube. The nature of the resulting gas properties depends upon the parameters of the input energy source. For our investigations, we vary the input source heating rate, $E_0$, from 0.2083 to 2083.0 ergs cm$^{-3}$ s$^{-1}$; For the source $w$, we use 110 and 440 km. These two values correspond to full width at half-maximum values of $\sim$175 and 700 km, respectively. We use source input durations of $\tau = 120$ and 30 s, and input heights $z_0$, at values ranging

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**Fig. 2a**—Plots of $\log_{10} T$ as a function of $z$ (a) and $\rho$ as a function of $z$ (b) for a pressure-gradient jet case. The lowest plot is at $t = 0$, and the time between each successively higher plot is 20 s. Each plot is displaced by one in the log on the vertical axis.

**Fig. 2b**

**Fig. 3.**—$T$ and $\rho$ as functions of $z$ at $t = 280$ s in the pressure-gradient jet case of Fig. 2. The properties of this jet are similar to those of spicules.

**Fig. 4.**—Trajectory of the transition region (solid line) as a function of time for the pressure-gradient jet of Fig. 2. The dashed and dotted lines are ballistic trajectories for initial velocities of 40 and 60 km s$^{-1}$, respectively.
over $z = 1000–1750$ km. We have no observational rationale for our selected \( w \) values. Rather, we use two relatively extreme values in which the larger \( w \) value simultaneously heats the entire upper chromosphere, and the smaller value of \( w \) results in heating of only a localized portion of the chromosphere. Three categories of features result: pressure-gradient jets, two-component jets, and gas plugs. In the following, we present examples from each category, and then discuss generalizations deduced from parameter variations.

3.1. Pressure-Gradient Jet Solutions

Figures 2 and 3 present results from the category we refer to as pressure-gradient jets. For this example, the source parameters are \( E_{\text{tot}} = 6.0 \times 10^{25} \) ergs, with a corresponding heating rate of 2.083 ergs cm\(^{-3}\) s\(^{-1}\), \( \tau = 120 \) s, \( w = 440 \) km, and \( z_0 = 1500 \) km. Figures 2a and 2b plot \( T \) and \( \rho \) as functions of height every 20 s for times \( 0 < t < 500 \) s, respectively, where the bottom-most plot displays the initial atmosphere and each succeeding plot is 20 s later than the plot immediately below. Each plot is displaced by 1 in the log. Thus, in Figure 2a for example, the log of the temperature at a particular abscissa on the \( n \)th plot from the bottom is the corresponding ordinate value minus \( n - 1 \). Figure 3 shows both temperature and density at \( t = 280 \) s.

Because the input source region is broad, virtually the entire upper portion of the chromosphere is substantially heated by
time $t = 20$ s. Associated with the heating is a pressure increase; the gradient in pressure between the heated and ambient regions drives a jet of chromospheric material and the transition region upward. We therefore call the resulting jet a pressure-gradient jet. (These same features are simply referred to as "jets" by Sterling & Mariska 1991.) Near $t = 280$ s, the transition region reaches its maximum height of $10,000$ km, and the portion of the jet between $z = 3000$ and $8000$ km has a relatively constant temperature profile at $T \approx 16,000$ K, with $\rho$ varying between $\approx 10^{-12}$ and $10^{-13}$ g cm$^{-3}$, as shown in Figure 3. These properties are similar to those found in spicules (e.g., Beckers 1968, 1972), and so this result can be regarded as a new spicule model. We will see later than only some of the pressure-gradient jets closely resemble "typical" spicules.

After achieving its maximum height, the jet retracts due to the radiative cooling and gravity. Cooling occurs nearly uniformly over the jet due to the radiation losses, but the base is reheated beginning at $t \approx 240$ s by a shock evolving in the middle chromosphere. This shock, clearly visible at the base of the jet in Figure 3, is similar to chromospheric "rebound shocks" of the type discussed by Hollweg (1982) and Sterling & Hollweg (1988). Between $t \approx 400$ and $500$ s, the shock's velocity approaches zero in the reference frame of the ambient chromosphere, since it is moving into gas downflowing with velocity near the sound speed, $c_s \approx 10$ km s$^{-1}$.

The velocity of the upward expanding jet is not ballistic. This is apparent in Figure 4, which plots the transition region location as a function of $t$. The dashed and dotted lines are ballistic trajectories based on initial velocities of 40 and 60 km s$^{-1}$, respectively. The transition region velocity is roughly constant for $t \approx 50$–$200$ s, over which time the pressure gradient force driving the transition region upward is comparable in magnitude to the gravitational force.

In order to address the question of whether or not a microflare results in response to the energy deposition in this case, we investigate the temperature in the chromosphere. A maximum value of $\approx 50,000$ K occurs around 60 s into the calculation, which corresponds to the time of maximum energy input. Chromospheric radiation in conjunction with reduction in the heating rate then leads to cooling of the region, until the rebound shock reheat it from $t \approx 240$ s. At no time does the chromosphere temperature reach $10^5$ K. Therefore we do not expect emission in ultraviolet (i.e., UV microflares) from this region, but enhancements in chromospheric lines, such as Hz, may result. As we will show later (see Table 1), UV emitting temperatures can be produced for some selections of input parameters resulting in pressure-gradient jets. But in the cases where those pressure-gradient jets resemble spicules, the chromosphere will generally not reach UV emitting temperatures.

### 3.2. Two-Component Jet Solutions

Figures 5a and 5b give the $T$ and $\rho$ distributions as functions of $z$ for a two-component jet at 20 s intervals. Here, each successively higher plot is displaced by 2 in the log. Two-component jets consist of a warm, pressure gradient generated lower component and a cool, shock-generated upper component. In this example, the total source energy is $3.1 \times 10^{26}$ ergs, with a corresponding heating rate of $83.33$ ergs cm$^{-2}$ s$^{-1}$, input over $\tau = 120$ s at $z_0 = 1000$ km, and $w = 110$ km. The two components are clearly visible in Figure 5a at $t = 240$ s, with the lower component between $z \approx 700$ and $2300$ km, and the upper component between $z \approx 2300$ and $5400$ km.

In this class of events, the region in the chromosphere directly heated by the source expands upward and downward in response to the increase in pressure due to the source, forming the pressure gradient component of the jet. This lower component resembles a small-scale pressure-gradient jet. In the case presented in Figure 5, the lower component extends upward in time, eventually reaching a maximum height of $\approx 2600$ km near $t = 180$ s, with a velocity of $v \approx 12$ km s$^{-1}$. The upper component of the jet forms as a result of a shock generated by the source. This shock is visible in the $t = 60$ s plot of Figure 5, where it is moving away from the heated lower component and interacts with the transition region near $t = 80$ s. As a consequence, the transition region is ejected away from the lower component, and eventually reaches a maximum.

### Table 1

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TABLE 2

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<td>5.0</td>
</tr>
</tbody>
</table>

3.4. Parameter Variation

Tables 1, 2, and 3 summarize our calculations resulting in pressure-gradient jets, two-component jets, and gas plugs, respectively, as source parameters are varied. In Table 1, columns (1)–(3) give the input source parameters, input height, $z_0$ (km); peak heating rate, $E_0$ (ergs cm$^{-2}$ s$^{-1}$); and heating duration, $\tau$ (s). Columns (1)–(4) give the resulting jet properties: maximum height, $H$ (10$^5$ km); average upward velocity during the rise phase, $v$ (km s$^{-1}$); and approximate average temperature, $T$ (10$^3$ K), and density, $\rho$ (10$^{-13}$ g cm$^{-3}$), of the jet near time of maximum extent. Column (8) gives the maximum temperature achieved in the chromosphere in direct response to the energy deposition, log$_{10} T_{\text{chrom}}$ (K). We do not give the temperature reached due to heating by rebound shocks, which in some cases can exceed that due to the source, but only for very brief time periods. Each of the jets in Table 1 used $w = 440$ km, with the single exception of the final entry in Table 1 ($z_0 = 1750$ km, $E_0 = 2.083$ ergs cm$^{-2}$ s$^{-1}$, log$_{10} T_{\text{chrom}} = 5.1$), which used $w = 110$ km. For two-component jets, Table 2 gives in columns (1)–(7), respectively, the source deposition height; heating rate; maximum height of the lower component, $H_1$ (10$^3$ km); maximum height of the upper component, $H_e$ (10$^3$ km); average velocities for the lower, $v_i$ (km s$^{-1}$), and upper, $v_s$ (km s$^{-1}$), components, and maximum temperature achieved in the chromosphere directly due to the source, log$_{10} T_{\text{chrom}}$ (K). We do not list the temperatures of the two components of the jets individually, since $T_{\text{chrom}}$ is an indicator of the temperature of the lower component, and, as discussed above, radiation from the surrounding atmosphere will probably drive the temperature of the upper component to values substantially larger than those resulting from our calculations. All two-component features were formed using $w = 110$ km. Table 3 gives, for gas plug solutions, the energy input heights, source heating rates, gas plug velocities, and maximum chromospheric temperature directly resulting from the source in columns (1)–(4), respectively. All the gas plug results use $w = 110$ km.

Some of the trends in our results are depicted visually in Figure 7. The coordinate axes of the figure represent two source input parameters: heating rate and energy deposition height. The different symbols represent differing types of solu-

TABLE 3

<table>
<thead>
<tr>
<th>$Z_0$ (km)</th>
<th>$E_0$ (ergs cm$^{-2}$ s$^{-1}$)</th>
<th>$v$ (km s$^{-1}$)</th>
<th>log$<em>{10} T</em>{\text{chrom}}$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>83.33</td>
<td>110</td>
<td>6.6</td>
</tr>
<tr>
<td>1750</td>
<td>8.33</td>
<td>60</td>
<td>6.5</td>
</tr>
<tr>
<td>1750</td>
<td>166.68</td>
<td>250</td>
<td>6.8</td>
</tr>
<tr>
<td>1750</td>
<td>416.70</td>
<td>450</td>
<td>6.9</td>
</tr>
</tbody>
</table>
Fig. 7.—Various solutions resulting from deposition of energy into the chromosphere, as a function of the energy input parameters heating rate, $E_0$, and input height, $z_0$. Some of the symbols are displaced slightly in $z_0$ for clarity. Circles and diamonds represent pressure-gradient solutions, crosses represent two-component solutions, stars represent gas plug solutions, and the box represents an evaporating gas plug. Filled circles and diamonds represent jets with spicule-like properties. Pressure-gradient jets represented by diamonds, the two-component jet at $z_0 = 1500$ km, and the two gas plugs are possibly associated with UV microflares. Only the two gas plugs may be associated with X-ray microflares.

peratures; they form at higher heating rate values than do two-component jets at the same height.

A second point apparent from Figure 7 is that the spicules tend to cluster in the lower right-hand side of the figure, i.e., at lower heating rates higher in the chromosphere. Of course, by altering our criteria for spicules, we could shift the location of spicule-like jets in Figure 7. But all the pressure-gradient jets at $z_0 = 1000$ km have densities $\geq 10^{-12}$ g cm$^{-3}$, which are an order of magnitude higher than densities commonly reported for spicules. Also from Figure 7 it is apparent that spicules are generally not associated with UV microflares.

As we would expect, Figure 7 also shows that more energetic microflares occur at higher heating rates for the same $z_0$ values, and the heating rates required to produce a microflare at a given temperature decreases with increasing $z_0$. Here, by energy of a microflare, we are referring to the energy of the spectral line in which it occurs, with Hz brightenings being the weakest we are considering, UV microflares at the next highest level, and X-ray microflares the most energetic. An example of this is the two-component feature at $z_0 = 1500$ km, which is a UV microflare associated event. Using the same set of source conditions at $z_0 = 1750$ km results in an X-ray and UV microflare associated gas plug. This inverse relationship between heating rate and deposition height for the production of microflares of a given energy category, say UV microflares, exists because less dense gas at greater heights can more easily be heated to higher temperatures. The Sterling et al. (1991) results are consistent with this trend in that they found that gas plugs, with associated X-ray (and UV) microflares, are produced by heating rate of order 1 erg cm$^{-3}$ s$^{-1}$ at $z_0 = 2000$ km. They also found that heating rates of order 100 ergs cm$^{-3}$ s$^{-1}$ result in evaporation of the gas plug at that height, since the radiation cannot balance such large heating rates at gas plug temperatures. Although the physical model used by Sterling et al. (1991) differs somewhat from that used here, we might expect the same type of evaporation to occur in our model for sufficiently large heating rates. We have verified that this is the case for $E_0 = 4167$ ergs cm$^{-3}$ s$^{-1}$, $z_0 = 1750$ km, and $w = 110$ km. Before evaporating, the resulting gas plug has $v = 450$ km s$^{-1}$ and $T_{\text{chrom}}$ reaches $10^6.9$ K. This feature is the last entry in Table 3 and is represented by the box in Figure 7.

4. DISCUSSION

We find that energy deposition into the middle or upper chromosphere can drive mass motions into the corona and raise the temperature of the chromosphere. Three categories of dynamic events result, which we refer to as pressure-gradient jets, two-component jets, and gas plugs. Microflares in the UV accompany some of the jets and all the gas plugs, while X-ray microflares accompany only the gas plugs. Increased chromospheric temperatures accompanying the non-UV or X-ray associated jets may appear as brightenings in chromospheric spectral lines, such as Hz.

Based on our results, we can provide a general set of conditions for producing each category of feature, assuming energies of the magnitudes used in this study. Pressure-gradient jets always form when a substantial portion of the upper chromosphere and transition region is directly heated by the energy source. This results in an expansion of the heated gas, leading to the formation of the pressure-gradient jet. When distributed in this fashion, the energies we use here are not sufficient to evaporate the gas, as happens in thick-target flare models (e.g., Emslie & Nagai 1985; Fisher, Canfield & McLemont 1985;
Mariska et al. (1989), and so a jet always results. By heating only an isolated portion of the chromosphere, meaning that there is chromospheric temperature material not directly heated by the source both below and above the source region, different features can result depending on the amount of heating. When the isolated chromospheric region is driven to temperatures less than those of the corona, a two-component jet generally forms. What happens is that the heating source causes the directly heated gas to expand, forming the lower component of the two-component jet. The same source initiates an upward-moving disturbance that evolves into a shock; this shock drives the transition region upward, leaving behind a cool, rarified region which forms the upper component of the two-component jet. A gas plug forms under the same circumstances as the two-component jets, except for a necessary condition that the source drives the gas in the energy deposition region up to coronal temperatures. Then there is coronal gas on either side of the ejected chromospheric material gas plug.

There is, however, an exception to our general set of conditions described above, in that the conditions for creating a two-component jet can sometimes lead to a pressure-gradient jet. This happens when the parameters are such that the expanding lower component created via direct heating from the source reaches the transition region before the upward propagating disturbance initiated by the source has time to evolve into a shock. Then the resulting jet effectively has only a lower component which resembles the standard pressure-gradient jets. An example of this type of pressure-gradient jet is the last entry in Table 1. This example differs in initial conditions from the first entry at \( z_2 = 1750 \) km in Table 1 only in that it uses \( w = 110 \) km, heating only an isolated portion of the chromosphere, whereas the first \( z_2 = 1750 \) km entry uses \( w = 440 \) km, heating a substantial portion of the upper chromosphere. The \( w = 110 \) km jet has \( \log_{10} T_{\text{chorm}} = 5.1 \), and therefore it is associated with a UV microflare and is represented by a diamond in Figure 7. The \( w = 440 \) km jet only has \( \log_{10} T_{\text{chorm}} = 4.8 \), and therefore is represented by a circle. The heating rates for the two cases are nearly identical, yet the \( w = 110 \) km case leads to a hotter chromosphere because virtually all the heating in that case goes into the chromosphere, whereas in the \( w = 440 \) km case a substantial portion of the heating spills over into the corona, which is only \( \approx 450 \) km above the energy input location at \( z = 1750 \) km.

We can interpret some of these results in terms of the Shibata et al. (1982) work. They study the consequences of a rapid (5–20 s) increase in pressure to several times the ambient value at different heights in the chromosphere. Their source input was taken as a boundary condition at the chromospheric end of their computational grid. They find two fundamentally different types of jets result, which they refer to as "crest-shock" jets and "shock-tube" jets. Crest-shock jets are essentially identical to our two-component jets, where the transition region is accelerated upward via a shock produced by the input pressure pulse, and a contact surface results from expansion of the gas directly heated by the source. Their shock-tube jets are, like our last entry in Table 1, characterized by expulsion of the transition region due to the propagating pressure gradient generated by the input pressure pulse. Thus we have found that the two types of jet solutions discovered by Shibata et al. (1982) remain valid in the presence of radiation losses and heat conduction.

Shibata et al. (1982) also found that, when other input parameters are the same, the type of jet which develops depends on the height of the source, with only shock-tube jets occurring for sources at heights above a critical height, and only the crest-type jets when the source is lower than that critical height. We find here, however, by comparing the last and the first entries in Table 1 (which have \( w = 110 \) and \( w = 440 \), respectively), that the same \( E_0 \), \( \tau \), and \( z_2 \) values can lead to different types of jets depending on the distribution of the source. Thus we find that the type of jet resulting, shock-tube type or crest-shock type, depends not only on the source height, but also on its distribution.

Although temperature enhancements in the chromosphere in response to the energy deposition range from tens of thousands of degrees to several million degrees, we do not produce temperatures of a few hundred thousand degrees for any length of time in the chromosphere in our model. This is because of thermal instability in this temperature regime. The radiative loss rate decreases with temperature between \( T = 10^{5.8} \) and \( T = 10^{5.7} \) K, and then becomes approximately constant with temperature until \( T \approx 10^{6.3} \) K (Rosner et al. 1978). In our model, gas heated by the input source always tries to maintain equilibrium between the input energy and radiation, along with the background heating and conduction. The background heating is weak compared to the heating source (the "microflare"), and the conduction term is small at temperatures in the \( T \approx 10^{5.4} \) K region compared to conduction at \( T \approx 10^{6.3} \) K (in the absence of extremely large temperature gradients), since conduction is strongly dependent on \( T \). As the source continues to heat the gas to temperatures higher than \( T \approx 10^{5.4} \) K, it becomes increasingly difficult to dissipate the excess heat (since the radiation losses are decreasing with temperature) until coronal conditions are created. At that time, balance is restored between input energy, radiation and conduction. This energy balance is retained even after the "microflare" source is turned off, when the system (including the gas plug and the two transition regions formed between it and the rest of the atmosphere) resembles our initial static solar corona and transition region atmosphere from an energy balance standpoint. Thus we produce \( 10^5 \) K UV microflares, and \( 10^6 \) K X-ray microflares, but no microflares at intermediate temperatures.

4.1. On Microflares

We have suggested that some of our results may appear as microflares in the solar atmosphere in some regions of enhanced gas temperatures. Actually, if these enhanced temperature regions are to appear as brightenings, emission measures in the temperature range of formation of the spectral lines where the microflares are to be observed must be enhanced. Numerically, the emission measure can be calculated by evaluating \( EM(T) = \int N_e^2 dV \) over a temperature range \( T \) to \( T + \Delta T \), where \( V \) is the volume of emitting gas (see, e.g., Mariska 1987). We have not performed emission measure calculations here because we do not adequately resolve the transition region (see § 2), and so are unable to make quantitative statements regarding the microflare brightenings based upon our simulations. Nonetheless, we base our definition of microflares on cases where temperature increases in the chromosphere at locations where densities become large compared to the original hydrostatic equilibrium densities at those locations. Early in the evolution of the system, densities may still be high enough to enhance emission measures at the enhanced temperatures, and produce microflares.

As in Sterling et al. (1991), we assume an unknown heating...
source for microflares in our model. One possible source they cite is energetic electron beams flowing along magnetic field lines from the corona; this could be a variation of the thick-target electron beam model for flares referred to above. It is perhaps, however, more difficult to understand how electron beams can be generated along open field lines used here than on the closed magnetic loop of Sterling et al. (1991). Another possible energy source could be reconnection of magnetic field lines in the chromosphere and transition region. Dere et al. (1991) have presented a scenario by which emerging intranetwork magnetic fields reconnect with cell boundary magnetic fields, producing "explosive events" in the transition region. A similar mechanism might result in the deposition of energy into the chromosphere in the manner described in this paper. Another possibility is that interactions between small bipoles of size \( \approx \) few 1000 km, such as those seen in association with UV microflares by Porter et al. (1987), and vertical field lines might be an energy source. These ideas, however, are purely speculative.

A prediction of this work, as in that of Sterling et al. (1991), is that the appearance of X-ray microflares is accompanied by ejections of compact gas plugs. Lin et al. (1984) saw transient, energetic bursts of energy in X-ray regions which they identified with microflares. Canfield & Metcalf (1987) found that those features were correlated in time with strongly blueshifted features occurring in active regions on the disk in Hz. Since no strong redshifts were seen, those results are not consistent with our predictions for gas plugs ejections, which should show blueshift (from the expelled gas plugs) and redshifts (from gas propelled downward by the microflare). It may be that the Lin et al. (1984) features are more energetic than the conditions leading to our gas plugs. Moreover, our work here assumes coronal hole initial conditions, and Sterling et al. (1991) assume quiet region initial conditions; energy depositions in active regions may lead to different results. Note also, however, that in the case where the input heating rate in our model is large enough to lead to evaporation of the gas plug, blueshifted gas would not be visible in Hz (or UV) after the evaporation is completed. This point is discussed further in terms of visibility in UV, and possible identification of gas plug with explosive UV events (e.g., Porter & Dere 1991) in Sterling et al. (1991).

Some of the instruments onboard the Yohkoh (previously known as Solar A) satellite launched in 1991 August may be able to identify microflares in X-rays. In particular, the Soft X-ray Telescope (SXT) may be able to image these features (see Sterling, Shibata, & Mariska 1991b). If these microflares reach temperatures of \( \approx 5 \) million K, they should also be detectable in the SXV channel of the Bragg Crystal Spectrometer (BCS).

4.2. On Spicules and Other Chromospheric Jets

In this work we have suggested a new model for solar spicules. These spicules are a subset of the pressure-generated jets which have properties roughly in agreement with those of observed spicules in terms of heights, densities, and temperatures. The velocities of the spicules tend to be higher than those quoted from observations, \( \approx 25 \text{ km s}^{-1} \). But the upward motion of our model spicule follows a trajectory which is relatively constant (compared to a ballistic trajectory), which is in agreement with some observations (see, e.g., Campos 1984). (But others, including Athay & Thomas [1957] and Nishikawa [1988] report that it is difficult to distinguish between constant and ballistic motions of spicules from their observations.) Our results also predict spicules which tend to be warmer at the base than at the top (see, e.g., Fig. 3); this is in disagreement with Matsuno & Hirayama (1988), who find a more complex variation of temperature with spicule height. The temperature profiles of spicules resulting from our model will, however, depend on details of the radiation losses, particularly at chromospheric temperatures, which we handle only in an approximate fashion.

We also find that spicules tend to form in regions of Figure 7 (i.e., in regions of energy source parameter space) which do not result in UV microflares. There can be exceptions, however, as in one case in our study (the filled diamond in Fig. 7), but there is a much wider selection of parameters which do produce spicule-like jets which may be associated with Hz microflares, but not with UV microflares. Sterling et al. (1991) also found that UV microflares are not associated with spicules using a different set of initial conditions and source parameters. We therefore conclude that UV microflares are not signatures of the primary driving force of spicules, if microflares are of the nature we assume here.

Incorporating into Figure 7 the photospheric driven spicule models referenced in § 1 would result in another region with spicule solutions near \( \chi_0 = 0 \). The fundamental physics of the spicule model presented here differs from the spicule model due to Hollweg (1982), in that the latter results in a spicule due to the propagation of a wave along a flux tube, instead of a pressure gradient force in our model. Suematsu et al.'s (1982) spicule model is, however, an example of one of our two-component jets, containing both wave- and pressure-driven components, where the lower pressure generated component is small compared to the shock-driven upper component. An advantage of the spicule model presented here over those, in terms of calculation efficiency, is that our model here depends less on the details of the radiation losses in the low chromosphere and photosphere than do the others. Radiation losses are more extreme in the very low atmosphere than at higher levels (e.g., Gibson 1972; Giovanelli 1978). Since the other models are based on a driving source in the photosphere or low chromosphere, the relatively large radiation losses in that region are an integral part of those models.

There are some weaknesses with the spicule model suggested here. Our velocities are generally higher than those typically quoted for spicules. Moreover, the densities of the jets we identify as model spicules tend to be higher than those observed in spicules by a factor of a few times. But some observers, e.g., Krat & Krat (1971) report values similar to those we calculate. We do not know how our model spicules' properties would be altered by changes in initial atmospheric conditions. Also, the model here does not address the question of why spicules often "fade from view" when observed in Hz (see Sterling & Hollweg 1984). We know of no spicule model to date which satisfactorily explains all these points.

We have chosen to label the pressure-gradient jets with spicule properties as model spicules in this study, but it is also possible that some two-component jets may appear as spicules. We also note the similarity between Hz mottles and two-component jets: Mottles appear to some observers to be bright at the end near the chromospheric network and dark further away (e.g., Athay 1976; Foukal 1990). It is not clear whether or not these represent two distinct features ("bright mottles" and "dark mottles") or one single jet (see Beckers 1972). If they are one jet, they may correspond to two-component features, where the bright end of the mottle near the network is the warm lower component and the dark portion of the mottle is
the upper component. Also, it is possible that among the
pressure-gradient jets resulting in our calculations which do
not resemble typical spicules, some may be less frequently
observed spicules and some may correspond to surges.
Another possibility is that the potential source which produces
the features we discuss here tends to operate only at higher
levels in the chromosphere, preferentially producing jets with
spicule-like properties.

Shibata et al. (1982) and Shibata (1982) suggest that energy
deposition in the middle or upper chromosphere may lead to
surges or Hz macrospicules (Moore et al. 1977). Surges can
reach heights of 20,000–200,000 km. The tallest features in
our studies are pressure-gradient jets with heights of 21,000
and 28,000 km (Table 1), and may represent surges. They may also
represent some component of Hz macrospicules, but Hz macrospicules are more complicated, “spraylike” features (Zirin 1988) than our calculations, which are limited to one
parameter sets are much higher than those of Hz macrospicules (≤ 10⁻¹⁴ g cm⁻³⁻¹). Withbroe et al. 1976). None of our two-component jets have heights in excess of 20,000 km. There is still the possibility, however, that there exists a range of input
parameters we have not explored in this work which can
produce more jets with heights in the range of 20–200,000 km.

Unfortunately, there seems to be no detailed data available
on surge densities at chromospheric temperatures, so it is not	not possible to closely compare our results with Hz observations of
surges. In particular, we do not know whether or not surge densities are larger than spicule densities. Densities for Hz
surges implied by length scales (∼10⁴ km) and total mass
(∼10¹⁵–10¹⁶ g) given in Rust et al. (1980) are ∼10⁻¹⁰–
10⁻¹³ g cm⁻³ s⁻¹. If the length scale of surge widths are
smaller than the quoted length scale, then surge densities may
be ∼10⁻¹⁰ g cm⁻³ or higher. Hirayama (1992) suggests Hz
surge densities of ∼10⁻¹² g cm⁻³. These density values are similar to densities of the jets in our simulations. Doschek,
Feldman, & Mason (1979) derive densities for surge material near 10⁴ K of ∼5.8 × 10⁻¹³ g cm⁻³. This is somewhat larger
than the density over much of the extent of the object in Figure
4, which we identified as a model spicule. If the density of the
cooler Hz surge material is larger than the 10⁴ K surge material, then our simulations yielding jets with densities larger than those typically found in spicules may represent surges. As noted above, however, the initial atmospheric condi-
tions in our models are appropriate for coronal holes, or
maybe quiet regions, whereas quoted surge parameters are
derived from active region observations (e.g., Roy 1973;
Schmahl 1981; Tamenaga, Kureizumi, & Kubo 1973; Doschek et al. 1979; Rust et al. 1980). It is not clear how changing our initial atmospheric parameters to mimic active
region conditions would alter our results.

In conclusion, this work may be thought of as a series of
predictions for the way the solar atmosphere will behave if
microflares similar to those observed by Porter et al. (1987) are
occurring in the middle or upper chromosphere. In particular,
if spicules are driven by microflares in the upper chromosphere as
described here, then we expect that our other predictions presented here also hold. Some of these predictions, such as the
ejection of compact gas plumes of chromospheric material in
association with X-ray microflares, may be testable with the
Yohkoh SXT in conjunction with ground-based Hz observations by, for example, looking for transient X-ray brightenings in quiet regions. It may be the case, however, that microflares occur only on small bipoles (see Porter et al. 1987) completely isolated from vertical fields, in which case the assumptions we use here would be incorrect. One consequence of this might be
that spicules are not driven by energy releases in the upper
chromosphere.

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