Proceedings of 12th Cambridge Workshop on Cool Stars, Stellar Systems, & The Sun, 2003 University of Colorado.

What Controls Spicule Velocities and Heights?

R. Hammer, A. Nesis

Kiepenheuer-Institut für Sonnenphysik

Abstract. Numerous mechanisms have been suggested to drive spicules. Many of them need a careful fine-tuning of free parameters in order to achieve the basic characteristics, like velocity and height, of observed spicules. There might, however, be general physical mechanisms that control these properties. We show that whenever upper chromospheric plasma is exposed to a significantly non-hydrostatic pressure gradient, it starts moving upward at the observed speeds. The plasma can reach significant heights, at least if it receives some net chromospheric heating during the rising phase. Therefore, such a hydrodynamic mechanism might help other (magnetic) drivers to control the basic properties of spicules. We suggest therefore to consider a new class of spicule driving mechanisms, in which the plasma is not only accelerated by wave or magnetic forces from below, but also by the generation of a low pressure region above the chromosphere. Such a situation could arise e.g. due to an instability in magnetic loops or as a result of the reconfiguration of open field lines.

1. Introduction

Classical spicules are needle-shaped chromospheric extensions, which can be seen in strong chromospheric lines to protrude out of the solar limb. They are highly dynamic and consist of plasma with properties characteristic of the upper chromosphere (temperature $\approx 10^4\,\mathrm{K}$, electron density of order $10^{11}\,\mathrm{cm}^{-3}$) that moves at supersonic speeds of $20-30\,\mathrm{km\,s}^{-1}$ up to heights of $5000-10000\,\mathrm{km}$, with a typical lifetime of $5-10\,\mathrm{min}$ (e.g., Beckers 1972). Since the associated mass flux is much larger than the solar wind mass flux, almost all of this plasma must eventually return, possibly at other temperatures or densities so that the return flow is often not seen from the ground.

The physical processes that generate spicules have not yet been uniquely identified. Dozens of suggestions have been put forward, including granular buffeting of magnetic flux tubes, which generates wave pulses (Hollweg 1982, Cheng 1992) or resonant waves (Roberts 1979); the reflection shock after the convective collapse of a flux tube (Grossmann-Doerth et al. 1998); reconnection jets (Uchida 1969); ion-neutral friction in medium-frequency Alfvén waves and gyrosynchrotron resonance in high-frequency Alfvén waves (Haerendel 1992, de Pontieu 1996, Budnik 1998); shear motions between flux tubes (van Ballegooijen and Nisenson 1999); or quite generally time-dependent coronal heating (Athay 2000).

A major difficulty is related to the strong expansion of magnetic flux tubes with height: any event triggered at the photospheric level of such flux tubes requires enormous initial energy densities, which are difficult to generate. Moreover, at least some of the suggested mechanisms are consistent with observations only after a careful fine-tuning of free parameters such as the Alfvén wave period.

Therefore, it is reasonable to search for generic physical mechanisms that might help to control the basic properties of spicules, such as their velocities. The observed velocities have for example been interpreted as the phase speed of acoustic-gravity waves (Campos 1984). They are also of the order of the Alfvén velocity, provided that the magnetic field strength has appropriate values. However, the latter is presumably quite variable in the upper chromosphere.

We concentrate here on a very simple, purely hydrodynamic mechanism: We discuss what happens to chromospheric plasma when it is exposed to a significantly steeper-than-hydrostatic pressure gradient that is formed within a sufficiently small time scale. We will first show (in Sect. 2) that such events quite naturally produce the right velocities and significant heights; and later (in Sect. 3) we will discuss how such events might be generated on the Sun.

2. Chromospheric Free Expansion

We now discuss the classical problem of the free expansion of a gas into a vacuum, adapted to the situation of the solar chromosphere. To this end we generalize the treatment found in standard textbooks by allowing for gravity, net energy addition, and a variable flux tube cross section (Fig. 1, left panel).

For a quasi-steady ($\frac{\partial}{\partial t} \approx 0$) outflow in a magnetic flux tube of cross section A with a net energy addition rate H, the energy equation describes the balance between changes of the flow energy, radiation, conduction, and mechanical heating

$$\begin{aligned} \nabla . F_{Flow} &= -\nabla . F_{Rad} - \nabla . F_{Cond} - \nabla . F_{Mech} =: H \\ \frac{1}{A}\frac{\partial}{\partial r} A\rho v \left(c_p T + \frac{v^2}{2} - \frac{GM_\odot}{r} \right) &= H . \end{aligned}$$

Here, ρ is the gas density, v the velocity, T the temperature, c_p the specific heat at constant pressure, G the gravitational constant, and $M_\odot$ the solar mass. The classical case (e.g., Landau & Lifshitz 1959, Sect. 80) corresponds to $A = 1, G = 0$, and $H = 0$.

With the mass flux $A\rho v =: j = \text{const}$ and the enthalpy per unit mass $c_p T = c^2/(\gamma - 1)$, where c is the sound speed and γ the ratio of specific heats, we obtain the generalized Bernoulli equation

$$\frac{c^2}{\gamma - 1} + \frac{v^2}{2} - \frac{GM_\odot}{r} = \frac{{c_0}^2}{\gamma - 1} + \frac{v_0^2}{2} - \frac{GM_\odot}{r_0} + \frac{1}{j}\int_{r_0}^{r} A\, H\, dr .$$

Here r_0 lies just below the outflow level (cf. Fig. 1), so that $v_0^2/2 \ll {c_0}^2/(\gamma - 1)$. Since on the "vacuum" side $c^2 \to 0$, we obtain

$$\frac{v^2}{2} = \frac{{c_0}^2}{\gamma - 1} + GM_\odot \left(\frac{1}{r} - \frac{1}{r_0} \right) + \frac{1}{j}\int_{r_0}^{r} A\, H\, dr .$$

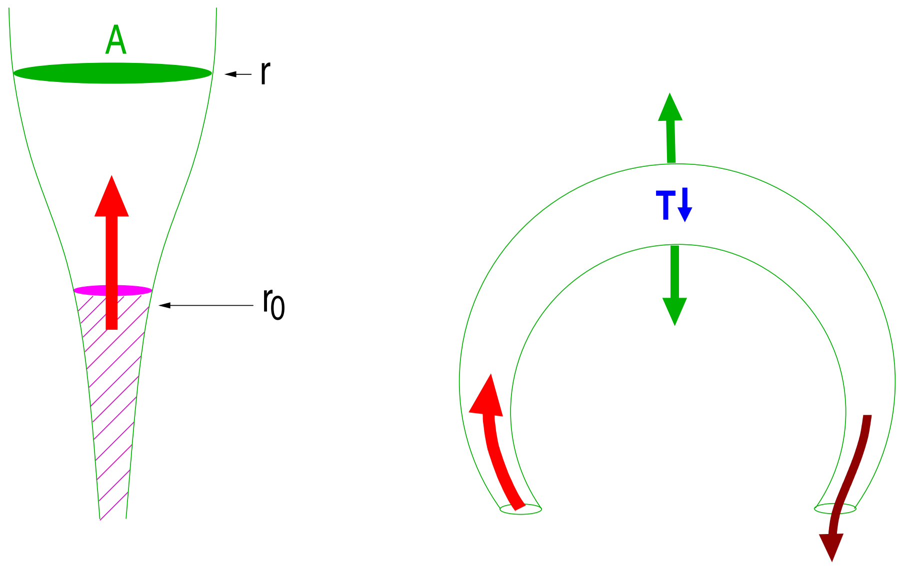

Figure 1. *Left.* When a vertical magnetic flux tube of cross section A is suddenly exposed to a strong pressure drop near height r_0, an upward flow is initiated. *Right.* In a magnetically closed region, such a flow (red) could be caused by an overpressure in the underlying chromosphere, by a temperature decrease (blue) or volume increase (green) in the upper atmosphere, or by a convective collapse in the other leg of the loop (brown).

The spicular extension is much smaller than the solar radius, hence $\Delta r := r - r_0 \ll r_0 \approx R_\odot$, and the second term becomes $GM_\odot\left(\frac{1}{r} - \frac{1}{r_0}\right) \approx -g_0 \Delta r$. Thus

$$v \approx \sqrt{\frac{2}{\gamma - 1} c_0^2 - 2g_0 \Delta r + \frac{2}{j}\int_{r_0}^{r} A\, H\, dr}. \tag{1}$$

Therefore, the initial speed near $r \approx r_0$ is given by $v_0 \approx c_0\sqrt{\frac{2}{\gamma-1}}$. This is the classical equation for the outflow speed in the case of a complete conversion of enthalpy into kinetic energy. For temperatures in the range $5000 - 20000$ and appropriate values of γ for the partially ionized chromospheric/spicular plasma (where γ becomes significantly smaller than $5/3$), this speed lies in the range $15 - 35\,\mathrm{km\,s^{-1}}$, in nice agreement with the observations.

The above estimate shows that chromospheric plasma can indeed be pulled up by an underpressure at the observed spicular speeds.

The maximum height that can be reached in such a situation can also be estimated from Eq. (1) by setting $v = 0$:

$$\Delta r_{\max} = \frac{1}{\gamma - 1}\frac{c_0^2}{g_0} + \frac{1}{j g_0}\int_{r_0}^{r} A\, H\, dr. \tag{2}$$

When we first neglect energy addition ($H = 0$), we obtain

$$\Delta r_{\max} = \frac{1}{\gamma - 1} \frac{c_0^2}{g_0} = \frac{\gamma}{\gamma - 1} H_p \quad \approx \ (2.5 \ldots 6)\, H_p \ \text{ for } \ \gamma = \frac{5}{3} \ldots 1.2,$$

where H_p is the scale height. Thus

$$\Delta r_{\max} \approx 2000 \ldots 2500\,\mathrm{km} \quad \text{for} \quad T = (10000 \ldots 20000\,K).$$

Therefore, even without extra energy addition, a gas flow into a low pressure region could already reach 20% – 50% of the observed spicule heights. The same heights would incidentally be reached for a ballistic motion (i.e., for a process in which the enthalpy is converted first into kinetic energy and then into potential energy).

However, it is reasonable to expect that the plasma receives some net heating H during a spicule event since due to its cooling and expansion the radiative losses decrease, while the mechanical energy that would otherwise have heated the chromospheric plasma should still be available. With a net heat input $H > 0$, the gas can reach much larger heights according to Eq. (2).

Moreover, a spicule is not a steady, but a *dynamic* phenomenon. Its physics depends critically on the complicated energy balance and ionization in the upper chromosphere, which must ultimately be investigated in time-dependent simulations.

3. Possible Scenarios

The suggested mechanism requires that a significantly non-hydrostatic pressure gradient be generated within a short time. This could be accomplished either by a pressure *increase* in the lower/middle chromosphere over a significant height range, or by a pressure *decrease* in the upper chromosphere, transition region and/or corona. Processes belonging to the former class have been investigated in the literature e.g. by Shibata et al. (1982) and Sterling et al. (1993). We will thus concentrate on the latter case.

According to the equation of state, $p = \rho RT/\mu$, a pressure decrease in the upper atmosphere could be due to either a temperature or a density decrease. A temperature decrease could, in turn, result from a thermal instability, as will be discussed in more detail below (in Sect. 3.1). A decrease of the density, on the other hand, could be caused by the onset of a convective collapse at the other end of a loop (cf. Fig. 1, right panel), or by a volume increase of the flux tube in the upper atmosphere, e.g. when neighboring closed loops open up, or when flux tubes move apart as a result of photospheric motions. The latter possibility will also be discussed below (Sect. 3.2).

3.1. Example 1: thermal instability

Thermal instabilities can be triggered by the presumably intermittent nature of coronal heating. A million degree coronal plasma has a radiative cooling time of the order of an hour, hence it will react only slowly to variations in the heating rate. By comparison, 10^5 K plasma can cool radiatively within seconds. If such

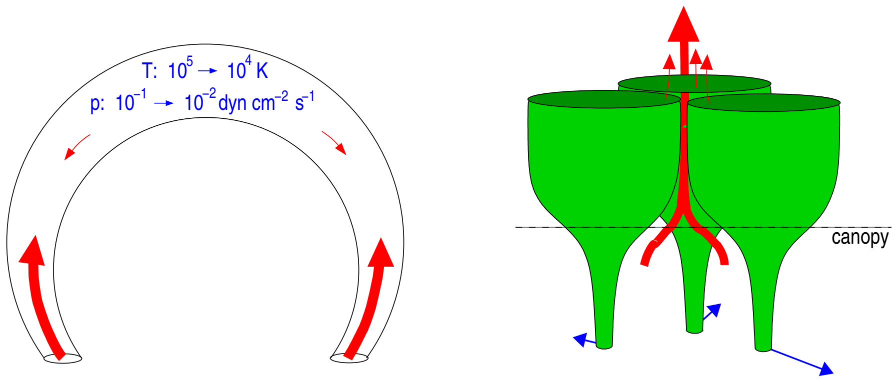

Figure 2. *Left.* When the heat input into a cool loop pauses for more than a few seconds, its temperature and pressure drop by an order of magnitude, and flows set in. *Right.* Upflows can also be generated when flux tubes move with respect to each other.

plasma is part of a regular "transition region" that is attached to a coronal heat reservoir, then thermal conduction can usually replenish the radiated energy before an instability develops.

This is not the case, however, in so-called "cool loops" with maximum temperatures in the 10^5 K region. If the heating in such a loop pauses for more than a few seconds, the plasma radiates away its internal energy and cools down rapidly. Then two thinks happen (cf. Fig. 2, left panel): The tenuous plasma in the loop loses its pressure support and falls down. But, more importantly, the much more massive upper chromosphere finds itself exposed to essentially a vacuum above, into which it can expand. Our analytical estimates suggest that the resulting flows look like spicules.

A number of authors have observed evidence of individual spicule events that appeared to occur in loops. But it is by no means clear how frequently spicules are associated with loops.

3.2. Example 2: magnetic forces

Due to the density stratification, magnetic flux tubes must expand with height throughout the photosphere and lower chromosphere, until they fill all available space in the upper chromosphere (Fig. 2, right panel). The motions of flux tubes are dictated by the high-density photosphere, where they are anchored. If they move apart, the plasma below the canopy may be exposed to an overlying region of lower density, either between flux tubes or inside them, in the vicinity of the separatrices. (What dominates depends on the speed at which the footpoints move apart, in relation to the Alfvén speed.) The resulting flows should again resemble spicules. This scenario is related to a proposal by van Ballegooijen and Nisenson (1999) that the forces generated by shear motions between flux tubes might generate spicules.

4. Summary

We assert that spicules might not only be pushed from below, but also pulled from above whenever an underpressure occurs in the upper atmosphere. The resulting flows have the observed speed. They reach significant heights if they receive further energy input. Moreover, this mechanism does not require any parameter fine tuning to yield the right speeds; and the required energy must not necessarily be pumped within a short time through the bottle neck of a narrow photospheric flux tube cross section. We suggest to look more systematically for scenarios where such a regulating mechanism might be at work, perhaps in addition to other spicule driving processes. We have proposed examples of such scenarios and have started collaborations to investigate them in more detail by means of numerical simulations.

Acknowledgments. We appreciate useful discussions with V. Andretta, H. Peter, I. Roussev, R. Schlichenmaier, and K.-P. Schröder.

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