

Are spicules driven by oscillations?

ChuXin Chen*

Chinese Academy of Sciences (CAS) Key Laboratory of Geospace Environment, Department of Geophysics and Planetary Sciences, School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China

Key Points:

- A spicule is initially driven by oscillation in a pattern analogous to the shaped charge.
- Dynamo action plays an important role in the life of a spicule.
- Fermi acceleration is responsible for the temperature increase up the solar atmosphere.

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Abstract: The formation of spicules on the solar surface is poorly understood. In the present investigation, we propose a mechanism that provides an explanation for this phenomenon. The squeeze of the enhanced downflow region in the intergranular lanes by oscillation results in an initial narrow, high-speed upward flow with a velocity on the order of several kilometers per second and a width on the order of 10 km. The underlying physics principle is the same as in the design of an anti-tank weapon, called a “shaped charge”. The life of a spicule is divided into two stages. The first stage is mechanical driving by the pressure gradient at its base; the second stage is electromagnetic driving. Dynamo action in the early lifetime of a spicule plays an important role in the transfer of mechanical energy to magnetic energy. The subsequent Fermi acceleration is responsible for the energy transfer from magnetic energy to thermal energy and kinetic energy. Depending on the strength of the ambient magnetic field, the formation of type I spicules (strong case) and type II spicules (weak case) can be naturally explained in this frame setting, which is one of the merits of our proposed mechanism. The variation in temperature along the height is consistent with prior observation-based models.

Keywords: spicule formation; shaped charge; initial narrow, high-speed upward flow; Fermi acceleration of charged particles

1. Introduction

Spicules can be seen at the solar limb (Beckers, 1972). They are elongated, jetlike structures on the solar chromosphere, emanating upward to a height of several thousand kilometers above the solar surface. Spicules are highly dynamic, with a lifetime on the order of several minutes. Some spicules show clear ascent (with a lift velocity on the order of 20 km s^{-1}) and descent phases (Suematsu et al., 1995), whereas others show only upward motion and then fade out of view. According to the similarity in properties and behavior, mottles in the quiet Sun and dynamic fibrils in the active region are thought to be counterparts of spicules on the solar disk. The base of a spicule on the photosphere is in the intergranular lane, coincidentally located with a magnetic concentration.

Even though spicules were first discovered more than 100 years ago, their origin is still poorly understood. The difficulty is twofold, both observational and theoretical. On the observational side, the width of a spicule is on the order of several hundred kilometers down to the limit of observation, whereas on the theoretical side, the initial velocity and the height of a spicule are not compatible with ballistic motion. Determining the force that could drive a flow to a height of several megameters above the solar surface is

an arduous task, and many theoretical models have been proposed to explain this phenomenon (Sterling, 2000).

In contrast, the corona, the outer layer of the solar atmosphere, has a temperature of a million degrees, much higher than that of the photosphere. How the corona is heated and where its energy comes from are challenging problems in solar physics. The ultimate energy for corona heating is generally believed to be the granular convection motion in the photosphere (McIntosh et al., 2007). How this energy is transported to the corona has been the research project of many solar physicists for over half a century.

Spicules have a mass flux of 100 times that of the solar wind (Pneuman and Kopp, 1978; Athay and Holzer, 1982). They play an important role in the mass balance of the solar atmosphere. Spicules were once proposed as a medium to transport energy from the photosphere to the corona but were dismissed because of the lack of a coronal counterpart (Withbroe, 1983). Recently, a type of spicule called the “type II spicule” was discovered (De Pontieu et al., 2007b; Pereira et al., 2012). The type II spicule has a shorter lifetime and a greater length than the type I spicule. This new type of spicule has its on-disk counterpart, identified as rapid blue-shifted excursions (RBEs; Langangen et al., 2008; Rouppe van der Voort et al., 2009). Rapid blue-shifted excursions are thought to be closely related to coronal heating.

In this article, we propose a new mechanism responsible for the formation of spicules. Depending on the surrounding magnetic

Correspondence to: C. X. Chen, chuxin@ustc.edu.cn
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field strength, our mechanism would explain the appearance of all types of spicules. This mechanism is described in detail in Section 2. A discussion is then provided in Section 3, and finally, conclusions are presented in Section 4.

2. The Mechanism Responsible for the Formation of Spicules

To determine what mechanism drives spicules, here we present an analysis step by step toward the final solution. To begin, let us list the basic constraints on spicules. The first is ubiquity. Spicules can be found throughout the solar surface. Granules would easily satisfy this constraint. The second is periodicity. Both granular convection and (global) oscillation are good candidates for interpreting periodicity. The third is slenderness. The width of a spicule can be as small as the limit of observation. It is difficult to find a candidate that matches this constraint. The potential source must have a width smaller than the size of a granule.

Before taking another step forward, it is important to remind ourselves of some characteristics of the solar atmosphere. Because of gravity, the solar atmosphere would be stratified under a possible positive vertical temperature gradient. The contours of pressure and density are horizontally oriented. Pure global oscillation would also create these contour oscillations. The negative vertical temperature gradient (as only one of the criteria) would cause granular convection, making these contours corrugated (Carlsson et al., 2004; see Appendix A in the Supplementary Materials).

Above all, granular convection, instead of oscillation, is no doubt a good starting point. The period of granular convection is on the order of 5 minutes, and granular convection is turbulent. The granules are irregularly shaped, and their sizes are not uniform, having an average diameter on the order of 1000 km (Chaisson and McMillan, 1996). The center of a granule shifts from one location to another at a time step of the period of granular convection. The distance between the original center and the subsequent one can reasonably be estimated to be less than the radius of a granule.

The flow moves upward at the center of a granule, then turns horizontal toward the edge of the granule and moves downward at the intergranular lanes (Beckers and Morrison, 1970). However, the downward motion is not uniform along the intergranular lanes. At some locations along the edge of a granule, downward motion is enhanced. Cusps (of density contours) occur at these enhanced downflow regions (Carlsson et al., 2004; see Appendix A). Two sketches of vertical and horizontal cross sections of granules are shown in Figures 1 and 2, respectively. It is important to point out that enhanced downflow regions favor the intersection of three granules but are not limited to these locations; they may appear at any place along the intergranular lanes.

The vertically oriented magnetic field lines are swept to the intergranular lanes by the horizontal motion (Carlsson et al., 2004; Chen CX, 2016). The magnetic field lines in a new cusp consist of magnetic field lines that are located at several different cusps one time step (the period of granular convection) ago, as the horizontal motions of newly formed granules bring them to their current

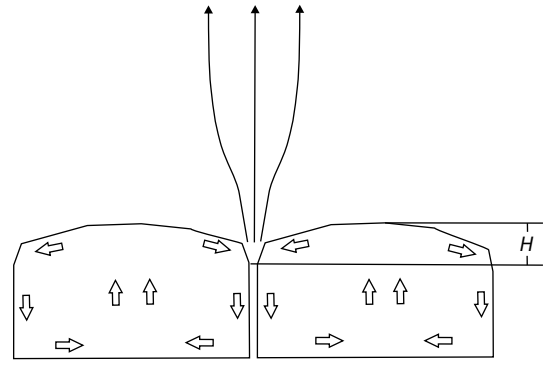


Figure 1. Sketch showing a vertical cross section of two granules through an enhanced downflow region (or cusp) and the centers of the granules. The hollow arrows represent flow, and the solid arrows represent the magnetic field. A cusp is located at the upper part of the boundary between the two granules. H is the height difference between the top of the granule and the tip of the cusp.

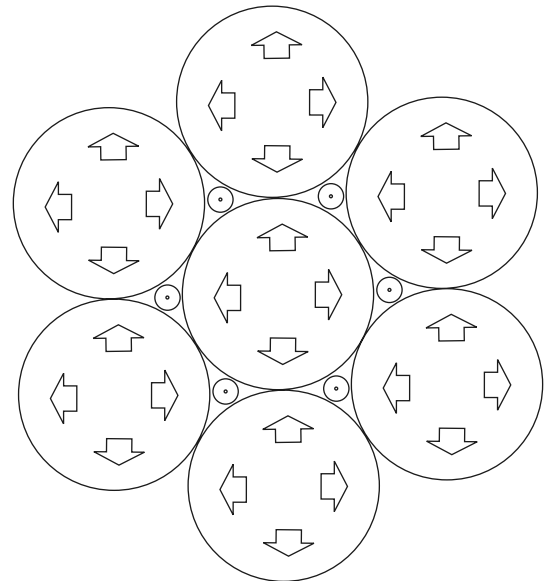


Figure 2. Sketch showing the horizontal surface of several adjacent granules. The seven large circles are the granules, and the arrows represent flow. The six small circles in the conjunctions of granules are the enhanced downflow regions (or cusps). These small circles with dots also represent the magnetic field. The direction of the magnetic field in this sketch is perpendicular to this surface and is pointed outward.

positions. Thus, the magnetic field lines in a cusp are divergent upward. Of course, another more important reason for the upward divergence of the magnetic field is the horizontal force balance between the magnetic field and the background plasma thermal pressure, which drops upward because of solar gravity.

Granular convection alone would be a possible source for a spicule because plasma flow on the photosphere brings the magnetic field lines located at different cusps one time step ago toward a new cusp. This process squeezes the material above the photosphere, leading to an upward flow along the magnetic flux tube. This upward flow can be interpreted as a spicule. However, if

the magnetic flux in a new cusp is simply shifted from an old cusp, no squeeze of material above the photosphere would occur; consequently, no spicule would form.

Next, let us add oscillation onto granular convection. The (global) oscillation would modulate the pressure distribution determined solely by granular convection, and the flow pattern would consequently be modulated.

A good approximation of a cusp is a cone with a semi-angle of α , as shown in Figure 3. When an oscillation propagates upward, these cusps are lifted and squeezed by newly incoming high pressure in the adjacent granules. The denser material is pushed toward the axis of the cone at a normal velocity of V . As demonstrated in Appendix B, a narrow upward flow of a circular cross section would form at the tip of a cusp. The formation of this flow is classically termed a “shaped charge”, a principle in the design of an anti-tank weapon. This is the origin of the spicule. Another good (or easily understandable) analogue to this process is the rebound of a water surface after being hit by a drop of water falling from some height. A narrow, circular cross section upward flow forms at the position of contact.

From Appendix B, the lift velocity of the cusp is $V \operatorname{cosec} \alpha$; thus, the velocity of the initial upward flow is $V(\cot \alpha + \operatorname{cosec} \alpha)$ (as expressed by Equation (B3)). When α is in the range of 1° to 5° , the contribution from $\cot \alpha$ and $\operatorname{cosec} \alpha$ together would be in the range of 114.6 to 22.9. This is a large amplifying factor for a normal velocity (V), resulting in a larger upward flow by one to two orders of magnitude.

Also from Appendix B, let A in Equation (B1) being the product of $2\pi r$ and H_s (the scale height of density, which is estimated as 180 km for the photosphere of 6000°C temperature), and α to be in the range of 1° to 5° . Here, r can be taken as H_s too. Then the initial diameter of an upward flow is in the range of 4.4 to 22.2 km, which is far below the limit of observation.

The next step in our investigation is to determine whether this upward flow would appear as a spicule on the chromosphere and if so, which kind of spicule it would be. For the sake of description,

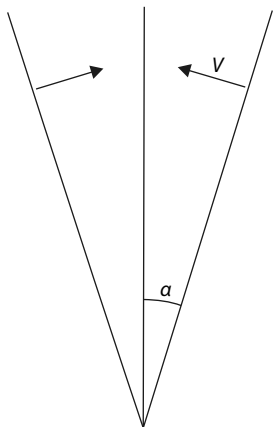


Figure 3. Sketch showing a vertical cross section of the shaped charge through the axis. α is the semi-angle of the cone. V is the normal velocity of the denser material being pushed toward the axis of the cone.

we will call this mechanical driving phase “the first stage of a spicule”.

The material in this first-stage spicule is partly ionized. Because the magnetic field lines in the cusp region are divergent upward, the flow interacts with the magnetic field through dynamo Equation (1) as it moves upward,

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}), \quad (1)$$

where \mathbf{u} is the flow velocity, \mathbf{B} is the magnetic field, and the dissipation of the magnetic field is omitted on the right side. The flow stretches the magnetic field lines upward, but with a slightly smaller velocity because of the partial ionization of the material (Vernazza et al., 1981). This dynamo action increases the magnetic field along the axis of the spicule. The magnetic field lines in the first-stage spicule are not parallel to its axis all the way upward. In the lower part of the spicule, the magnetic field lines are along the axis of the spicule, whereas in the upper part of the spicule, the magnetic field lines turn away from the axis and connect to their original locations high up in the corona. The second stage of the spicule comes when the turning point moves upward to a height where the local Alfvén wave speed equals the flow velocity. Because of solar gravity, the density drops exponentially as the height increases above the solar surface. The magnetic field strength also drops as the height increases but at a rate (determined by the divergence-free law) smaller than the density. As a consequence, the local Alfvén wave speed increases as the height increases. Above the point where the second stage of the spicule begins, the Alfvén wave speed is larger than the flow velocity, and the driving force becomes the electromagnetic force. One subtle point that needs to be emphasized here is that at a horizontal level, the Alfvén wave speed inside a spicule is substantially smaller than that outside (the term “ambient” is used hereafter to refer to the location outside a spicule) because the flow brings higher density charged particles from a lower height upward to a higher height.

In the second stage, the turning point moves upward at the local Alfvén wave speed. Because the magnetic field lines in the turning point connect to different original locations high up in the corona, the aggregation of the magnetic field lines forms the shape of a reversal umbrella. As the reversal umbrella moves upward, it will evolve from a more open shape to a less open one as the local Alfvén wave speed increases (as shown in Figure 4). The motion of this reversal umbrella drives the material ahead of it, not only plasma but also neutral material (through collision between charged particles and neutral particles), forming the second stage of a spicule. This reversal umbrella can reach the corona. The driving mechanism for the second stage of a spicule can readily be seen as simply Fermi acceleration (or Lorentz force).

It is worth pointing out that the density of the second stage of a spicule is smaller than that of the first stage. Most mass in the initial upward flow will fall back to the solar surface. The falling begins from the second stage and is a graduated process. The minor mass of a spicule continues its way upward by Lorentz force, and the major mass falls back under the action of solar gravity. The material falling back has a higher ratio of neutral particles

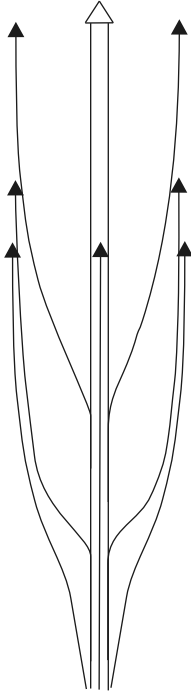


Figure 4. Sketch showing a vertical cross section of the upward flow region. The hollow arrow represents the upward flow, and the solid arrows represent magnetic field lines. The low pair of magnetic field lines is outside the upward flow, and the middle and high pairs are inside.

to charged particles than those continuing upward.

The magnetic field is the most important and subtle quantity in spicule formation. For regions with a very strong magnetic field (e.g., the area around sunspots), turbulent granular convection is inhibited, and spicules will not form. Outside these regions, in principle, an initial narrow, high-speed upward flow has a chance to appear on the photosphere. However, the appearance of a spicule is dependent on the ambient magnetic field strength.

Let us first consider the situation in which the ambient magnetic pressure is larger than the thermal pressure and ram pressure of the upward flow:

$$\frac{B^2}{2\mu_0} \geq p, \quad (\text{on the chromosphere}) \quad (2)$$

where B is the ambient magnetic field, p is the thermal pressure of the upward flow, and μ_0 is the permeability of free space,

$$\frac{B^2}{2\mu_0} \geq \rho u^2, \quad (\text{on the chromosphere}) \quad (3)$$

where ρ and u are the density and velocity of the upward flow, respectively.

Inequality (2) can be rewritten as

$$\frac{B^2}{\mu_0 \rho} \geq \frac{2kT}{m_p}, \quad (\text{on the chromosphere}) \quad (4)$$

where m_p is the mass of protons, k is the Boltzmann constant, and T is temperature. Inequality (4) is roughly equivalent to the condition that the ambient Alfvén wave speed is larger than the speed

of sound.

In addition, Inequality (3) can be rewritten as

$$\frac{B^2}{\mu_0 \rho} \geq 2u^2. \quad (\text{on the chromosphere}) \quad (5)$$

Inequality (5) is roughly equivalent to the condition that the ambient Alfvén wave speed is larger than the speed of the upward flow. Under such conditions, a mechanical driving spicule forms. This is exactly a type I spicule; thus, a stronger ambient magnetic field favors the development of a type I spicule.

From the dynamo Equation (1), it can be seen that in the type I spicule, the interaction between upward flow and the magnetic field does not show the result (a physical phenomenon) clearly or observationally because the relative change in the magnetic field depends on the strength of the flow velocity, which is smaller compared with the magnetic field (more precisely, the ambient Alfvén wave speed). This tiny disturbance on the magnetic field will propagate along the magnetic field line much faster than the upward flow. In the type I spicule, the second stage of a spicule will not appear because the ambient Alfvén wave speed is much faster than the upward flow.

The magnetic field strength varies from region to region on the solar surface. As the ambient magnetic field decreases, the first stage of a spicule will be less and less developed and will finally disappear. In that case, a spicule degenerates to only the second stage, that is, an Alfvénic pulse propagating upward. This is exactly a type II spicule.

For an intermediate magnetic field, spicules appear whose properties and behavior are between type I and type II. A linear spicule (Pereira et al., 2012) would be one such type of spicule.

After having outlined the formation and evolution of a spicule, it would be instructive to have some quantities estimated. The first quantity we would like to know is the initial upward velocity of a spicule. The p-mode oscillation (as an example but not limited to this mode) has a period of 5 minutes and then an ascent time of approximately 2.5 minutes. The height difference H between the top of the granule and the tip of the cusp (as shown in Figure 1) is a function of the phase of p-mode. It will change between 0 and 500 km (the depth of the photosphere). Then the lift speed of the cusp will be 3.33 km s^{-1} , and the velocity of the initial upward flow will be approximately 6.66 km s^{-1} , as shown in Appendix B. It should be pointed out here that this value is the lower limit of the initial upward flow speed. The process of reducing the height difference between the top of the granule and the tip of the cusp may take less time than the ascent time of the p-mode oscillation, resulting in a much higher initial upward flow velocity than the 6.66 km s^{-1} estimated above.

The second quantity we would like to estimate is the diameter of a spicule on the chromosphere. As a spicule rises upward, it will expand as the ambient pressure drops. Because the density of the chromosphere is more than two orders of magnitude smaller than that of the photosphere (Vernazza et al., 1981), the cross-sectional area of a spicule will increase by more than two orders of magnitude. Because the initial diameter of an upward flow on the photosphere is in the range of 4.4 to 22.2 km, the width of a

spicule on the chromosphere will be in the range of 44 to 222 km.

With estimations of some quantities, the next thing we would like to know is how velocity or temperature increases along a spicule as the height increases. Appendix C does not seem too trivial to be used in the current circumstance. As shown in Appendix C, if Ball 2 is taken to be the turning point of the magnetic field lines and Ball 1 is taken to be a charged particle, then V_2 is the Alfvén wave speed and V_1 is the velocity of the particle, which can be set to zero. From Equation (C6), we can write the energy gain by the proton as

$$\Delta E_p = 2m_p V_A^2 \tag{6}$$

where V_A is the Alfvén wave speed.

Equation (6) demonstrates that charged particles will gain speed that is comparable to the local Alfvén wave speed by Lorentz force (or Fermi acceleration). Equation (6) can be rewritten as

$$\frac{3}{2} k \Delta T_p = \frac{2B^2}{\mu_0 n}, \tag{7}$$

where T_p is the temperature of the proton, and n is the number density of the plasma.

Equation (7) may explain why (or how) the temperature of the charged particle increases as the height increases from the chromosphere to the corona because the number density decreases exponentially as the height increases. Although the magnetic field strength also decreases as the height increases, it reduces at a rate much smaller than the number density.

It would be helpful to compare our results with observations. Figures 5 and 6 show the number densities of plasma and temper-

atures of the models by Vernazza et al. (1981), respectively, together with temperatures calculated by Equation (7). Both temperatures show the same variation tendency as the height increases. The two temperatures are closer to each other at the greater height. The reason may be that the approximation of the turning point in Appendix C—where Ball 2 has a much larger mass than Ball 1—becomes more accurate as the height increases. For most points, the difference between the two temperatures is within 15%. This difference may have originated in rewriting Equation (6) as Equation (7): Some energy gain by charged particles through Fermi acceleration may be in the form of kinetic energy other than thermal energy.

Finally, let us investigate the height and lifetime of a spicule. Although these issues are spectral line or temperature dependent, it would be helpful to have a look from a dynamical point of view. The momentum equation is

$$\rho \frac{d\mathbf{u}}{dt} = \rho \mathbf{g} - \nabla p - \nabla \left(\frac{B^2}{2\mu_0} \right) + \frac{1}{\mu_0} (\mathbf{B} \cdot \nabla) \mathbf{B}, \tag{8}$$

where \mathbf{g} is the solar gravity, which is the most obvious factor dominating the rising and falling of a spicule. The second term on the right side of Equation (8), the negative pressure gradient, is less clear for a spicule. In our shaped charge depiction, the downward pressure gradient formed at the bottom of a spicule is much larger than that at the equilibrium condition. This is the initial drive for a spicule. The duration of this drive depends on the phase difference between granular convection and oscillation. The third and the fourth terms on the right side of Equation (8), the Lorentz force, are the most obscure factors for the evolution of a spicule. For a spicule that reaches a height greater than 2 Mm (megameters), a drive of the electromagnetic type seems a must.

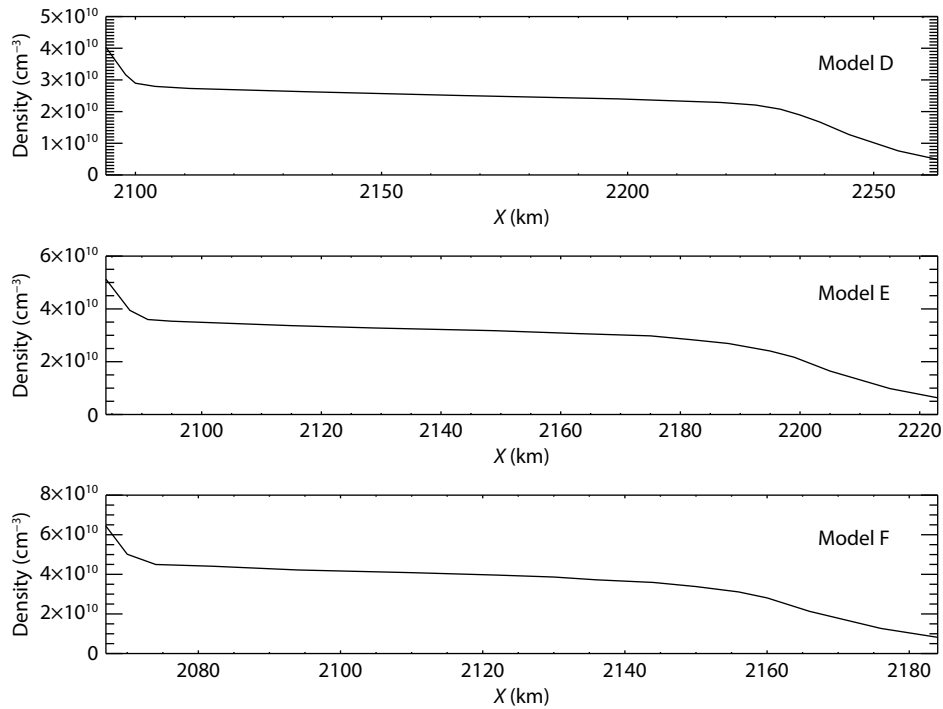


Figure 5. Number densities of plasma from the models by Vernazza et al. (1981). The top panel is for Model D (the average network), the middle panel is for Model E (a bright network element), and the bottom panel is for Model F (a very bright network element).

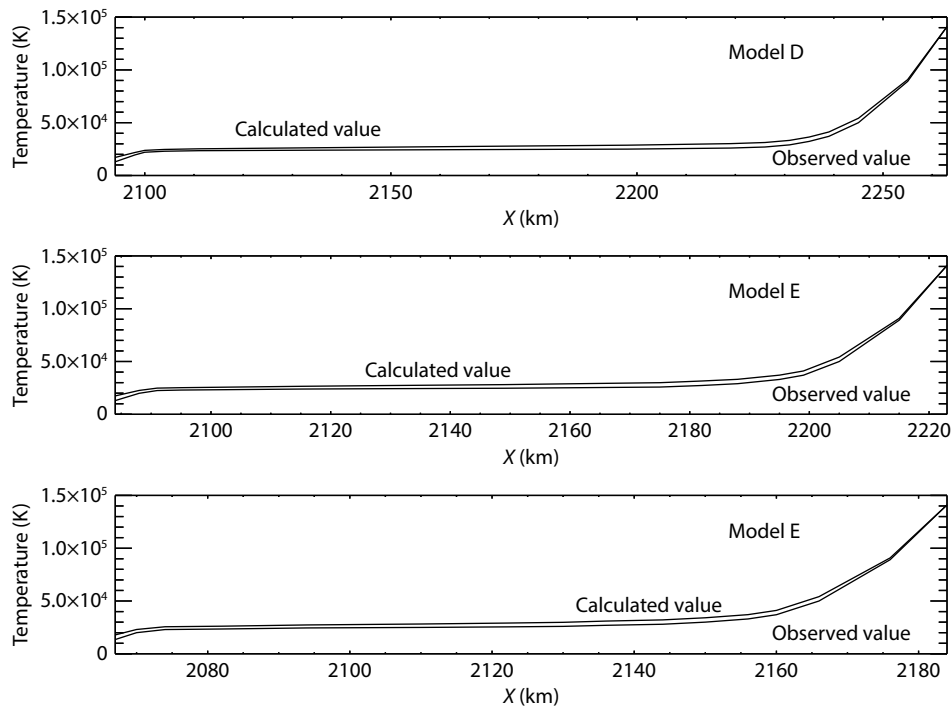


Figure 6. Temperatures from the models by Vernazza et al. (1981) and temperatures calculated from Equation (7) with the number density of plasma taken from the corresponding model. The top panel is for Model D (B is set to 9.475×10^{-5} T [tesla]), the middle panel is for Model E (B is set to 1.077×10^{-4} T), and the bottom panel is for Model F (B is set to 1.225×10^{-4} T).

3. Discussion

The crucial point of this proposal is whether the initial narrow, high-speed upward flow would form under oscillation. Oscillation (globally) has a much greater horizontal length scale than that of a granule, which can be viewed as a uniform upward momentum flux. The dents at the edge of a granule make the surface of the granule appear as a layer of nonuniform mass. The response of this nonuniform layer of mass to a uniform upward momentum flux would be nonuniform upward motion. A narrow, high-speed upward flow is a natural response of the much smaller mass edge region to oscillation.

Although no metal layer or explosive exists in the real solar photosphere, the underlying physics is the same. A layer of solar atmosphere of a scale height may play the role of the metal layer, and the upward pressure pulse in oscillation may play the role of detonation. The geometry of the mass distribution near the granular surface is what makes the initial flow possible under the coming pressure pulse.

For simplicity, the analysis on the photosphere is basically mechanics other than magnetohydrodynamics. This seems reasonable because the photosphere is a low-beta (ratio of magnetic pressure to thermal pressure) region.

In the present investigation, we take p-mode oscillation as an example. Other modes of oscillation may have their roles in producing the initial upward flow, especially those of higher frequency that would lead to a higher initial upward velocity.

The merit of our proposal is that, depending on the ambient magnetic field strength, the same mechanism could naturally

explain the formation of type I, type II, and linear spicules between them. Prior work has demonstrated that the type I spicule is related to a sound wave shock (De Pontieu et al., 2004), but the cause of the type II spicule is much less understood. The proposal of magnetic reconnection for the type II spicule faces the difficulty that the magnetic bipolar region is not as ubiquitous as the spicules themselves. It is not likely that nature would invoke so many mechanisms to produce the corresponding spicules.

Because the governing factor for the development of the first stage of a spicule is solar gravity and that of the second stage is the local Alfvén speed, the height and lifetime of a spicule are contributed by these two stages with quite different lengths and time scales. A linear spicule, which we interpret as an intermediate type of spicule between the type I and type II spicules, would have a lifetime that is shorter than that of the type I spicule and longer than that of the type II spicule. Its velocity would be greater than that of the type I spicule and less than that of the type II spicule. And its height would be higher than that of the type I spicule and lower than that of the type II spicule.

Our proposal for spicule formation has observational support (Pereira et al., 2012). For example, in active regions, most spicules are parabolic or linear, and linear spicules behave very similarly to parabolic spicules. The lifetime of linear spicules is approximately half that of parabolic spicules. The spicules in a quiet Sun are mostly type II (which is also the more frequently occurring type of spicules in general). They are typically higher than those in the active region. Many seem to lack a sharply defined edge at their top, and significant fading often occurs throughout their lifetime (Roupe van der Voort et al., 2007).

The greatest difference between our model and previous models is the initial narrow, high-speed flow. The width of the source of a spicule on the photosphere is on the order of 10 km, which is two orders of magnitude smaller than the size of a granule. The slenderness, isolation, or both of the initial upward flow make it possible for the initial upward flow to interact with the magnetic field.

The interaction between the upward flow and the magnetic field plays an important role in the evolution of a spicule. The dynamo action deposits a minor portion of flow energy into the magnetic energy in the early ascent phase, whereas in the later ascent phase, the magnetic field transfers some of its energy back to the flow energy through the Lorentz force. This may explain why the observed deceleration of a spicule path is typically only a fraction of the solar gravity and is incompatible with a ballistic path at solar gravity (De Pontieu et al., 2007a), a fundamental problem in spicule dynamics. It is the interaction between the upward flow and the magnetic field that makes the height and lifetime completely different from those dominated by mechanical sources alone.

Direct observational evidence of the dynamo may be the bright points in the intergranular lanes. The bright point at the base of a spicule appears in the blue after the spicule forms or disappears in the blue wing (Suematsu et al., 1995). Although the horizontal motion at the surface of a granule moves the vertical magnetic field lines into intergranular lanes, magnetic concentrations (bright points) at the base of a spicule in the ascent phase may partly be the result of the dynamo action, that is, the stretch (or pull) of magnetic field lines by the upward flow. Most of the bright points have a lifetime of 2.5 minutes (Sánchez Almeida et al., 2004), half that of a spicule, which may support this suggestion.

How the mechanical energy of the photosphere is transported to the corona and transferred to the thermal energy of the plasma is investigated in the present study. It is clear that the ultimate energy for corona heating is oscillation, rather than the convective granular motion of the photosphere. The oscillation energy is first transferred to magnetic energy by a dynamo, and subsequently, magnetic energy is transferred to the kinetic or thermal energy of plasma by Fermi acceleration. The connection between the photosphere and corona is the magnetic field lines that are threaded through. From our analysis, the rising speed of the type II spicule is clearly the local Alfvén wave speed. Because the Alfvén wave propagates along magnetic field lines, the wave energy will not dissipate in all directions. The upward propagation of the turning point of the magnetic field lines carries energy up to the corona.

The bright ring above the top end of a spicule may be the manifestation of Fermi acceleration. The increase in width of the absorbing component along RBEs and the sudden disappearance or fading of RBEs at the end of their lifetime (Roupe van der Voort et al., 2009) are highly compatible with Fermi acceleration of plasma along the jet. The transition zone between the chromosphere and corona may be a relic of the second stage of spicule formation, or closely related to it, because only in this zone and farther up is temperature roughly inversely proportional to the number density of plasma, as expressed by Equation (7). The

circular cross section of initial upward flow and the upward divergence of the magnetic field make Fermi acceleration possible.

In previous impulse models, high pressure or velocity is not well explained. Such an impulse is interpreted as the leaking of granular convection, oscillation of the photosphere into the chromosphere, or both. However, this explanation of leaking should have the spicule rooted in the center of a granule, rather than at the enhanced downflow regions where the magnetic field is divergent upward. In contrast, the magnetic field at the center of a granule is convergent upward, and the strength of the impulse on the chromosphere increases along convergent magnetic field lines or decreases along divergent field lines. The fact that the driving mechanism for spicules is oscillation agrees with the observation that spicules around a granule are close in phase (De Pontieu et al., 2007a).

Another difference between our theory and previous models is the source of magnetic flux at the enhanced downflow region. In our model, magnetic flux at one such newly formed location comes from those at several different locations one period of granular convection motion ago. This is consistent with observations of the splitting of an old spicule located in the old enhanced downflow region and the merging of spicules as magnetic field lines (shaped as a reversal umbrella) at the top of a newly formed spicule that evolve from a more open shape to a less open one (Pietarila et al., 2009). Previous models proposed that magnetic flux is shifted from only one location a time step ago, and component magnetic reconnection is thought to be the energy source of the corona. By contrast, in our theory, Fermi acceleration is proposed to be the energy source. As the consequence of granular motion, at a location high up in the solar atmosphere, the intermittent densification and rarefaction of magnetic flux is dominant over the shearing of the magnetic field.

Our depiction of the spicule may have a close relationship with solar wind formation. Because the velocity of a spicule high up in the corona is comparable to the local Alfvénic wave speed (on the order of hundreds of kilometers per second), we have reason to believe that spicules are important sources of solar wind and may even be the initial state of solar wind.

4. Conclusions

In this work, we propose a mechanism that could explain the formation of spicules. In the ascent phase of oscillation of the photosphere, high pressure propagating upward will squeeze the enhanced downflow region, resulting in a narrow, high-speed upward flow. The initial flow has a velocity on the order of several kilometers per second and a width of approximately 10 km. A spicule will undergo two stages in its lifetime. The first stage is mechanical driving, which will lift the spicule to a height of 1 Mm, and the second stage is electromagnetic driving, which will accelerate it all the way up to the corona. Consequently, the heating of the corona is accomplished by Fermi acceleration. The merit of our proposal is that a single mechanism can explain the formation of all types of spicules, depending on the surrounding magnetic field strength.

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Supplementary Materials
Appendix A

One layer of a fluid is placed horizontally in a gravity field and the temperature at the bottom is kept higher than that at the top. When the temperature difference between the bottom and the top is small, heat transfer from the bottom to the top takes the form of conduction. The contours of temperature are horizontally oriented. When the temperature difference between the bottom and the top becomes large, heat transfer takes the form of convection. The contours of temperature or density have the shapes shown in Figure A1.

The contours of temperature at the center of a convection cell are shifted upward to have enhanced heat conduction at the top of the fluid layer, and the contours at the edge of the convection cell are shifted downward to have enhanced heat conduction at the bottom of the layer. The shapes of temperature or density contours have the typical configuration of two mushrooms mutually embedded, with one oriented up and the other oriented down. Dents in the density contours can clearly be seen near the edge of the convection cell.

Appendix B

The type of shaped charge considered here consists of a hollow metal cone with an open base and with an explosive packed around the outside of the cone (Batchelor, 1967). The cone has a semi-angle of α . When the explosive is detonated simultaneously, the metal will melt and move toward the axis at a normal velocity

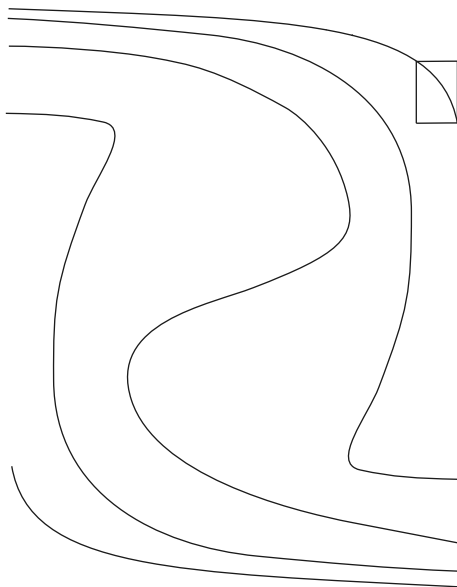


Figure A1. Sketch showing the contours of temperature or density in a vertical cross section through the center of a granule. The left side is the center of the granule, and the right side is the edge of the granule. The rectangle in the upper right corner is the left part of Figure 3. A (half of a) dent or cusp is located in the rectangle.

of V (Figure 3). The metal will accumulate at the apex and two opposite-directed axial jets will emanate from the apex under enormous pressure.

It is convenient to view the relative velocities in the reference frame of the moving apex of the cone, as shown in Figure B1. Three velocities are shown in this frame. One conical velocity is toward the apex, and two opposite axial velocities are away from the apex. All have the value of $V \cot \alpha$ at some distance from the apex because of the conservation of energy.

Let the metal have a thickness of $A/2\pi r$, where A is a constant and r is the distance from the cone axis. The conservation of mass and momentum yields the upward jet cross-sectional area as

$$A_1 = \frac{1}{2}A(1 - \cos \alpha) \tag{B1}$$

and the downward jet cross-sectional area as

$$A_2 = \frac{1}{2}A(1 + \cos \alpha). \tag{B2}$$

Because the velocity of the moving apex is $V \csc \alpha$ (Figure 3), the upward jet velocity relative to the undetonated charge is

$$V(\cot \alpha + \csc \alpha). \tag{B3}$$

Appendix C

Considering a face-to-face elastic collision between Ball 1 and Ball 2, Ball 1 has mass m_1 and velocity V_1 , and Ball 2 has mass m_2 and velocity V_2 . The conservation of momentum requires

$$m_1V_1 + m_2V_2 = m_1V'_1 + m_2V'_2, \tag{C1}$$

where V'_1 is the velocity of Ball 1 after the collision, and V'_2 is the velocity of Ball 2 after the collision. The conservation of energy gives

$$\frac{1}{2}m_1V_1^2 + \frac{1}{2}m_2V_2^2 = \frac{1}{2}m_1V'^2_1 + \frac{1}{2}m_2V'^2_2. \tag{C2}$$

From Equations (C1) and (C2), one obtains

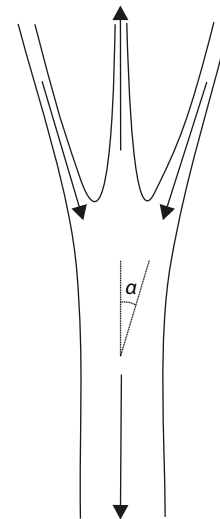


Figure B1. Sketch showing a vertical cross section of the shaped charge in a reference frame of the moving apex. The arrows represent velocity.

$$V_1' = \left(\frac{m_1 - m_2}{m_1 + m_2} \right) V_1 + \frac{2m_2}{m_1 + m_2} V_2. \quad (\text{C3})$$

When m_2 is much larger than m_1 , Equation (C3) becomes

$$V_1' \approx -V_1 + 2V_2. \quad (\text{C4})$$

The energy increment of Ball 1 after the collision is

$$\Delta E_1 = \frac{1}{2} m_1 V_1'^2 - \frac{1}{2} m_1 V_1^2. \quad (\text{C5})$$

Substituting Equation (C4) into Equation (C5) yields

$$\Delta E_1 \approx 2m_1 V_2^2 - 2m_1 V_2 V_1. \quad (\text{C6})$$

It is worth noting that in a face-to-face collision, velocities V_1 and V_2 will have different signs.

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