

THERMAL FINE STRUCTURE AND MAGNETIC FIELDS IN THE SOLAR ATMOSPHERE: SPICULES AND FIBRILS

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ABSTRACT

The relationship between observed structures in the solar atmosphere and the magnetic fields threading them is known only for the solar photosphere, even then imprecisely. We suggest that some of the fine structures in the more tenuous chromosphere and corona—specifically some populations of spicules and fibrils—correspond to warps in two-dimensional sheet-like structures, as an alternative to conventional interpretations in terms of tube-like structures. The sheets are perhaps related to magnetic tangential discontinuities, which Parker has argued arise naturally in low- β conditions. Some consequences of this suggestion, if it can be confirmed, are discussed.

Key words: Sun: atmosphere – Sun: chromosphere – Sun: corona – Sun: surface magnetism

Online-only material: color figure

1. INTRODUCTION

Unlike data obtained in the laboratory, astrophysical data, with a few important exceptions, are principally obtained by remote sensing. Nevertheless with ingenuity, physical models, and luck (the existence of stars in clusters, standard candles, etc.), astrophysics has even been able to challenge fundamental physics, by revealing the solar neutrino problem, for example. Many situations exist, however, where the physical system observed is too complex for observations to permit clear-cut conclusions. In these cases we are armed with Occam’s razor—the principle that says we should take the simplest physical picture compatible with the data—in order to make progress. The Sun’s atmosphere, from photosphere to corona, is one area where Occam’s razor provides a useful first approach. But this astrophysical system is highly nonlinear, energy transport is anisotropic and it is strongly driven by turbulent convection. Understanding the transport of mass, momentum, and energy within the solar atmosphere and outward into the heliosphere is manifestly important for life on Earth. It is also an astrophysical object uniquely suited to the direct observational study of naturally occurring magnetized plasmas.

In this Letter we address the simple question: are straw-like fine structures seen in the chromosphere and corona essentially narrow magnetic flux tubes (one-dimensional-like) or something else? Expressed more broadly, what is the relationship between the magnetic fields threading the solar chromosphere and corona, and the observed fine structures?

2. A CASE STUDY OF LOW- β SOLAR STRUCTURES: SPICULES AND FIBRILS

The solar limb seen in strong (i.e., chromospheric) spectral lines reveals dynamic, straw-like structures called “spicules,” famously reported in early visual spectroscopic observations (Secchi 1877), captured in photographs and visually observed by Roberts (1945), quantified by Beckers (1969, 1972), and

now presented in exquisite detail in data from the seeing-free platform of the *Hinode* spacecraft (De Pontieu et al. 2007). Some spicules have been linked with the fine structures seen on the solar disk, called chromospheric “fibrils”—recent examples of which are shown in Figure 1—associated with underlying magnetic flux concentrations (Langangen et al. 2008; Ruppe van der Voort et al. 2009). In 1973 *SkyLab* revealed coronal plasma organized into “loops” over active regions. The loops were envisaged as plasma entrained in tubes of magnetic flux along which plasma flows under low- β conditions (β = gas pressure/magnetic pressure). The “tube” or “straw” picture has become a generally accepted picture of the low- β regions of the Sun’s atmosphere—the magnetized chromosphere, corona, and even the penumbrae of sunspots. *STEREO* observations of active region coronal loops confirm that, on observable scales ($> 1\text{--}2$ Mm), the tube picture appears reasonable (Aschwanden et al. 2008). Yet the plasma inside such tubes must consist of unresolved “strands” whose physical nature is poorly known (e.g., Klimchuk 2009).

2.1. A Hypothesis

The literature on spicules assumes explicitly or implicitly that these chromospheric phenomena correspond to plasma within magnetic tubes or straw-like structures. In Sterling’s (2000, p. 80) review, we find “All of the simulations begin with some form of deposition of energy in the photospheric or chromospheric portion of a magnetic flux tube which extends from the photosphere into the corona.” We find in Wikipedia: “...a spicule is a dynamic jet of about 500 km diameter in the chromosphere of the Sun... their mass flux is about 100 times that of the solar wind.” While not a formal scientific source, Wikipedia nevertheless summarizes the current paradigm: we must understand spicules in terms of field-aligned flows which are more of a one-dimensional than a two-dimensional or a three-dimensional cool structure embedded in the magnetoplasma.

Noting that no stereoscopic observations of spicules are yet possible, which would decide the issue once and for all, we hypothesize that at least some spicules are the *observational manifestations of two-dimensional sheet structures, physical counterparts of mathematical magnetic tangential*

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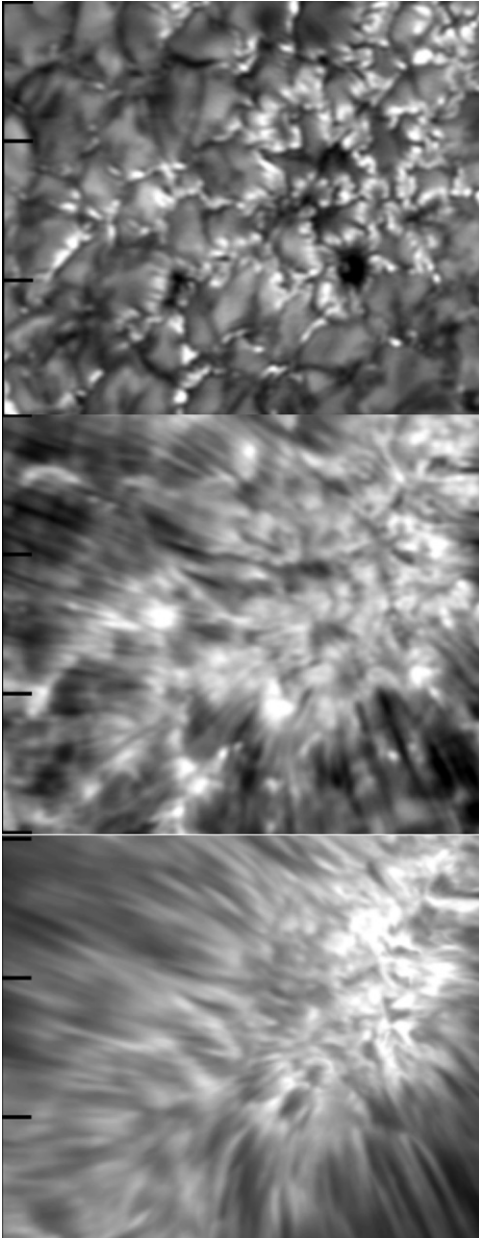


Figure 1. Images of pores in the Ca II 854.2 nm line, obtained with the Swedish Solar Telescope, extracted from de la Cruz Rodriguez (2010, Figure 1.5). The upper panel shows photospheric wing images including granulation and the tortuous sheets of bright emission associated with the magnetic network. The middle panel shows the low chromosphere with reverse granulation, and some fine chromospheric fibrils which have some opacity at this wavelength. The bottom panel is a line center image. The FOV is $18'' \times 15''$ (13×11 Mm).

discontinuities (e.g., Parker 1994). The spicules would then be analogous to the fluted parts of curtains. Parker argues that as a low- β system tries to maintain its equilibrium and magnetic topology, tangential discontinuities will form naturally where the magnetic field direction, but not its magnitude, changes across the sheet. Following Parker (1988), we envisage sheets which have a dominant “guide” magnetic field component, the angles between the discontinuous magnetic field vectors being small (see Figure 2).

Plasma may naturally accumulate in such sheets, either by the heating associated with the dissipative relaxation of the sheet (increasing the pressure scale height and filling the sheet with plasma from below) and/or as different magnetic flux bundles

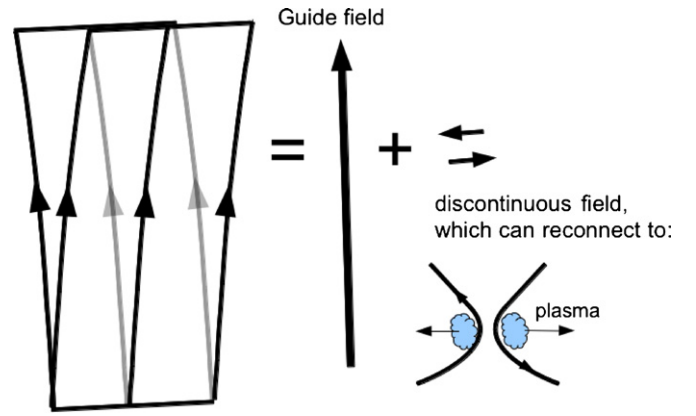


Figure 2. Sketch of the envisaged magnetic configuration across a current sheet, plasma is assumed to be sandwiched between the two magnetic surfaces shown. The right hand side of the figure shows a decomposition of the field across the sheet into the continuous guide field and the discontinuous tangential components. The latter can recombine in the manner shown leading to acceleration of plasma perpendicular to the guide field in the plane of the sheet.

(A color version of this figure is available in the online journal.)

are brought together, via the convective flows (van Ballegoijen et al. 1998). Figure 3 shows how a smoothly, harmonically fluted or warped sheet, containing optically thin emitting plasma, can produce what appears to be a straw-like structure, just from a line-of-sight integration. The equation for this particular sheet in Cartesian coordinates is simply

$$y = f(x, z) = 0.01 (e^{z/z_s} - 1) \sum_{j=0}^5 \frac{1}{j+1} \sin\left(2\pi j \frac{x}{x_s}\right),$$

where x_s and z_s are arbitrary characteristic scales, we chose values of 0.6876 and 0.5, respectively. No “tube” or “straw” exists in this configuration.

The motivations behind the sheet hypothesis are twofold. First, the highest resolution images of the underlying photospheric magnetic structures (line-of-sight flux density and/or proxies such as the *G* band) show few obvious “flux tubes,” instead they appear as fluted sheets (Berger et al. 2004; Riethmüller et al. 2010). Figure 13 of Berger’s paper, reproduced with permission in Figure 4, shows a region of decaying active network.⁵ In locally unipolar magnetic regions, such sheet-like structure must continue into the overlying chromosphere. In the above equation the sheet displacements y grow with height z to mimic the combined growth of Alfvénic fluctuations and natural development of sheet structures.

This leads to the second motivation, magnetic tangential discontinuities must develop in the low- β environment above the photosphere according to Parker’s magnetostatic theorem (Parker 1994; Low 2010; Janse et al. 2010). Coronal magnetic fields are braided into complex three-dimensional topologies as their footpoints are shuffled untidily in the convective turbulence of the high β photosphere. This theorem makes the basic point that preserving the coronal field topologies, under conditions of high electrical conductivity, naturally drives the fields to equilibrium states embedding such surfaces of discontinuity.

Our proposal is simply that magnetic structures, arising naturally from the fluted sheet configurations commonly measured

⁵ “Classical” and “type II” spicules are more prevalent away from active network. The figure was selected here in spite of this because it is one of the clearest examples of data revealing the nature of magnetoconvection.

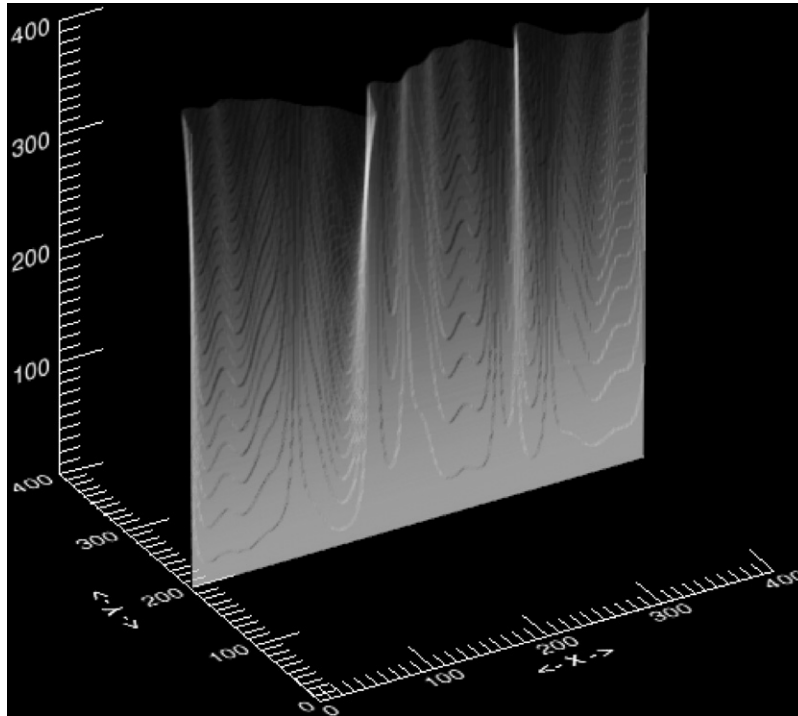


Figure 3. Warped sheet rendered in three dimensions. The brightness is proportional to a “density” integrated along the line of sight, the density is uniform at each “height” z within the sheet and zero outside it. The amplitude of the “warps” increases with z . (Axes are in arbitrary units.)

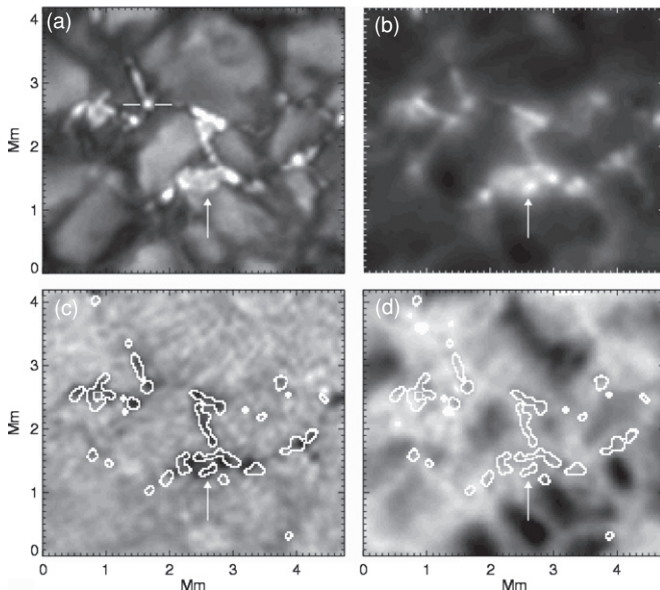


Figure 4. Figure 13 of Berger et al. (2004), showing (a) G -band filtergram, (b) Ca H-line filtergram, (c) Fe 630.2 nm magnetogram, (d) Ni I 676.8 nm Dopplergram.

in the photosphere (Figure 4) and subject to the formation of tangential discontinuities, extend into the chromosphere and corona, where they may explain some of the fine structures seen there.

2.2. Spicules and Fibrils as Straws

While almost universally accepted, explicitly or implicitly, the straw picture has some difficulties. How can large numbers of the observed long, thin chromospheric fibrils (Figure 1) and spicules (De Pontieu et al. 2007) be formed as tube-

like straws from the kind of magnetic sources found in the photosphere (Figure 4)? In this picture, observed kinematics must be interpreted as real fluid flow—how then are Mach 10–20 flows suggested by properties of spicules of type II generated in the chromosphere (see below)?

2.3. Spicules and Fibrils as Sheets

We recall known properties of spicules. Spicules are defined empirically, but owing to problems of atmospheric seeing, the relation between “classical” spicules observed from the ground and the far more dynamic and finer scale *Hinode* “types I and II” spicules is as yet unclear (Pasachoff et al. 2009). Nevertheless we summarize observed properties in Table 4. Here, we focus on the “classical” spicules of Beckers and the “type II” spicules observed with the SOT instrument on the *Hinode* spacecraft, of De Pontieu et al. (2007). We do not discuss “type I” spicules described by De Pontieu et al.⁶

What do the best constrained spicule data—those for type II spicules—imply if all such spicules are interpreted as warped sheets? At any time there are $\approx 6 \times 10^6$ granules on the Sun (Namba & Diemel 1969) and, as listed in the table and discussed further below, $\sim 2 \times 10^7$ type II spicules (Judge & Carlsson 2010). With these data we would need on average 4 warps per granule or 1600 per 20 Mm diameter supergranule. Since spicules are gathered along network lanes, this requires $\lesssim 20$ warps per Mm along a supergranular lane or a length scale for the warps of $\gtrsim 50$ km. (The inequalities arise because more

⁶ Type I spicules have a satisfactory explanation in terms of one-dimensional field-aligned recurrent up/down flows driven by work done on network flux concentrations by granular motions (Hansteen et al. 2006). Their material falls back down and so does not “reach” the corona, and they are apparently rare in coronal holes, where the classical spicules and type IIs are most obvious. Type I spicules cannot all correspond to the “classical” spicules, which are most obvious in coronal holes, even though some authors equate classical and type I spicules (Martínez-Sykora et al. 2010).

than one warped sheet can exist per unit length of the lane. The same statistics apply of course to the “straw” picture.)

Lifetimes of type II spicules are on the order of 35–45 s and lie within 10–60 s in a Gaussian-like distribution (De Pontieu et al. 2007). Granular lifetimes, defined as the time taken for an entire granule to lose its identity, are ≈ 10 minutes. Horizontal granular flows are $v \sim 1\text{--}2 \text{ km s}^{-1}$, and near downflow lanes, characteristic dynamical length scales are $\ell \sim 120 \text{ km}$. It seems likely that we should expect to see dynamical timescales $\ell/v \sim 1\text{--}2$ minutes at the base of warped sheets.

Unlike straws, warps do not require apparent motions to be attributed to fluid flow, since they result from line-of-sight integrations. As the photospheric field is buffeted by convection, the fine structures come and go as the plasma along each line of sight evolves in response to the driving. The apparent motions along type II spicules are only upward. In the warp picture this can occur if the phenomenon is driven mostly from below. Magnetic stresses propagate upward at the Alfvén speed, which increases with height. The combination of a vertical gradient in Alfvén speed, a driver from below, and optically thin emission will tend to produce upward apparent motion along warps that is not related to flows. If warps are also influenced from above and/or more than one warp evolves along a given line of sight, then downward propagation would be seen and interference may produce extremely fast apparent speeds. In this regard, De Pontieu and colleagues (De Pontieu et al. 2007, p. 5659) note that type II spicules “often disappear over their whole length within one or a few time steps (5–20 s)” and some have apparent velocities $>250 \text{ km s}^{-1}$. De Pontieu et al. (2007, p. 5659) also note that “a significant number [of type II spicules] appear to be slower during [the] very short initial phase and seem to accelerate as they reach greater heights.” This behavior is also naturally expected in the warp picture, as the warps propagate upward with the increasing Alfvén speed.

The hydromagnetic effects discussed above are still rudimentary but they merit further theoretical investigation. As a tangential discontinuity develops on a flux surface the strength of the current singularity is greatest at the intersection of that surface with the lowest, densest parts of the atmosphere (Low 1990). Current dissipation there may result in upward motion and magnetic disturbances everywhere on the surface of this continuity that then appear enhanced where the surface is fluted.

The magnetic fields of spicules have been explored using polarimetry (López Ariste & Casini 2005; Centeno et al. 2010), from which it is clear that the field is largely oriented along the apparent axis of the spicule. This is no problem for the warp picture in that tangential discontinuities formed in the Parker picture (as opposed to the “between tubes” picture of van Ballegoijen et al. 1998) have a dominant guide field within the plane of the sheet.

2.4. Dynamics and Connections to the Corona

EUV and optical imaging spectroscopy has revealed blueshifted features which have been ascribed indirectly to type II spicules. Weak coronal blueshifted emission has been found which some authors have identified with a hot component of the assumed outflow from type II spicules, since the velocity distributions of spicules seen at the limb correspond approximately to the observed Doppler shift distribution of coronal lines seen against the solar disk (De Pontieu et al. 2009). In this picture, upflowing spicular plasma is assumed to be heated to $>10^6 \text{ K}$ and the continued upflow is seen directly in blueshifted coronal lines. Disk counterparts of type II spicules have been

sought as absorption features in $H\alpha$. A class of rapid blueshifted events (RBEs; Langangen et al. 2008; Rouppe van der Voort et al. 2009) has been proposed as the type II counterpart. Langangen et al. (2008, p. L167) note that “however, the magnitude of the measured Doppler velocity is significantly lower than the apparent motions seen at the limb.” The latter authors too find Doppler shift velocities mostly at or below 50 km s^{-1} . De Pontieu et al. (2011) examine $H\alpha$ and EUV data from *Hinode*, finding correlations of RBEs with short-lived brightenings in a wide range of EUV lines observed.

This tidy picture of upflowing, cool spicular plasma, that is heated to 10^5 and 10^6 K , explaining the disappearance of the spicule itself and the appearance of blueshifted emission in, e.g., He II and coronal lines, has a basic physical problem. The proposed heating, required to make the plasma visible as EUV emission, means that the plasma is overpressured. The huge additional pressure will broaden velocity distributions as the plasma dynamically evolves on sound crossing timescales of a minute or less and radiates He II and coronal lines. In this picture, therefore, *different, broader* velocity distributions in the hotter plasmas should be expected. The energy required to drive such flows is potentially enormous. Judge & Carlsson (2010) estimated that type II spicules, interpreted as flows, carry a few times $10^7 \text{ erg cm}^{-2} \text{ s}^{-1}$ locally in enthalpy flux. This is on the order of the heating rate required to sustain the entire chromosphere (Vernazza et al. 1981). But the associated kinetic energy flux is an order of magnitude higher since the flows have Mach numbers of 10 or so. Can the apparent 100 km s^{-1} motions can really be field-aligned flows?

The scenario proposed by De Pontieu and colleagues may have other issues. Rouppe van der Voort et al. (2009) find 10^5 RBEs on the Sun at any given time, and claim that this is commensurate with the number of observed type II spicules (1–3 per linear arcsecond along the limb). However, the number of type II spicules on the Sun is probably far larger (see Table 1). The estimate of 10^5 is below even Beckers’ (1972) estimate of 10^6 “classical” spicules at zero height and would correspond to the number of spicules estimated by Beckers’ Equation (2) at 4000 km above the limb. This would be a surprising result given the superior quality of the *Hinode* data. The much larger number of 2×10^7 type II spicules given in the table, from Judge & Carlsson (2010), was derived by comparing Monte Carlo radiative transfer calculations with observations. This significant difference probably depends on where in radius one decides to count limb spicules per unit length along the limb and contrast thresholds. We regard the synthesis approach of Judge and Carlsson as more reliable. We can only speculate that perhaps RBEs are not then type II spicules, but are more energetic events more easily seen on the solar disk.

3. DISCUSSION

Our proposal extends an earlier idea of van Ballegoijen et al. (1998), who suggested that spicules form in between coherent bundles of photospheric flux as they expand in height and they interpret the apparent velocities as real flows. In our work, we recognize that current sheets can also form within otherwise continuous configurations (Parker 1994) and we propose that slow modulation of warped sheets can lead to supersonic apparent motion seen in off-limb data. On balance, it seems reasonable to identify some of the fine structures seen in the cool low- β component of the solar atmosphere with warped current sheets.

Table 1
Typical Spicule Properties

Parameter	Unit	“Classical”	“Type II”
Length	Mm	6.5–9.5 ($H\alpha$)	~ 5 (Ca II H)
“Diameter”	Mm	0.4–1.5	“Very thin” (down to 0.2 Mm?)
Lifetime	minutes	5–20	0.5–2
Apparent upward velocity	km s^{-1}	20	40–200, sometimes >250
Apparent horizontal motion	km s^{-1}	Usually <5	~ 20
Line widths (FWHM)	km s^{-1}	20–40	n/a
Number on the Sun		$\gtrsim 10^6$	2×10^7 ^a

Notes. Sources: Beckers (1972, classical) and De Pontieu et al. (2007, type II).

^a Estimate from Judge & Carlsson (2010), see the text for other estimates.

There are several important consequences if indeed significant numbers of spicules correspond to warped current sheets. First, such an interpretation presents the prospect of subjecting Parker’s theory of tangential discontinuities (Parker 1988, 1994) to observational scrutiny. Second, as the apparent speeds are a mixture of the phase speeds of warps (long lines of sight) and Alfvén speeds, previous estimates of mass flux ($\sim 100\times$ that of the wind; Beckers 1972; Athay & Holzer 1982), which assume that the apparent speeds are real flows, would be too large, re-opening the debate as to the contribution of spicules to the supply of mass to the corona and wind. Third, the two-dimensional geometry is important as the sheets present a far larger area of interaction between cool and hot material than is apparent from using the straw interpretation, enhancing processes which perhaps can help explain the unknown energy balance and peculiar observed properties of the lower transition region (Athay 1990; Judge 2008).

The association of warped tangential discontinuities with spicules may naturally explain the broad line widths always observed above the solar limb, even (perhaps especially) in “unipolar” regions. The sheets exist as changes in direction of the field are needed to accommodate force balance and topological constraints. Parker (1988) proposed that, at least in active regions, relaxation of the changes in field direction may account for coronal heating, even when the changes are small fractions of a radian. The significance of this is that if the current sheets are continually jostled then forced reconnection of the non-vertical component, involving a sudden reduction of the angle between the magnetic fields across the sheet may be a ubiquitous process. The reconnecting component of the field naturally leads to flows in direction perpendicular to the guide field, perhaps explaining the line widths, as well as supplying some heat to help keep the sheets replenished with plasma.

Even if it is later proven that warped sheets are inconsistent with data, our suggestion highlights a basic problem: how can one get straw-like structures out of the fluted sheet fields that appear to dominate the photospheric network at the current observational limit? If straws, why is the observed distribution of widths so small and at the resolution limit of current instrumentation? Warps have an advantage in that one need not perform theoretical contortions to make thin straws out of the observed photospheric sheets. The problem then becomes one of finding a natural physical explanation, analogous to Parker’s current sheet theory, to explain how such thin, essentially one-dimensional structures must naturally arise.

Still unanswered is the important question: how does the Sun make such long cool structures with lengths say $40\times$ the hydrostatic pressure scale height (e.g., Sterling 2000)? This issue is exacerbated with the realization that a pressure

gradient that is steeper than hydrostatic is the only force that can accelerate upward flows along a one-dimensional flux tube. Martínez-Sykora et al. (2010) present an example of a type II spicule candidate taken from a three-dimensional simulation of horizontal flux emerging into pre-existing vertical granular fields, in which Lorentz forces squeeze the chromosphere horizontally leading to vertical deflections of plasma. The upward components resemble properties of type II spicules, of the “straw” variety. The model appears promising, but may have potential problems. Extrapolation of the rate of occurrence of their numerical spicule produces just 10^4 such events on the Sun, far smaller than estimated above. The upwardly accelerated cool plasma also expands with height, perhaps in contradiction with observations. While these authors point to the role of a current sheet in their numerical experiment, it should not be confused with the scenario we propose. We emphasize more generally that the magnetic environment in which spicules are created—the constrained global field topology and the tendency for current sheets to form and dissipate—may naturally explain spicule-like structures in terms of sheets. The work of Martínez-Sykora et al. (2010) is important in producing events that produce straw-like spicules, to be further studied and tested observationally. We suggest that new numerical models that deal directly with sheet-like processes and structures should also be developed.

4. CONCLUSIONS

Sometimes our eyes deceive us: forests appear solid from a distance; spiral nebulae, once believed to be gas clouds, were first resolved into stars by Hubble (1929). Warped current sheets present an alternative physical hypothesis for the nature of spicules that is worthy of further study. The tube versus warps picture is not an either/or proposition—both have advantages and disadvantages when pitted against critical observational data. Further studies of both hypotheses, observational and theoretical, should help our continued understanding of this difficult area of research.

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