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CHROMOSPHERIC FINE STRUCTURE DIDACTICALLY

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Abstract. The solar chromosphere is occupied with a wealth of fine structures referred to by diverse nomenclature. Recent identification of slow-mode magnetoacoustic shocks, excited by p-modes of photospheric oscillations, as plausible drivers of dynamic fibrils and spicules was followed by a surge of observational studies and numerical simulations attempting to reveal the role of chromospheric fine structure in energizing of the upper solar atmosphere. The paper summarizes didactically this breakthrough and provides ample references on the pertinent literature.

Key words: Sun - chromosphere

1. Introduction

The chromosphere and transition region form a very warped and highly dynamic interface between the solar photosphere and corona. Its complexity cannot be characterized better than by the quotation widespread in the physic of solid surfaces/interfaces: *“God made the bulk, but the Devil created the surface.”*, credited to Wolfgang Pauli, but also to Enrico Fermi (Swathi and Sebastian, 2008). Judge (2010) argues in his aptly named paper *“The chromosphere: gateway to the corona? . . . Or the purgatory of solar physics?”* that understanding this challenging interface is important not only for its own sake, but also for the physics of the corona, astrophysical dynamos, space weather, partially ionized plasma, and helisopheric UV radiation. He gives seven reasons why the chromosphere is important putting on the first place: *“We do not understand from first principles why the Sun is obliged to manifest these phenomena.”*, meaning spicules, fibrils, and surges. It was motivated by an issue of a missing driver catapulting chromospheric plasma much higher than expected from purely ballistic motion with onset velocity of $20 - 30\,\mathrm{km\,s^{-1}}$ observed typically for spicules (Lippincott, 1957) and fibrils. Various mechanisms and models have been discussed in the review by Sterling (2000).

In fact, a breakthrough concerning so-called Hα dynamic fibrils (DFs) and mottles has been made prior to publishing Judge (2010) in the studies of De Pontieu *et al.* (2004,2007a), Hansteen *et al.* (2006), Rouppe van der Voort *et al.* (2007), Heggland *et al.* (2007), and Langangen *et al.* (2008a,b) following earlier work by Suematsu *et al.* (1995). These studies have established that Hα DFs, which are rows of dark fibrilar features jutting out from plage and network with periodic extension and retraction, display repetitive mass loading by upward propagating magnetoacoustic shock waves driven by the global solar oscillations. Reduction of the effective gravity along tilted magnetic channels lowers their cutoff frequency and lets them propagate into the chromosphere, steepen into shocks, and repetitively lift the chromospheric-transition region interface. The shock hypothesis of formation of Hα DFs implies parabolic trajectories of their tops and positive correlation between their maximum velocity and deceleration. These are well documented by observations and reproduced by simulations.

The change in the cutoff frequency for wave propagation along slanted fields had earlier been described by Michalitsanos (1973) and Bel and Leroy (1977), but was not appreciated in the subsequent literature, except for Suematsu (1990). The idea of inclined magnetic fields as "portals" through which low-frequency ($< 5\,\mathrm{mHz}$) magnetoacoustic waves can propagate into the solar chromosphere was put forward again in Jefferies *et al.* (2006) and Cally (2007) calling it "ramp effect" (Steiner, 2010). Later simulations by Martínez-Sykora *et al.* (2009) and Heggland *et al.* (2011) elaborated the idea that long-period waves can propagate into the chromosphere along inclined magnetic fields. However, the former study showed that spicules can be driven by a variety of mechanisms including p-modes[1], collapsing granules, magnetic energy release, and convective buffeting of flux concentrations. Pereira *et al.* (2012) found that properties of active-region spicules at the limb, showing parabolic top trajectories, are consistent with a magnetoacoustic shock driver, and with Hα DFs as their likely disk counterparts. Finally, Rouppe van der Voort and de la Cruz Rodríguez (2013) concluded that short DFs in sunspots chromospheres are also driven by long-period waves propagating along inclined magnetic fields into the chromosphere.

This paper is neither comprehensive, coherent nor well balanced review

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[1] which are solar global resonant acoustic oscillations visible in the photosphere as quasi-sinusoidal velocity and intensity pulsations.

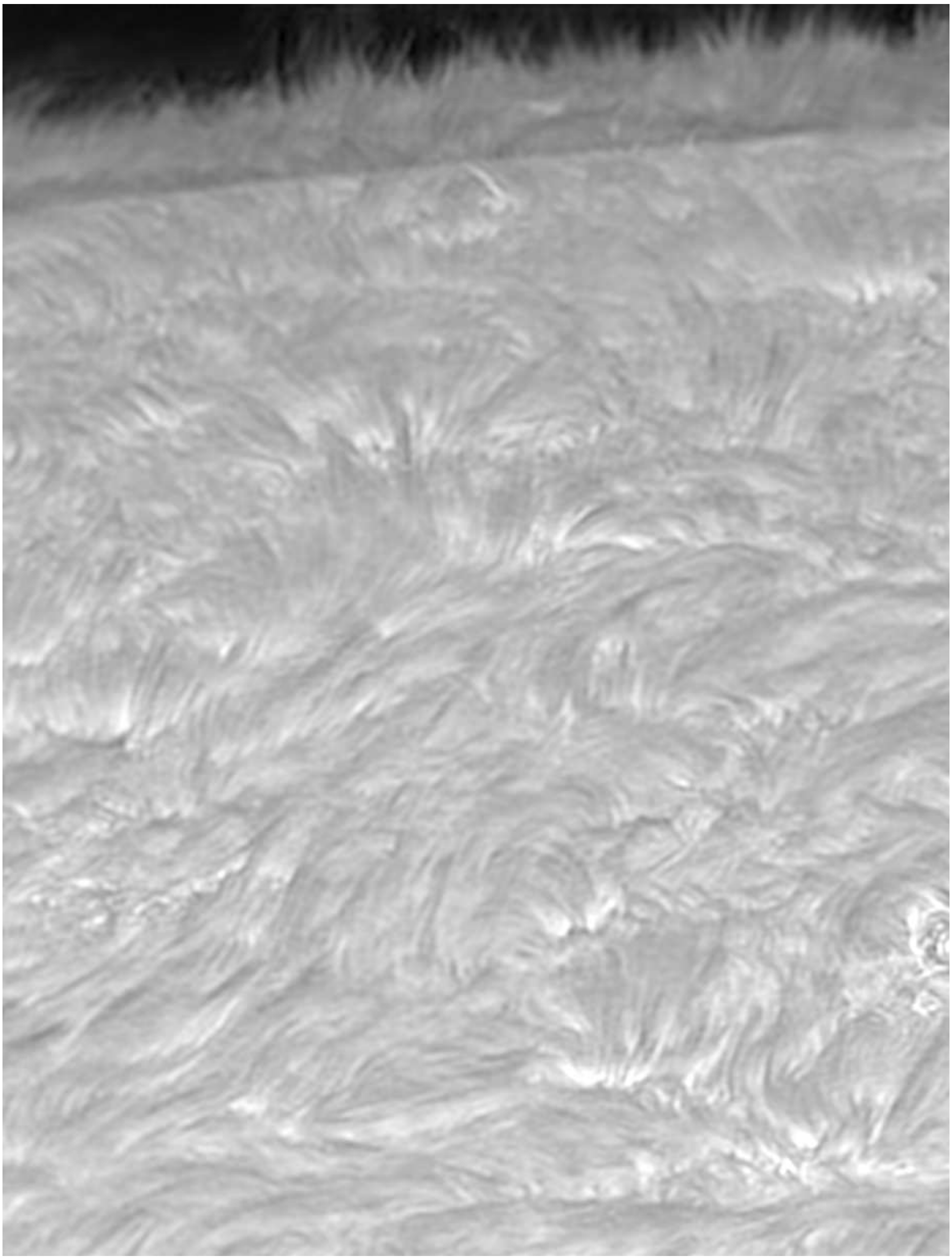

Figure 1: Chromospheric fine structure near and at the limb in the Hα line center. Field of view: $66 \times 87\,\mathrm{arcsec}^2$.

of current state of understanding of chromospheric fine structure. It is split up into didactic part explaining graphically the mechanism of possible leakage of p-modes into the chromosphere and reviewing part describing alternative scenarios of generating the chromospheric fine structure. Readers, looking rather for a respectable and full-fledged reviews, are advised to inspect the following literature and presentations:

Reviews in peer-reviewed journals: Tsiropoula *et al.* (2012), Rutten (2012), Sterling (2000), Judge and Peter (1998), Beckers (1972, 1968)

Reviews and topical papers in proceedings: Rutten (2013, 2010a,b,c, 2008, 2007, 2006), Judge (2010, 2009, 2006), Ayres *et al.* (2009), De Pontieu (2007), Peter (2002), Kneer and von Uexküll (1999), Suematsu (1998), Ulmschneider (1981)

Presentations and lecture notes: Judge and Casini (2012), De Pontieu *et al.* (2008), Koza (2011), Kneer (2002)

Conference proceedings: Heinzel *et al.* (2007), Guyenne (1998), Carlsson (1994), Lites (1985), Athay (1974)

Monographs: Athay (1976), Bray and Loughhead (1974)

2. What drives chromospheric fine structure?

Figure 1 portrays the chromosphere in the Hα line center. It shows a thick hedge-row of limb spicules and bewildering mass of on-disk fibrils. The image was taken by the Dutch Open Telescope[2] (Hammerschlag and Bettonvil, 1998; Bettonvil *et al.*, 2003; Rutten *et al.*, 2004) on 2005 October 4 at 09:38:40 UT. Figure 2 shows historical histograms of true heights of spicules after correction for the limb truncation, the average being $h = 9800\,\mathrm{km}$ (left panel), and the upward velocities of spicules with the average $v = 24\,\mathrm{km\,s^{-1}}$ (right panel). The distributions were obtained by Lippincott (1957) and the plots are from Bray and Loughhead (1974). Beckers (1972) reported similar values of spicule lengths of $6500-9500\,\mathrm{km}$ and velocities of $25\,\mathrm{km\,s^{-1}}$. Modern values for active-region parabolic spicules are $h = 6870 \pm 1.28\,\mathrm{km}$ and $v = 30 \pm 9\,\mathrm{km\,s^{-1}}$ inferred by a sample of 112 spicules identified by a semi-automated procedure (Pereira *et al.*, 2012).

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[2] http://dotdb.strw.leidenuniv.nl/DOT/

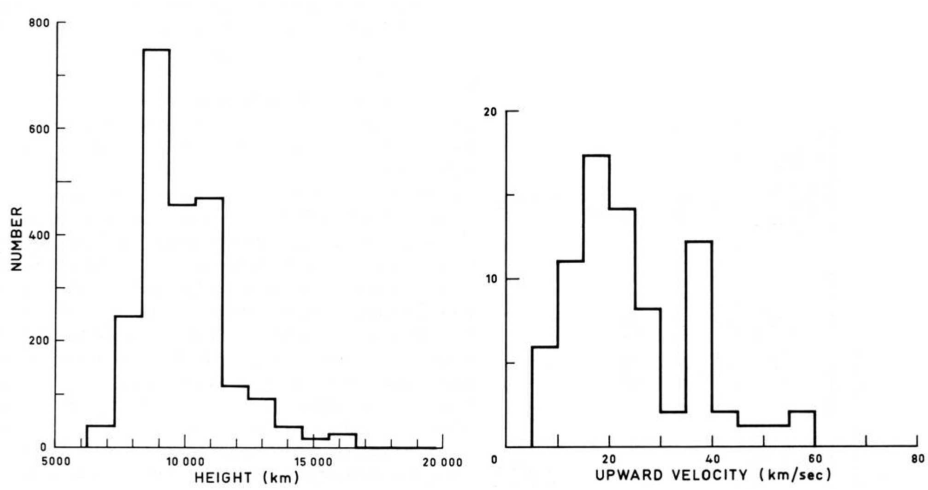

Figure 2: The histograms of true heights (left) and upward velocities (right) of spicules.

Assuming that observed extensions and retractions of spicules are due to a brief initial impulse followed by a ballistic motion with a parabolic trajectory (see: Nishikawa 1988; Christopoulou *et al.* 2001; De Pontieu *et al.* 2007c; Anan *et al.* 2010; Pereira *et al.* 2012) in homogeneous gravitational field with an apex at h and that v represents the onset or maximum velocity allotted by the impulse, than measured h and v should obey approximately $h = v^2/2g$, where $g = 274\,\mathrm{m\,s^{-2}}$ is the solar gravity acceleration. However, this concept clearly fails, because observed h and v imply large onset velocity of $\approx 60 - 70\,\mathrm{km\,s^{-1}}$ and short spicules with heights $\approx 1000 - 2000\,\mathrm{km\,s^{-1}}$. This apparent discrepancy invoked an array of models and mechanisms, summarized in Sterling (2000), furnishing spicular plasma with additional lift pulling it higher than given by small onset velocity.

Plausible physical mechanism, generating active-region spicules and DFs as their very likely disk counterparts (Pereira *et al.*, 2012), was suggested in De Pontieu *et al.* (2004) and elaborated later in the studies referred to in introduction. An important clue provided cospatiality of a plage region with slanted magnetic fields dominated by 5-min oscillations containing Hα DFs with lifetimes of order 5 min. But the presence of acoustic p-modes of 5-min oscillations in the chromosphere was a mystery, because these should be evanescent in the photosphere. This is governed by the acoustic cutoff

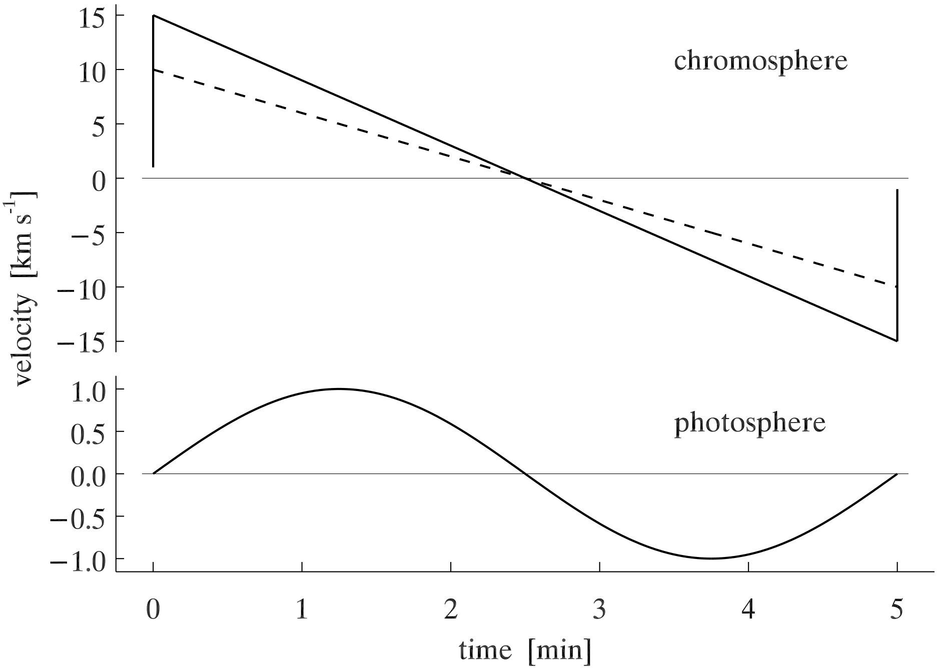

Figure 3: Conversion of a sinusoidal photospheric oscillation into the N-shaped sawtooth-like chromospheric shock wave of the same period but with much higher amplitude than the photospheric oscillation. The dashed line illustrates the case of shock wave with lower amplitude and smaller deceleration than the shock represented by the solid line. Ordinate values are arbitrary.

period $P_{\rm ac}$ given for an isothermal atmosphere by

$$P_{\rm ac} = \frac{4\pi H}{c_{\rm s}} = \frac{4\pi}{g\cos\theta}\sqrt{\frac{RT}{\gamma\mu}}\ , \qquad (1)$$

where $H = RT/\mu g$ is pressure (density) scale height, $c_{\rm s} = \sqrt{\gamma RT/\mu}$ is sound speed, $R = 8314.51\,{\rm JK^{-1}kmol^{-1}}$ is gas constant, T is temperature, μ is mean molecular weight, $g = 274\,{\rm m\,s^{-2}}$ is surface gravity acceleration, $\gamma = 5/3$ is adiabatic index, and θ is an inclination angle of wave propagation from vertical. At the temperature minimum region $T \approx 4200\,{\rm K}$ and $\mu \approx 1.25$ atomic mass unit, then $c_{\rm s} \approx 7\,{\rm km\,s^{-1}}$ and $H \approx 100\,{\rm km}$. The acoustic cutoff period for vertically propagating waves at $\theta = 0$ is $P_{\rm ac} \approx 3\,{\rm min}$, meaning that p-modes with period $P < P_{\rm ac}$ can propagate into the upper atmosphere

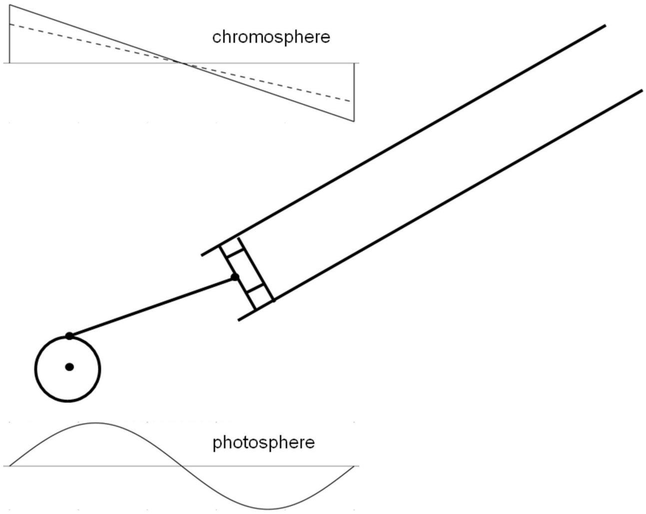

Figure 4: Model of an inclined magnetic fluxtube as a waveguide represented by a barrel and a piston with a periodic sinusoidal driver at the photosphere (Steiner, 2012). The oscillations steepen into N-shaped sawtooth-like shock waves as they propagate into the chromosphere along the fluxtube.

above the temperature minimum, but those with $P > P_{\mathrm{ac}}$ are rebound back. Since most of the photospheric oscillatory power is concentrated in the range of periods from 3.7 to 6.7 min, slant of a waveguide may increase P_{ac} above 3 min and let this power leak into the chromosphere. Assuming conservation of wave energy density with height $E = 0.5\rho v^2 = \mathrm{const.}$, where ρ is gas density, the wave velocity v increases fast due to exponential fall of density. Thus, originally sinusoidal wave may steepen into N-shaped sawtooth-like shock wave propagating up along an inclined fluxtube waveguide (Figs. 3 and 4). The field-guided shock may then uplift the chromosphere − transition region interface and load a magnetic fluxtube with chromospheric plasma seen as a spicule or fibril. According De Pontieu *et al.* (2007a,b), instant velocity $v(t)$ of the N-shaped sawtooth-like shock wave can be approximated by

$$v(t) = v_{\mathrm{max}} - at\,, \tag{2}$$

where v_{max} is shock amplitude, a is deceleration, and t is time. Integration of Eq. 2 yields a quadratic polynomial

$$y(t) = y_0 + v_{\max} t - \frac{a}{2} t^2 \,, \tag{3}$$

representing parabolic path of a plasma parcel experiencing the shock. A trivial consequence of Eq. 2 for $v(t = P/2) = 0$ is a linear relationship

$$v_{\max} = \frac{P}{2} a \,, \tag{4}$$

where P is a shock wave period. A positive correlation of the maximum velocity *versus* the deceleration and parabolic top trajectories of DFs, spicules, and mottles have been confirmed in many studies given in introduction. These support an idea of a piston driver converting power of 5-min photospheric oscillations into strong chromospheric shocks guided up along inclined magnetic fluxtubes (Fig. 4). This mechanism was suggested for active-region Hα DFs, but later it was applied for explaining quiet-Sun mottles, short DFs in sunspot, and active-region parabolic spicules, because Pereira *et al.* (2012) demonstrated similarity of their characteristics with on-disk DFs and mottles. Finally, Tian *et al.* (2014) found a positive correlation between the maximum velocity and deceleration in sunspot oscillations observed by the Interface Region Imaging Spectrograph (IRIS), suggesting also upward propagating magnetoacoustic shock waves.

3. Alternative scenarios

So far, we have concentrated only on 5-min oscillations as a plausible driver of piston in Fig. 4. However, simulations by Martínez-Sykora *et al.* (2009) showed that spicules can be driven by a variety of other mechanisms including collapsing granules, magnetic energy release, and convective buffeting of flux concentrations. Tziotziou *et al.* (2003) suggested that magnetic reconnection is the mechanism responsible for formation and dynamics of mottles arguing by bi-directional flows along these structures. But as numerical simulations in Hansteen *et al.* (2006) and De Pontieu et al. (2007a) showed, bi-directional flows occur also in some period of shock propagation.

Judge *et al.* (2011) has brought up a provocative idea, corroborated observationally by Judge *et al.* (2012), that spicules are not manifestations of plasma motion but instead warped current sheets, related perhaps to magnetic tangential discontinuities, analogous to striations of curtains blowing in the wind. This conjecture has been discussed extensively in Pereira *et al.* (2012) and Lipartito *et al.* (2014) concluding that chromospheric fine structures seem to bee populated by both tube-like and sheet-like structures.

Steiner (2012) also contemplates in his presentation other than 5-min-oscillation nature of the piston driver in Fig. 4. He puts forward that transverse swings of a flux tube with subsequent mode coupling to longitudinal waves could produce extensions and contractions of chromospheric fine structures (Ulmschneider *et al.*, 1991; Zhugzhda *et al.*, 1995; Osin *et al.*, 1999). Opposite longitudinal-to-transverse mode conversion was reported in Jess *et al.* (2012) showing that transverse waves of spicule was a direct result of longitudinal pressure oscillations occurring in the photosphere.

Finally, Murawski and Zaqarashvili (2010) explored the spicule formation in the framework of the rebound shock model. Their numerical simulations show that the strong initial pulse may lead to the quasi periodic rising of chromospheric material into the lower corona in the form of spicules with bi-directional flows.

4. State of the art and prospects

What is the state of the art and what are the next prospects in research of chromospheric fine structure? Radiation-MHD simulations and 3D non-LTE radiative transfer computations became sophisticated enough to reproduce Hα scene in first ever synthetic images with fibril-like dark structures tracing magnetic field lines (Leenaarts *et al.*, 2012). Observationally, since 17 July 2013 NASA's IRIS[3] spacecraft (De Pontieu *et al.*, 2014) delivers simultaneous spectroscopy and imagery of fine structure in UV Mg II h & k lines probing the upper chromosphere. Transition-region and coronal consequences are monitored in C II, Si IV, O IV, Fe XII, and Fe XXI lines with formation temperature from $\log T = 4.3$ up to 7.0 K. Interpretation of the IRIS observations is supported with results of dedicated state-of-the-art numerical simulations by Leenaarts *et al.* (2013a,b), Pereira *et al.* (2013), and Heinzel *et al.* (2014), yielding truly detailed insight into the formation of IRIS diagnostics. This complex approach promises to bring better understanding of a role of chromospheric fine structure in energizing of the upper solar atmosphere (De Pontieu *et al.* 2007d,2011; McIntosh *et al.* 2011).

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[3] `http://iris.lmsal.com/`

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