The Dynamic Chromosphere:
A Gentle Introduction to (some) Chromospheric Physics

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Second and third contact of the solar eclipse of March 29, 2006.
'Direct photographies of the chromosphere in the moment of the second and third contact [...] show, that it has a rough boundary and that it consists of a forest of flame-like light-tongues. [...] Despite that this “grass structure” of the upper chromosphere was already known at times of Secchi and nobody doubted that it is of greatest significance for the understanding of the entire solar atmosphere, is our knowledge about it still very limited. The chromospheric hairs are 1′′-2′′ thick and about 10′′, maximal 15′′ high and have a life-time of a few minutes'
1. The morphological vs. the physical picture (cont.)

Pietro Angelo *Secchi* S. J., 1818–1878

From *Le Soleil* (1875), Gauthier-Villars, Paris
For a brief moment the chromosphere flashes into view, its spectrum consisting of bright lines, appropriate to the tenuous gas. […] ‘Low density, however, is not alone the answer to the peculiarities of the flash spectrum.’ […] ‘A relatively simple calculation shows that the observed degree of excitation [of neutral helium] can arise only by the action of either intense ultraviolet radiation or fast-moving electrons. […] A temperature of 20,000° or 25,000° is indicated.’
1. The morphological vs. the physical picture (cont.)

‘[...] the prominences are merely local aggregations of a gaseous medium which entirely envelopes the sun [...]’ ‘The term *Chromosphere* is suggested for this envelope [...]’ in the *Proceedings of the Royal Society of London, 1868*
1. The morphological vs. the physical picture (cont.)

Construction of the VAL model

- Start with hydrostatic model atmosphere in radiative equilibrium.
- Solve the equations of statistical equilibrium together with the radiative transfer for spectral lines and continua and calculate the emergent spectrum.
- By trial and error, adjust the temperature distribution while keeping hydrostatic equilibrium so that the computed spectrum gets in best agreement with the observed one. → integrated over the chromospheric height range, radiative cooling $4600 \, \text{W} \, \text{m}^{-2}$.

Model C from Vernazza, Avrett, and Loeser (1981)

2. The dynamic chromosphere of network-cell interiors

Theoretical Ca II K (λ = 3933.7 Å) spectral-line profile. $K_{2V}$ and $K_{2R}$ denote the emission peaks on the violet side and the red side of the line-center absorption-dip $K_3$. $K_{1V}$ and $K_{1R}$ denote the dips near $Δλ = ±0.3$ Å from the line center. From Rutten & Uitenbroek (1991).
2. The dynamic chromosphere of network-cell interiors (cont.)

Observed Ca\textsc{ii} $K$ spectral line profile as a function of time. The abscissa corresponds to dispersion (wavelength), the ordinate to time. From Grossmann-Doerth et al. (1974).

2. The dynamic chromosphere of network-cell interiors (cont.)

Narrow-band (60 pm) filtergrams centered on the Ca II $K_{2\nu}$ emission reversal peak.

**Left:** Cumulative number of bright points over a time period of 350 min.

**Right:** Cumulative number in the subfield of the white square over a time period of 10 min. Distance between minor ticks $2''$. From Tritschler et al. (2007).
2. The dynamic chromosphere of network-cell interiors (cont.)

*Observed Ca II K* line spectrum as a function of time (*1st and 3rd column*) compared to the spectrum from the *simulation* (*2nd and 4th column*). The agreement exists not only in a statistical but in a true predictive sense. First $\sim 1000 \text{s}$ of the simulations suffer start-up effects. The velocity $100 \text{ km below}$ $\tau_{500} = 1$ was derived from the observations and served as time-dependent boundary condition for the simulation. From *Carlsson & Stein (1997).*

See also *Rammacher & Ulmschneider (1992, A&A 253, 586)* for similar simulations of the Ca II K and Mg II k lines.
2. The dynamic chromosphere of network-cell interiors (cont.)

DOES A NONMAGNETIC SOLAR CHROMOSPHERE EXIST?

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ABSTRACT

Enhanced chromospheric emission, which corresponds to an outwardly increasing semiempirical temperature structure, can be produced by wave motion without any increase in the mean gas temperature. Hence, the Sun may not have a classical chromosphere in magnetic field–free internetwork regions. Other significant differences between the properties of dynamic and static atmospheres should be considered when analyzing chromospheric observations.
2. The dynamic chromosphere of network-cell interiors (cont.)

**Solid thick:** $\langle T \rangle_t(z)$ of the dynamical model. **Thick dashed:** $T_{\text{rad}}(z)$ derived from the emerging radiation of the dynamical model. **Thin solid:** Boundaries of the temperature fluctuations in the dynamical model. **Dot-dashed:** Semi-empirical model derived from observed intensities. From Carlsson & Stein (1995).
2. The dynamic chromosphere of network-cell interiors (cont.)

- Carlsson & Stein (1995) demonstrated that a one-dimensional, hydrodynamical model that produced Ca II K grains was capable of producing the chromospheric temperature rise of the hydrostatic, semi-empirical model atmospheres (HSRA-type models) despite that the mean temperature would monotonically drop with height. They concluded that ‘the Sun may not have a classical chromosphere in magnetic field-free internetwork regions’.

- One could also say that the chromosphere in these regions is made up of the thin, hot post-shock material only. It produces enough photons in the UV to substantially rise the radiative temperature.

- This is indeed a very dynamic chromosphere, radically different from the hydrostatic chromosphere of the semi-empirical model atmospheres.
3. Towards a physical description of the morphological picture

- The morphological picture is now getting increasingly *enriched with physics*, rendering the former physical picture more and more obsolete.

- The *dynamic modeling* of the chromosphere in network cell interiors requires shock capturing hydrodynamic simulations with simultaneous solution of the non-LTE radiative transfer with time-dependent ionization and level population. It results in a chromosphere that is *radically different from the semi-empirical models*.

- Other objects of the morphological picture are about to be enriched with physics. For example, the *spicules*, the most conspicuous feature of the chromosphere.
3.1. Spicules

*Type I* spicules  
*Type II* spicules

Spicules at the Sun limb in *Ca II H 3968 Å* with Hinode SOT/BFI.

From *De Pontieu et al. (2007).*
### Properties of spicules as seen in Ca\(\text{II} H\) filtergrams

<table>
<thead>
<tr>
<th>properties</th>
<th>type I</th>
<th>type II</th>
</tr>
</thead>
<tbody>
<tr>
<td>max. length [km]</td>
<td>10’000, mostly &lt; 5000</td>
<td></td>
</tr>
<tr>
<td>diameter [km]</td>
<td>700 down to res. limit</td>
<td></td>
</tr>
<tr>
<td>life-time</td>
<td>3–7 min.</td>
<td>10–60 s</td>
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<tr>
<td>movement</td>
<td>up and down</td>
<td>up only</td>
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<tr>
<td>(xt)-plot</td>
<td>parabolic shape</td>
<td>acceleration with height</td>
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<tr>
<td></td>
<td></td>
<td>sudden disappearance</td>
</tr>
<tr>
<td>deceleration m s(^{-2})</td>
<td>50 &lt; (a) &lt; 400</td>
<td></td>
</tr>
<tr>
<td>speed km s(^{-1})</td>
<td>10–40</td>
<td>40–200</td>
</tr>
<tr>
<td>location</td>
<td>active region limb</td>
<td>coronal holes</td>
</tr>
<tr>
<td>on-disk counterparts (tentative)</td>
<td>dynamic fibrils</td>
<td>straws</td>
</tr>
<tr>
<td></td>
<td>mottles</td>
<td>RBEs/RREs</td>
</tr>
</tbody>
</table>
3.1. Spicules (cont.)

**Type I spicules**

Space-time diagrams of type I and type II spicules from Hinode SOT/BFI Ca II H filtegrams. From De Pontieu et al. 2007.

see also, e.g., Suematsu et al. (1995, ApJ 450, 411) or Christopoulou et al. (2001, S.P. 199, 61) for parabolic space-time paths. ⇒ type II in “hotter” channels
Wide scatter of decelerations. Linear correlation between maximal speed and deceleration for type I spicules, fibrils, and quiete Sun mottles.

From *De Pontieu et al. 2007*.

See also *Hansteen et al. (2006)* and *Rouppe van der Voort et al. (2007)*.
3.1. Spicules (cont.)

Space-time plot of the temperature. Envelopes of the cool chromospheric material are parabolae. From *Heggland et al.* (2007)

3.1. Spicules (cont.)

- Many earlier (magneto-)hydrodynamic models.

- Shock-train model proposed by

- Two-dimensional magneto-hydrodynamic simulations from the convection zone to
  the corona including radiation transfer taking coherent scattering effects into
  account, and including thin radiative losses and magnetic field-aligned heat
  conduction in the transition zone and corona by *Hansteen et al. (2006), ApJ L73,

- Three-dimensional type I spicule simulations by
  They find various driver mechanisms: p-mode oscillations, collapsing granules,
  breaking granules, flux emergence through the photosphere, magnetic energy
  release in the photosphere or in the lower chromosphere.
3.2. Magnetic pumping as a driver for dynamic fibrils

Schematic of the magnetic pumping effect. Downdrafts adjacent to a magnetic flux tube squeeze it and pump the internal plasma in the downward direction. As soon as this process stops, a strong, upward traveling rebound shock evolves with subsequent resonant oscillations. Courtesy, Y. Kato.

3.2. Magnetic pumping as a driver for dynamic fibrils (cont.)

*Left:* $z$-$t$-Diagram of the temperature up to 10’000 [K] from a two-dimensional simulation featuring the magnetic pumping effect. *Right:* Maximal velocity vs. deceleration of the jets seen in the left-hand panel. Courtesy, *Y. Kato.*
4. Vortical flows and photospheric-chromospheric coupling

Vortical flows in the photosphere

- Vortex flows: Brandt et al. (1988), Bonnet et al. (2008, 2010), Attie et al. (2009), Vargas Domínguez et al. (2010), Balmaceda et al. (2010), Manso Sainz et al. (2011);
- Vortex tubes (horizontal): Steiner et al. (2010).

Vortical flows in the chromosphere and transition region

- Giant tornadoes: Li et al. (2012), Su et al. (2012), Wedemeyer-Böhm et al. (2012), Su & van Ballegooijen (2013);
- Magnetic tornadoes: Wedemeyer-Böhm & Rouppe van der Voort (2009), Wedemeyer-Böhm et al. (2012);
- Rotating magnetic network fields: Zhang & Liu (2011);
- Explosive events: Curdt et al. (2012);
4. Vortical flows and photospheric-chromospheric coupling (cont.)

Chromospheric swirls

CRISP data. $\approx 0.25$ swirls arcmin$^{-2}$ s$^{-1} = 7.6 \times 10^{-3}$ swirls Mm$^{-2}$ min$^{-1}$

From *Wedemeyer-Böhm & Rouppe van der Voort (2009)*
Layered atmosphere from the *photosphere* (bottom panel: magnetogram, Fe I 630.2 nm continuum), through the *chromosphere* (Dopplergram, Ca II 854.2 nm) and the *transition region* (He II 30.4 nm) to the *low corona* (top: Fe IX 17.1 nm). Co-temporal observations with SDO/AIA (cadence, 12 s; image scale, 0.699'' per pixel) and SST/CRISP (cadence, 14 s; Ca II 854.2 nm; image scale, 0.0699'' per pixel).

Close-up of a swirl event that extends vertically from the surface to the top of the chromosphere at 2000 km. \( \tau_c = 1 \)-surface (grey) with overlaid magnetic field strength (colors) and magnetic field lines (red). The plasma flows along and co-rotates with the magnetic field (spiral streamlines). From www.solartornado.info.
An observed swirl (a-d) is compared to a simulated swirl (e-h) from a CO5BOLD model. The comparison includes magnetograms (a, e), the wide-band intensity (b, f), the core of the spectral line of Ca II at 854 nm (c, g), and the corresponding Doppler shift of the line core wavelength (d, h).

The successful reconstruction strongly suggests that chromospheric swirls are indeed the observational tracers of rotating magnetic flux structures.
4. Vortical flows and photospheric-chromospheric coupling (cont.)

3D, top, and side view of 1000 representative particle tracks over a time period of 10 min. Particles near the surface spiral downwards, particles in the chromosphere spiral up or down.

From Wedemeyer & Steiner (2014), PASJ.
5. Transition region loops

Small-scale transition region loops. IRIS Si iv 1400Å slit jaw images. From Hansteen et al. (2014), Science 346.
5. Transition region loops: photospheric/chromospheric counterparts?

*Left:* Continuum intensity (*top*) linear polarization (*middle*) circular polarization (*bottom*) of a granular loop.

*BOTTOM:* Granular loops in the photosphere and chromosphere in numerical 3-D simulations.

From *Ishikawa, Tsuneta & Jurčák (2010)*

From *Steiner et al. (2008)*
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Rompolt, B.: 1975, Spectral features to be expected from rotational and expansional motions in fine solar structures, S.P. 41, 329–348
De Pontieu, Rouppe van der Voort, L.H.M., McIntosh, S.W., et al.: 2014, On the prevalence of small-scale twist in the solar chromosphere and transition region, Science 346, id 1255732
Results from the Interface Region Imaging Spectrograph IRIS.

Left: Space-time diagrams for two spicules (A and B) in different channels. Top: Spicule images of two IRIS slit-jaw filtergrams, SOT Ca II H filtergrams, and the AIA He II 30.4 nm channel. The dotted line indicates the slit along which the space-time diagram for spicule A was constructed.

From Pereira et al. 2014. → back to §3.1
IRIS Dopplergrams in the chromospheric Mg II h 2803 Å line show a multitude of elongated red- and blueshifted features parallel and adjacent to each other.