

14th European Solar Physics Meeting, 8-12 September, 2014, Dublin, Ireland

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

Oskar Steiner

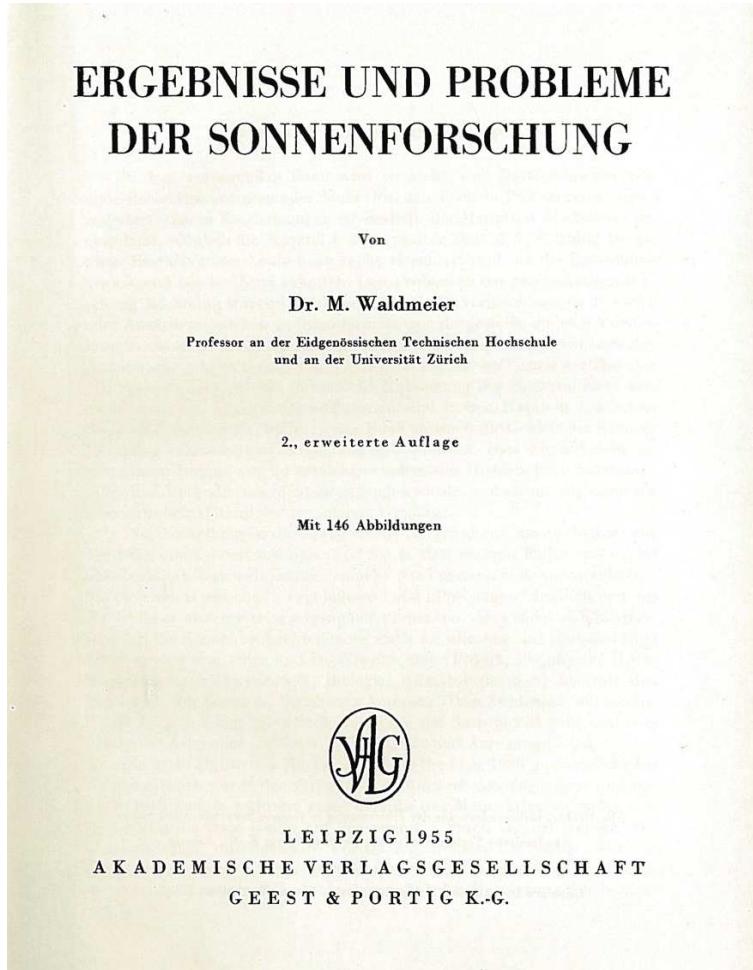
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Second and third contact of the solar eclipse of March 29, 2006.

1. The morphological vs. the physical picture

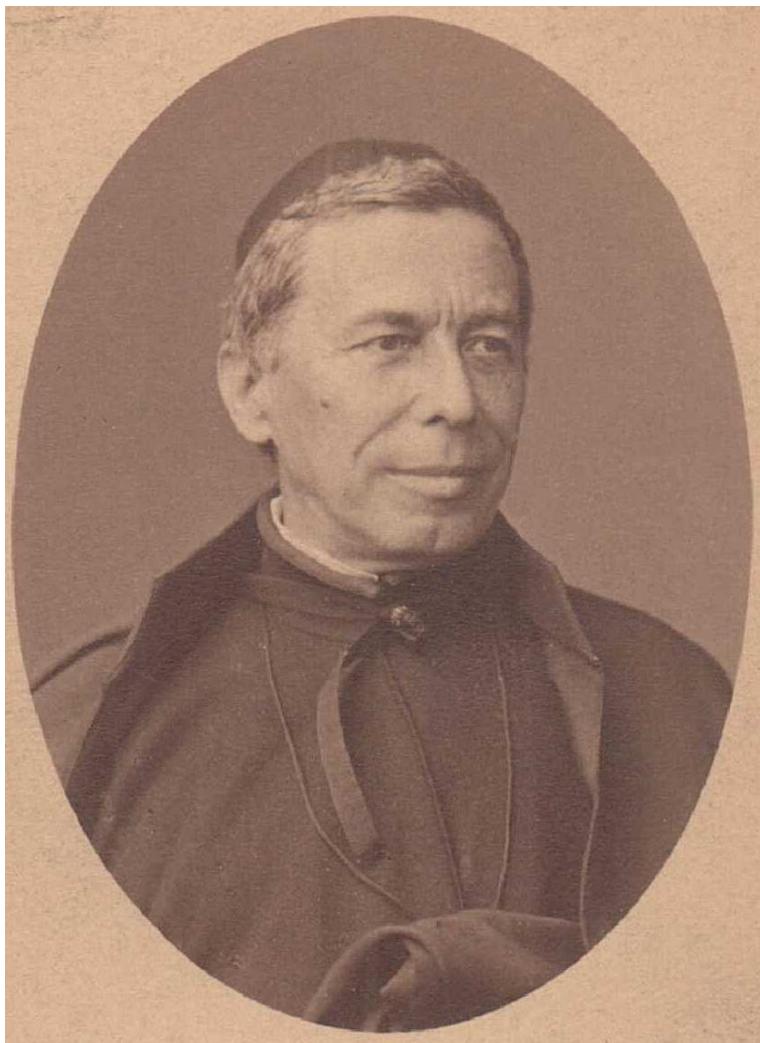


2nd edition, 1955

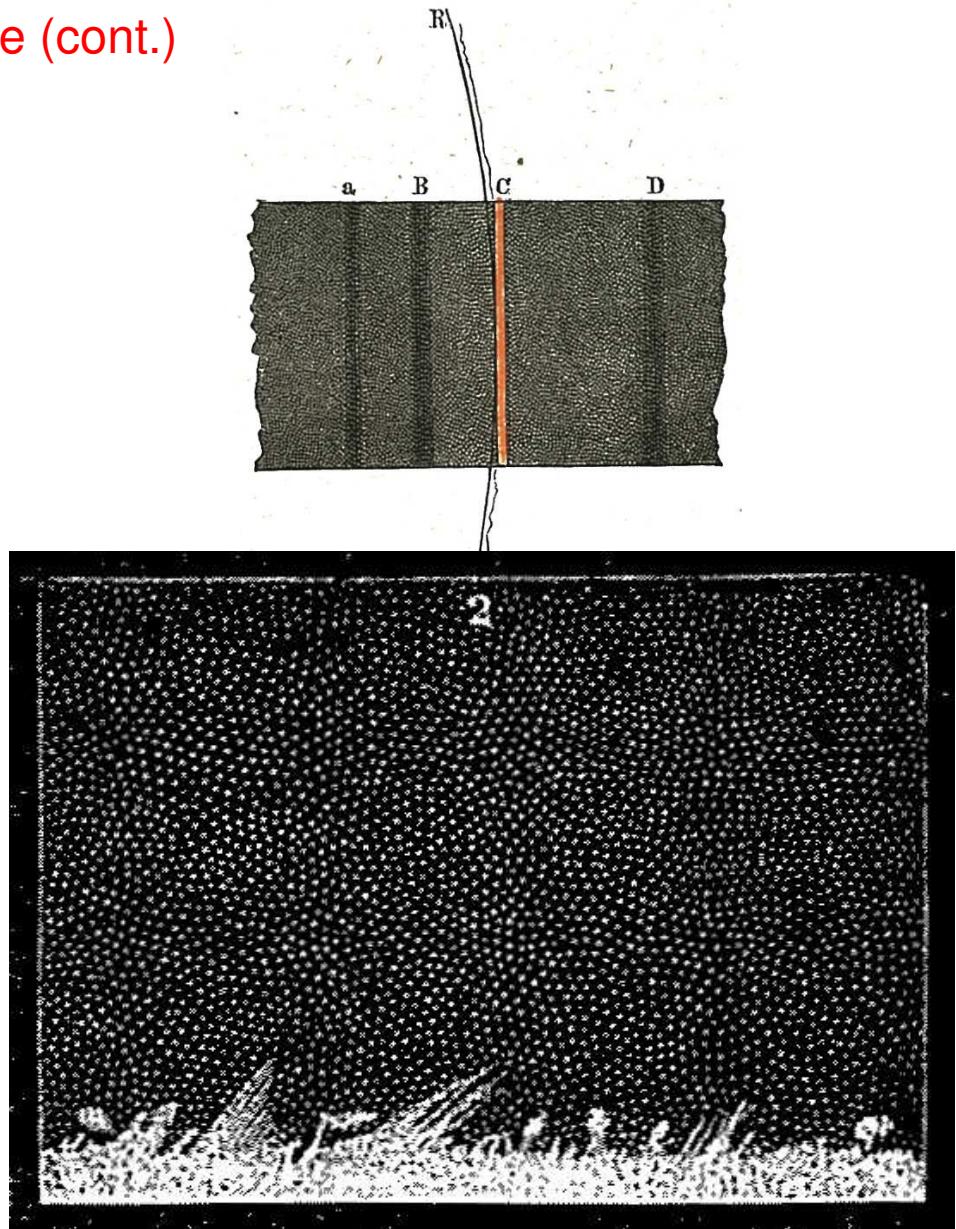
'Direct photographies of the chromosphere in the moment of the second and third contact [...] show, that it has a rough boundary and that it consists of a *forest of flame-like light-tongues*. [...] Despite that this "*grass structure*" of the upper chromosphere was already known at times of Secchi and 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*'

Max *Waldmeier*, 1912–2000

1. The morphological vs. the physical picture (cont.)

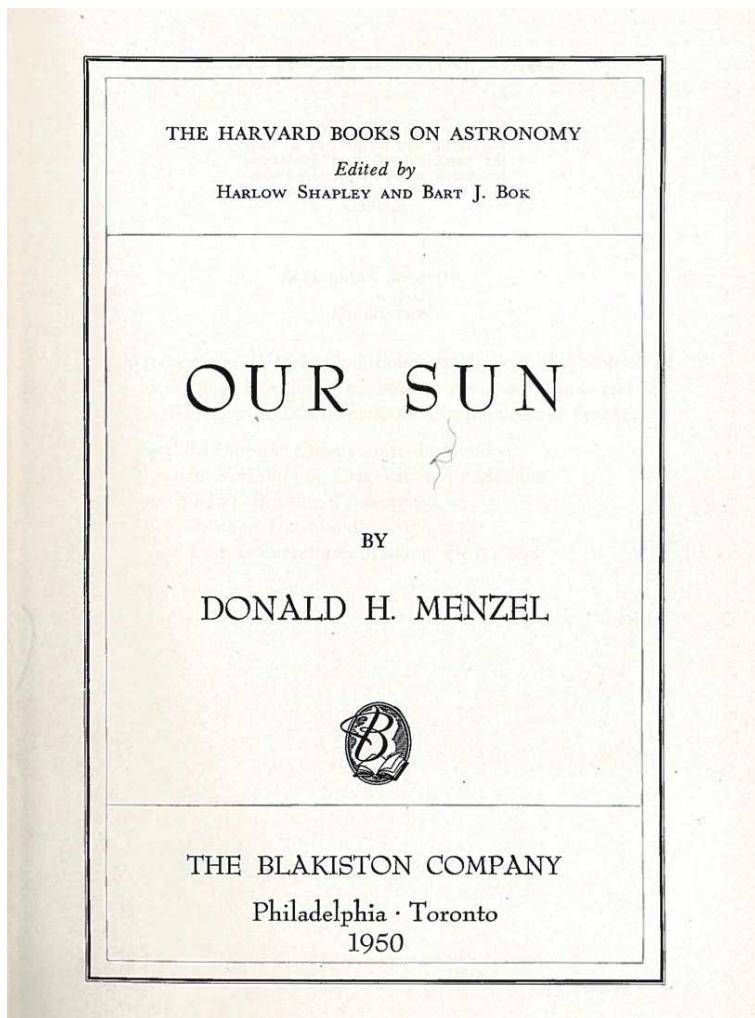


Pietro Angelo *Secchi* S. J., 1818–1878



From *Le Soleil* (1875), Gauthier-Villars, Paris

1. The morphological vs. the physical picture (cont.)



Our Sun, 1950

'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.'

Donald H. *Menzel*, 1901–1976

1. The morphological vs. the physical picture (cont.)



Sir Joseph Norman *Lockyer*, 1836–1920

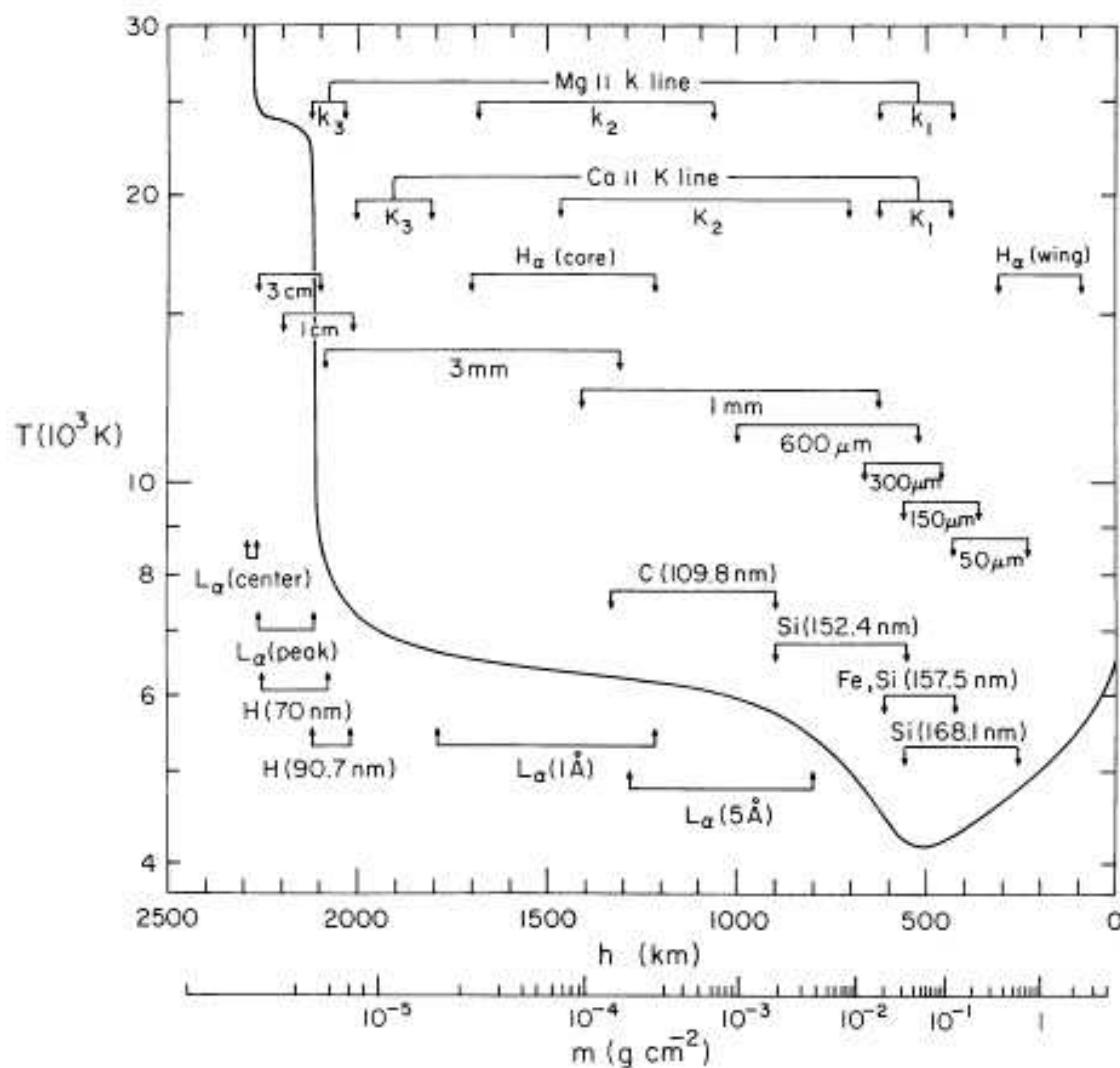


Sir Edward *Frankland*, 1825–1899

[...] 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*

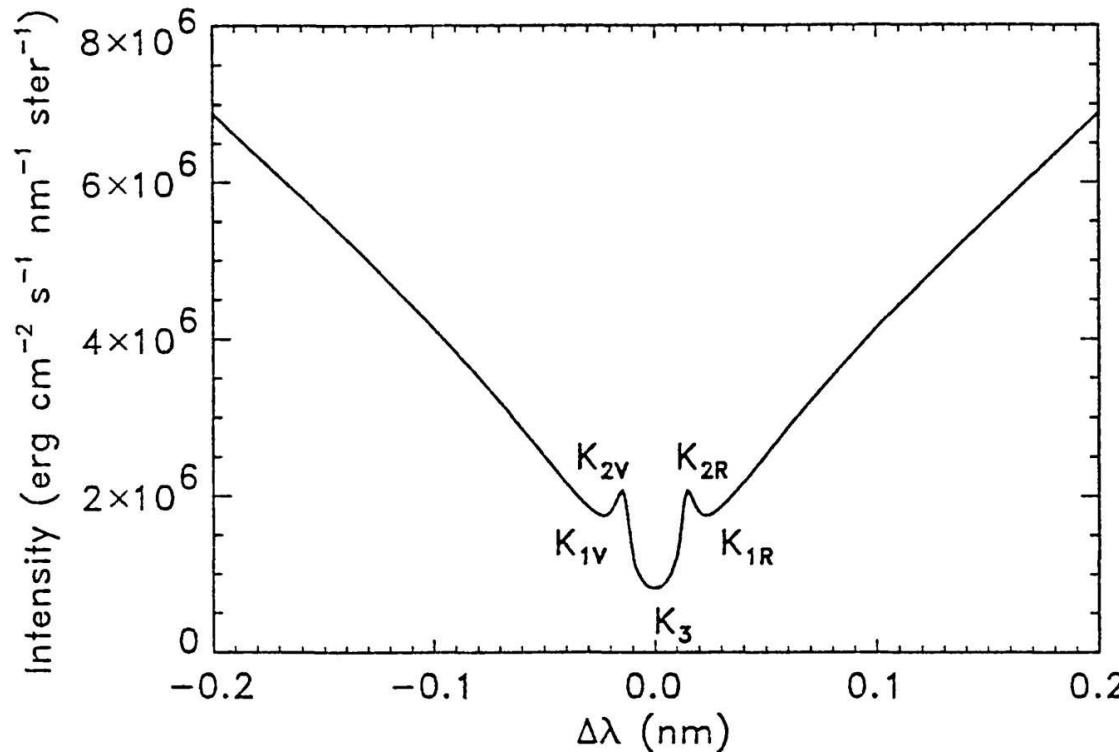


Model C from *Vernazza, Avrett, and Loeser (1981)*

ApJ Suppl. Ser. 45, 635-725

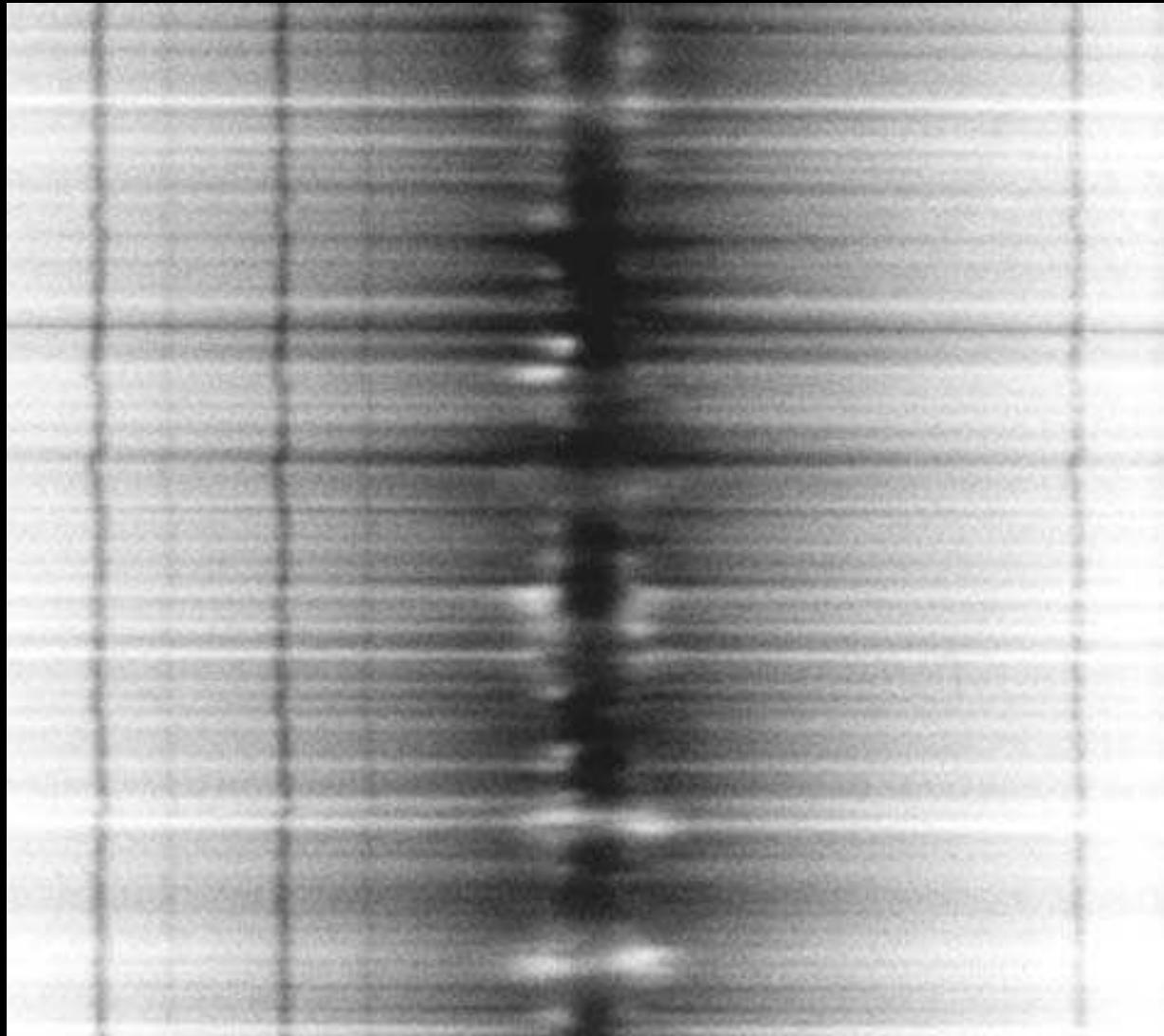
- Start with *hydrostatic model* atmosphere in radiative equilibrium.
- Solve the equations of statistical equilibrium together with the radiative transfer for spectral lines and continua and *calculate the emergent spectrum*.
- By trial and error, *adjust the temperature distribution* while keeping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

2. The dynamic chromosphere of network-cell interiors



Theoretical Ca II K ($\lambda = 3933.7$ 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 $\Delta\lambda = \pm 0.3$ Å from the line center. From *Rutten & Uitenbroek (1991)*.

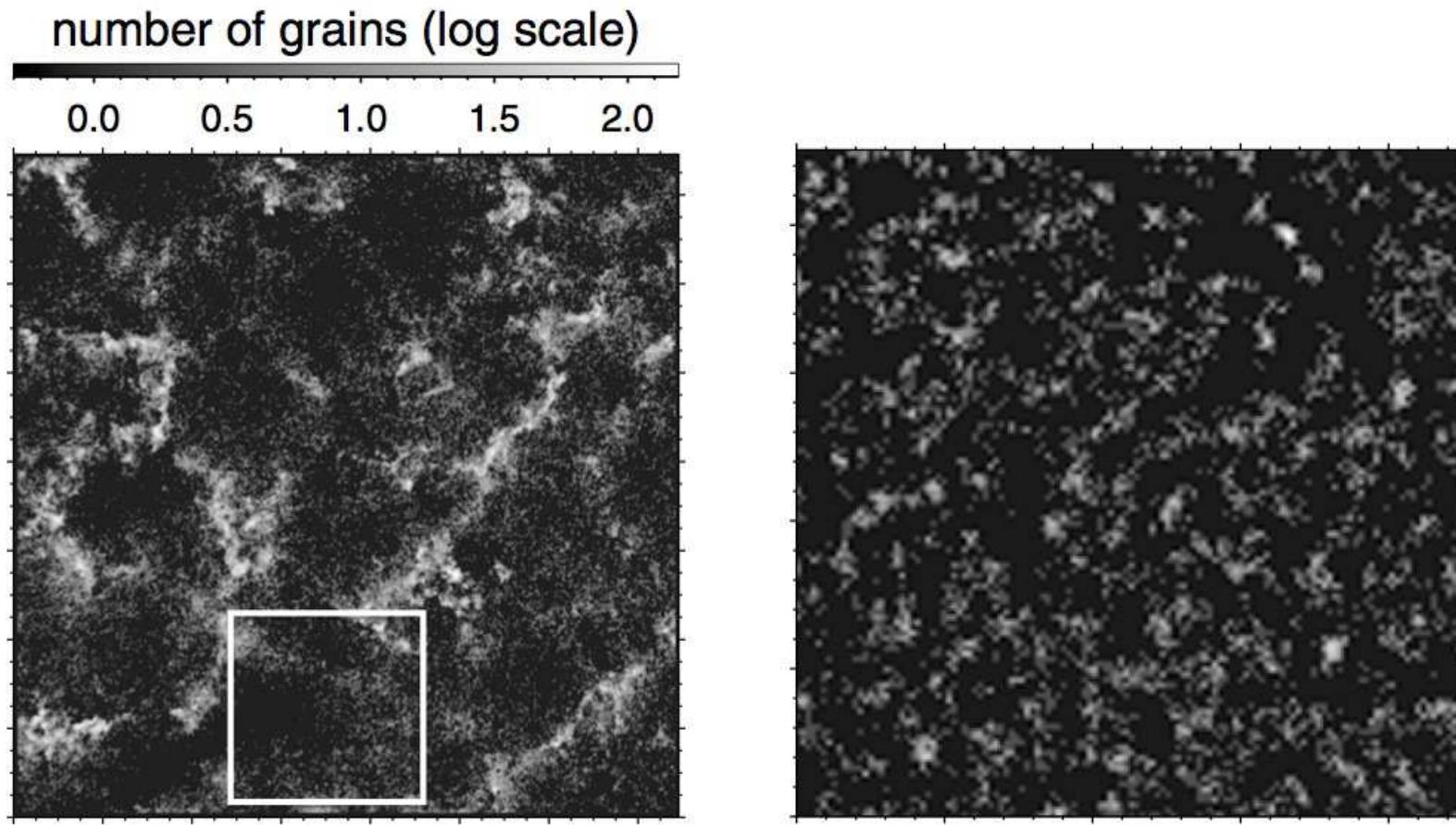
2. The dynamic chromosphere of network-cell interiors (cont.)



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

Explanation in terms of shock waves by *Rutten & Uitenbroek (1991)*.

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

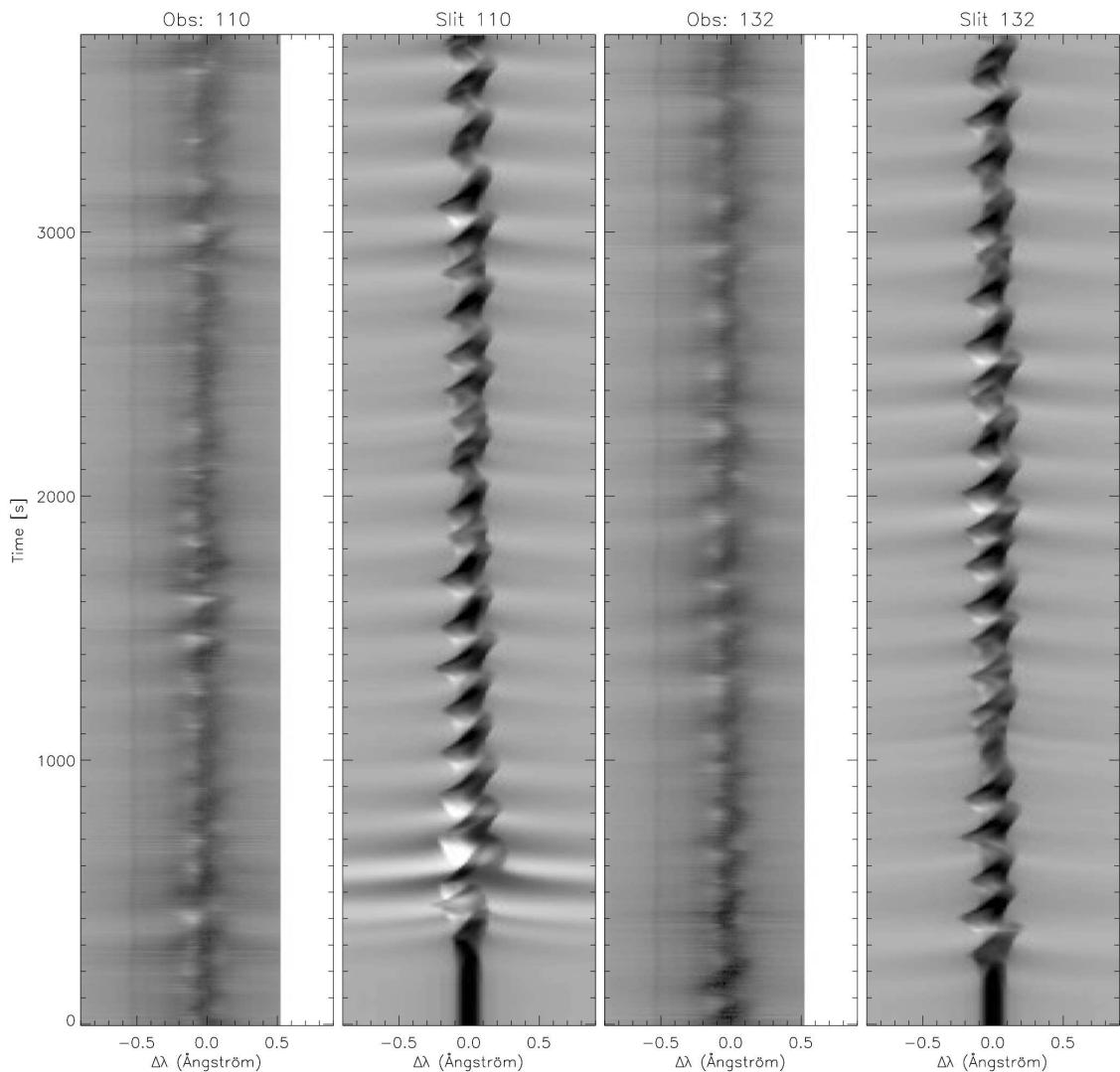


Narrow-band (60 pm) filtergrams centered on the Ca II K_{2V} emission reversal peak.

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 ~ 1000 s of the simulations suffer start-up effects. The velocity 100 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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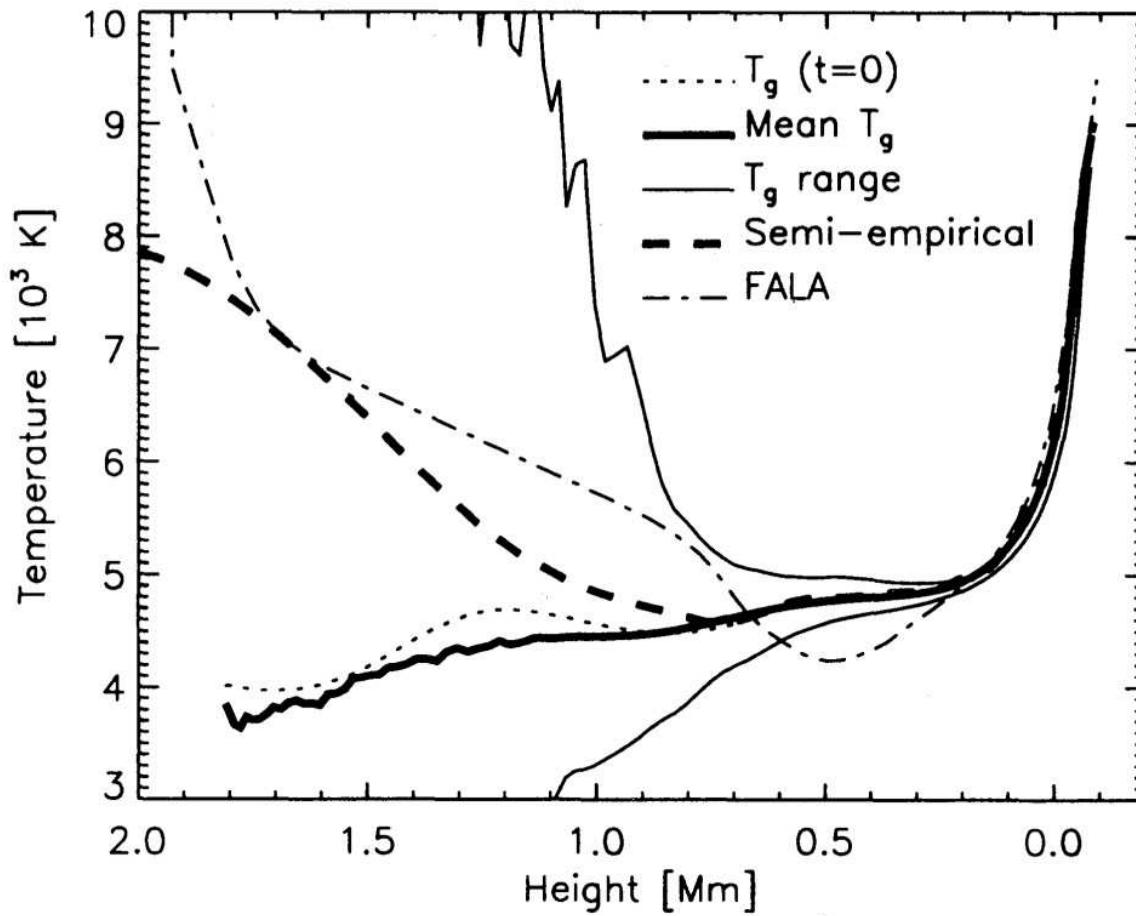
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Received 1994 August 25; accepted 1994 November 3

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.)

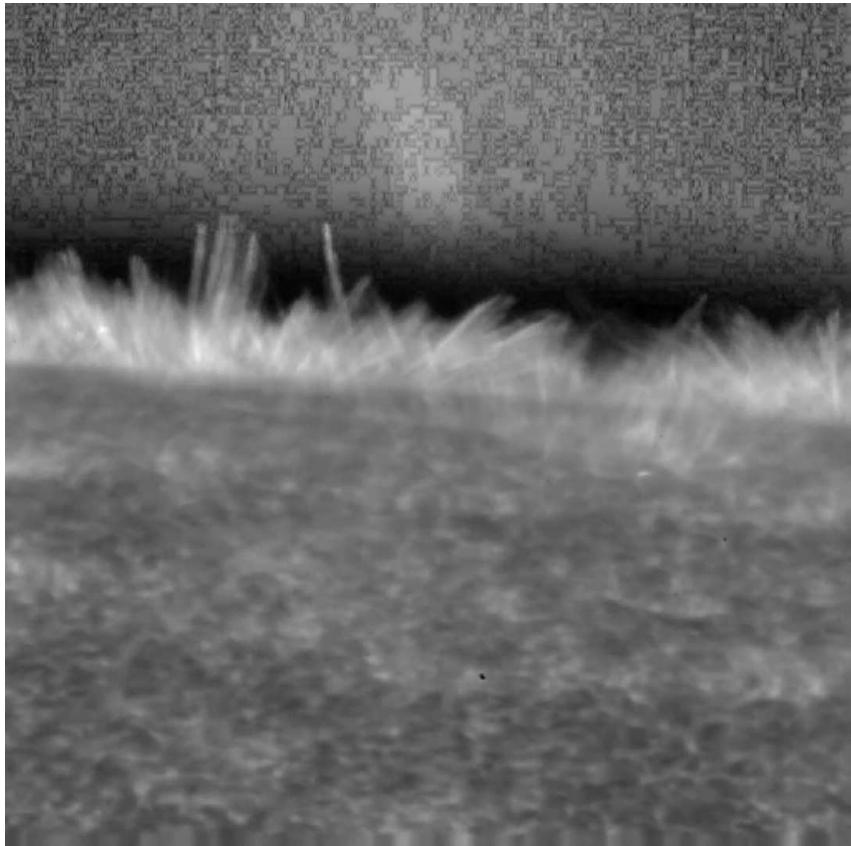
- Carlsson & Stein (1995) demonstrated that a one-dimensional, hydrodynamical model that produced Ca II K grains was capable of producing the *chromospheric temperature rise* of the hydrostatic, semi-empirical model atmospheres (HSRA-type models) *despite that the mean temperature would monotonically 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

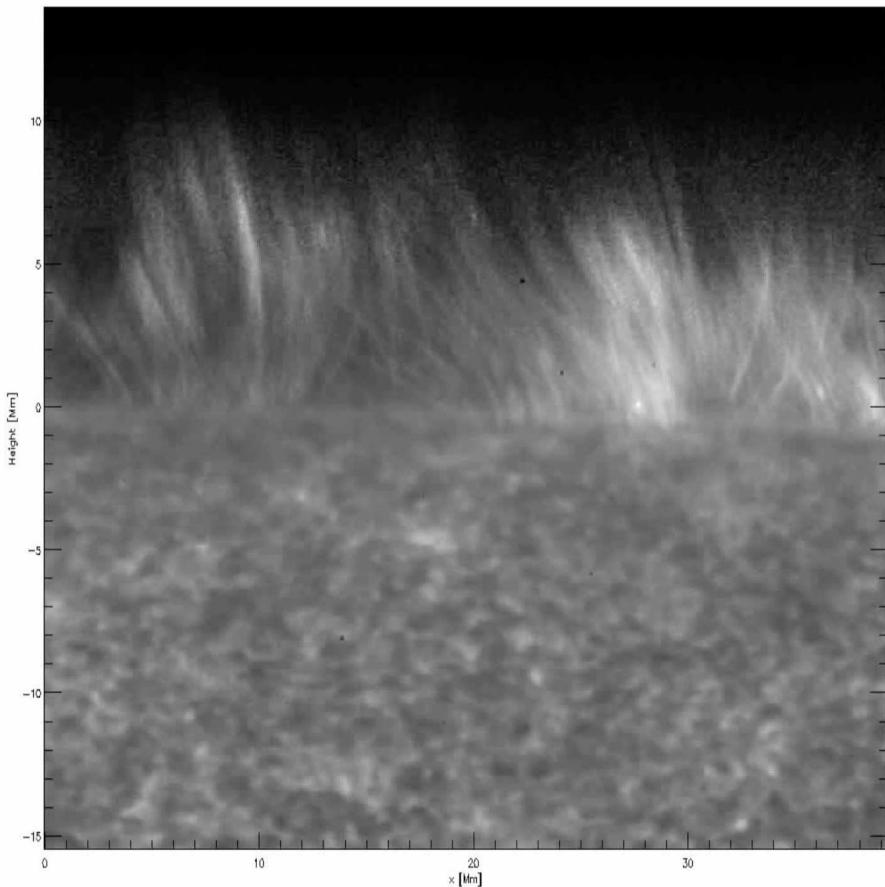
- The morphological picture is now getting increasingly *enriched with physics*, rendering the former physical picture more and more obsolete.
- The *dynamic modeling* of the chromosphere in network cell interiors requires shock capturing hydrodynamic simulations with simultaneous solution of the non-LTE 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 CaII H 3968\AA with Hinode SOT/BFI.

From *De Pontieu et al. (2007)*.

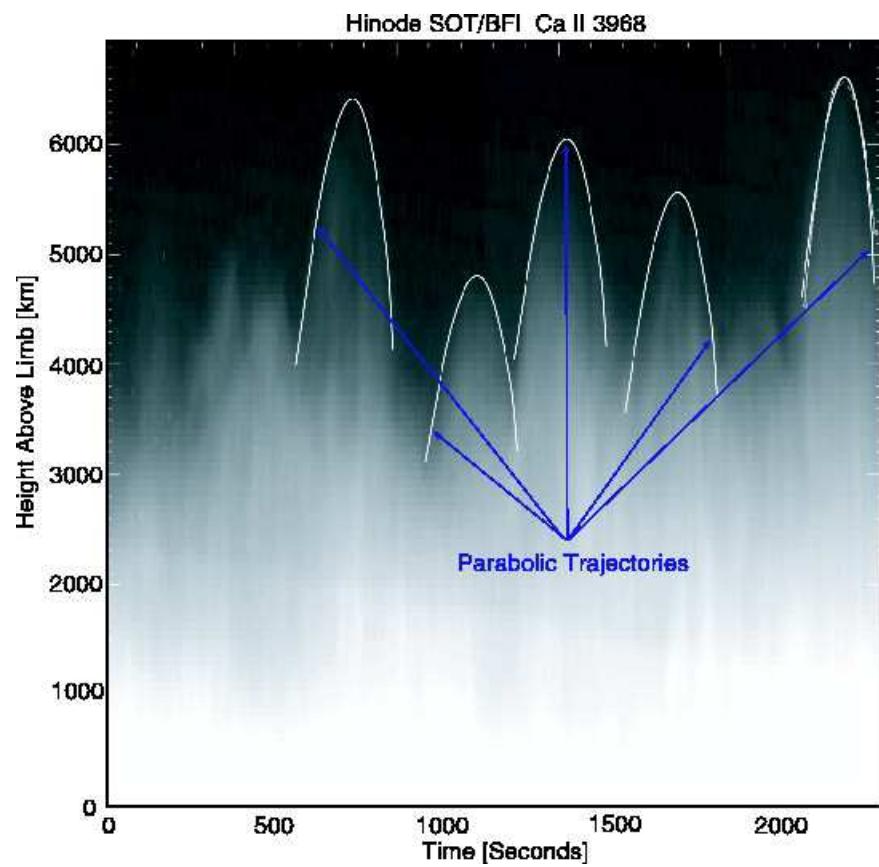
3.1. Spicules (cont.)

Properties of *spicules* as seen *in Ca II H filtergrams*

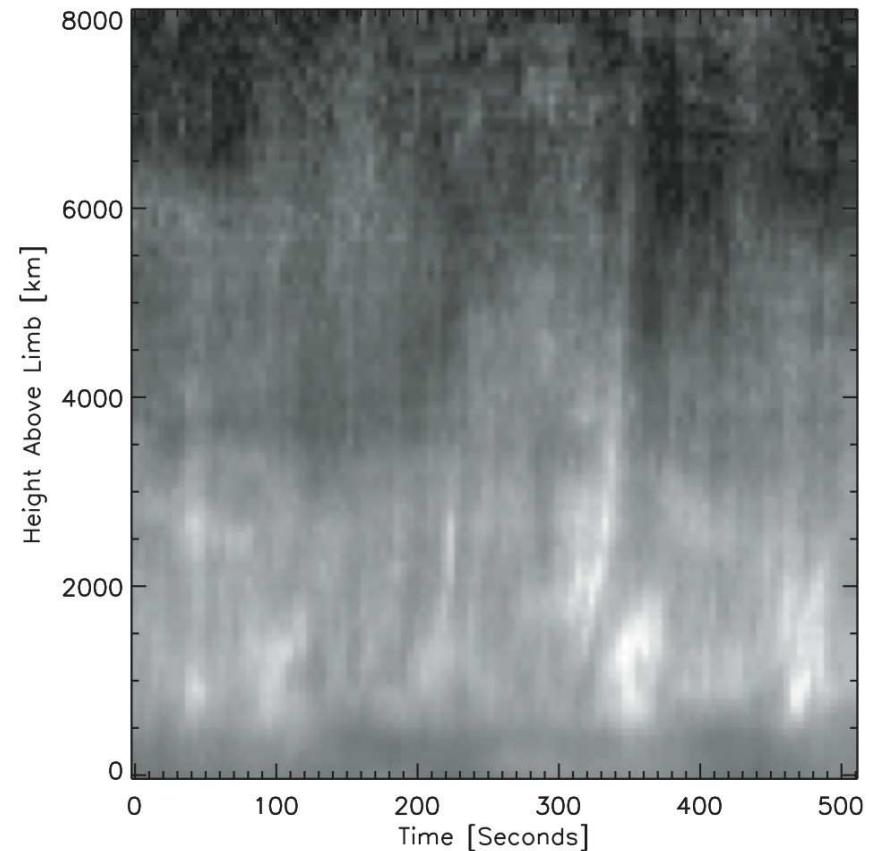
properties	type I	type II
max. length [km]	10'000, mostly < 5000	
diameter [km]	700 down to res. limit	
life-time	3–7 min.	10–60 s
movement	up and down	up only
<i>xt</i> -plot	parabolic shape	acceleration with height sudden disappearance
deceleration m s^{-2}	$50 < a < 400$	—
speed km s^{-1}	10–40	40–200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

3.1. Spicules (cont.)

Type I spicules



Type II spicules

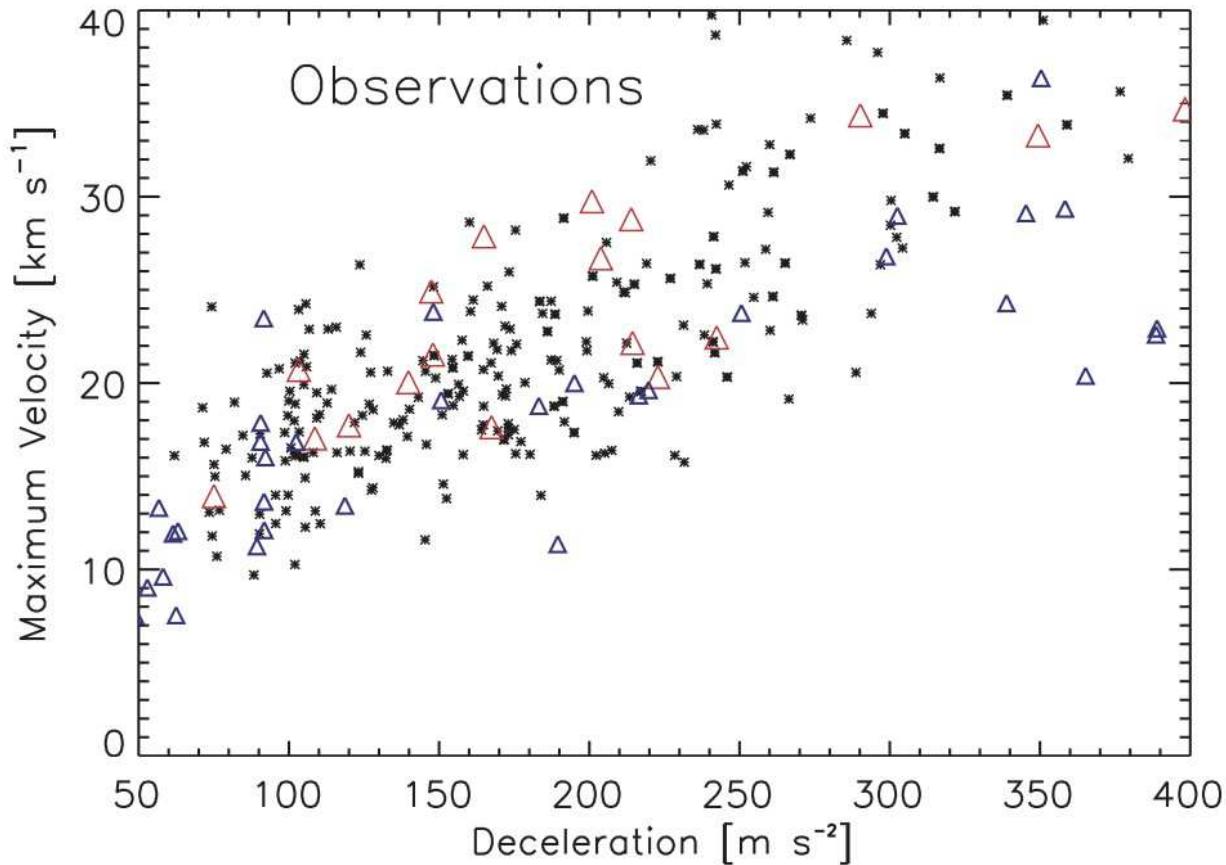


Space-time diagrams of type I and type II spicules from Hinode SOT/BFI Ca II H filograms. From *De Pontieu et al. 2007*.

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

3.1. Spicules (cont.)

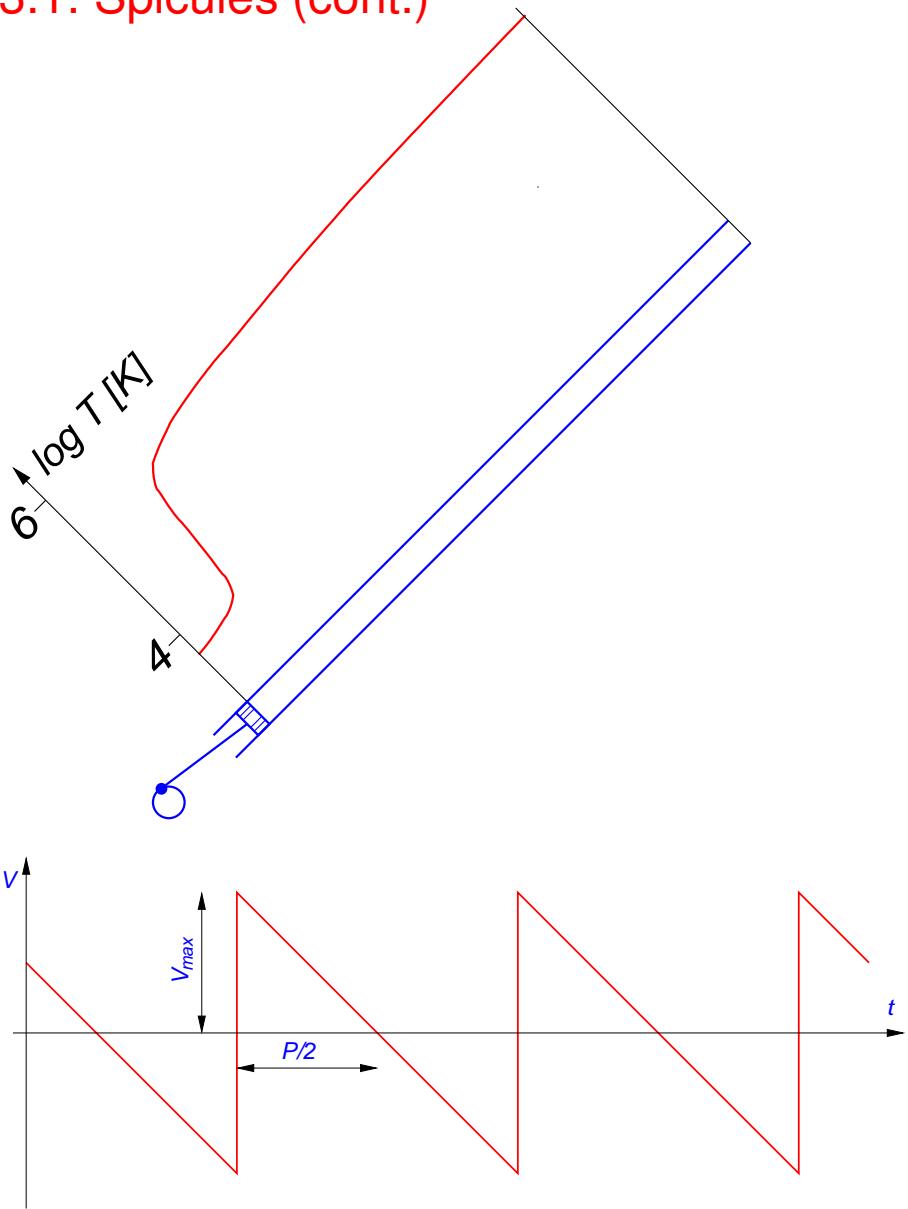


Wide scatter of decelerations. Linear correlation between maximal speed and deceleration for type I spicules, fibrils, and quiet Sun mottles.

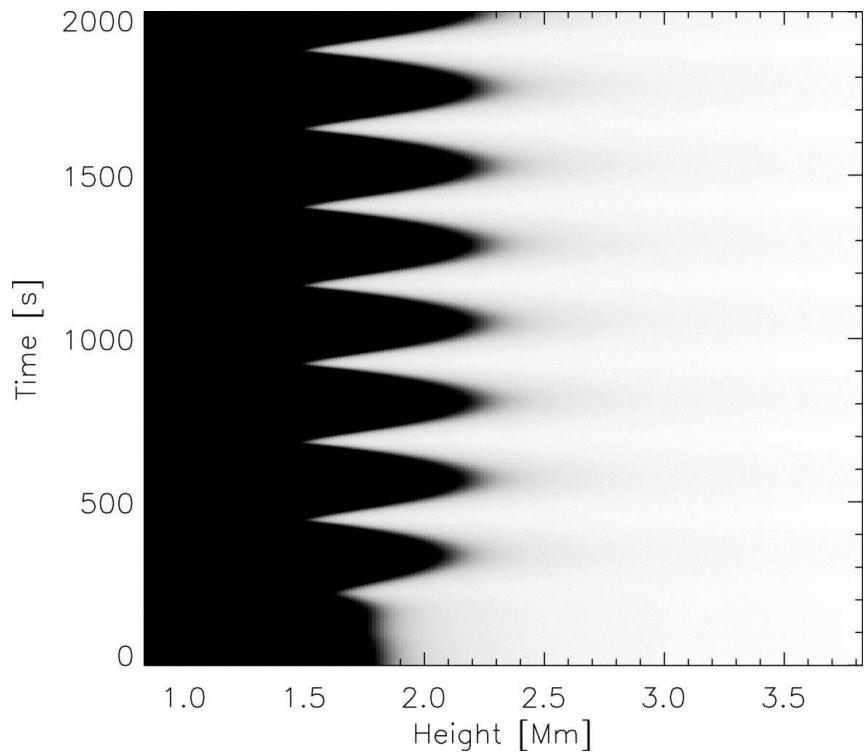
From *De Pontieu et al. 2007*.

See also *Hansteen et al. (2006)* and *Rouppé van der Voort et al. (2007)*.

3.1. Spicules (cont.)



Shock train. *Mihalas & Mihalas (1984)*



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.

See *Stirling (2000) S.P. 196, 79–111* for a review.

- Shock-train model proposed by

De Pontieu, Erdélyi & James (2004), Nature 430, 536.

- 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,*

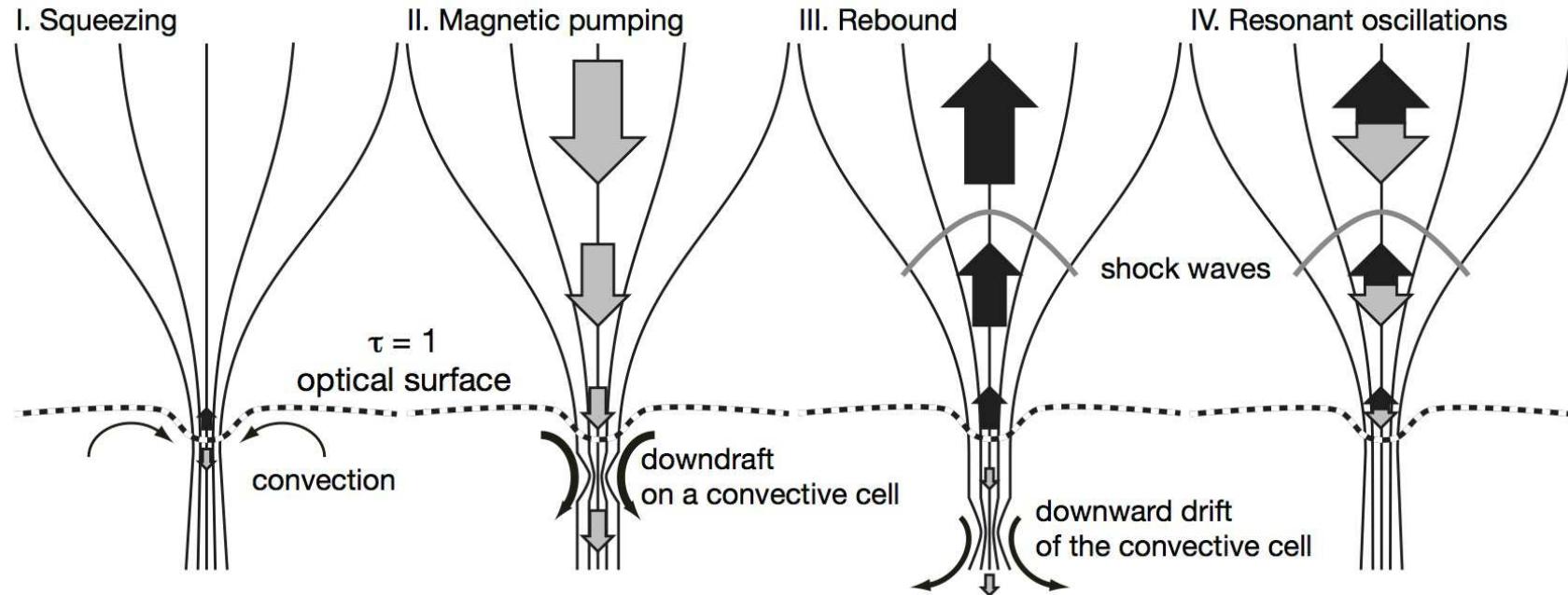
De Pontieu et al. (2007) ApJ 655, 624, and *Heggland et al. (2011) ApJ 743, 142.*

- Three-dimensional type I spicule simulations by

Martínez Sykora et al. (2009) ApJ 701, 1569

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.

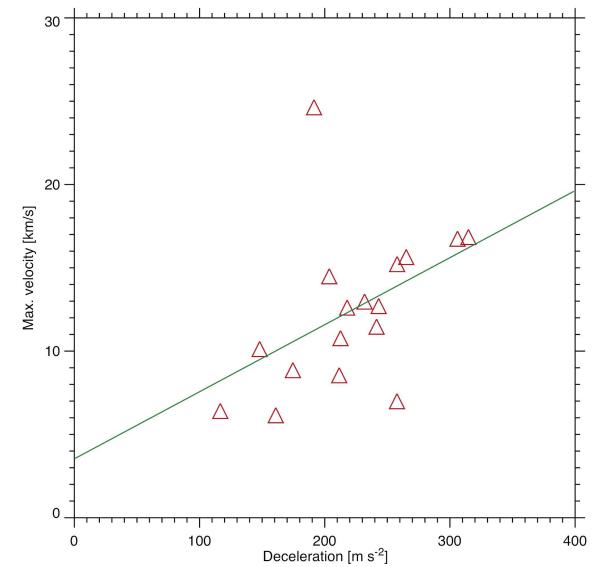
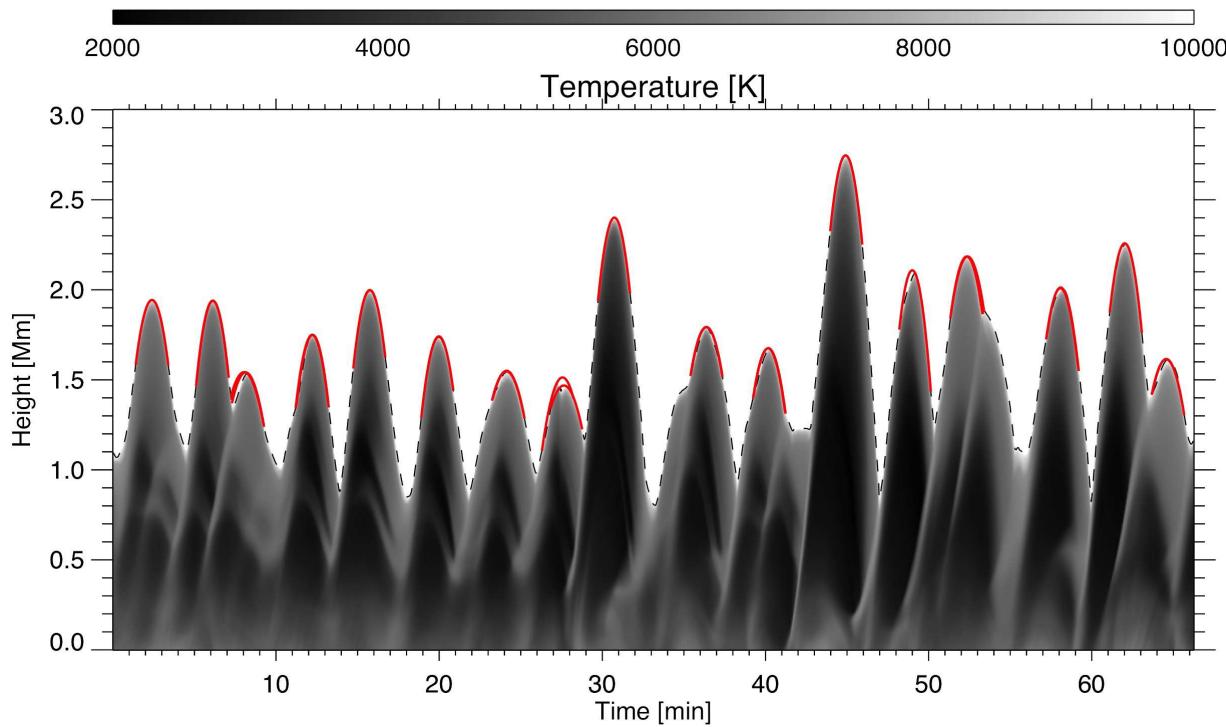
3.2. Magnetic pumping as a driver for dynamic fibrils



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*.

For 2-D simulations of it see *Kato et al. (2011) ApJ 730, L24*.

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

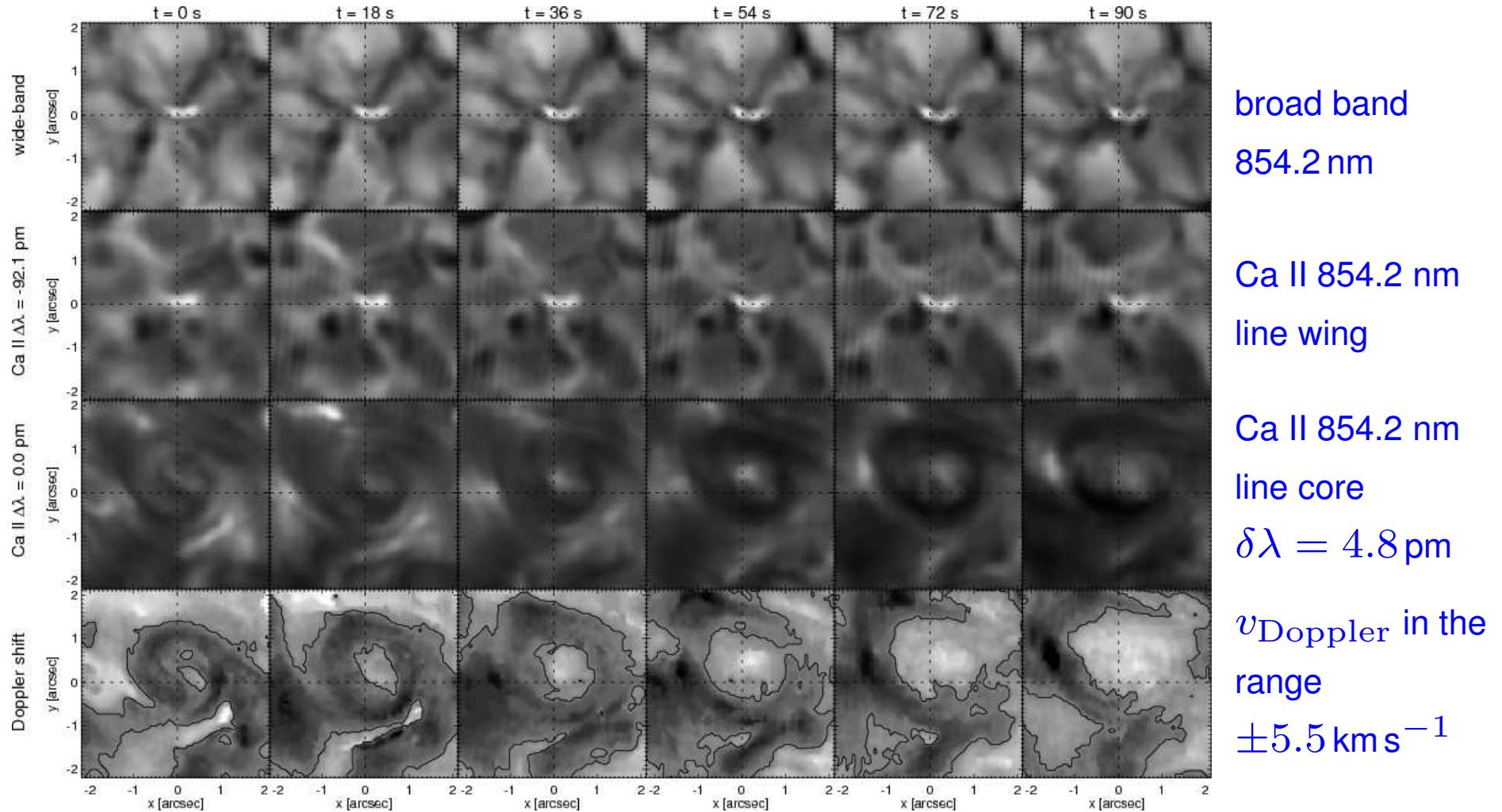
- Vortex flows: *Brandt et. al. (1988), Bonnet et al. (2008, 2010), Attie et al. (2009), Vargas Domínguez et al. (2010), Balmaceda et al. (2010), Manso Sainz et al. (2011);*
- Vortex tubes (horizontal): *Steiner et al. (2010).*

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);*
- Spicules: *Beckers (1968, 1972), Rompolt (1975), Pishkalo (1994), Pike & Mason (1998), Kamio et al. (2010), De Pontieu et al. (2012), De Pontieu et al. (2014).* \Rightarrow small-scale twist

4. Vortical flows and photospheric-chromospheric coupling (cont.)

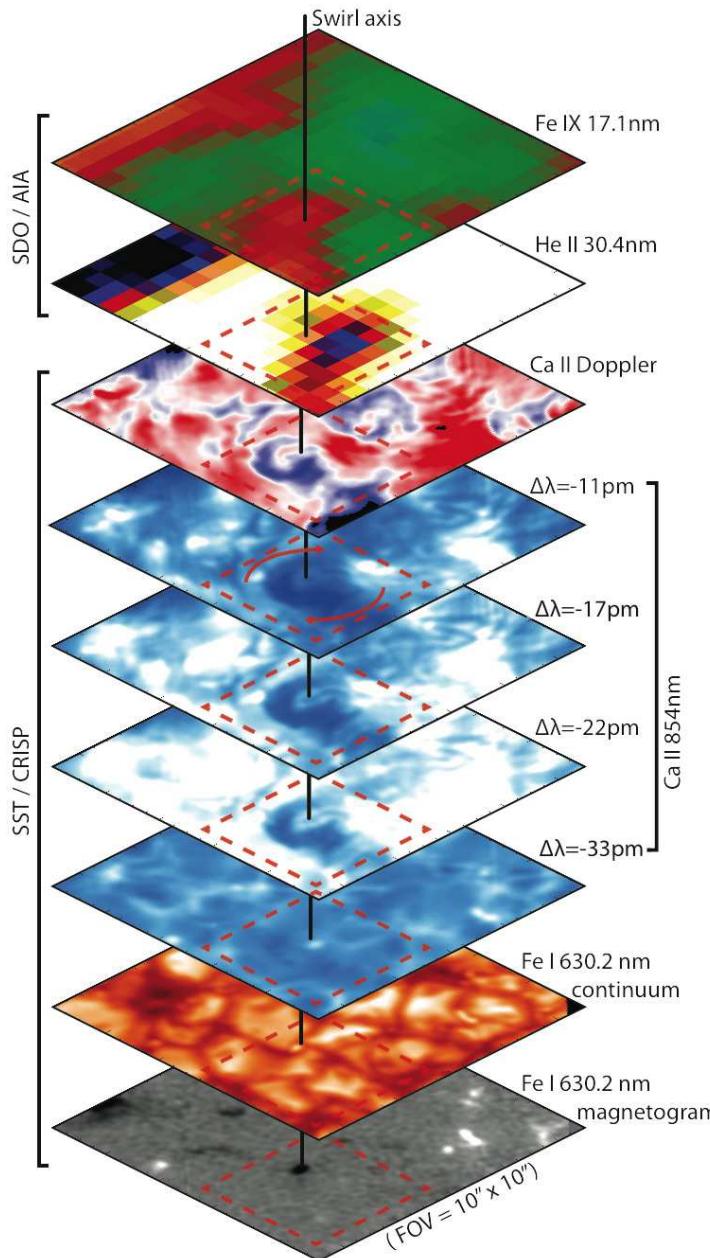
Chromospheric swirls



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

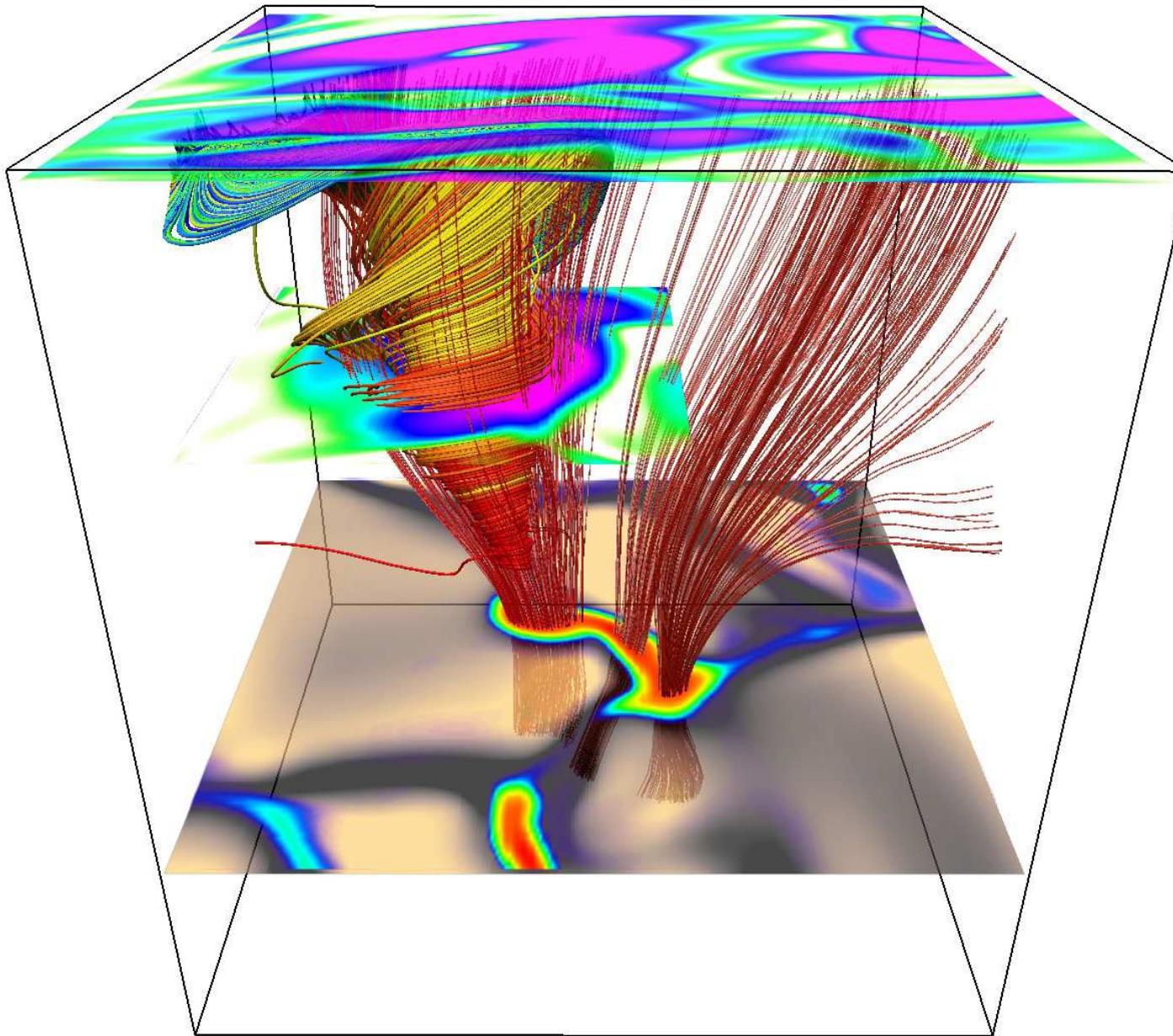
From *Wedemeyer-Böhm & Rouppe van der Voort (2009)*

4. Vortical flows and photospheric-chromospheric coupling (cont.)



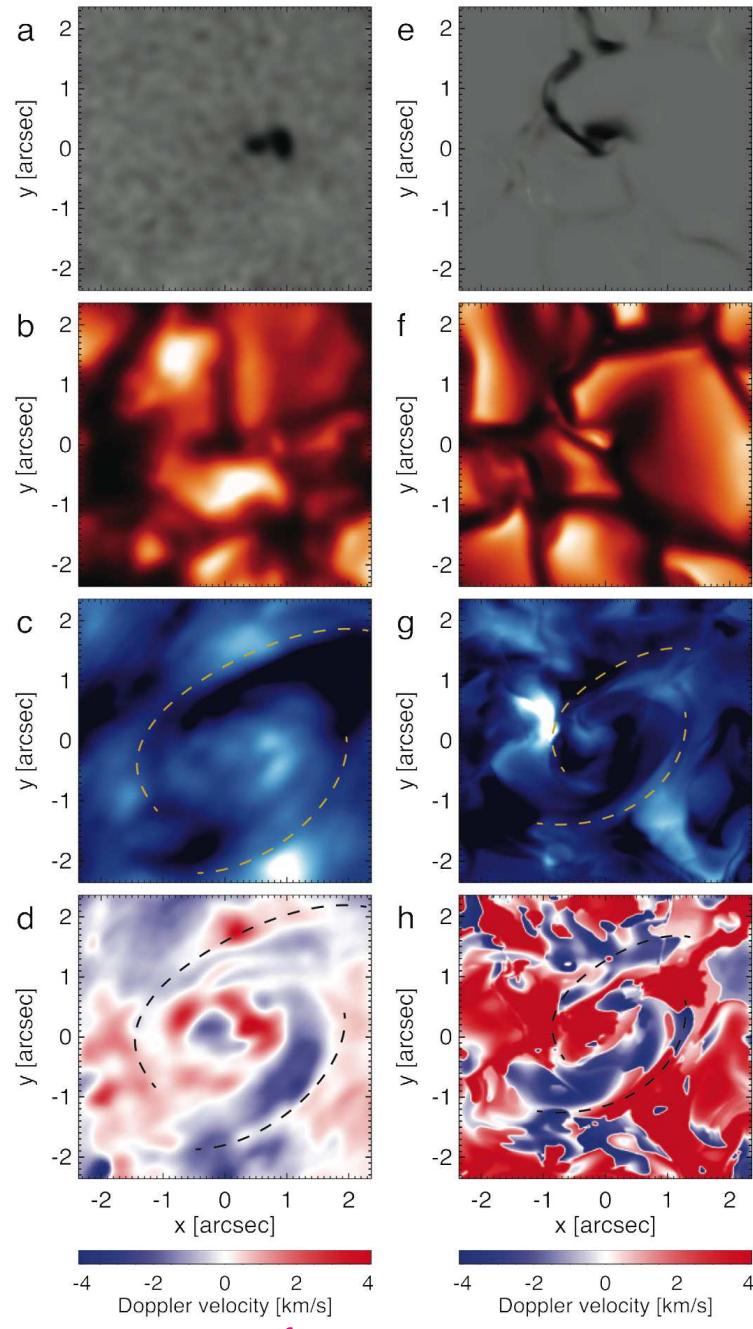
Layered atmosphere from the *photosphere* (bottom panel: magnetogram, Fe I 630.2 nm continuum), through the *chromosphere* (Dopplergram, Ca II 854.2 nm) and the *transition region* (He II 30.4 nm) to the *low corona* (top: Fe IX 17.1 nm). Co-temporal observations with SDO/AIA (cadence, 12 s; image scale, 0.699'' per pixel) and SST/CRISP (cadence, 14 s; Ca II 854.2 nm; image scale, 0.0699'' per pixel). From *Wedemeyer-Böhm et al. (2012) Nature 486, 505*.

4. Vortical flows and photospheric-chromospheric coupling (cont.)



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.

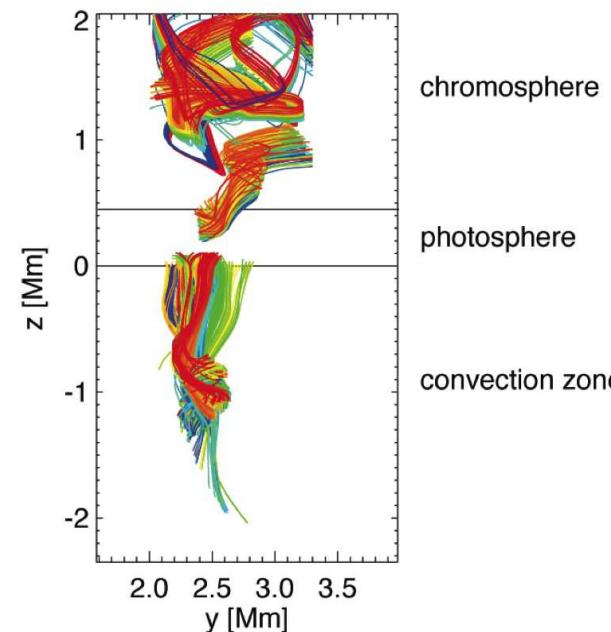
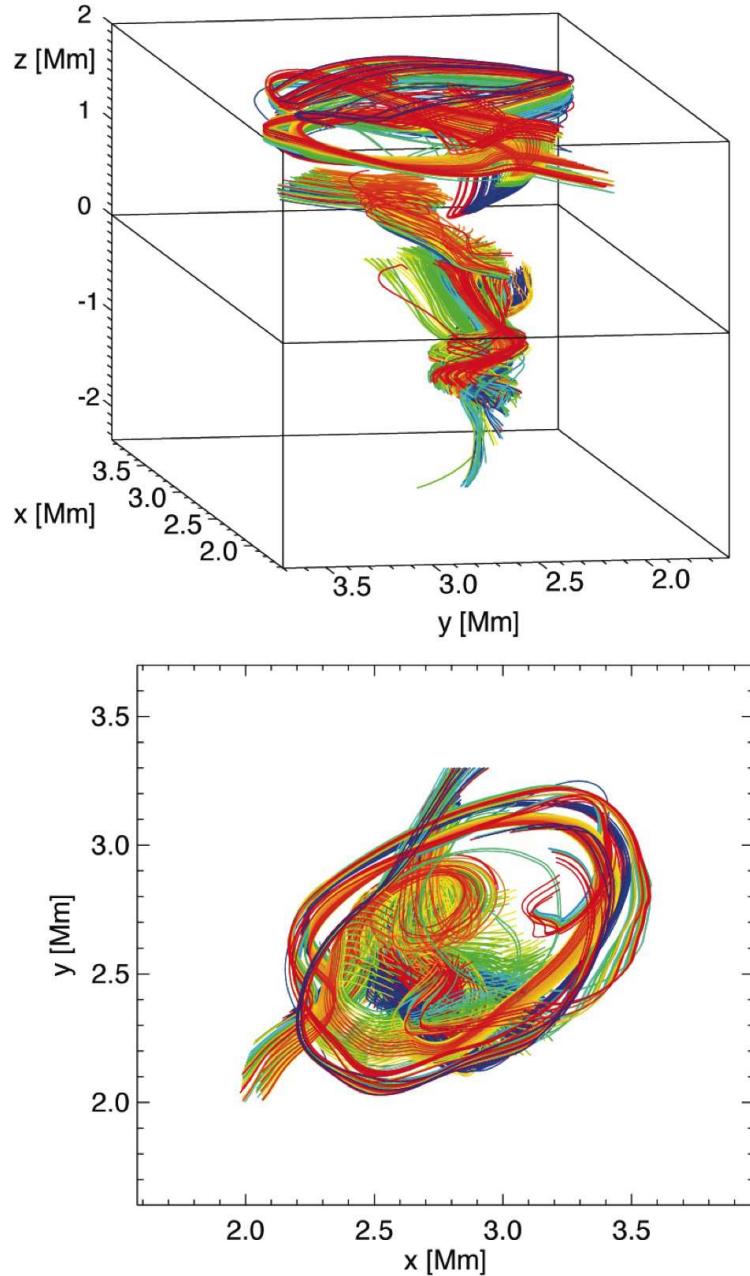
4. Vortical flows and photospheric-chromospheric coupling (cont.)



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.

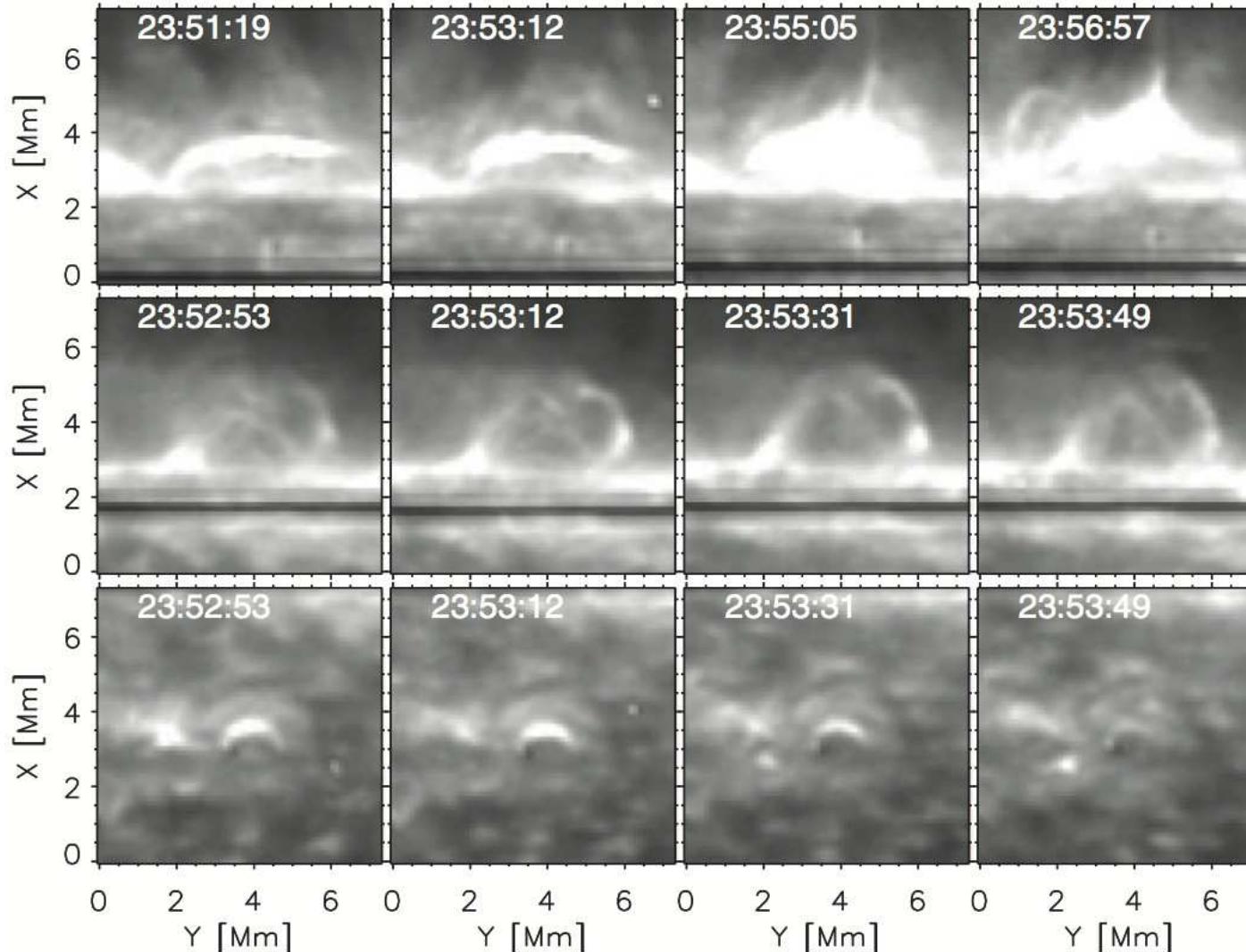
4. Vortical flows and photospheric-chromospheric coupling (cont.)



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.

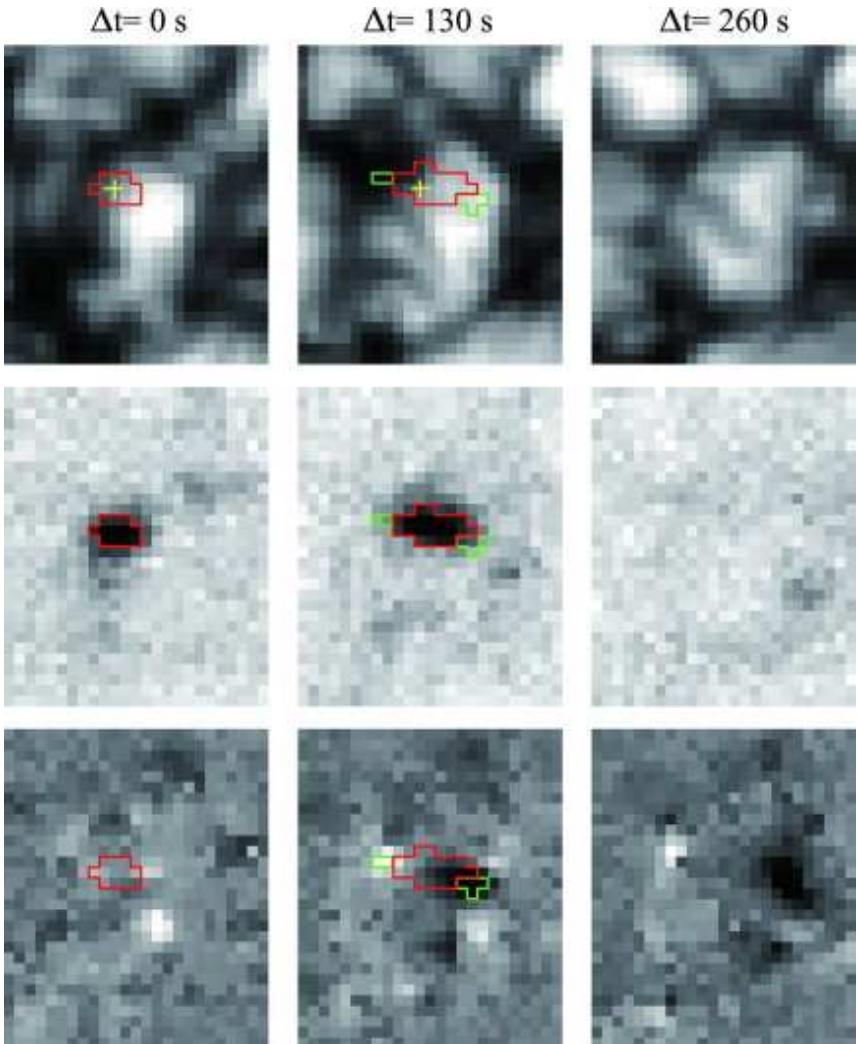
From *Wedemeyer & Steiner (2014), PASJ.*

5. Transition region loops



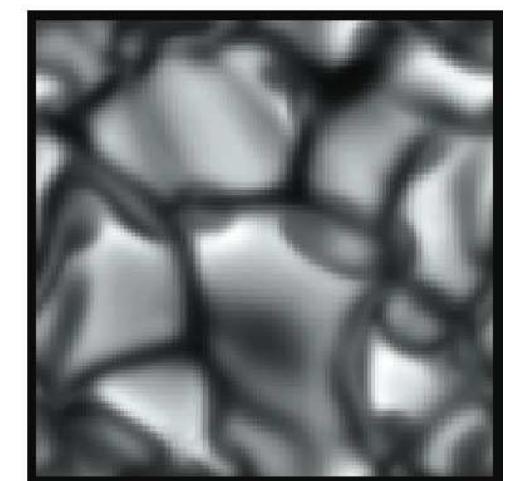
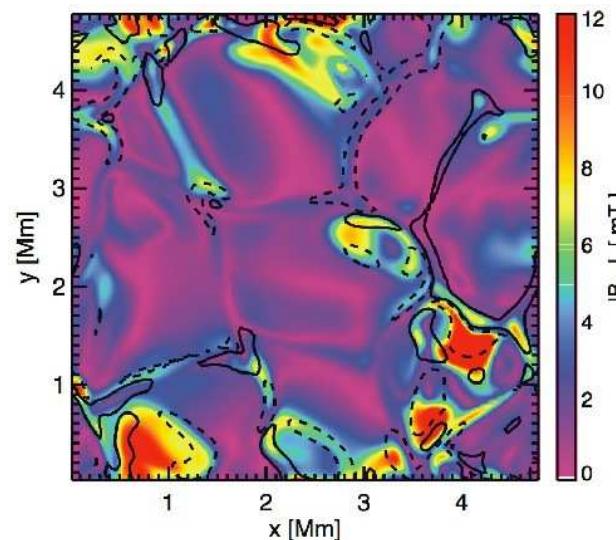
Small-scale
transition region
loops. IRIS Si IV
1400Å slit jaw
images. From
Hansteen et al.
(2014), Science
346.

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)*

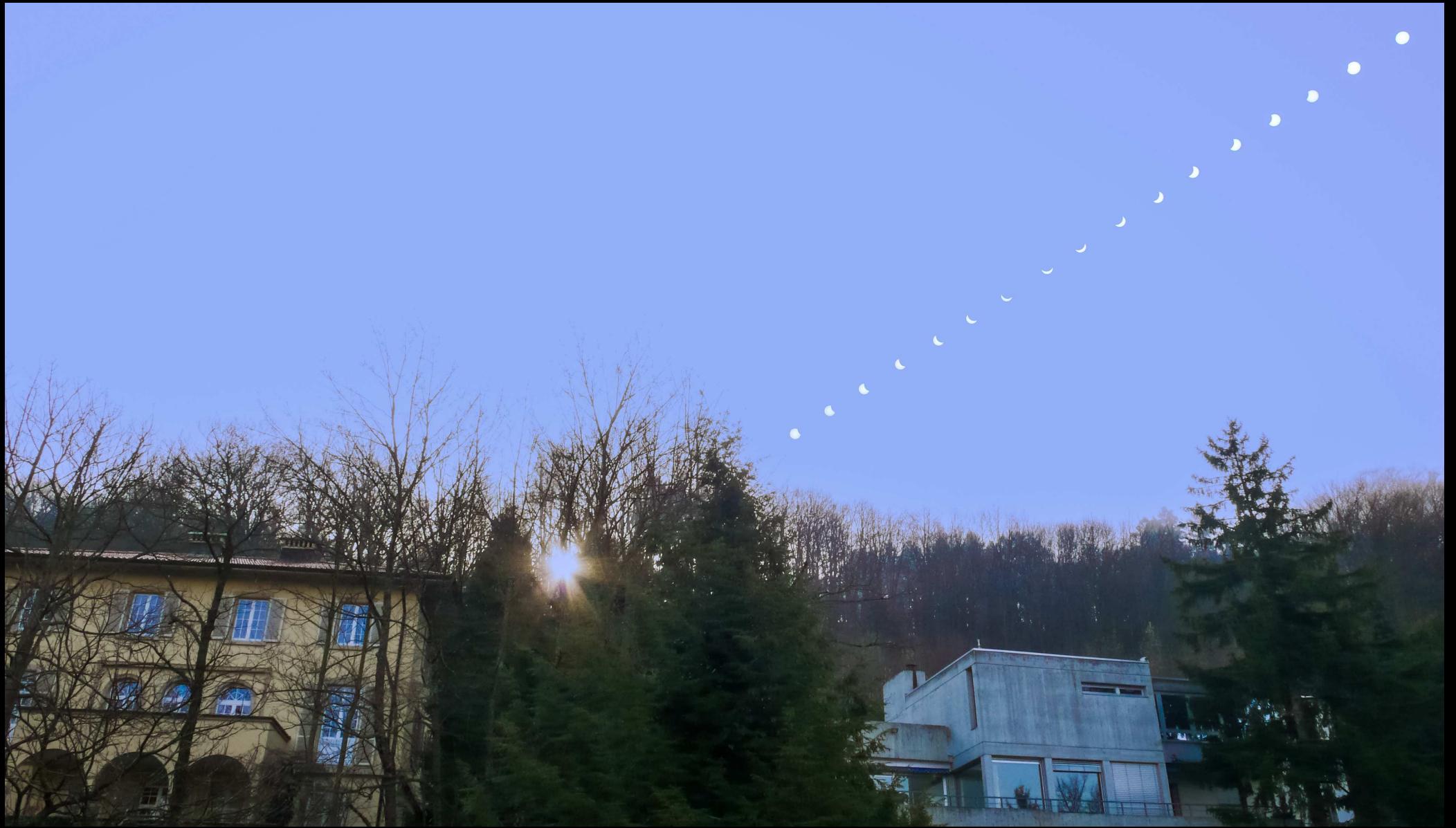


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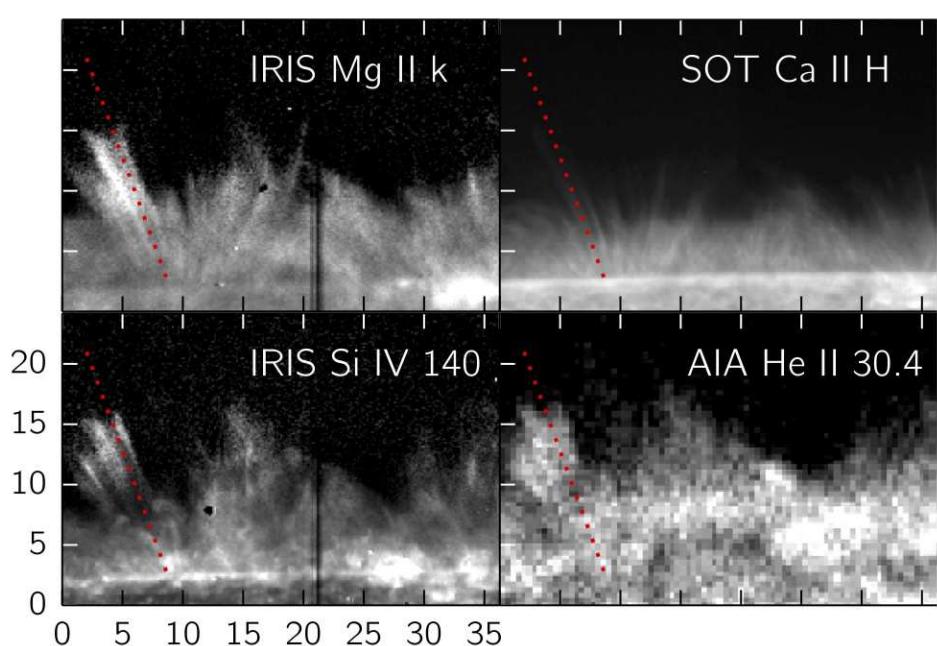
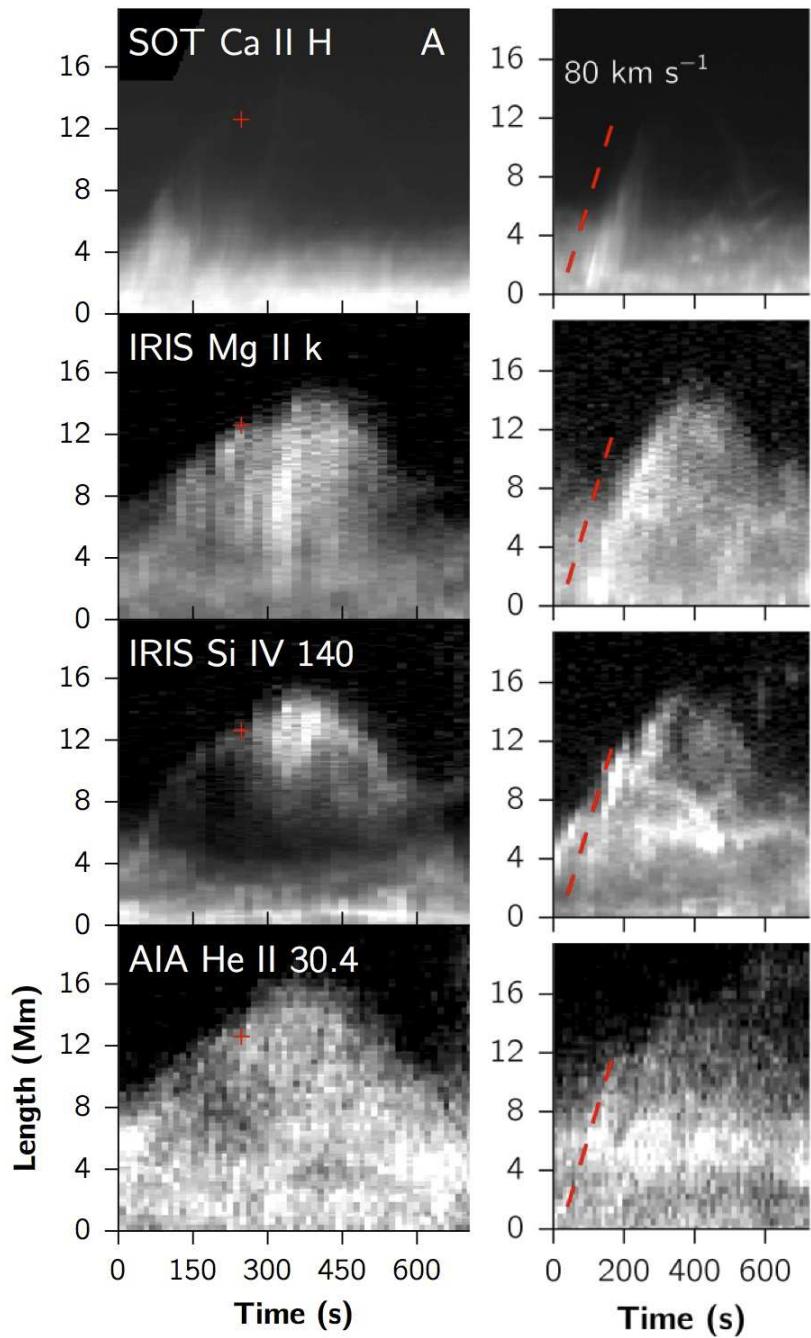
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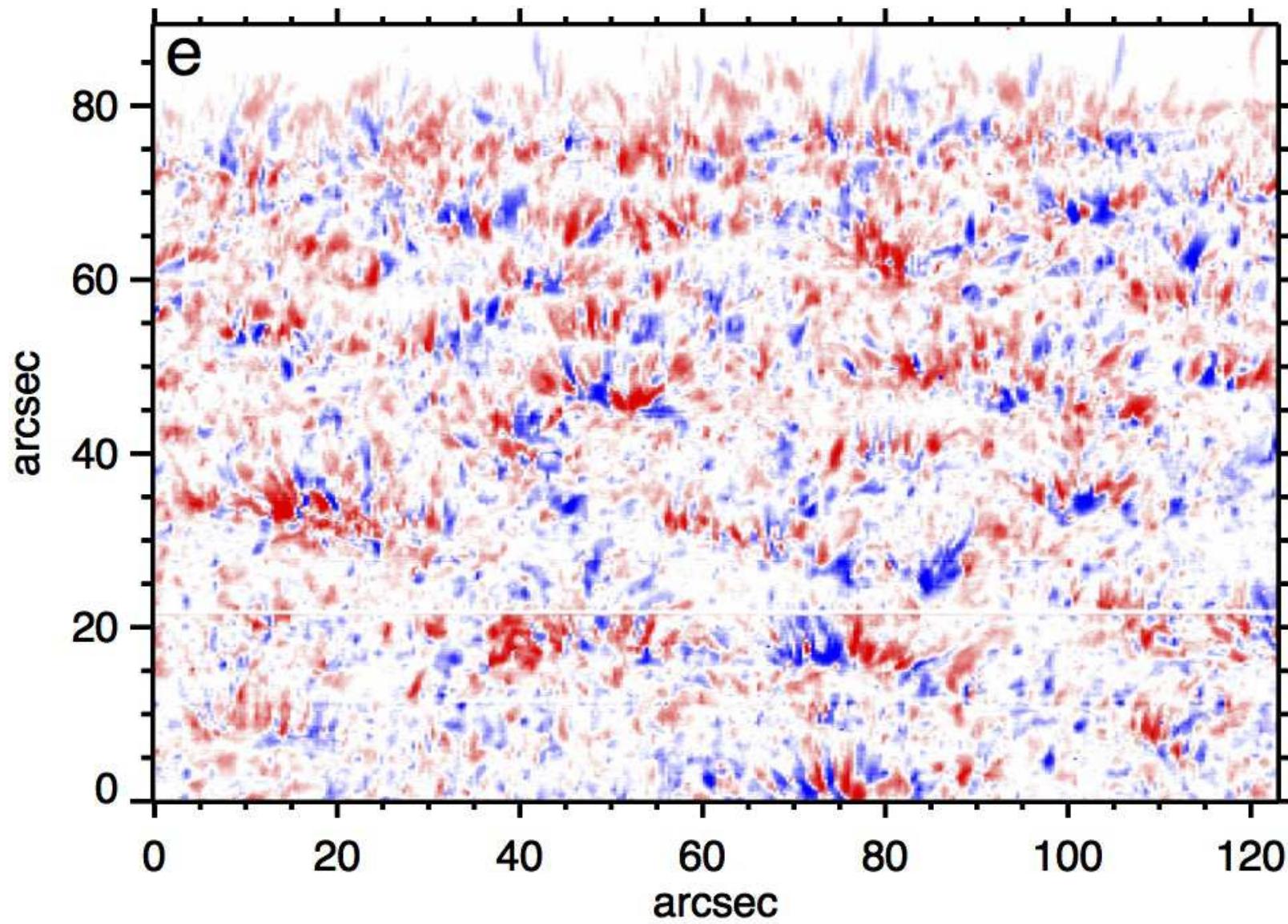
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Results from the *Interface Region Imaging Spectrograph IRIS*.



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.

From *De Pontieu et al. 2014, Science 346*.

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