An estimate of chromospheric heating by acoustic waves - reloaded

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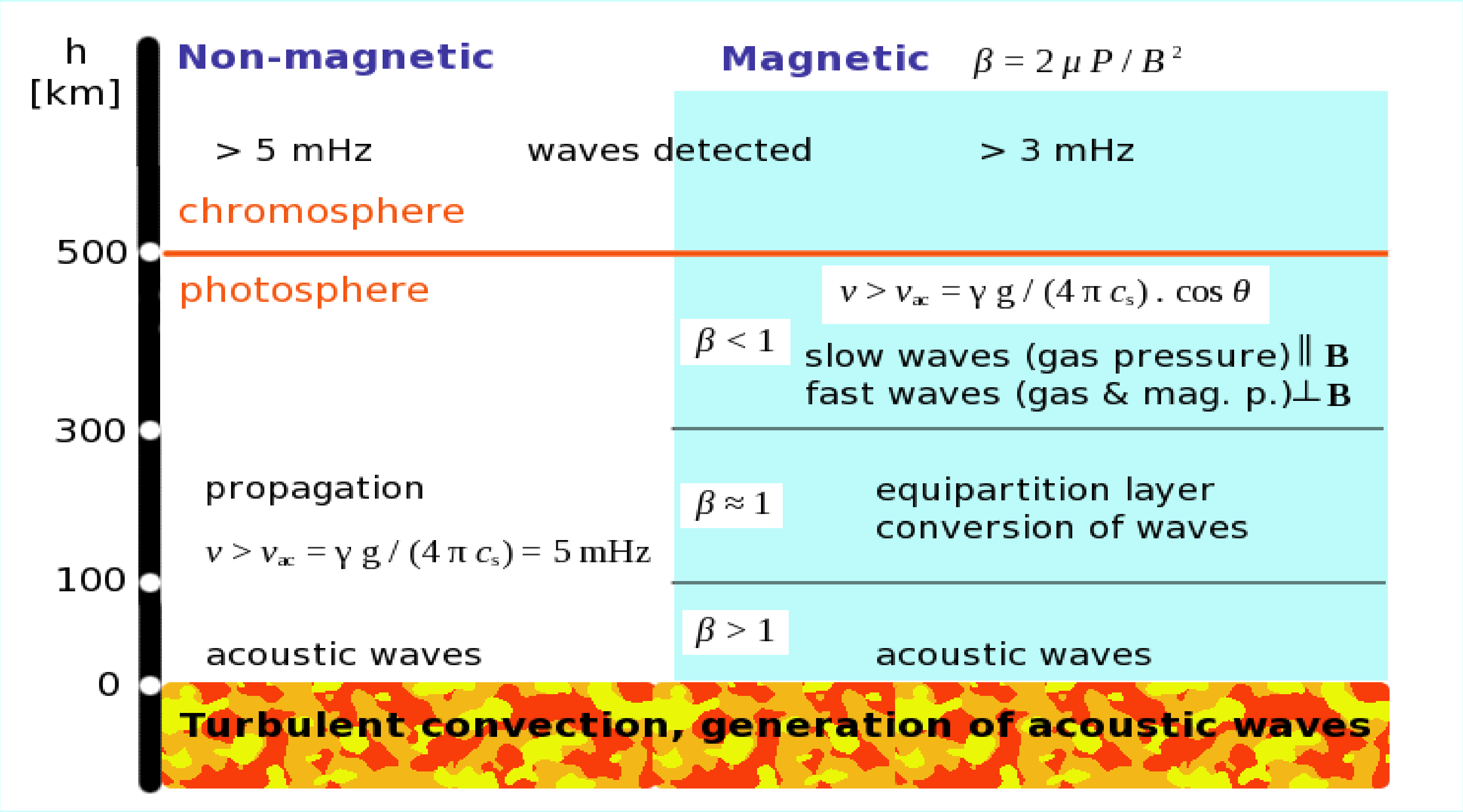
Introduction

How to heat the chromosphere?

- **Acoustic and magnetoacoustic waves:**



- **Other heating mechanisms**:

Alfvén waves (not seen in Doppler signal)

Magnetic reconnections (nanoflares, *Parker 1988, ApJ, 330, 474*)

We have shown (*Sobotka et al. 2013, A&A, 560, A84*) that the chromosphere above a light bridge can be heated by acoustic waves thanks to wave leaking in inclined magnetic field.

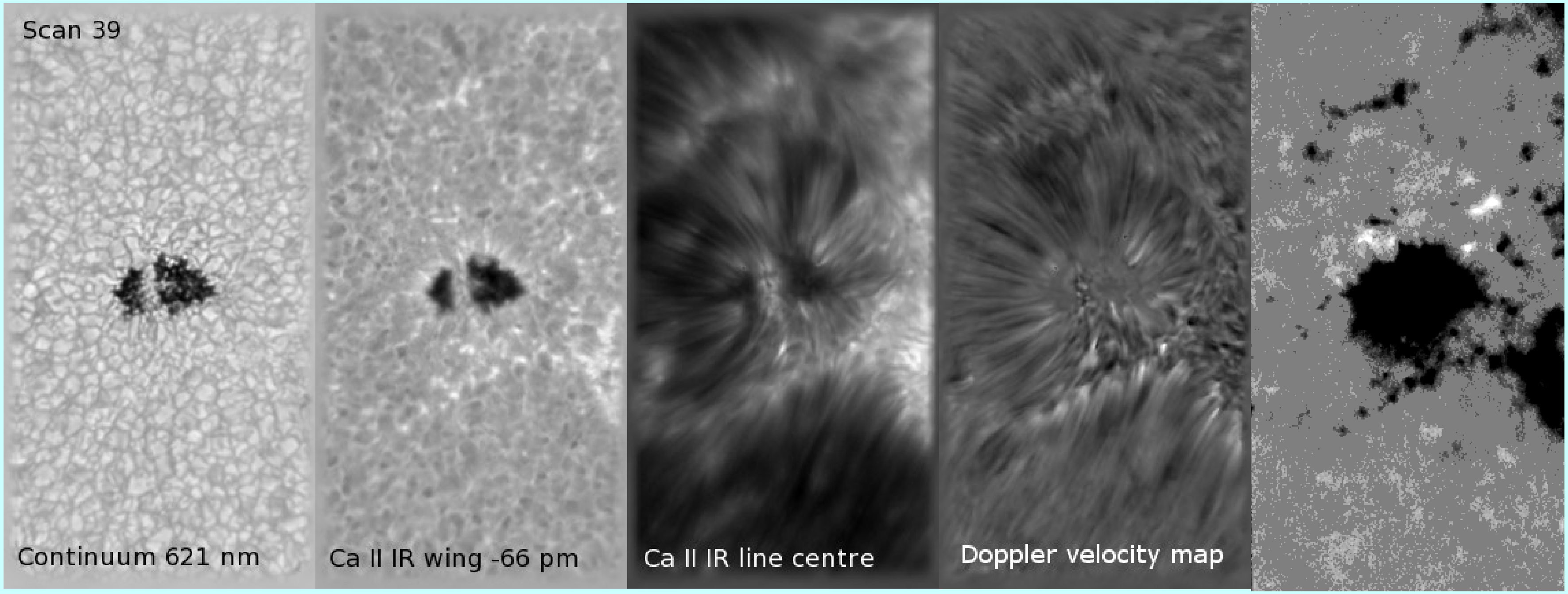
In this work we attempt to estimate the contribution of acoustic energy flux to the chromospheric heating in quiet and plage regions.

Observations

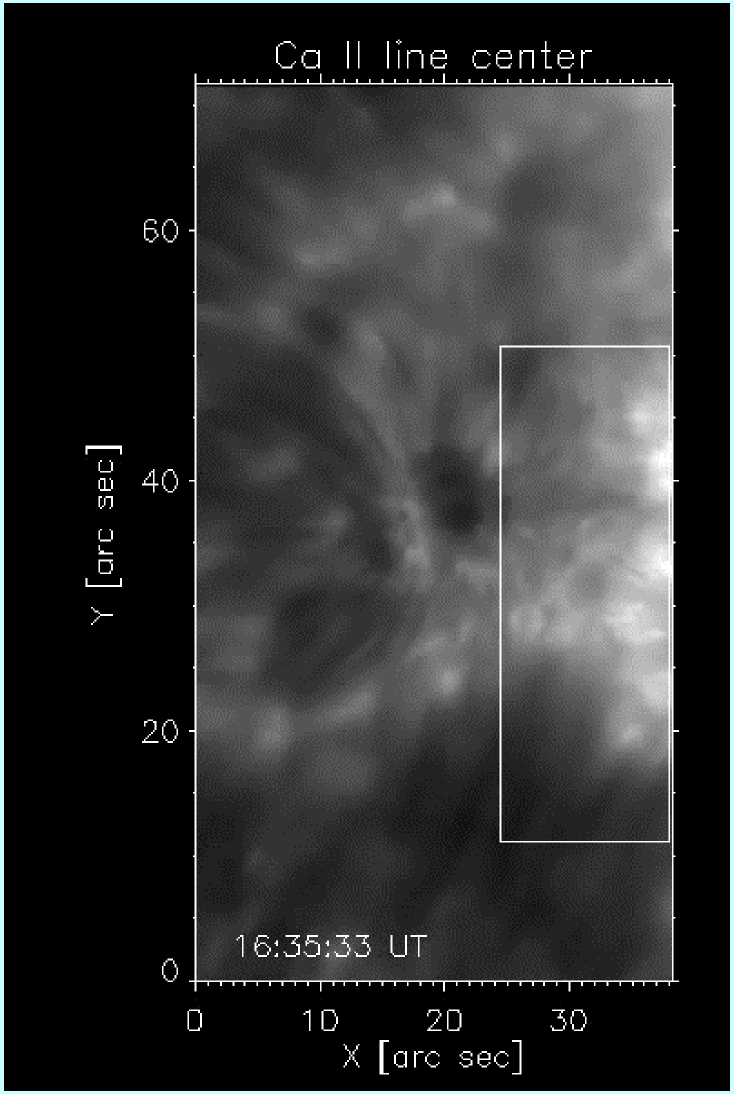
- A large (8.5") pore with light bridge, leader of NOAA 11005, slowly decaying, position 25 N, 10 W ($\mu = 0.92$)
- 15 October 2008, 16:34–17:43 UT
- 2D spectrometer IBIS at DST, with adaptive optics
- 21-point *I*-scans of Ca II 8542 Å ($\Delta\lambda$ = 60 mÅ), simultaneously with 21-point *I,Q,U,V*-scans of Fe I 6173 Å (*Sobotka et al. 2012, A&A, 537, A85*)
- Time series of 80 scans (69 minutes)
- Sampling 0.167 arcsec/pixel, Δt = 52 s
- Ca II 8542 Å formation heights (*Cauzzi et al. 2008, A&A, 480, 515*):

Line centre: 1400 km (middle chromosphere)
Line core ± 180 mÅ: 1000 km (Doppler)
Wings ± 600 mÅ: 250 km (middle photosphere)

Intensity maps at heights 0, 250, and 1400 km, Doppler map, and a LOS magnetogram



The most luminous areas in the chromosphere are a light bridge and a plage near the right edge of the FOV.



- Measurement of Doppler signals in the Ca II IR line at two heights: 1000 km (± 180 mÅ wings) and 1400–1500 km (line center)
- Power spectra of Doppler velocity oscillations for frequencies 1–9 mHz at the two heights
- Inversion (SIR) of the Fe I 6173 Å line from a scan in the middle of the series to obtain the magnetic field vector, its transformation to local reference frame

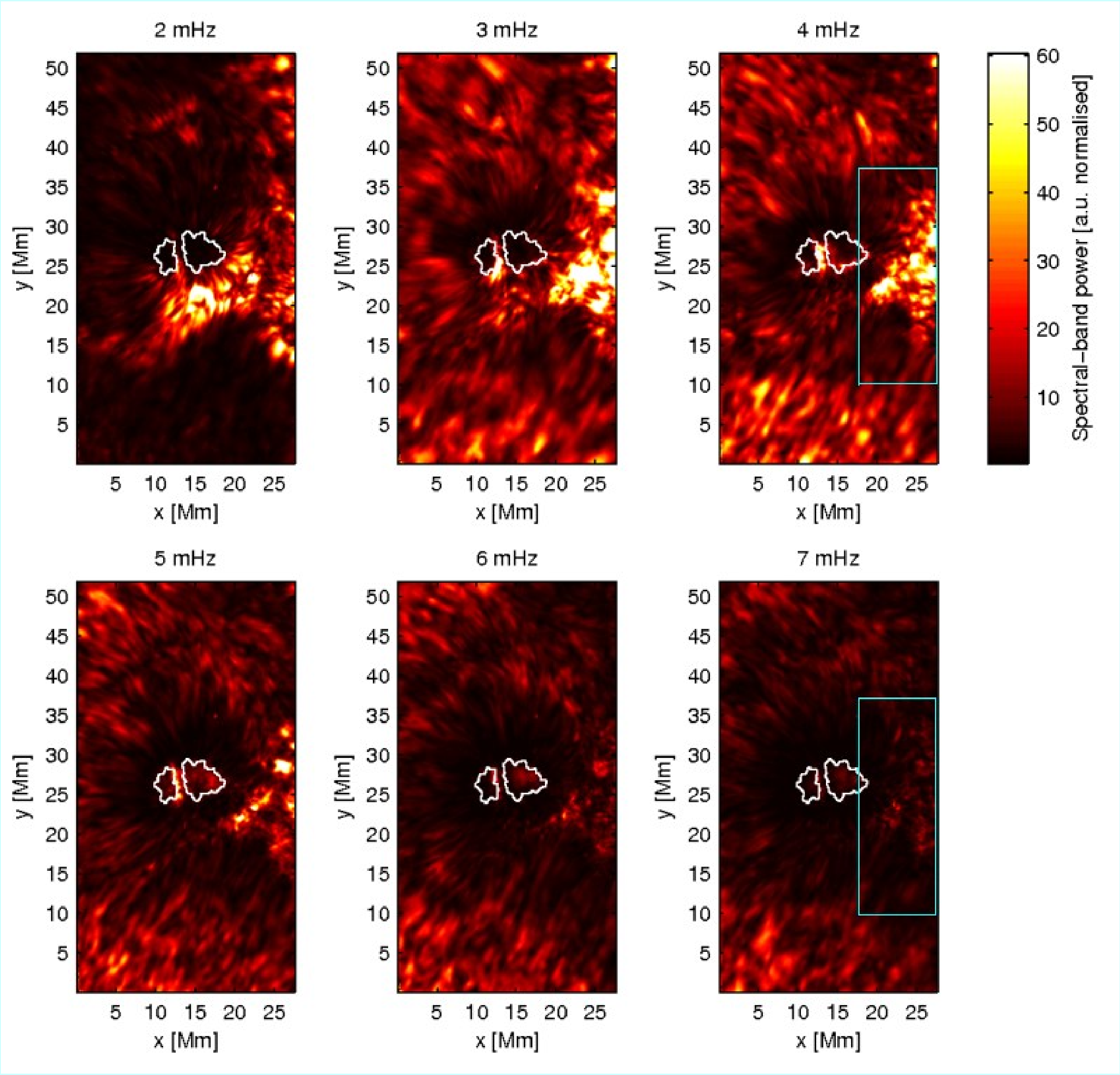
Time series of Ca II line-center images (69 minutes, 80 frames). Region of interest (white rectangle)

Oscillation power maps (Doppler) at 1000 km

3-4 mHz ~ 5 min,
5-6 mHz ~ 3 min

Max. ν = 9.6 mHz

The power of acoustic oscillations is enhanced in the light bridge and in the plage. An area marked by blue rectangle was selected for further analysis.

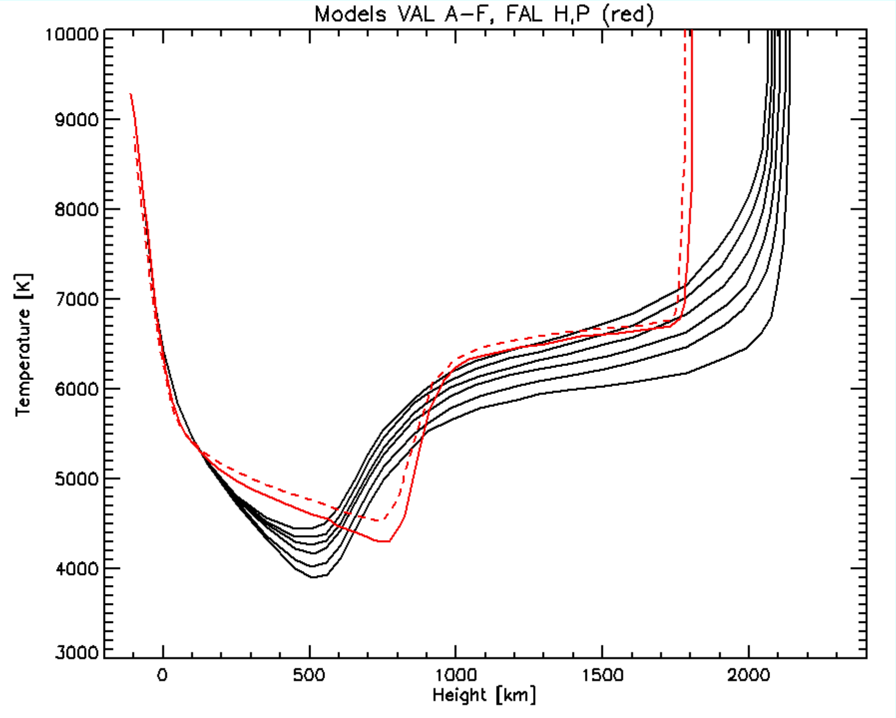


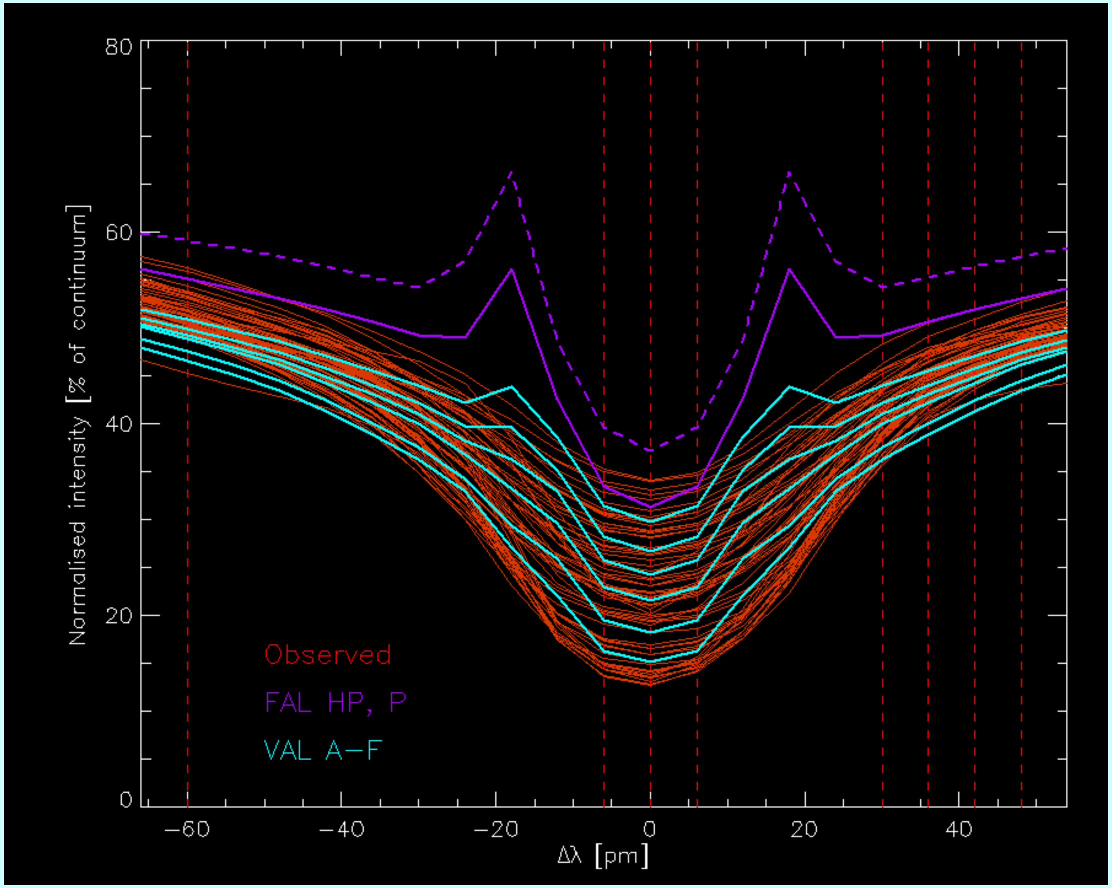
Radiative losses in the chromosphere

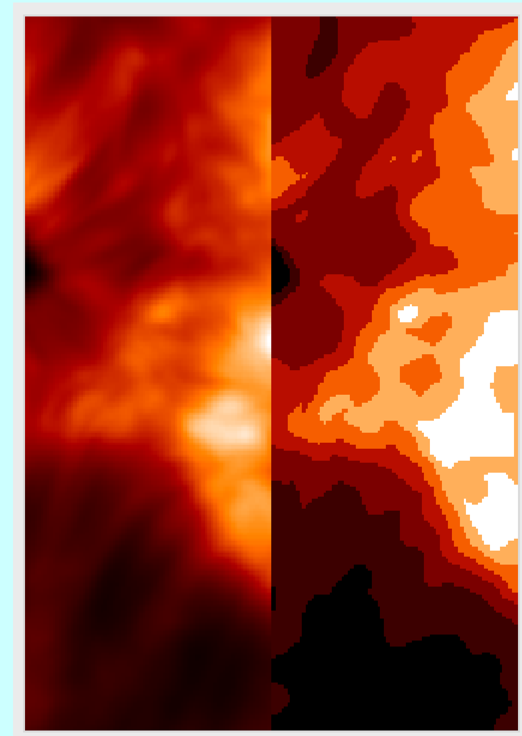
A model atmosphere at each point in the FOV is needed to calculate radiative losses (net radiative cooling rates). We took a grid of models **VAL A–F** (*Vernazza et al. 1981, ApJS, 45, 635*) and **FAL H, P** for facula/plage (*Fontenla et al. 1999, 2006, ApJ*).

A - dark point in intranetwork
B - average intranetwork area
C - average quiet Sun
D - average network
E - bright network element
F - very bright network element
H - plage without facula
P - facula

A non-LTE code with partial redistribution is used to compute synthetic profiles and radiative losses.



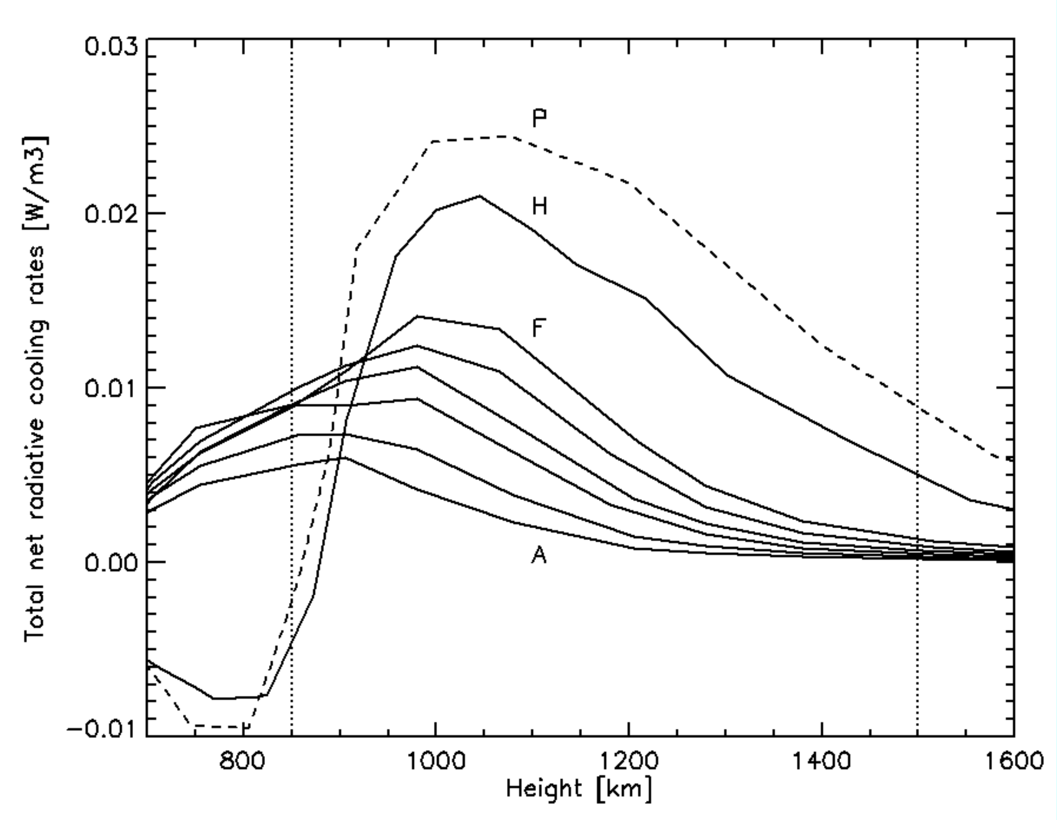


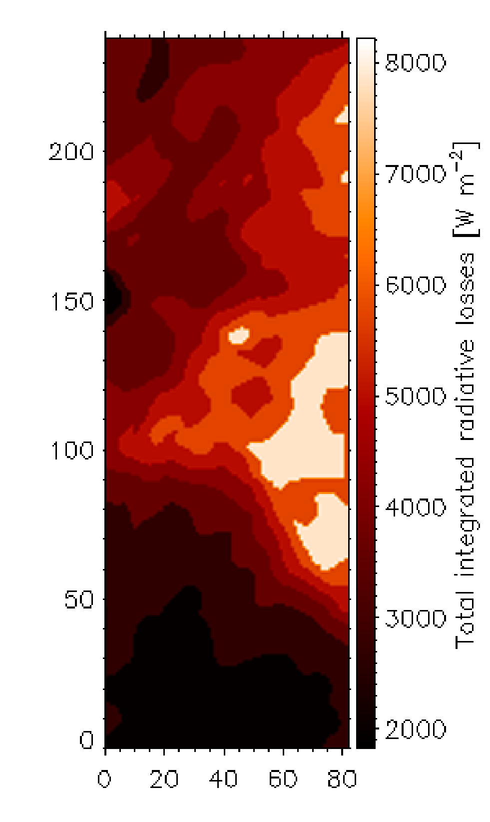


Line core Model map

Examples of time-averaged observed profiles of Ca II 8542 Å (red) together with synthetic VAL (blue-green) and FAL (violet) profiles. For FAL H, micro-turbulence of FAL P is used. Models are assigned to each point in the FOV according to the best match in 8 wavelengths. FAL P does not match.

Net radiative cooling rates indicate the amount of non-radiative heating that sustains the temperature at a given height. They were computed for the lines Ca II K, H and IR triplet, Mg II k, h, hydrogen lines and continua. The total radiative losses were integrated in the height range 850–1500 km, where we measure the Doppler signal. Hydrogen contribution is very small in this range.





Energy deposited by acoustic waves

The acoustic energy flux can be derived from the power spectrum of Doppler velocities $P_v(\nu)$ (*Bello González et al. 2009, A&A, 508, 941*):

$$F_{\mathrm{ac,tot}} = \int_{\nu_{\mathrm{ac}}}^{\infty} \rho P_v(\nu) \upsilon_{\mathrm{gr}}(\nu) / TF(\nu)\, \mathrm{d}\nu,$$

$$\upsilon_{\mathrm{gr}} = c_{\mathrm{s}} \sqrt{1 - (\nu_{\mathrm{ac}}/\nu)^2},$$

is the group velocity with which the acoustic energy is transported,

$$c_{\mathrm{s}} = \sqrt{\gamma p / \rho},$$

is the sound speed (about 8 km/s) and

$$\nu_{\mathrm{ac}} = \frac{\gamma g \cos\theta}{4\pi c_{\mathrm{s}}},$$

is the acoustic cutoff frequency, which depends on surface gravity *g* and magnetic field inclination *θ.*

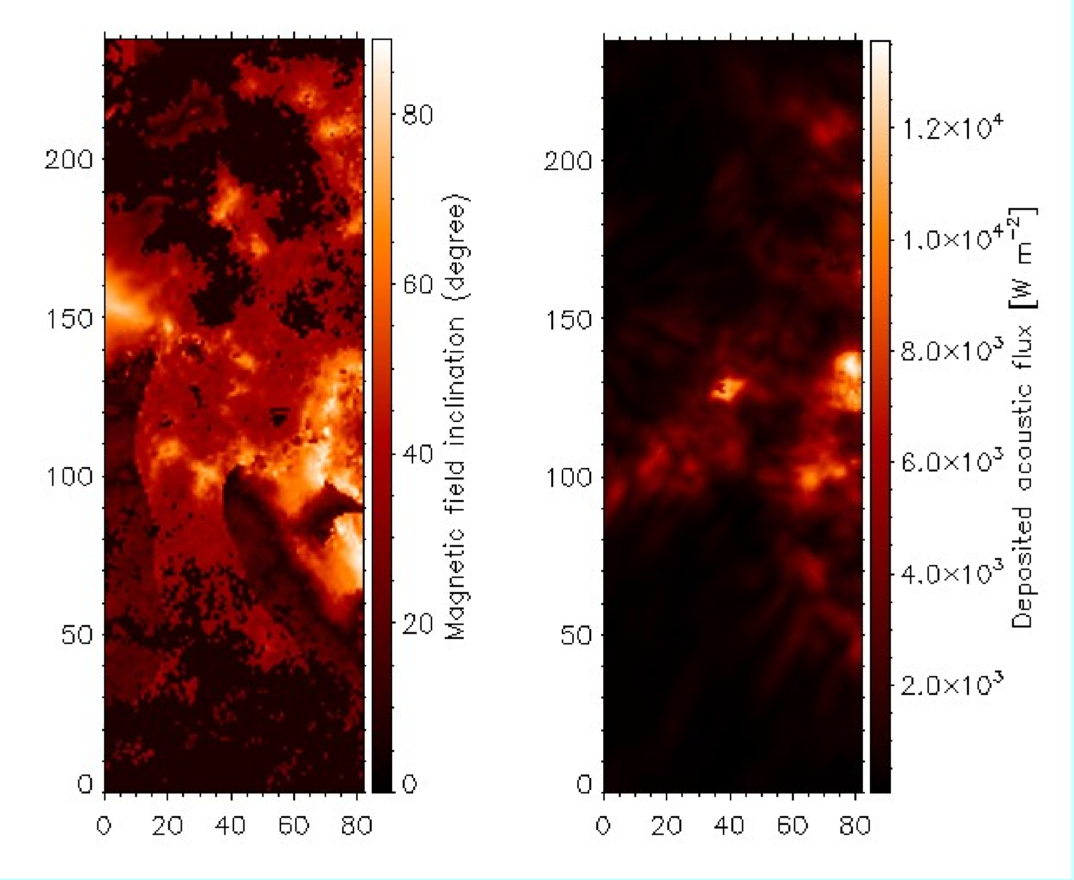
$TF(\nu)$ is a so-called transfer function, which was set to 1 (see *Bello González et al. 2009*). Gas pressure p and density ρ are taken from the corresponding semi-empirical models.

The energy deposited by acoustic flux at the formation height of the Ca II 8542 Å core, 900–1400 km (*Cauzzi et al. 2008*), was computed as a difference of ac. fluxes $F_{1000km} - F_{1400km}$, calculated from Doppler velocities measured at λ ± 180 mÅ and in the line centre, using gas parameters from VAL models at corresponding heights and magnetic field inclination obtained from the inversion of Fe I 6173 Å.

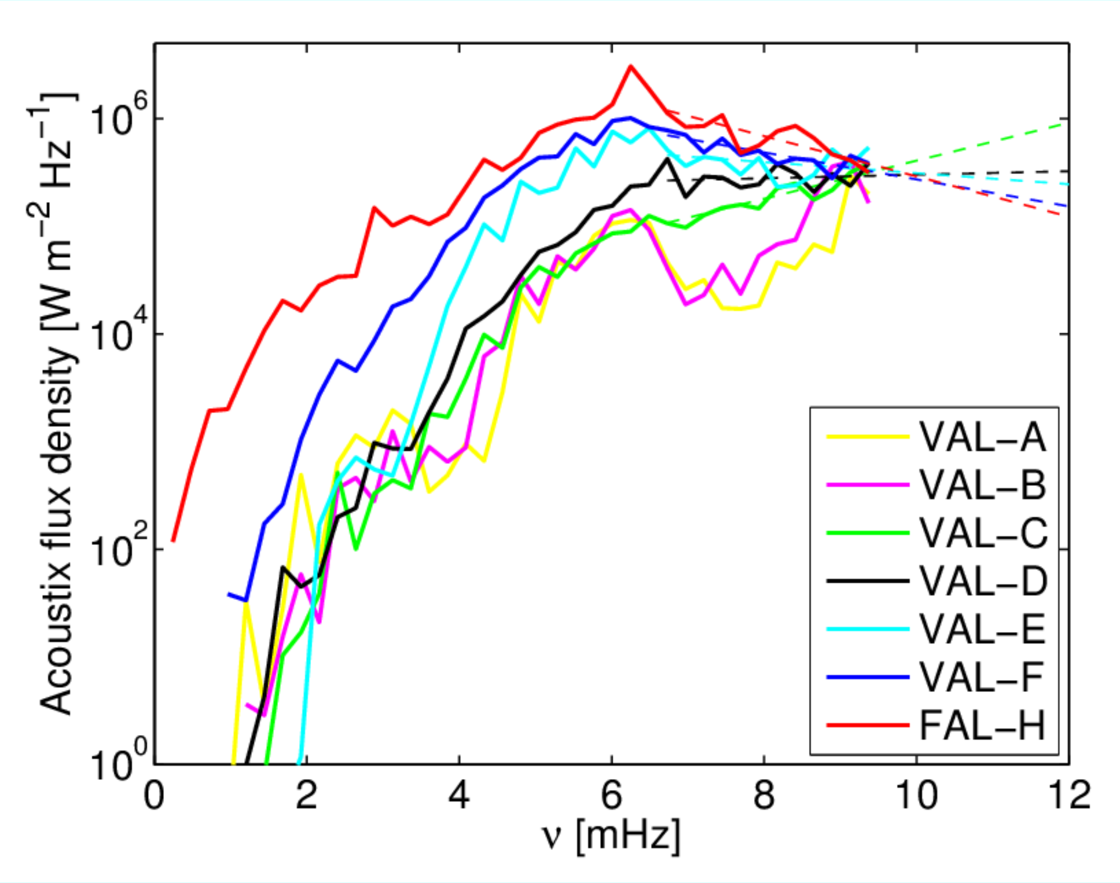
Left: Magnetic field inclination in the photosphere, calculated with respect to the local normal (LRF), scan 41.

Right: Map of deposited acoustic flux.

Note:
Due to contribution of waves with $\nu > 9$ mHz and possible $TF(\nu) < 1$, we obtain lower limits of the deposited flux.

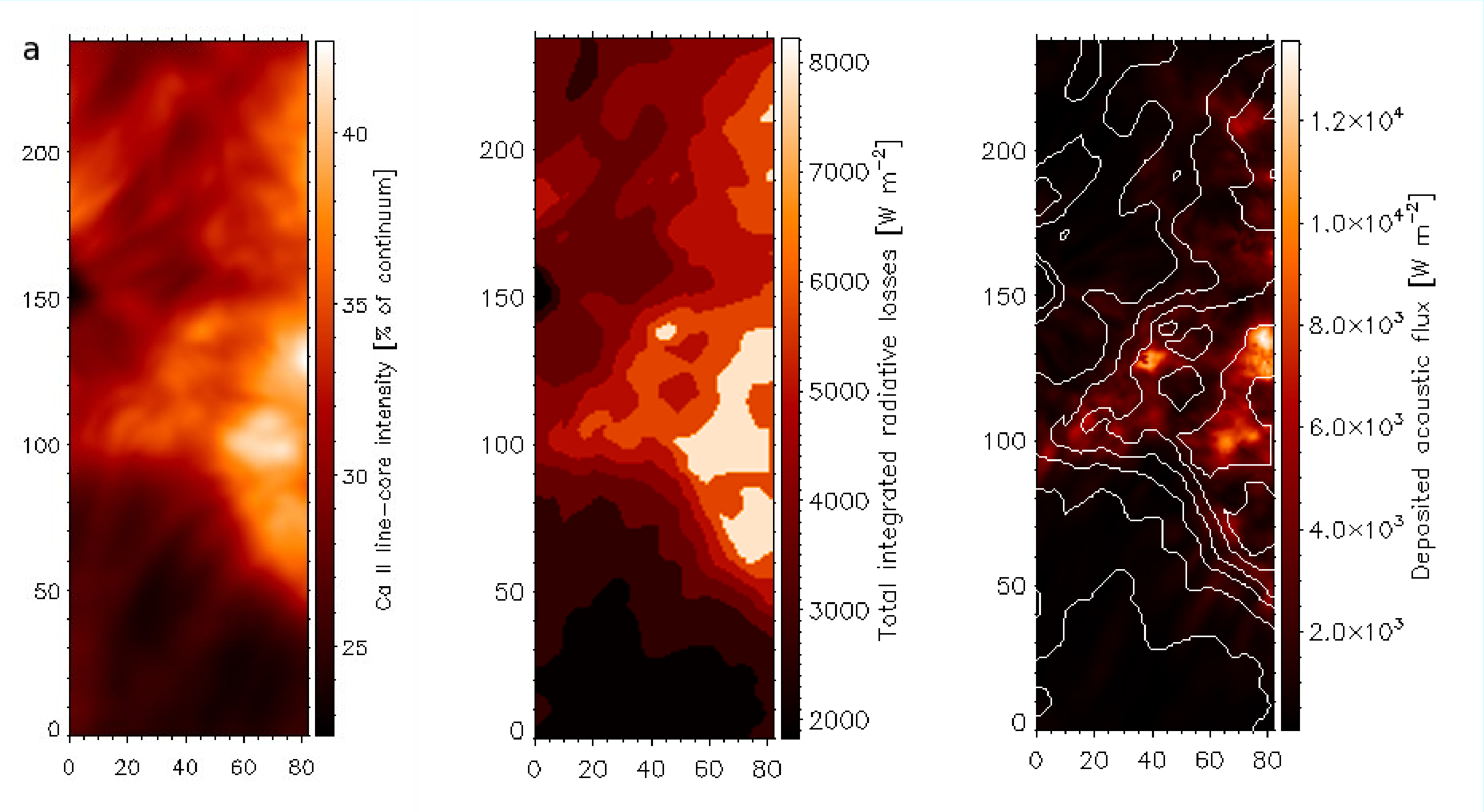


Frequency distribution of the deposited acoustic flux for different models. High frequencies >10 mHz may increase our measured flux by 50–100% in quiet regions (models A–C) - *Bello González et al. 2009, 2010.* Low frequencies are important for the heating of active chromosphere (models E–H).

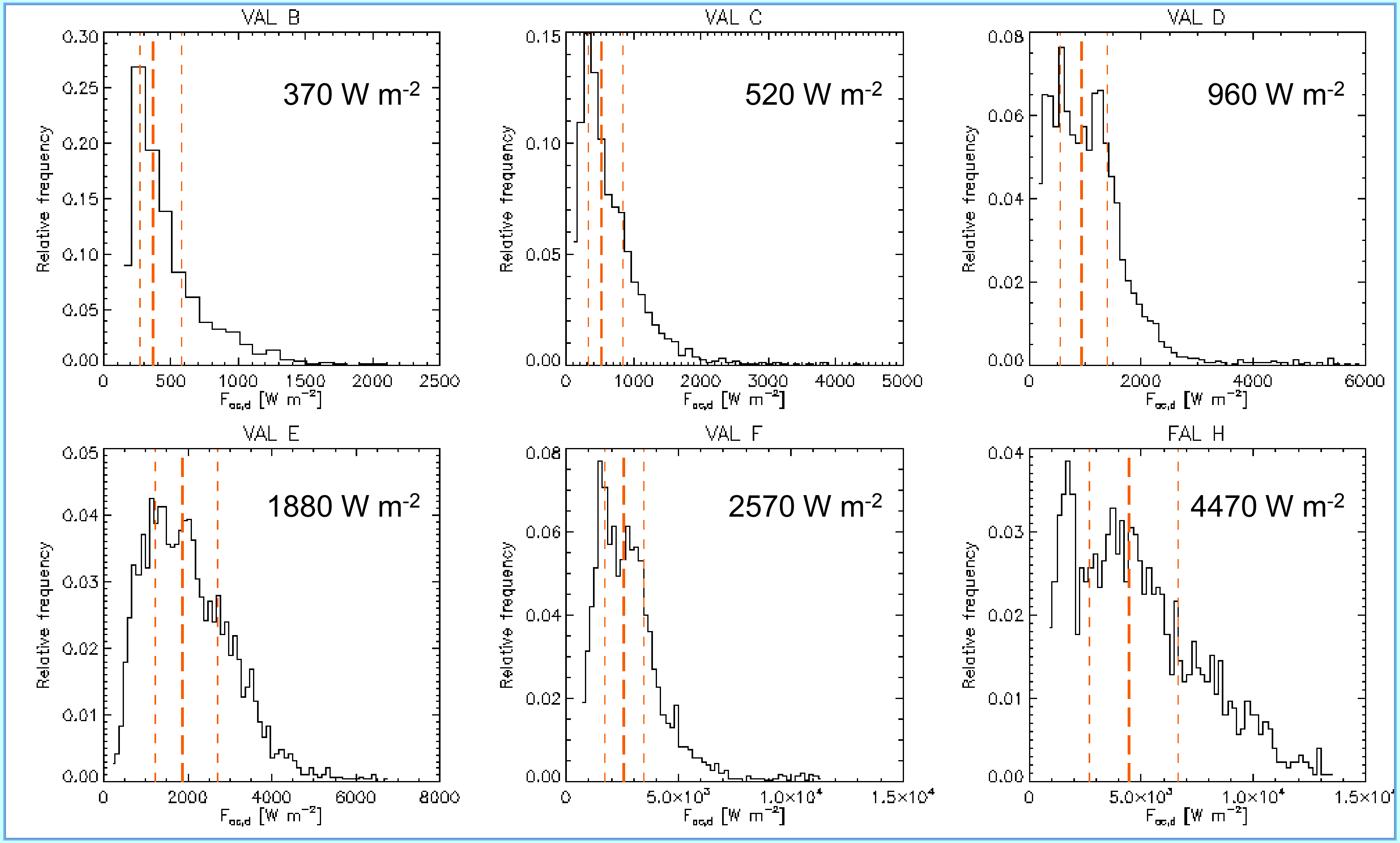


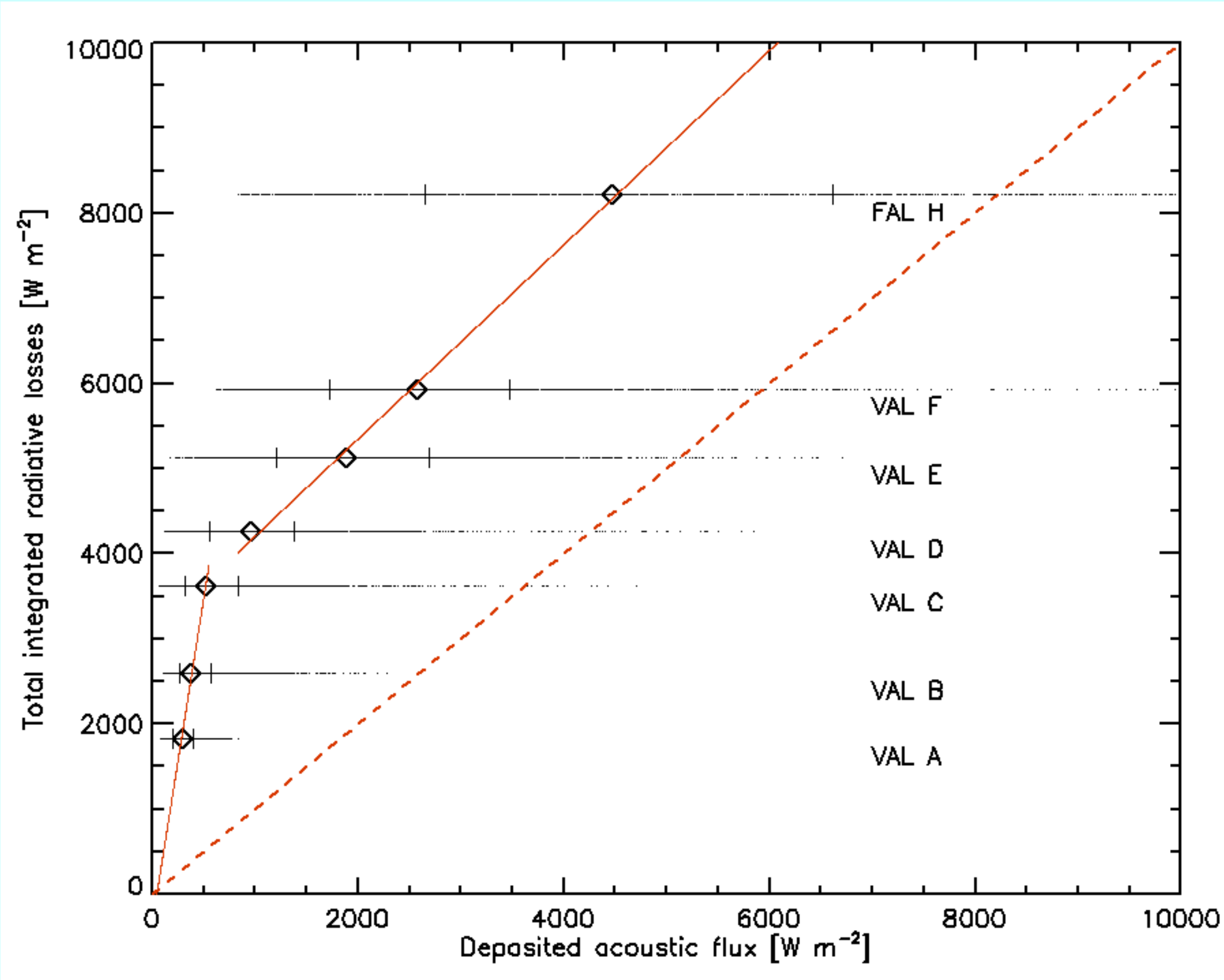
Comparison

of total radiative losses and deposited acoustic flux.
The coefficient of spatial correlation is 72 %.



Histograms of deposited acoustic flux (lower limit), its <u>median values</u> and median deviations for models B – H





Lower limits of
acoustic-flux share
in radiative losses

H 0.54

F 0.43

E 0.37

D 0.23 active

C 0.14 quiet

B 0.14

A 0.16

Total radiative losses L versus deposited acoustic flux F together with median values and deviations of acoustic fluxes. Linear fits of the median values:
quiet: $L = -300 + 7.63\ F$; active: $L = 3100$ *(other heating mechanism?)* $+ 1.14\ F$

Discussion

- The deposited acoustic flux and radiative losses are spatially correlated (72 %). This indicates the importance of acoustic waves for the heating of solar chromosphere.
- The spatial correlation of magnetic field inclination with radiative losses is 63 %. This supports the idea of enhanced chromospheric heating in regions with inclined magnetic field (“magnetic portals”).
- In quiet regions, the contribution of acoustic flux is small (**15** %) due to the absence of low-frequency waves below the acoustic cutoff.
- In active areas (B between 300 and 1300 G, inclination 20°– 60°), the contribution increases from **23** % (network) to **54** % (plage).
- These values are lower limits. The real acoustic energy flux can be higher than the observed one and it may become the main contributor to the heating of bright network elements and plages (models E – H).
- Our results, based on 1D hydrostatic semi-empirical models and statistical approximations of the deposited acoustic flux, do not take into account the highly dynamic nature of the solar chromosphere. However, they may provide a general estimate of the contribution of acoustic waves to the heating of long-lived chromospheric structures.

Thanks for your attention