Towards understanding the role of waves in the solar corona using spectroscopic techniques

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Abstract

To heat the corona or accelerate the solar wind, many models use MHD waves. In absence of in situ measurements in the very low solar corona, one has to rely on remote sensing observations only. We present a method using line profile analysis to both constrain the potential source of energy (the Alfvén wave amplitude as a function of altitude) and measure the effects of wave absorption on ions species of different charge and mass (the spectral distribution of the wave power). We apply this method on data from SOHO/SUMER and Hinode/EIS spectrometers, acquired below 1.3 Rs. The observed preferential heating of minor ions must still be explained: resonance with ion cyclotron waves, with kinetic Alfvén waves or other wave-particle interactions?

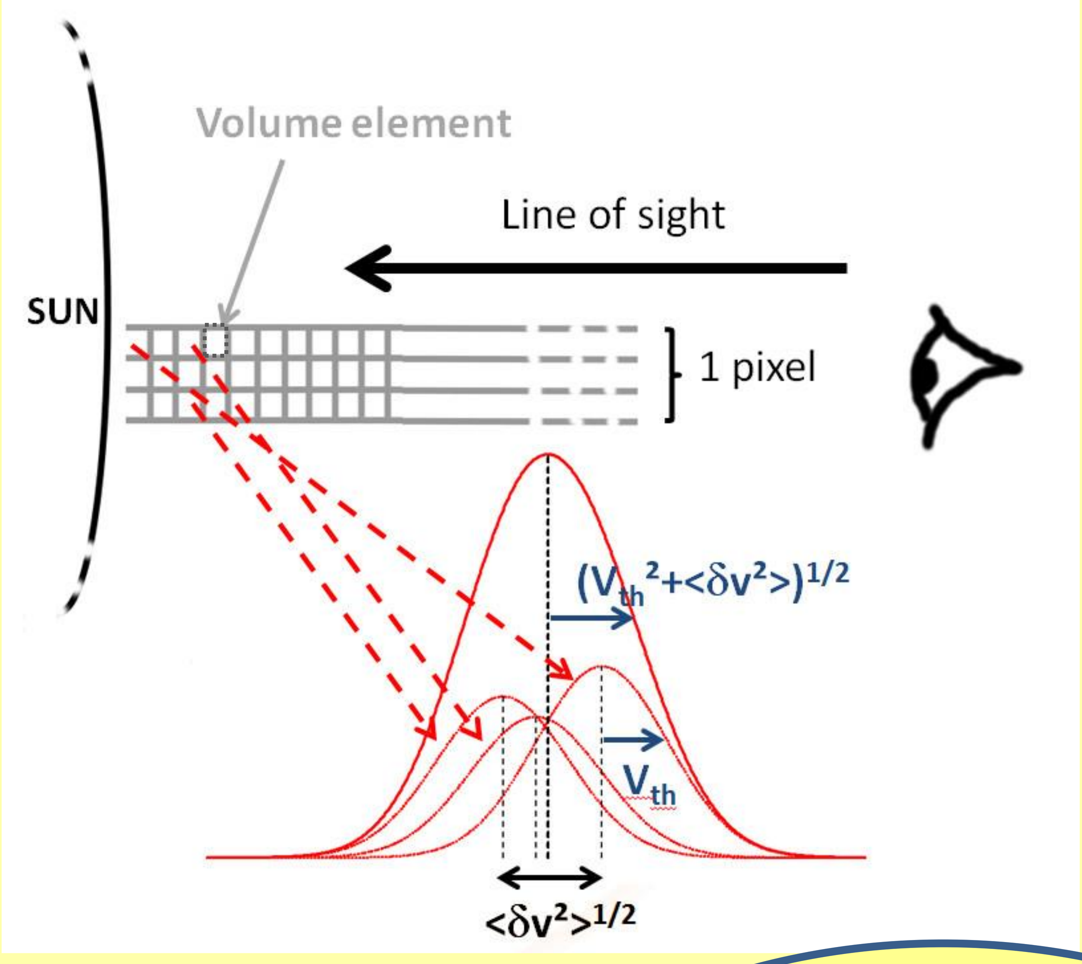
What does the non-thermal velocity correspond to?

In each volume element, ions emit photons in spectral lines. The width of these lines is broadened by thermal motions of the emitting ions (v_{th}, Maxwellian)

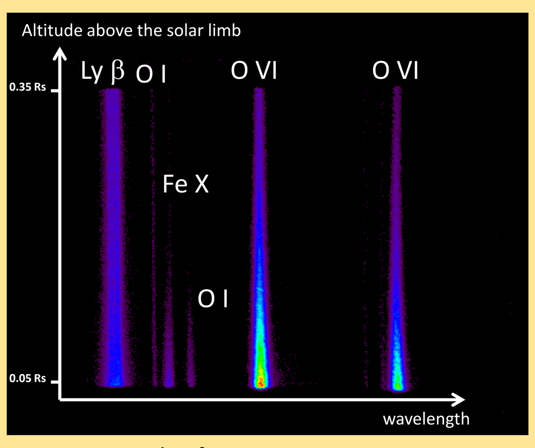
The observed spectral line results from integration over:
- the line of sight
- scales smaller than the resolution scale
- exposure time

In the integration process, the bulk velocity of each volume element may be different due to MHD waves, turbulence, etc… (let us assume a Gaussian distribution of width $<\delta v^2>^{1/2}$)

The addition of all those lines with different centres result in a broader spectral profile, with the added "non-thermal" or "unresolved" velocity $\xi \propto <\delta v^2>^{1/2}$

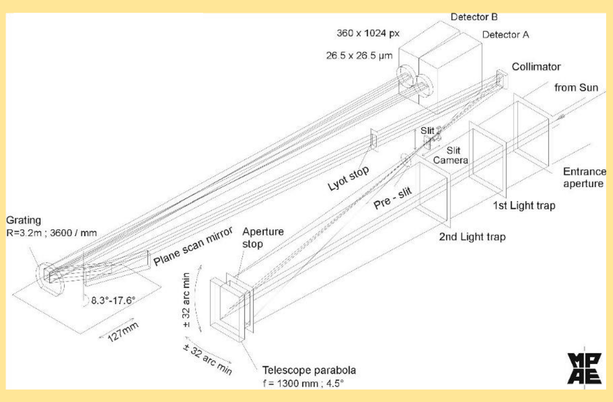


Spectrometers

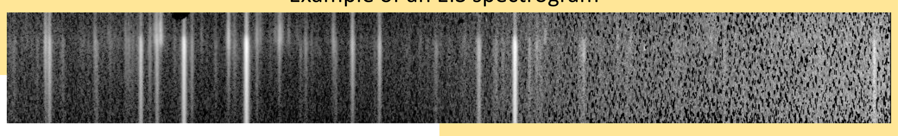


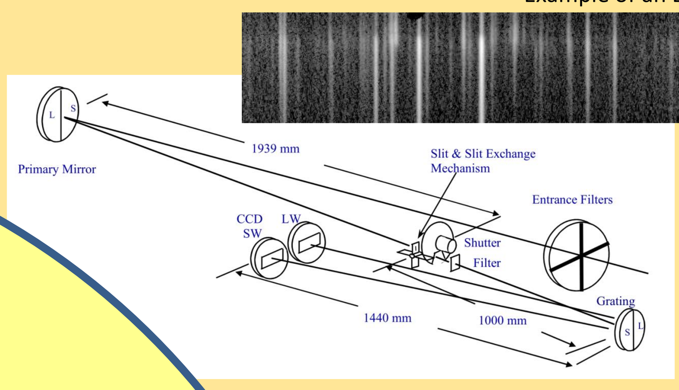
Example of a SUMER spectrogram
(raw data, image recorded on the detector)

SOHO/SUMER
500-1600 Å (Wilhelm et al. 1995)



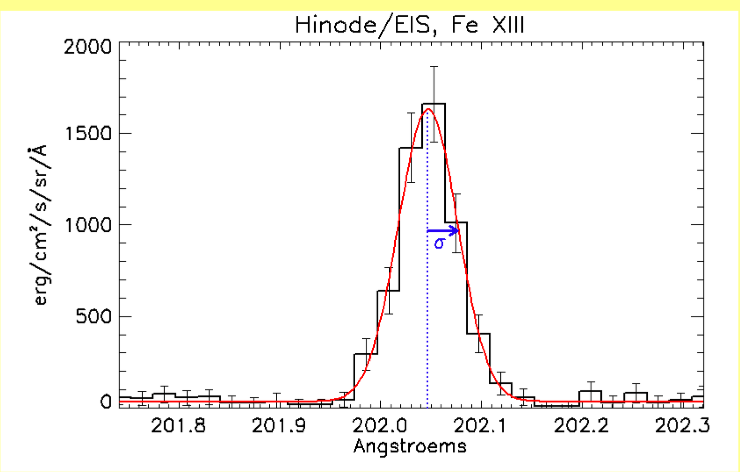
Example of an EIS spectrogram





Hinode/EIS
170-211 Å + 246-292 Å (Culhane et al. 2007)

The width of spectral emission lines in the solar corona



Example of a spectral emission line and Gaussian fit
(Fe XIII at 202.04 Å, Hinode/EIS)
Each spectral bin corresponds to a pixel on the detector. A slit isolates a portion of the image of the Sun. Its image is dispersed by a grating and projected on the detector.

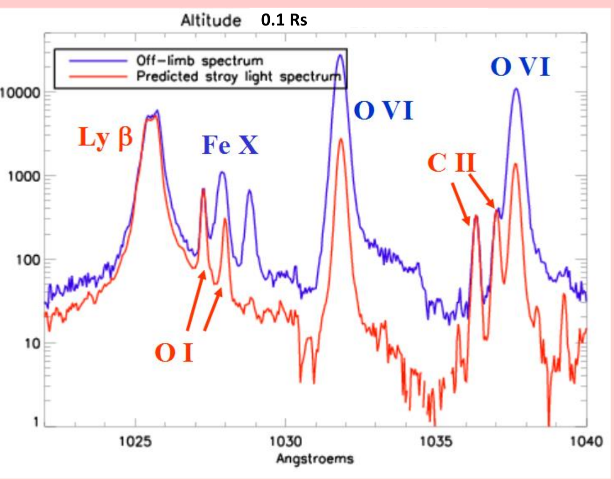
$$\sigma^2 = \frac{\lambda^2}{2c^2}\left(\frac{2kT}{M} + \xi^2\right) + \sigma_I^2.$$

Thermal Doppler broadening ($\frac{2kT}{M}$) — Non-thermal velocity (ξ^2) — Width of the instrumental profile (σ_I^2)

The Gaussian line width
The Gaussian width σ depends on the ion **temperature T** and the so-called **non-thermal velocity ξ**, introduced to take into account the excess of line width with respect to the temperature of maximum ionisation of the ion species as observed in the atmosphere of the Sun.
σ_I is an effect of the width of the spectrometer slit and of the grating step (diffraction).

Instrumental stray light

Stray light contribution becomes substantial at large heights (at least with SOHO/SUMER).
In the stray light spectrum, lines are narrower or have different centres => one need to subtract an estimate (high altitude spectrum rescaled with "cold lines" like O I)



Two unknowns in one observable!

- ξ is a potential energy source for the heating of the solar corona (e.g. proportional to the average Alfvén wave amplitude)
- T_{ion} is the result of this heating process (with dissipation at small scales through ion cyclotron resonance (e.g. Tu & Marsch 1997) or through kinetic Alfvén waves (Voitenko & Goossens 2004))

How can we disentangle temperature and non-thermal velocity?

Many methods have been used in the literature (see Dolla & Solomon 2008)

Here we assume (Dolla & Solomon 2008, Dolla & Solomon 2009) that:
- All ions species show the same non-thermal velocity but can have different temperatures (as a results of charge and mass dependence of a potential wave-particle interaction)
- Non-thermal velocity ξ is due to plasma motions induced by Alfvén waves
- Radial variation of ξ above the limb is constrained (upper limit) by conservation of flux of the undamped Alfvén waves in the density stratified corona: $\xi \propto \rho^{-1/4}$ (Moran 2001)

Difficulties during the data processing

Poor spectral resolution

Typically, with Hinode/EIS, 8-10 pixels per line profile (twice as more with SOHO/SUMER).

Better-than-a-pixel resolution can be achieved with a Gaussian fit.

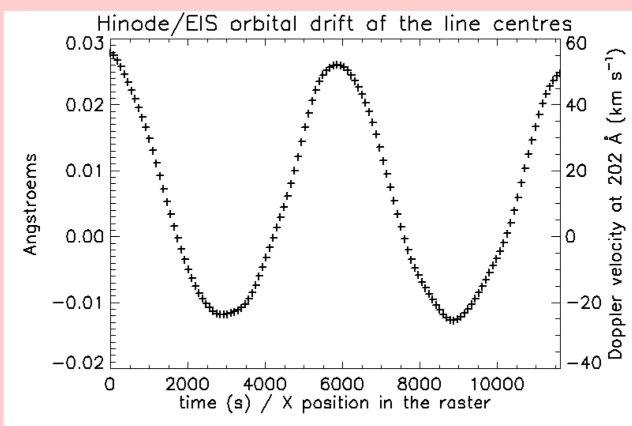
This is more tricky when two or more lines are blended with close centres so that multi-Gaussian fits are necessary.

Lack of photon statistics

One needs rebinning for faint lines and at high altitudes, but:
- At the cost of a loss of spatial resolution
- Problem with the orbital drift of line centres across time (and consequently in the X direction of rastering) with Hinode/EIS, which produces an artificial broadening.

Orbital drift of the line centres

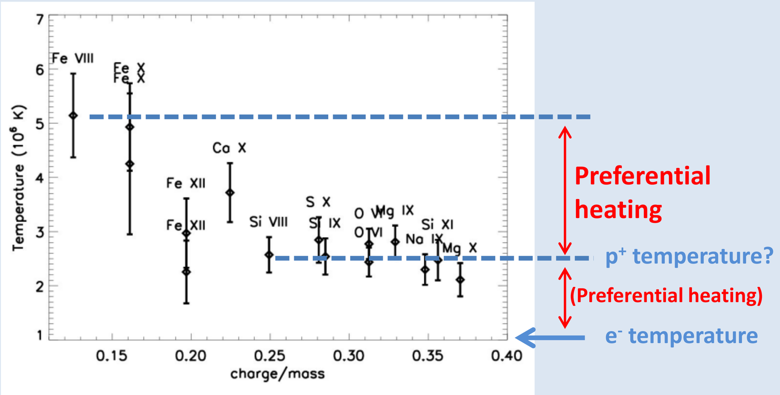
Non-negligible problem with Hinode/EIS: due to thermal variations during the orbit (≈90 min), the optical set up moves. As the optical length is large (≈ 1.4 m), a small angle variation produces large effects (≈3-pixels amplitude).



What for?

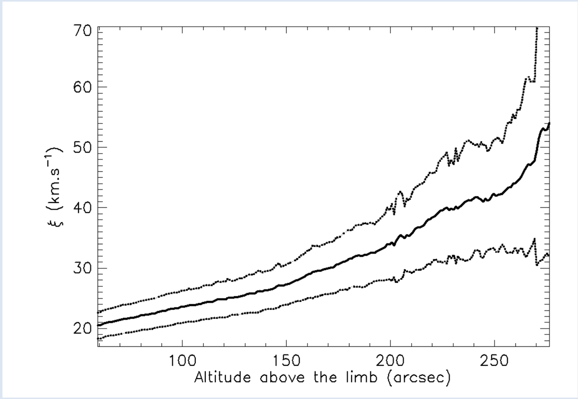
Analysing the preferential heating of ions with low charge/mass ratio

0.06 Rs above a coronal hole



⇒ **Possible signature of ion-cyclotron resonance** in the source region of the fast solar wind
(this is one way of transferring energy from the MHD waves to the solar plasma when coupled with turbulence cascade)

Determining the amplitude of Alfvén waves in the corona from 0.06 to 0.25 Rs



(Upper boundary determined using the gradient of the width of Mg X, less likely to be heated by cyclotron absorption)

⇒ **Constrain for models using MHD waves and turbulence**

What about kinetic Alfvén waves?

The larger width of the spectral lines of Fe ions can be also interpreted in terms of energy deposition in the low charge/mass species by the non-adiabatic ion acceleration by Alfvén waves (Voitenko & Goossens 2004).
In the simplest case of steady state plasma and weak dispersion of Alfvén waves, the non-adiabatic threshold can be estimated as:

$$\delta_p k_\perp \frac{B_k}{B_0} \simeq \frac{q_i/m_i}{q_p/m_p} \lesssim 0.2$$

δ_p - proton inertial length
B_k - wave amplitude
$k_\perp$ - perpendicular wavenumber

To double the temperature of the q/m=0.125 ions one needs the Alfven wave with the super-critical amplitude B_k/B_0=0.01 at the scale $k_\perp\delta_p$=20. Both numbers seem to be realistic.

If the ions "surf" on a wave, then they will present different non-thermal velocities

The effect depends on the Larmor radius ρ_i.

Theoretical predictions for the apparent widths of spectral lines in the wave field with the perpendicular scale $2\pi/k_\perp$

$$V_{obs}^2 = V_{Ti}^2 + I_0\left(\rho_i^2 k_\perp^2\right)\exp\left(-\rho_i^2 k_\perp^2\right)V_{waves}^2$$