University of Warwick

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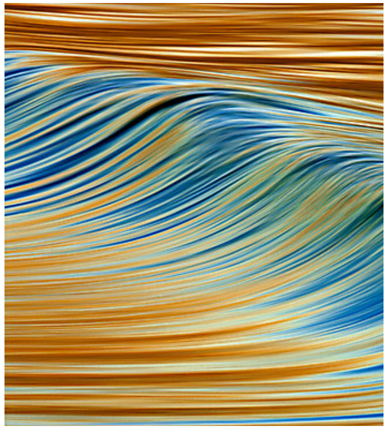

Periodic Spectral Line Asymmetries In Solar Coronal Structures From Slow Magnetoacoustic Waves

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Verwichte et al. ApJL 724 194 (2010)

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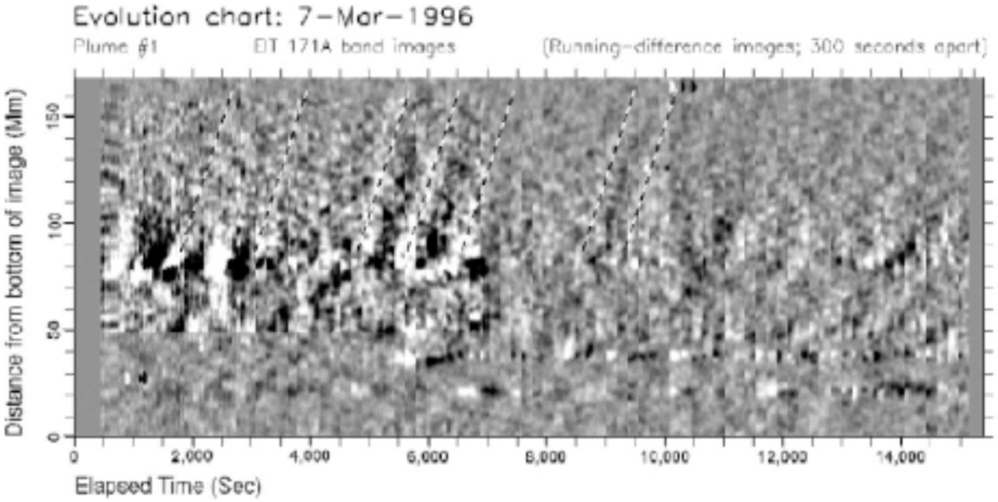
Propagating intensity perturbations...

Since SoHO we see intensity perturbations propagating along large coronal structures

[Ofman 1997, De Forest & Gurman 1998, Berghmans & Clette 1999].



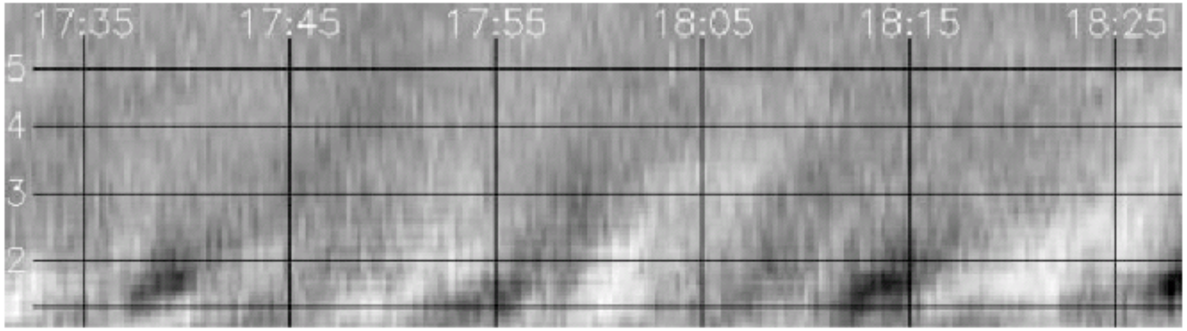


Figure 11. The temporal evolution (horizontal axis) of the EUV intensity along (vertical axis) the path 'E' of Figure 3. The calculated background (see Appendix) has been subtracted. The inclination in this figure corresponds to apparent propagation speeds in the range of 75 – 125 km s^{-1}.

...are slow magnetoacoustic waves

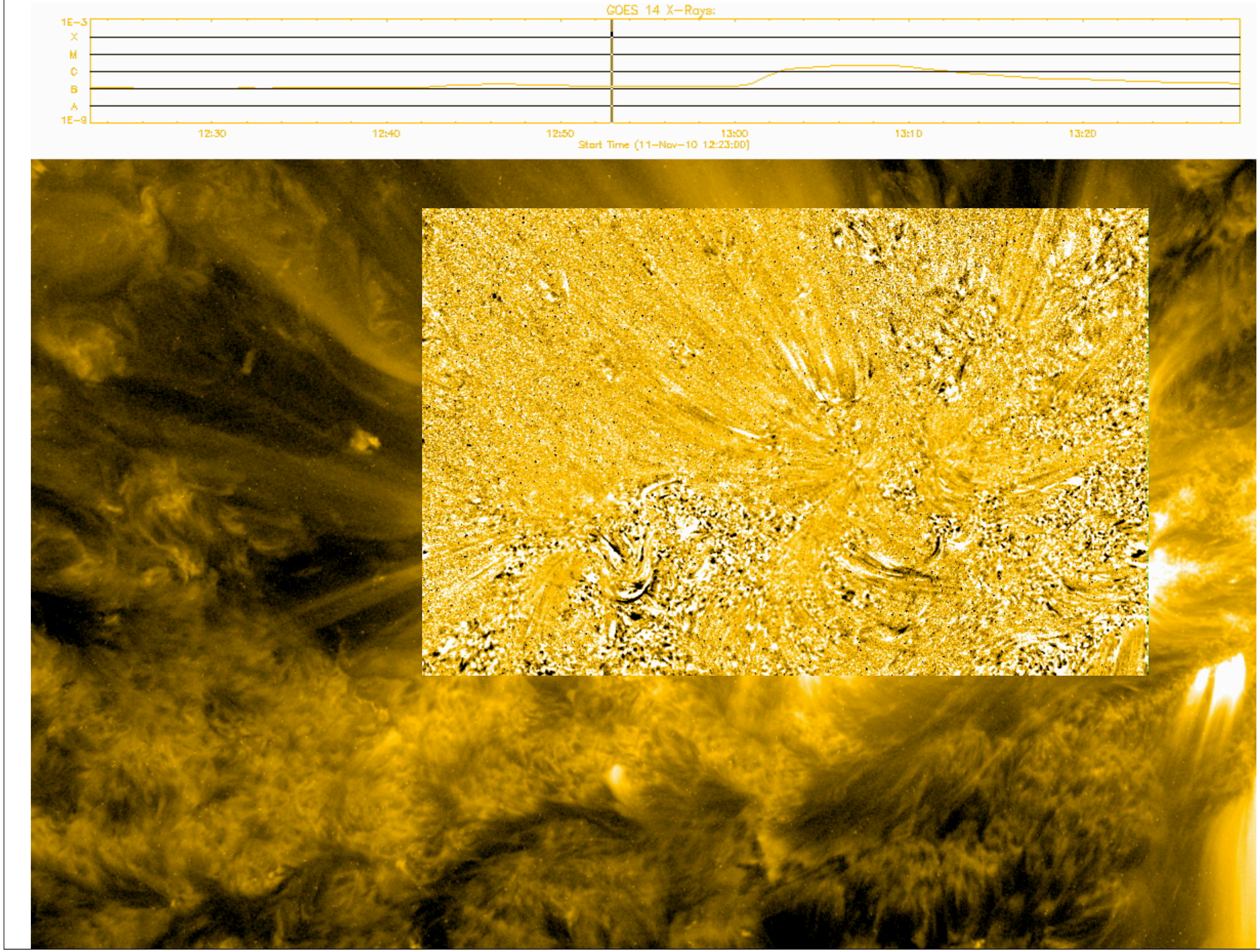
These perturbations have been interpreted as slow magnetoacoustic waves propagating along plume/loop structures.

[De Moortel et al. 2000, Nakariakov et al. 2000, Robbrecht et al. 2001, ..., ...].

Characteristics:

- Projected propagation ≤ sound speed (tube speed) of structure
  Multi-bandpass observations [Robbrecht et al. 2001; King et al. 2003]
  STEREO showed that $V_{ph} = C_s$ [Marsh et al. 2009]
- Periods of 3,5, 10, ... minutes
- Long duration of quasi-periodic behaviour
- Damped over a short distance (thermal conduction)
- In phase intensity and velocity perturbations [Wang et al. 2009]

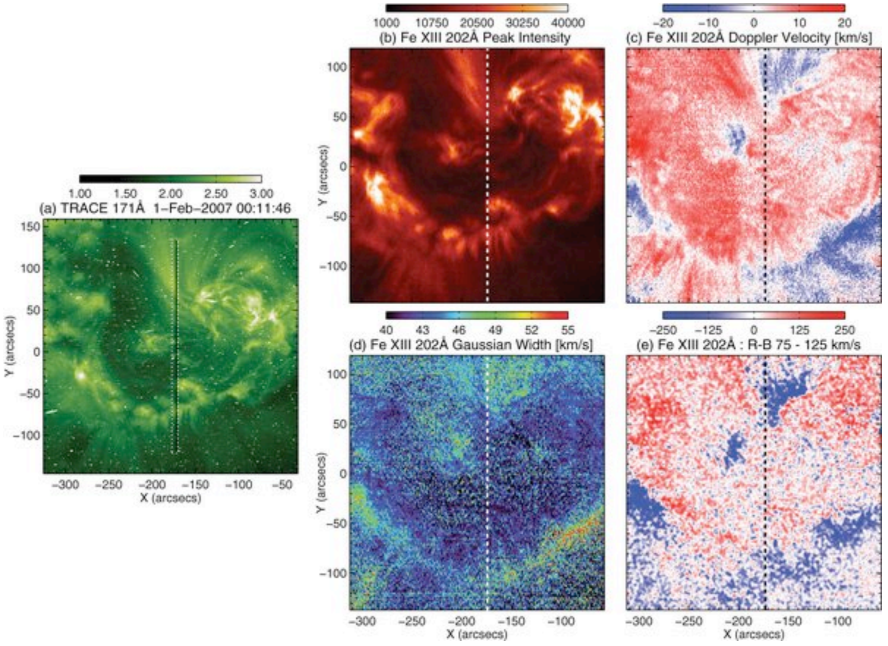
Example: this week’s SDO

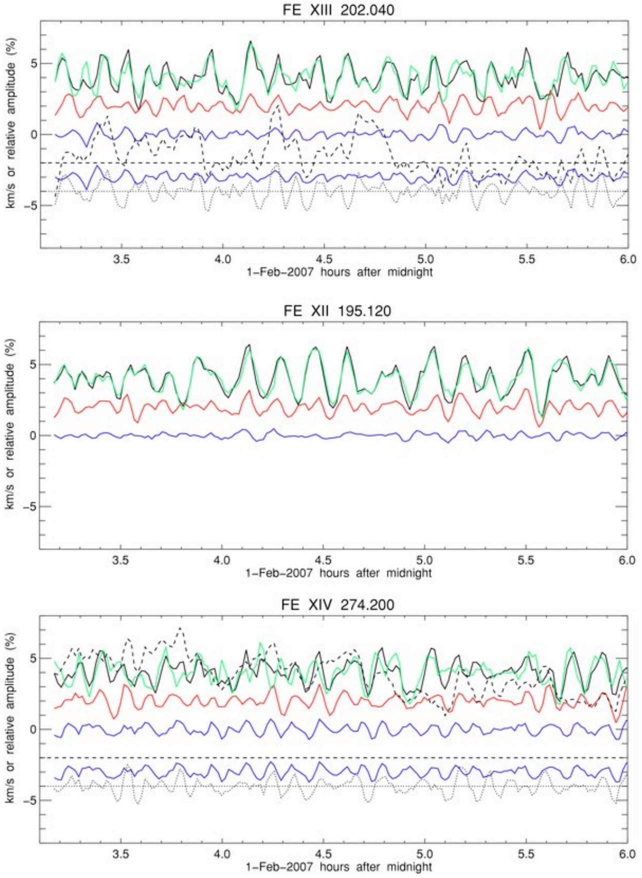


But are we all wrong? They are flows!

Recently a new ‘school of thought’ has appeared that claim that the intensity perturbations are signatures of high-speed flows(~100 km/s), based on measurements of periodic spectral line asymmetries.

[Schrijver et al. 1999, Sakao et al. 2007, hara et al. 2008, De Pontieu et al. 2009, McIntosh et al. 2010].





Their arguments

- Many of the observed propagating disturbances (especially in coronal loops emanating from quiet Sun network and active region plage) do not show evidence of significant quasi-periodic signals.

- The wave interpretation was compatible with the lack of strong Doppler shifts.

- EIS measurements of intensity and velocity oscillations are accompanied by oscillations in the line width and recurring asymmetries in line profiles across a range of temperatures.

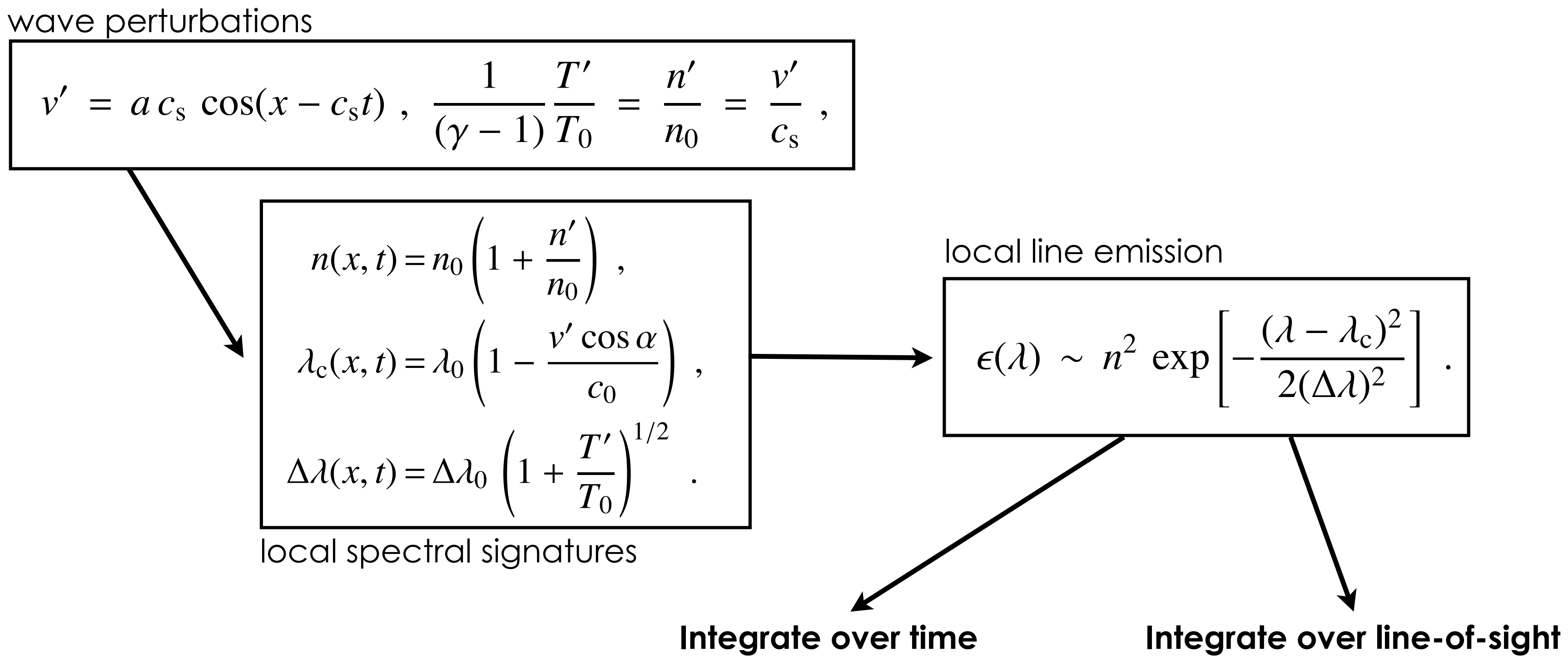
However, a periodic flow model does not yet exist. The whole alternative is a superposition of a periodic upflow component in the blue wing on top of a static background

$$I(\lambda, t) = I_0 e^{-(\lambda-\lambda_0)^2/(2\sigma_0^2)} + a I_0 \cos^2(2\pi t/P) e^{-(\lambda-\lambda_1)^2/(2\sigma_1^2)}, \quad (1)$$

Can slow waves explain spectral features?

Why throw away 10 years of slow wave work? Can we possibly explain periodic line-asymmetries and large line-width variations with slow waves?

We model the spectral line in the presence of a simple slow wave:



wave perturbations

$$v' = a\, c_{\rm s} \cos(x - c_{\rm s} t)\ , \quad \frac{1}{(\gamma - 1)} \frac{T'}{T_0} = \frac{n'}{n_0} = \frac{v'}{c_{\rm s}}\ ,$$

$$n(x,t) = n_0 \left(1 + \frac{n'}{n_0}\right)\ ,$$

$$\lambda_{\rm c}(x,t) = \lambda_0 \left(1 - \frac{v' \cos\alpha}{c_0}\right)\ ,$$

$$\Delta\lambda(x,t) = \Delta\lambda_0 \left(1 + \frac{T'}{T_0}\right)^{1/2}\ .$$

local spectral signatures

local line emission

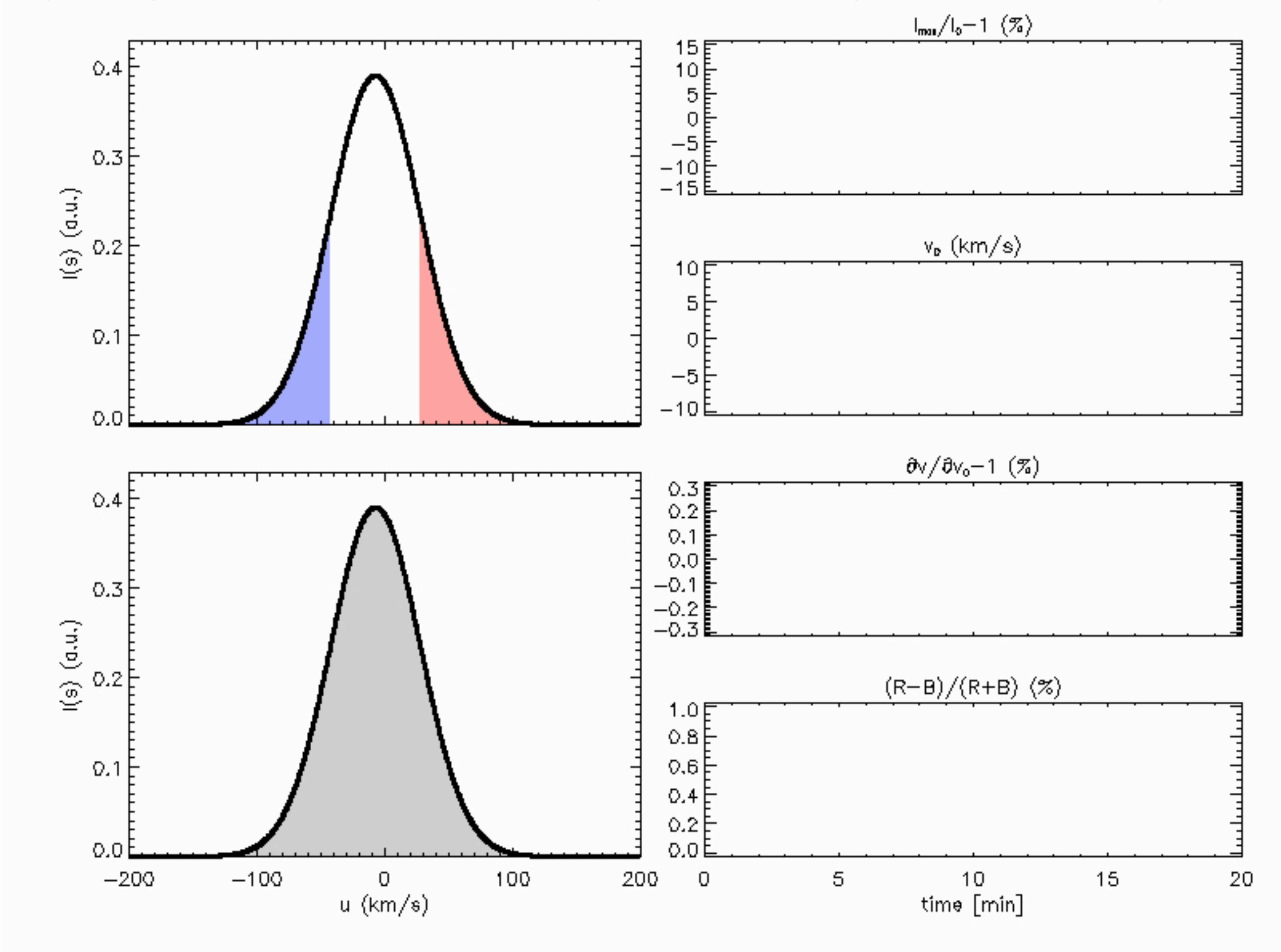
$$\epsilon(\lambda) \sim n^2 \exp\left[-\frac{(\lambda - \lambda_{\rm c})^2}{2(\Delta\lambda)^2}\right]\ .$$

Integrate over time

Integrate over line-of-sight

Slow waves have inherent spectral asymmetry

Because velocity and density perturbations are in-phase, upwards propagating waves have a stronger blue wing than red wing!



Time-averaged spectral line

When we average over an oscillation period, the blue wing receives more emission than the red wing.

$$\boxed{\bar{\epsilon}(s) \approx n_0^2\left[\left(\bar{f}_0 - \frac{\bar{f}_2}{2}\right)F(s_*) + \sum_{m=3}^{4}\frac{\bar{f}_m}{m!}\frac{\mathrm{d}^m F(s_*)}{\mathrm{d}s^m}\right],}$$

$$s_* = \frac{s + \bar{f}_1}{\sqrt{1 + \bar{f}_2}} = \frac{s v_{\mathrm{th},0} - v_{\mathrm{D}}}{\sqrt{v_{\mathrm{th},0}^2 + (\Delta v_{\mathrm{NT}})^2}}.$$

$$\bar{f}_0 - \frac{\bar{f}_2}{2} = 1 + \frac{a^2}{16}\left(8 - 3(\gamma - 1)^2\right) - \frac{a^2}{4}\left(\frac{c_{\mathrm{s}}\cos\alpha}{v_{\mathrm{th},0}}\right)^2,$$

$$\bar{f}_1 = \frac{a^2}{4}(\gamma + 3)\frac{c_{\mathrm{s}}\cos\alpha}{v_{\mathrm{th},0}},$$

$$\bar{f}_2 = \frac{a^2}{4}(\gamma - 1)(3\gamma + 1) + \frac{a^2}{2}\left(\frac{c_{\mathrm{s}}\cos\alpha}{v_{\mathrm{th},0}}\right)^2,$$

$$\bar{f}_3 = \frac{3a^2}{2}(\gamma - 1)\frac{c_{\mathrm{s}}\cos\alpha}{v_{\mathrm{th},0}}, \quad \bar{f}_4 = \frac{3a^2}{2}(\gamma - 1)^2.$$

- Doppler shift to the blue wing

$$v_{\mathrm{D}} = -\bar{f}_1 v_{\mathrm{th},0}$$

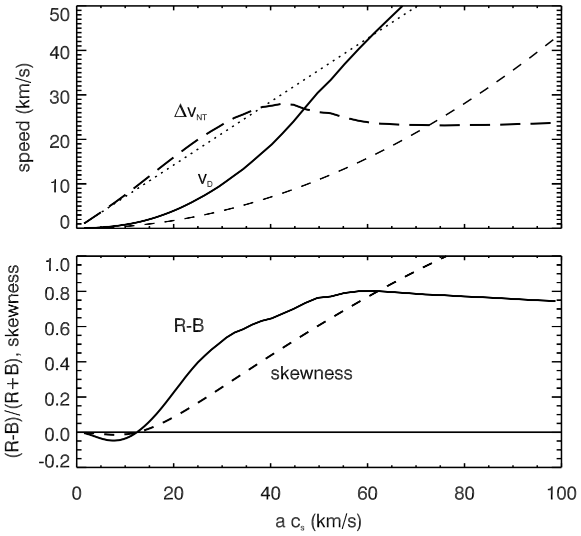
- Non-thermal broadening

$$\Delta v_{\mathrm{NT}} = \bar{f}_2^{1/2} v_{\mathrm{th},0} \approx a c_{\mathrm{s}} \cos\alpha/\sqrt{2}.$$

ac_s=5km/s ⇒ Δv_{NT}=20 km/s [Hara et al 2008]

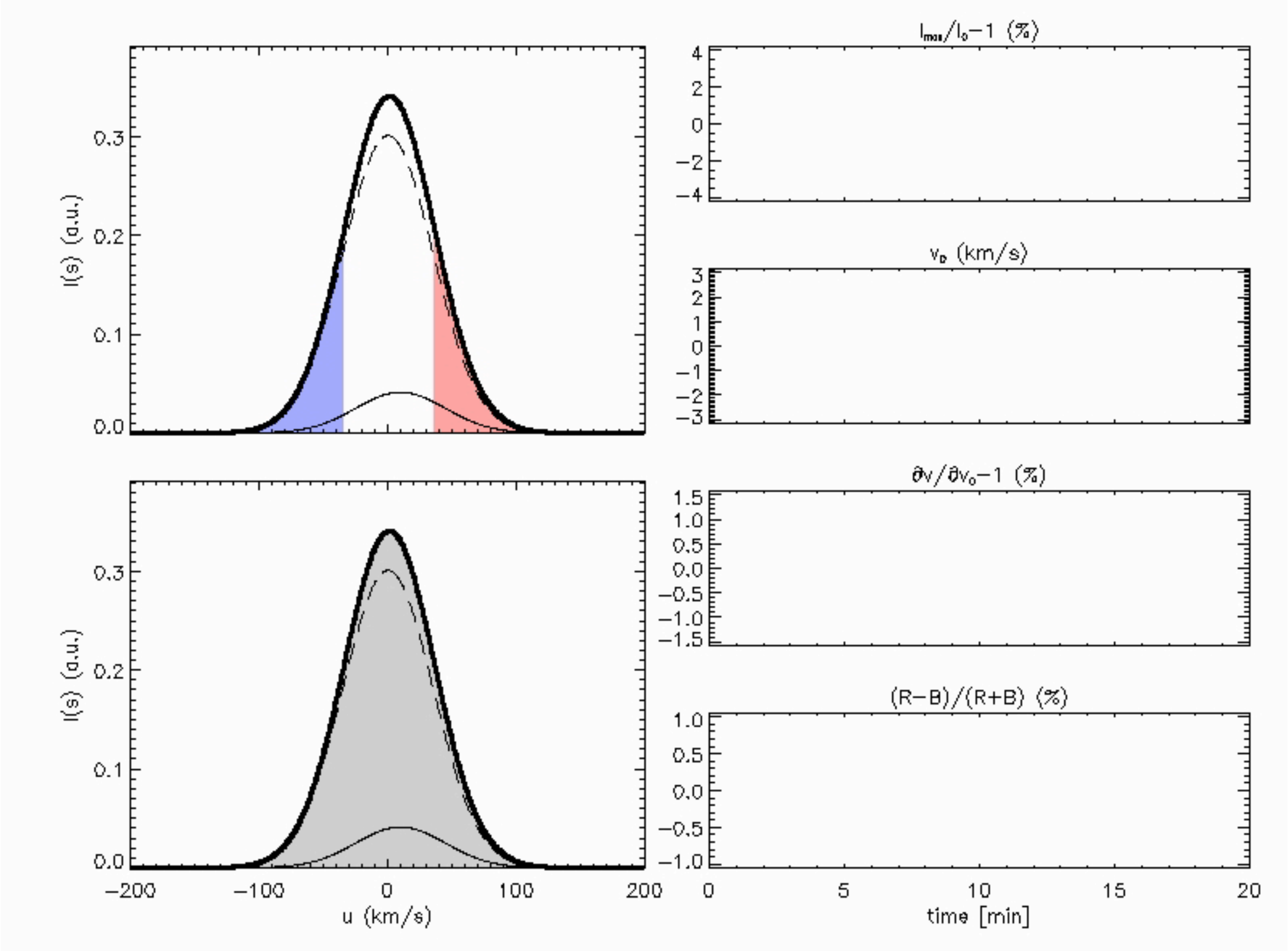
- Line asymmetry

$$\bar{f}_3 \approx 10a^2$$



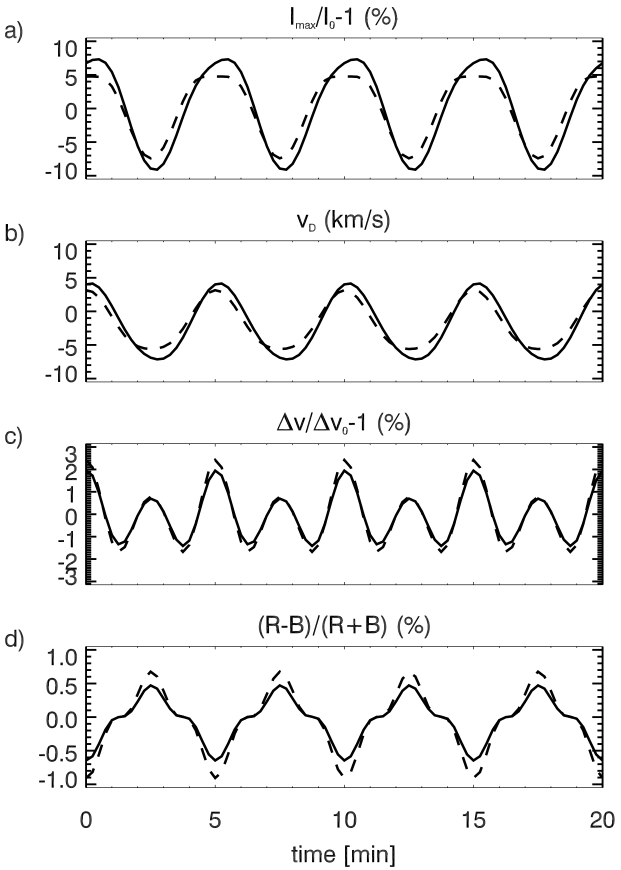
Multiple component spectral line

We consider the line-of-sight integration of plasma with a slow wave and a static background plasma component.



Multiple component spectral line

Intensity amplitude and Doppler shift reduce by factor $1/(1 + I_{bg}/I_0)$.

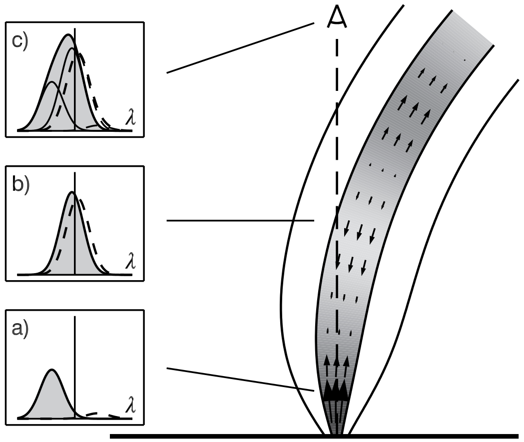


The real wave amplitude may be quite large.

Appearance of line width and line asymmetry variations

Line width may have half period.

Multiple components may be integation along loop where amplitude changes with height.



Conclusions

Slow wave can naturally produce (periodic) signatures of spectral line asymmetry and line-width.

The flow model requires always the presence of a static plasma component in the line-of-sight everywhere whilst a slow wave model does not need it to produce intensity, velocity and line-width perturbations!

Slow waves can naturally explain:
- Sonic propagation speed
- Damping
- Persistence of quasi-periodic signals

The claim more careful spectral observations are needed to distinguish the two models may be a red herring as these spectral observations are done at (beyond?) the limit of spectrometer capabilities!

In order to test models, a physical model of periodic upflows needs to be formulated!