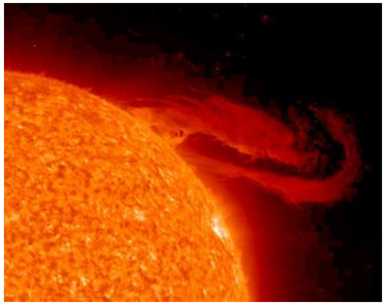
University of Glasgow

Solar prominence science with ALMA

N. Labrosse, P. Antolin, J.L. Ballester, R. Brajsa,
S. Gunár, B. Schmieder, M. Temmer, S. Wedemeyer

INSPIRING PEOPLE

Key points

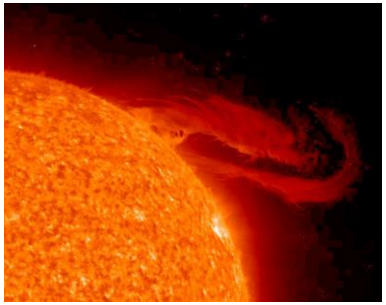


ALMA will
- provide precise temperature estimates at high cadence
- benefit from the support from other instruments (Hα, HMI, ...)

ALMA can help to answer important open questions about prominences and filaments

- What is their thermal structure?
- What is their spatial fine-structure?
- Can we constrain the magnetic field structure?

Prominence 101



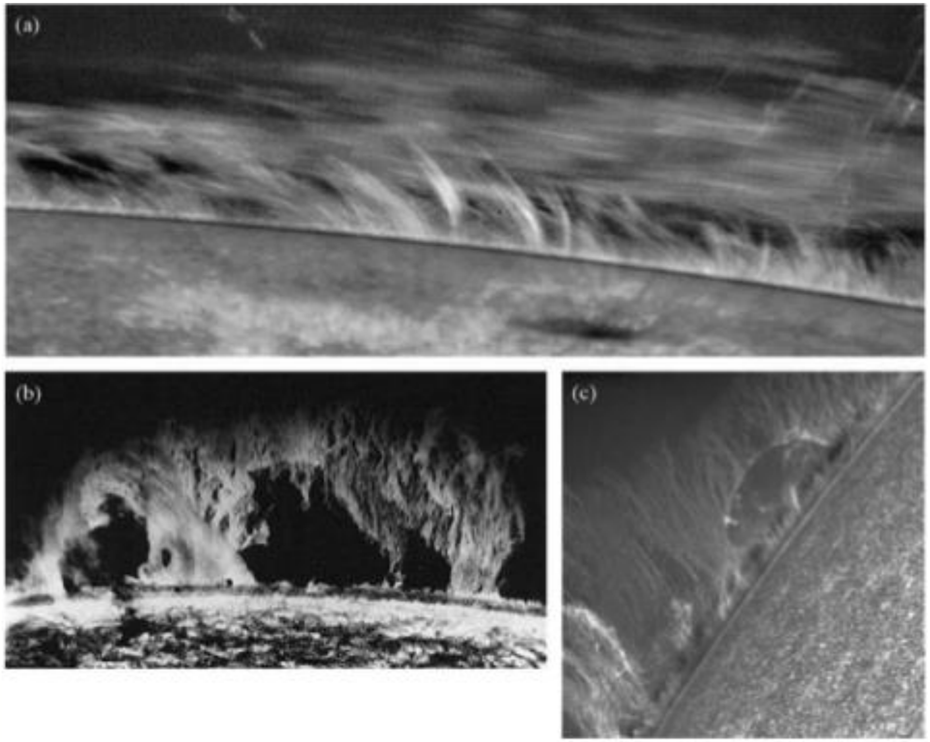
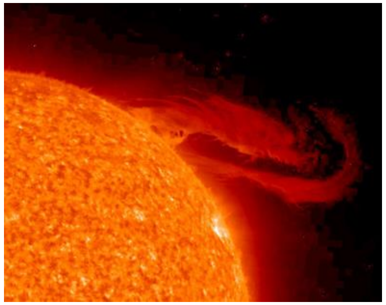


Fig. 3 Examples of solar prominences at the limb in different wavelengths: (**a**) Ca II H HINODE/SOT image from November 9, 2006 (from Okamoto et al. 2007); (**b**) BBSO Hα image from 1970; (**c**) Ca II H HINODE/SOT image (courtesy of T. Berger)

- Range of scales
- Respond to heating processes
- Magnetic field
- Eruptions, flares, CMEs
- Cool, dense plasma at chromospheric temperatures

Above figure from Mackay et al (2010)
See also Labrosse et al (2010), Parenti (2014), Vial & Engvold (2015)

Some questions to be addressed by ALMA



The thermal structure of solar prominences at millimetre wavelengths

- What is the fine-scale thermal structure of solar prominences and filaments at high spatial resolution in their main body and in the prominence-corona transition region?
- How does the prominence plasma react to various heating processes?
- How is the dynamics of the plasma related on small scales and on large scales to the structure in temperature of solar prominences?

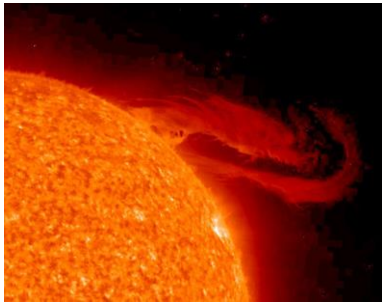
The spatial structure of solar prominences at millimetre wavelengths

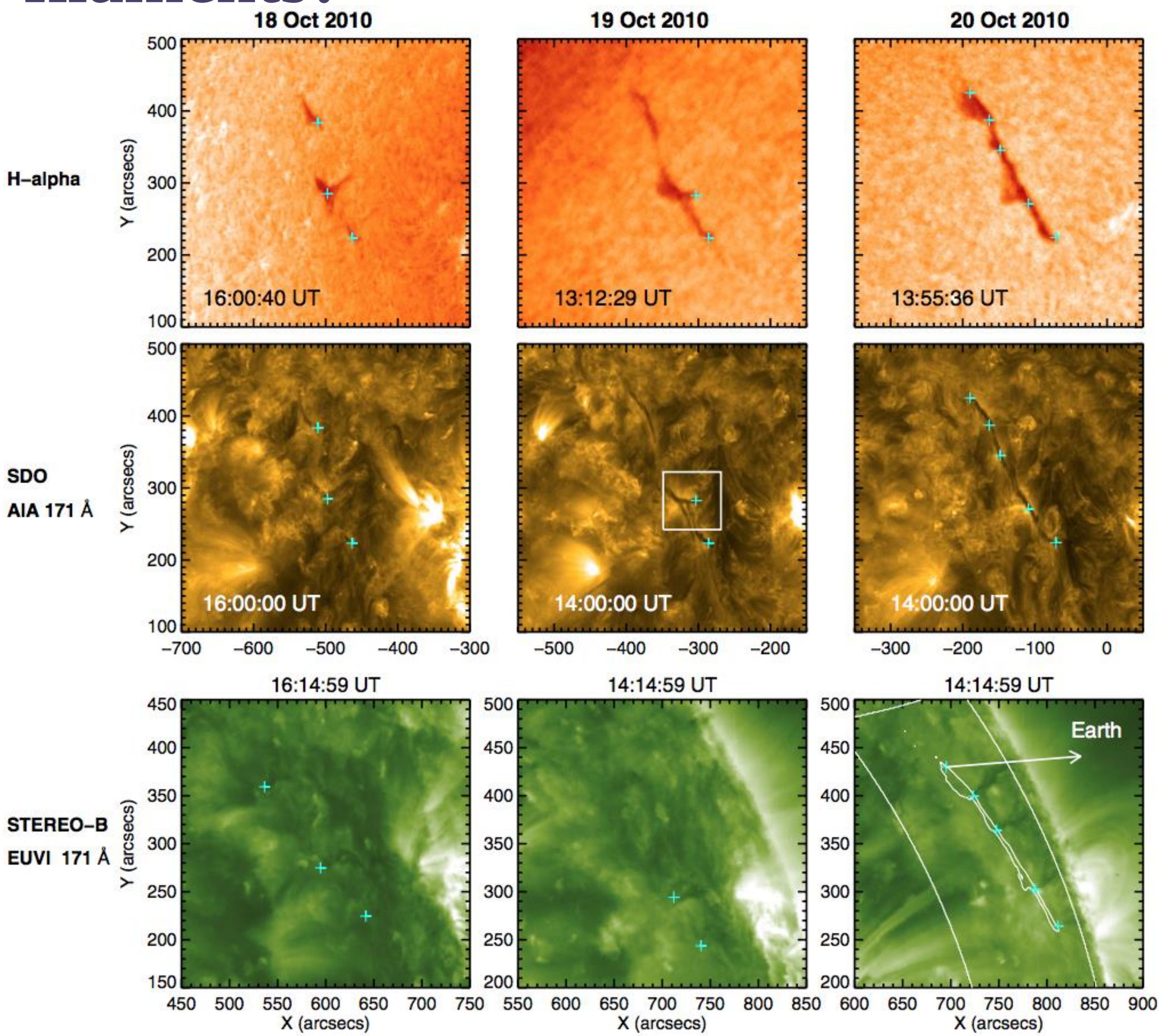
- How is the fine-scale structure of prominences shaped by the magnetic field?
- How do Active Region and Quiet Sun prominences differ in millimetre wavelengths?

Observables provided by ALMA

- height dependence of thermal emission - wave power versus period - flow magnitudes - timescale / range of temperature changes - onset of prominence activation	- distribution and sizes of the fine structures - dynamics and temporal evolution of the fine structures - filling factor, corresponding to the fraction occupied by the fine structures

How is the fine-scale structure of filaments shaped and what is their role in erupting filaments?



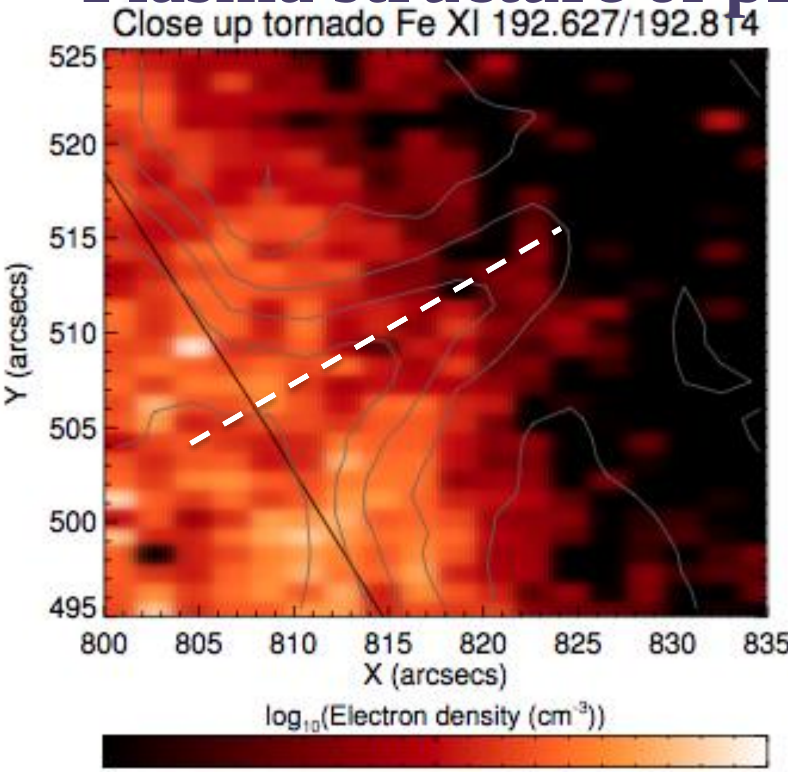


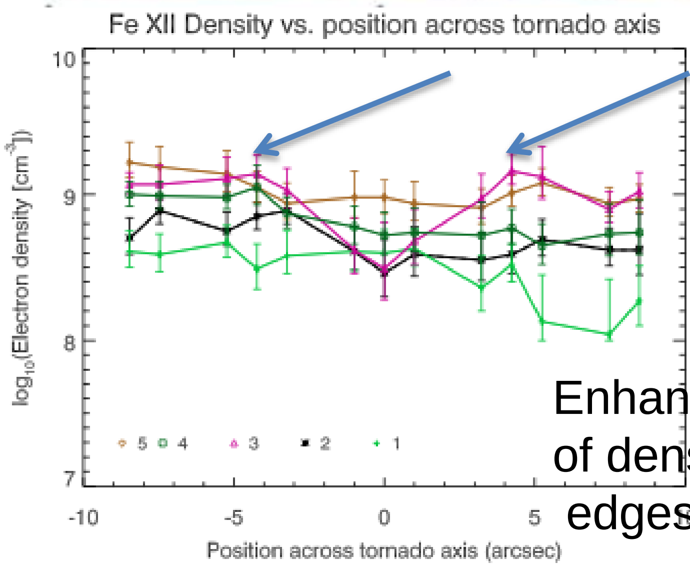
Observational study by Su et al. (2014) and simulations by Wedemeyer-Böhm et al. (2012) showed magnetized “tornado” structures at the basis of filament formation. Those structures are assumed to play a role in the eruption of a filament.

ALMA high-resolution data of such fine structures will enable us to thoroughly study their physical characteristics (mass flows, oscillations, relations to magnetic field) and association to mass eruptions.

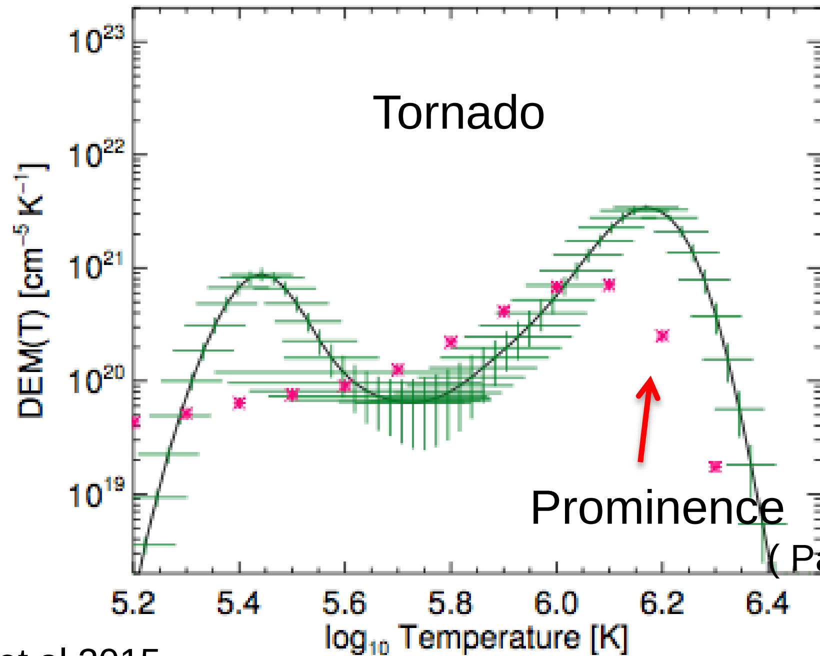
Powerful combination: ALMA, SDO, Hα observations (e.g., Kanzelhöhe, Paris-Meudon)

Plasma structure of prominence legs



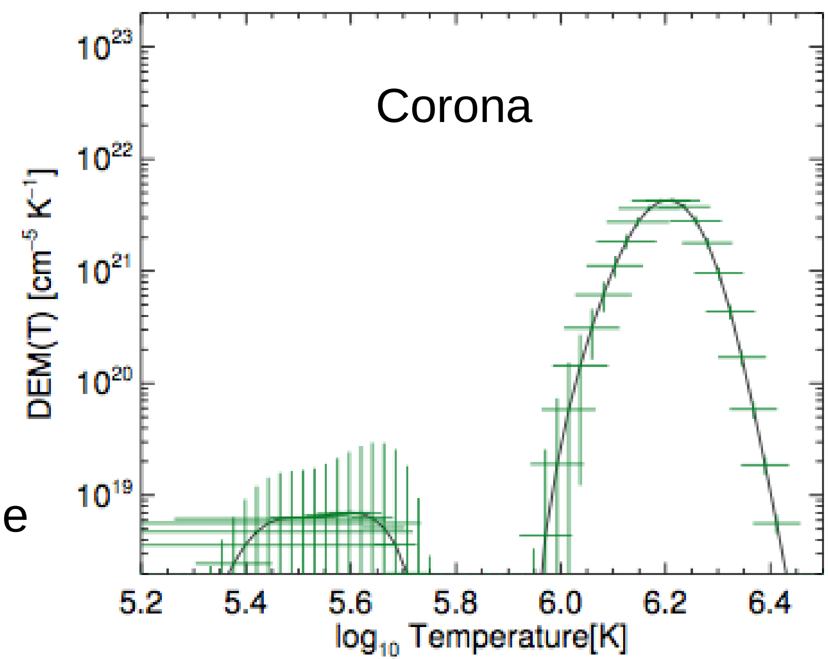


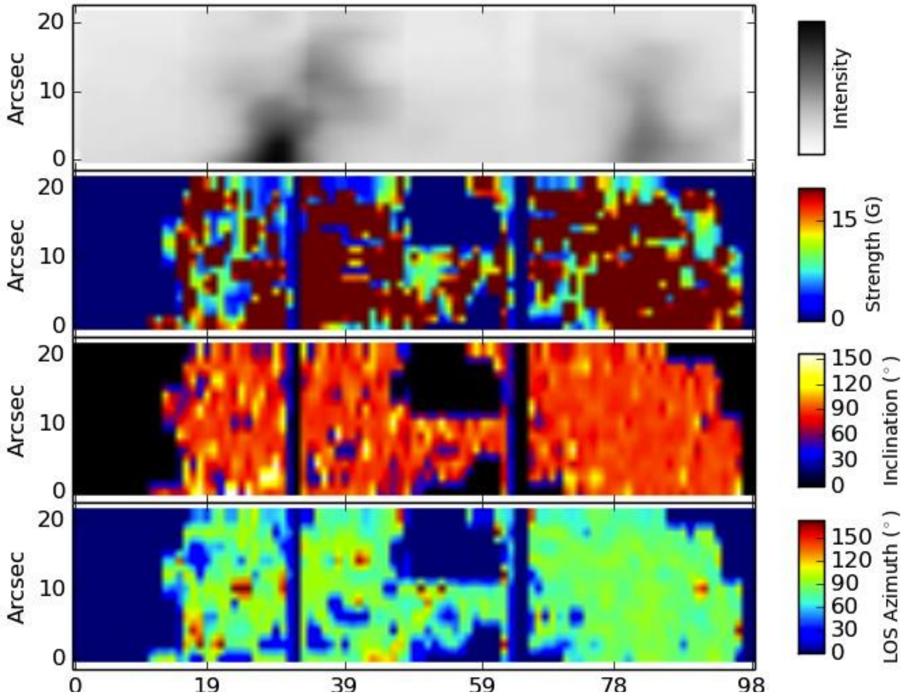
Enhancement of density at the edges

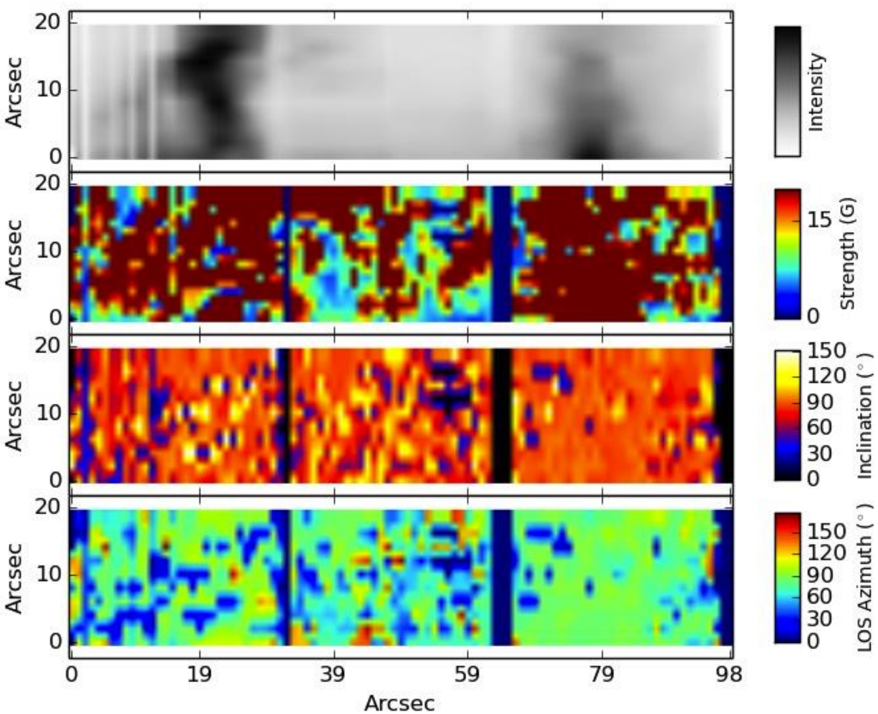


(Parenti)

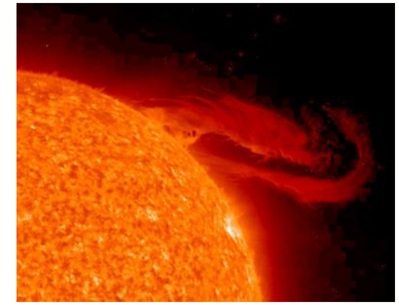
Levens et al 2015

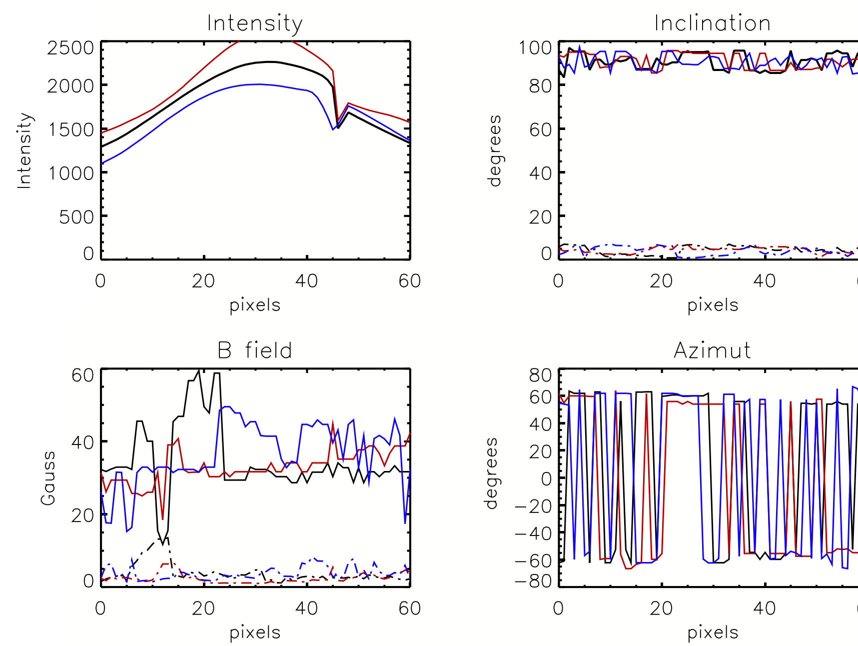






Magnetic field structure and orientation

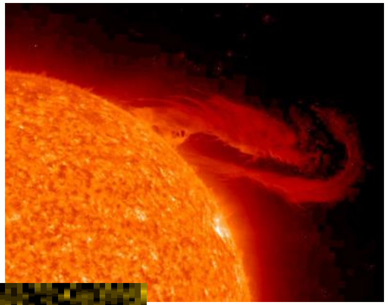




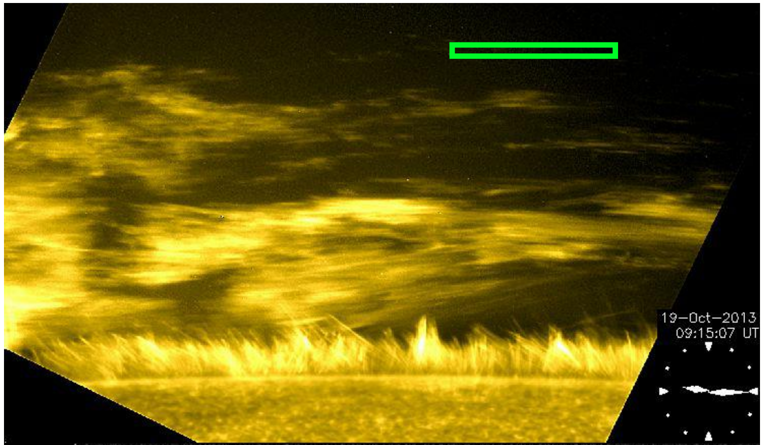
The magnetic field is between 25 - 60 G
The inclination is 90 degrees: horizontal field

(Schmieder et al 2015, Levens et al 2016)

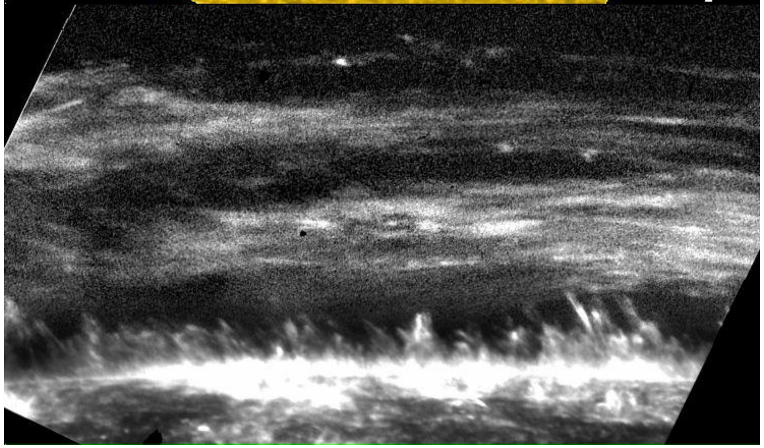
IRIS/Hinode observations



Hinode/SOT（Ca II, 10,000 K)



Hinode/SOT（JAXA/NAOJ)

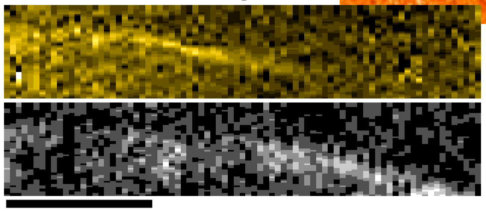


IRIS（NASA)

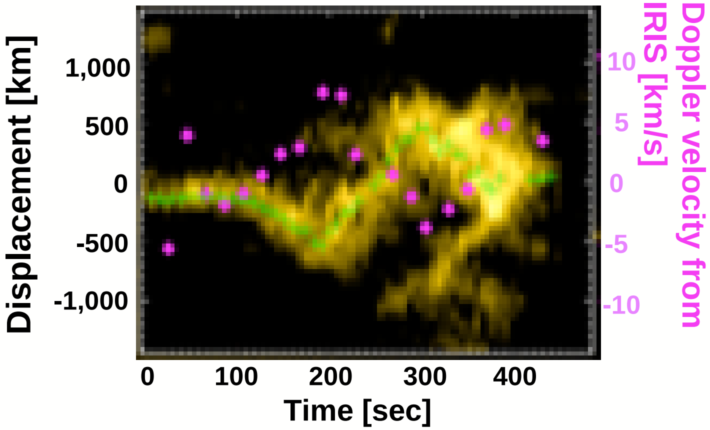
IRIS/SJI (Si IV, 100,000)

(Okamoto+2015, Antolin+2015)

x-t diagram

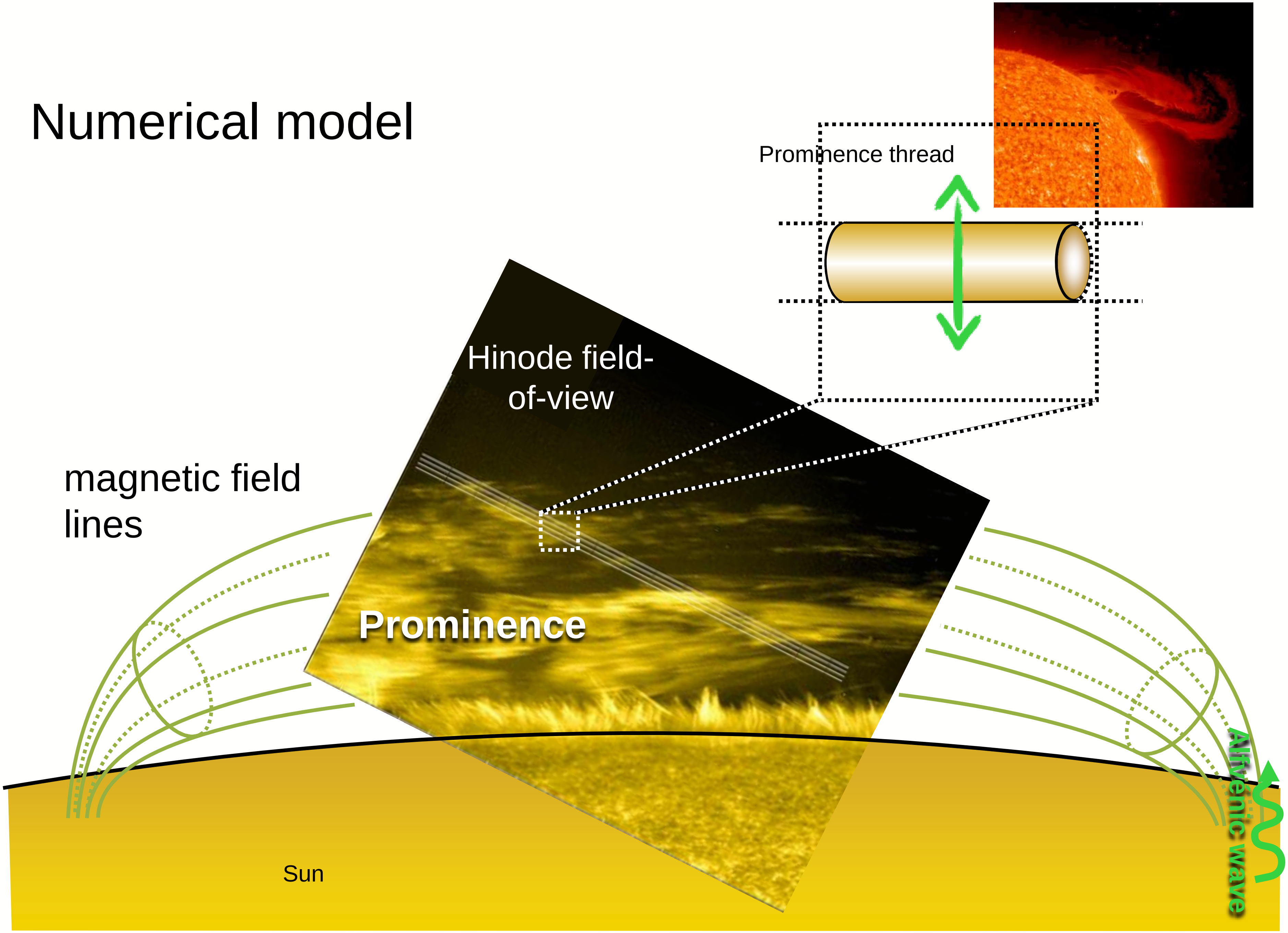


Motion of prominence plasma crossing the slit

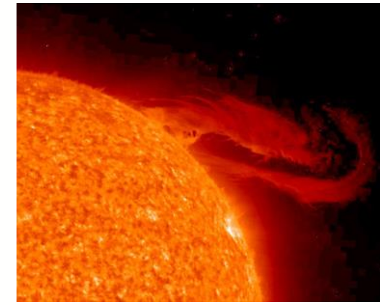


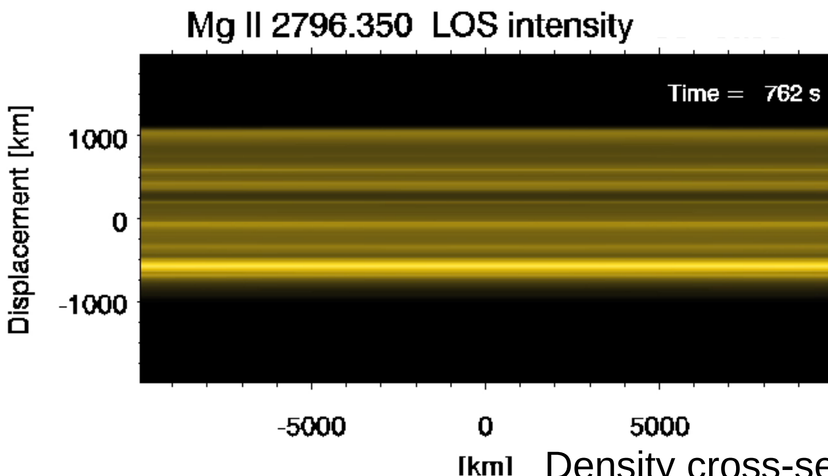
- Ubiquitous transverse MHD waves
- Heating: Fading in cool line (10^4 K), subsequent appearance in hot line (10^5 K)
- Out-of-phase POS motion & LOS velocity
- Thread-like structure

Numerical model

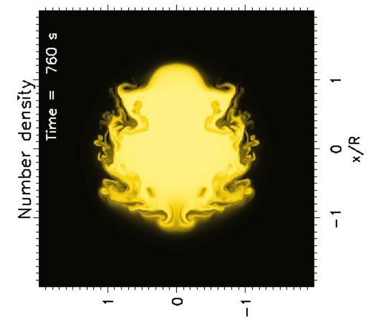


Numerical simulations



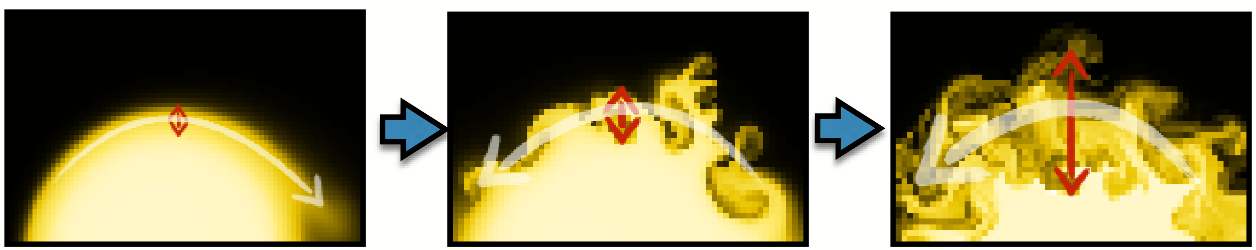


Cross-section

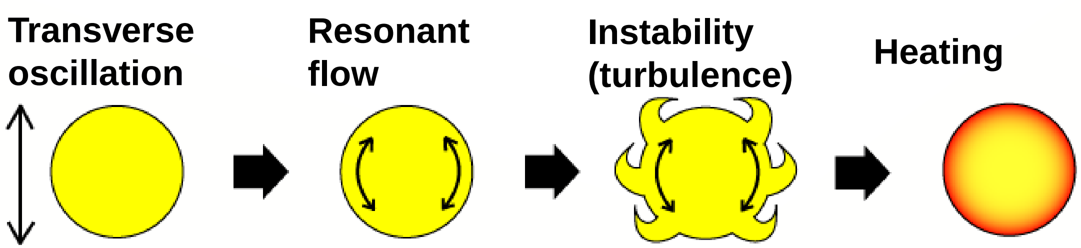


Resonant absorption transfers energy from transverse waves to torsional waves near the boundary

Density cross-section of prominence thread

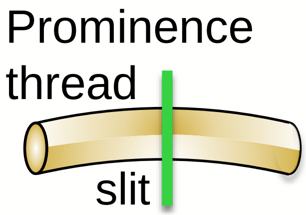


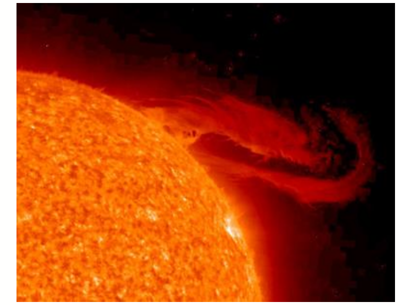
Kelvin-Helmholtz instability converts energy from resonance into heat through turbulent dissipation



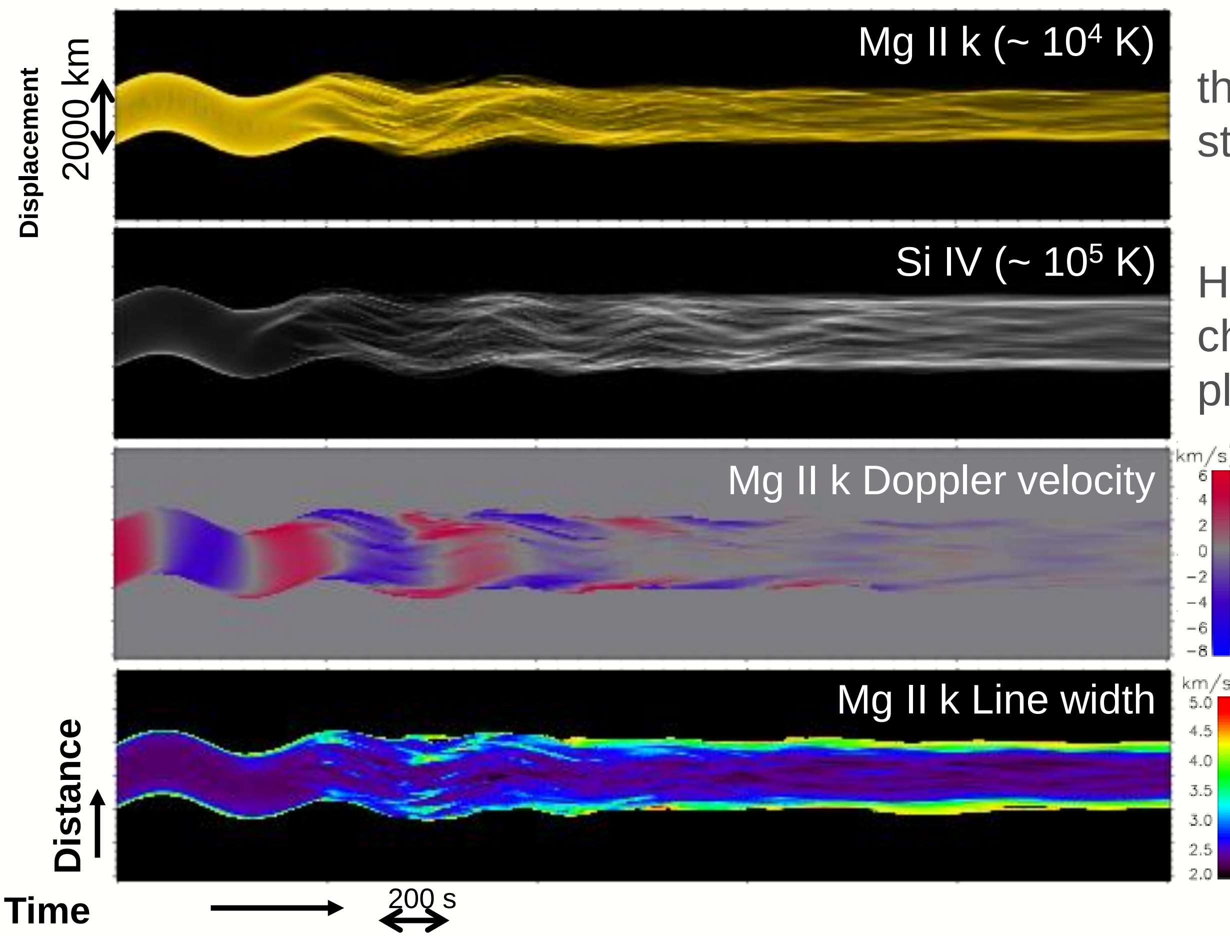
(Antolin+2015, Okamoto+2015)

Observational signatures





45° LOS plane



Observable with ALMA

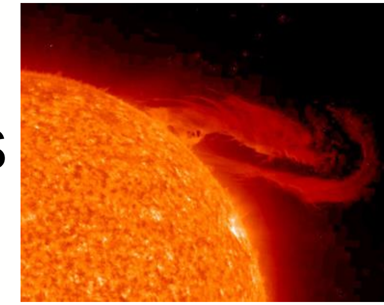
thread-like structure ✓

Heating of chromospheric plasma ✓

Small-scale vortices → Turbulent spectrum ✓ ← Line broadening

(Antolin+2015, Okamoto+2015)

Background temperature fluctuations effect on propagation of slow MHD waves



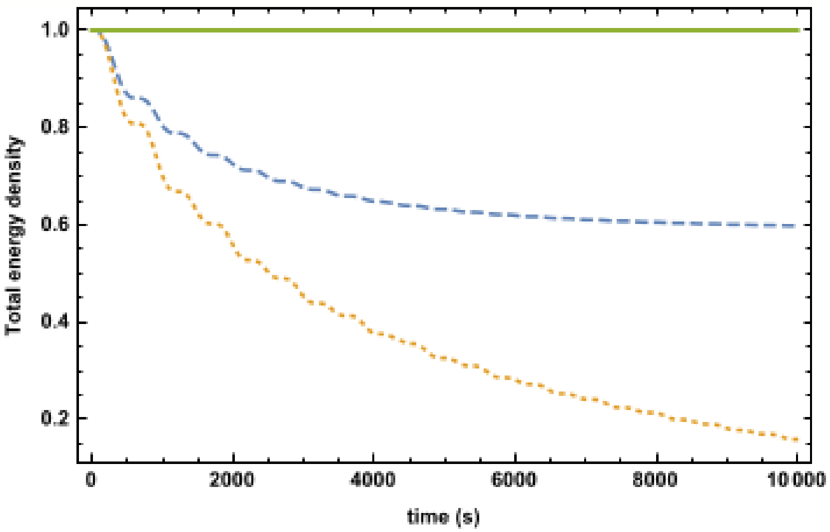


Fig. 17. Temporal behaviour of the slow wave total energy density for a prominence plasma (a) with a constant temperature (continuous line); (b) with a temperature that increases with time (dashed line); (c) with a temperature that increases with time and radiative damping of the perturbations included (dotted line). $H = 1 \times 10^{-5}$ W·m^{-3}, $\tau = 3000$ s, $T_{0i} = 10{,}000$ K, $k_z = 3 \times 10^{-7}$ m^{-1}. The total energy density has been normalized with respect to its initial value.

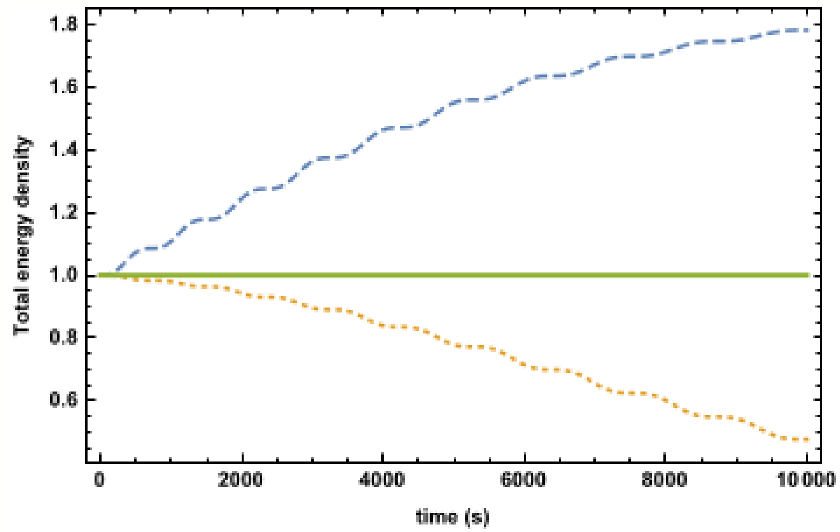
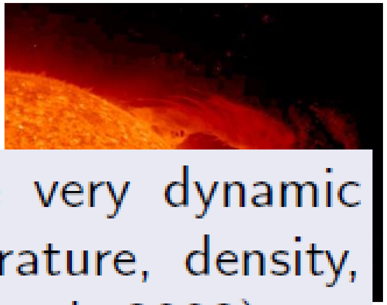


Fig. 18. Temporal behaviour of the slow wave total energy density for a prominence plasma (a) with a constant temperature (continuous line); (b) with a temperature which decreases with time (dashed line); (c) with a temperature that decreases with time and radiative damping of the perturbations included (dotted line). $H = 1 \times 10^{-6}$ W·m^{-3}, $\tau = 3000$ s, $T_{0i} = 10{,}000$ K, $k_z = 3 \times 10^{-7}$ m^{-1}. The total energy density has been normalized with respect to its initial value.

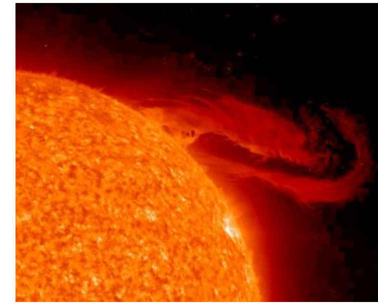
Ballester et al, A&A, accepted

Temperature fluctuations

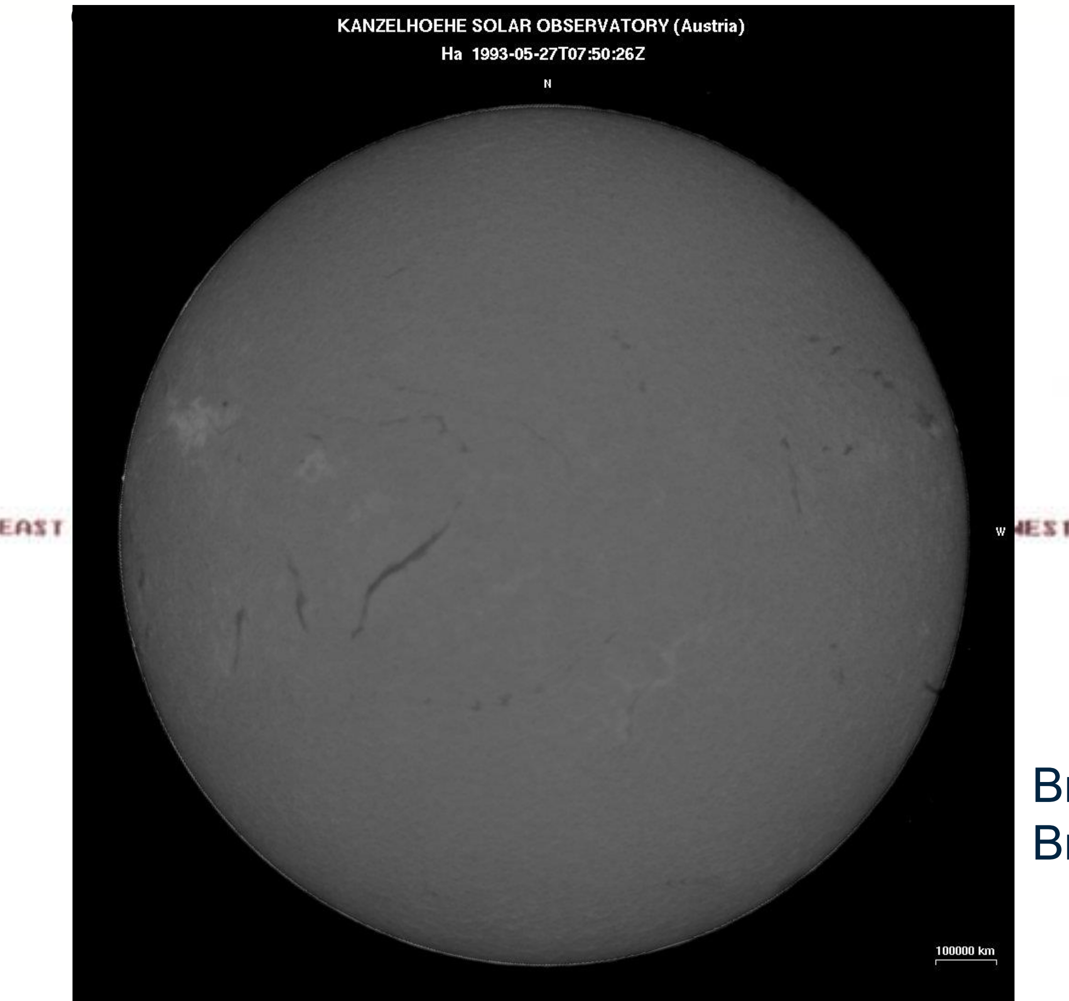


- Observations of prominences suggest that they are very dynamic plasma structures whose physical properties (temperature, density, pressure, etc.) could be changing with time (Berger et al. 2008)
- A variable background temperature could give place to time amplified or damped oscillations (Molowny-Horas et al. 1999; Terradas et al. 2002; Lin, 2004) produced by slow waves while, at the same time, the oscillatory period increases or decreases, respectively
- When the background temperature increases with time the velocity and density perturbations decrease with time while, on the contrary, pressure and temperature perturbations increase with time
- Therefore, while Doppler velocity information would suggest attenuation of the oscillations, spectral line parameters such as intensity, line width, etc., which could be related to pressure or temperature perturbations (Heinzel et al. 2014), would give the opposite information
- All this could happen, simultaneously, in different places of the same prominence. Difficulty in the interpretation of prominence oscillations

Filaments on the disc



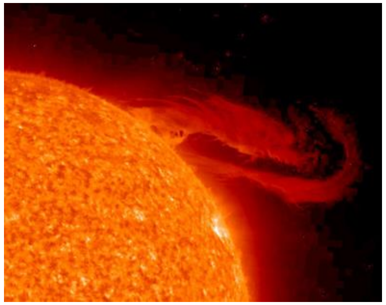
1.0 - quiet Sun level

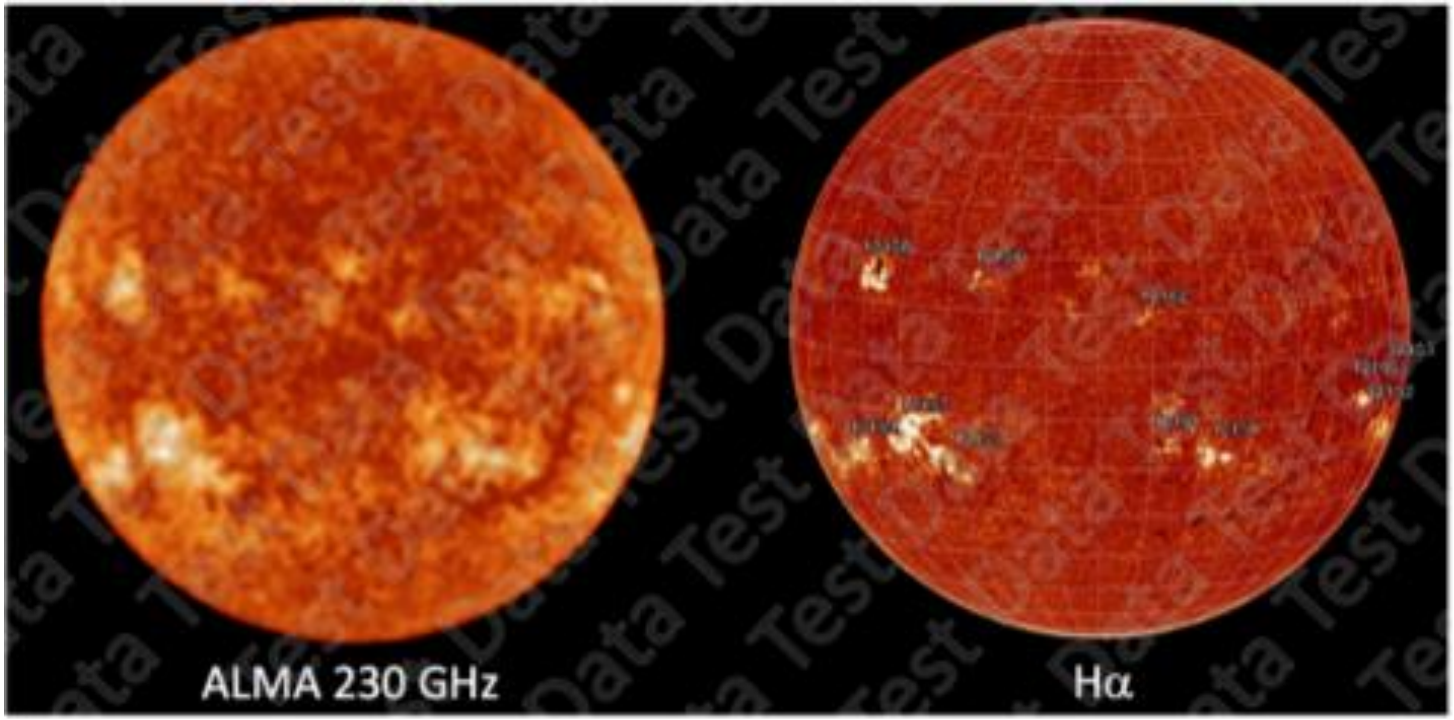


Metsähovi
λ = 8 mm
27 May 1993
HTRs, Tb > TQSL
LTRs, Tb < TQSL

Brajša et al., 2007, Sol.Pys. 245, 167
Brajša et al., 2009, AA 493, 613

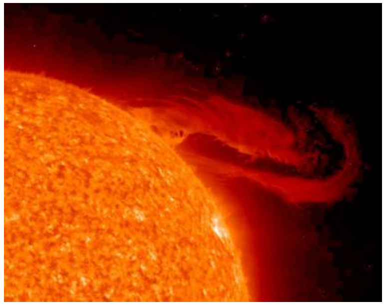
Filaments on the disc





From Phillips et al (2015)

What will ALMA see?



See Wedemeyer et al (2015), Heinzel et al (2015)

For prominence plasma, radiation at ALMA wavelengths has its origins in free-free continuum emission

- LTE can be assumed, so source function is Planck function

$$I_\nu = \int B_\nu(T) e^{-t_\nu} \, dt_\nu = \int \eta_\nu e^{-t_\nu} \, dl, \quad \eta_\nu = \kappa_\nu B_\nu, \; dt_\nu = \kappa_\nu \, dl.$$

- Radio wavelengths: Rayleigh-Jeans approximation

$$I_\nu = \frac{2\nu^2 k}{c^2} T_b, \qquad B_\nu = \frac{2\nu^2 k}{c^2} T$$

- Hence brightness temperature is

$$T_b = \int T e^{-t_\nu} \, dt_\nu = \int T e^{-t_\nu} \kappa_\nu \, dl$$

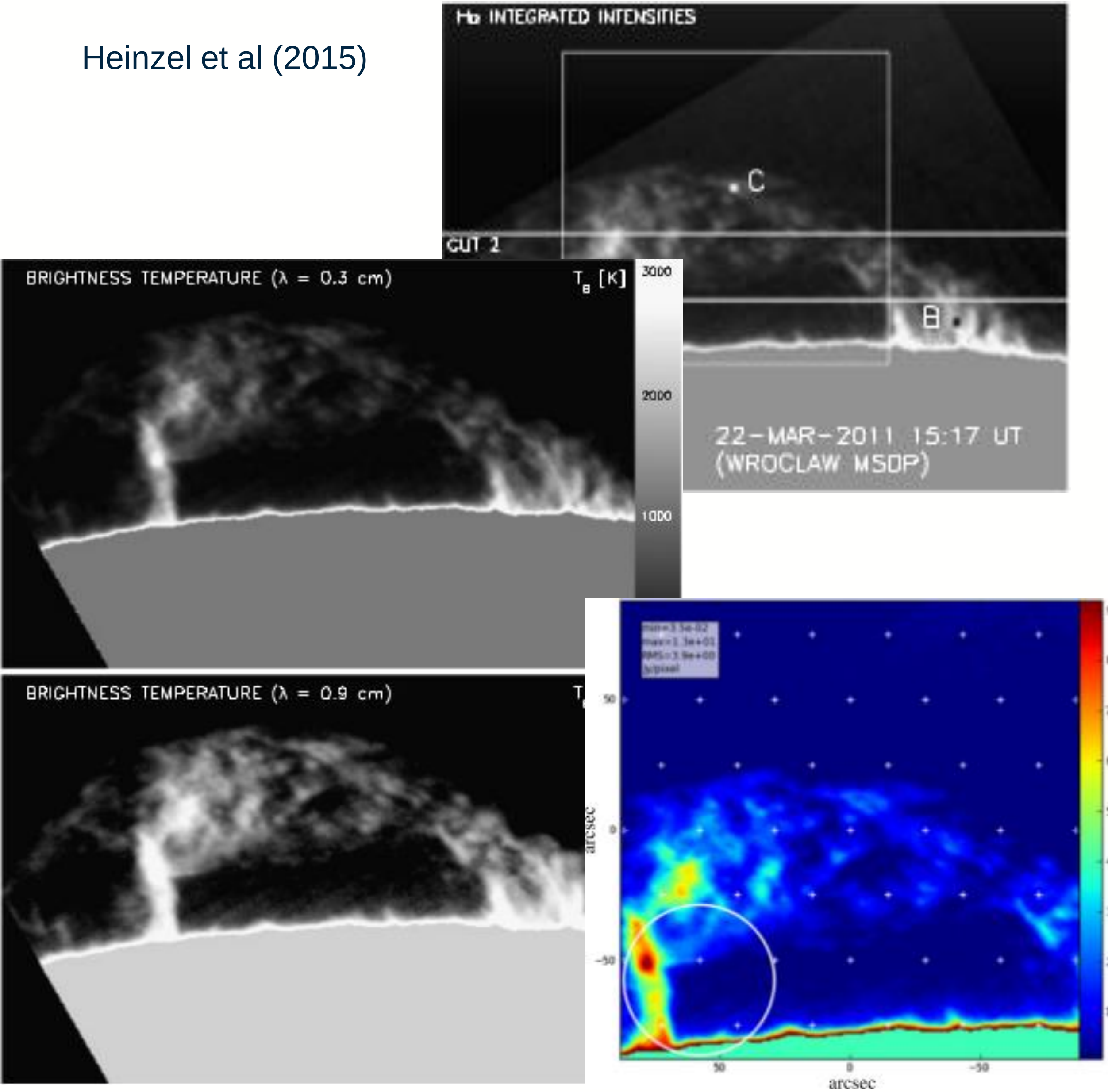
- We take the absorption coefficient as in Dulk (1995) and get for κ_ν

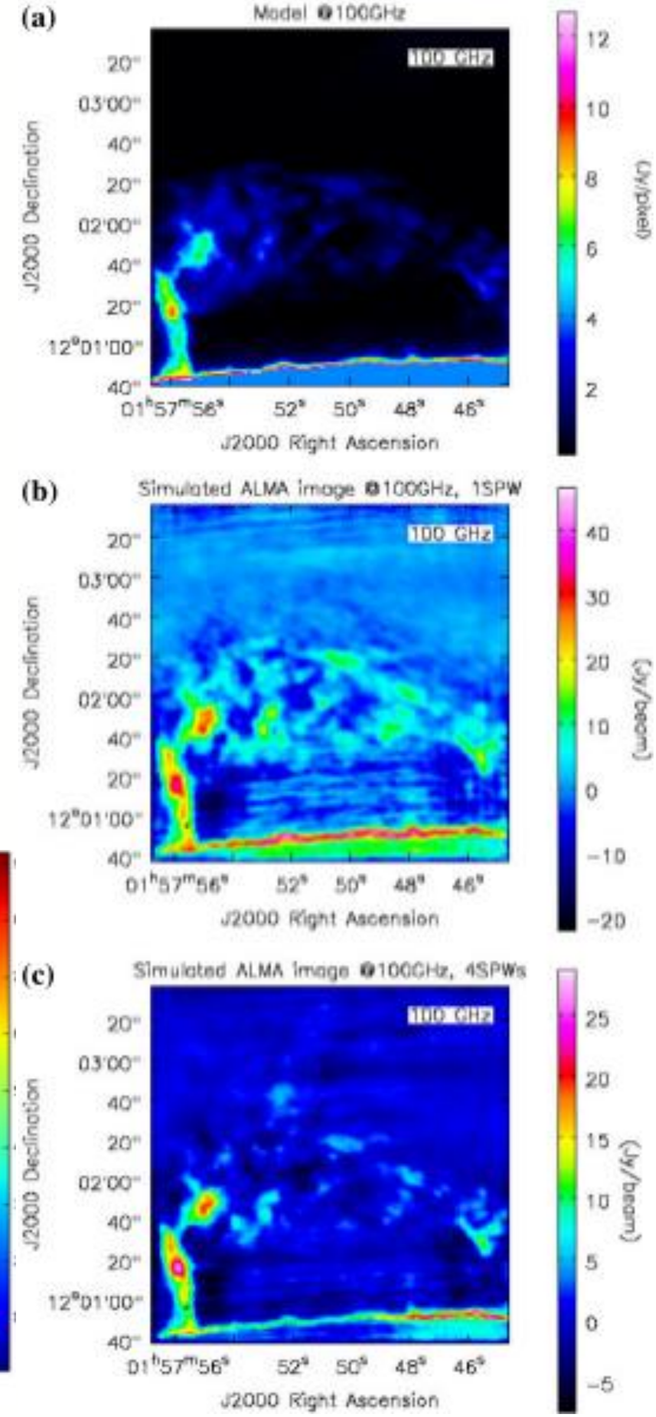
$$9.78 \times 10^{-3} \frac{n_e}{\nu^2 T^{3/2}} \sum_i Z_i^2 n_i \times \left(17.9 + \ln T^{3/2} - \ln \nu\right) \left[\mathrm{cm}^{-1}\right]$$

NB: All population densities may depart from their LTE values

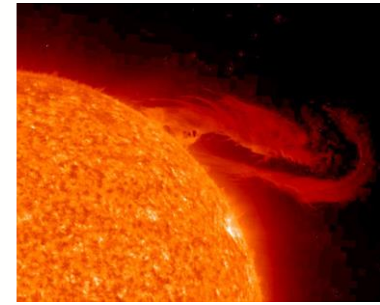
Prominence Fine Structures

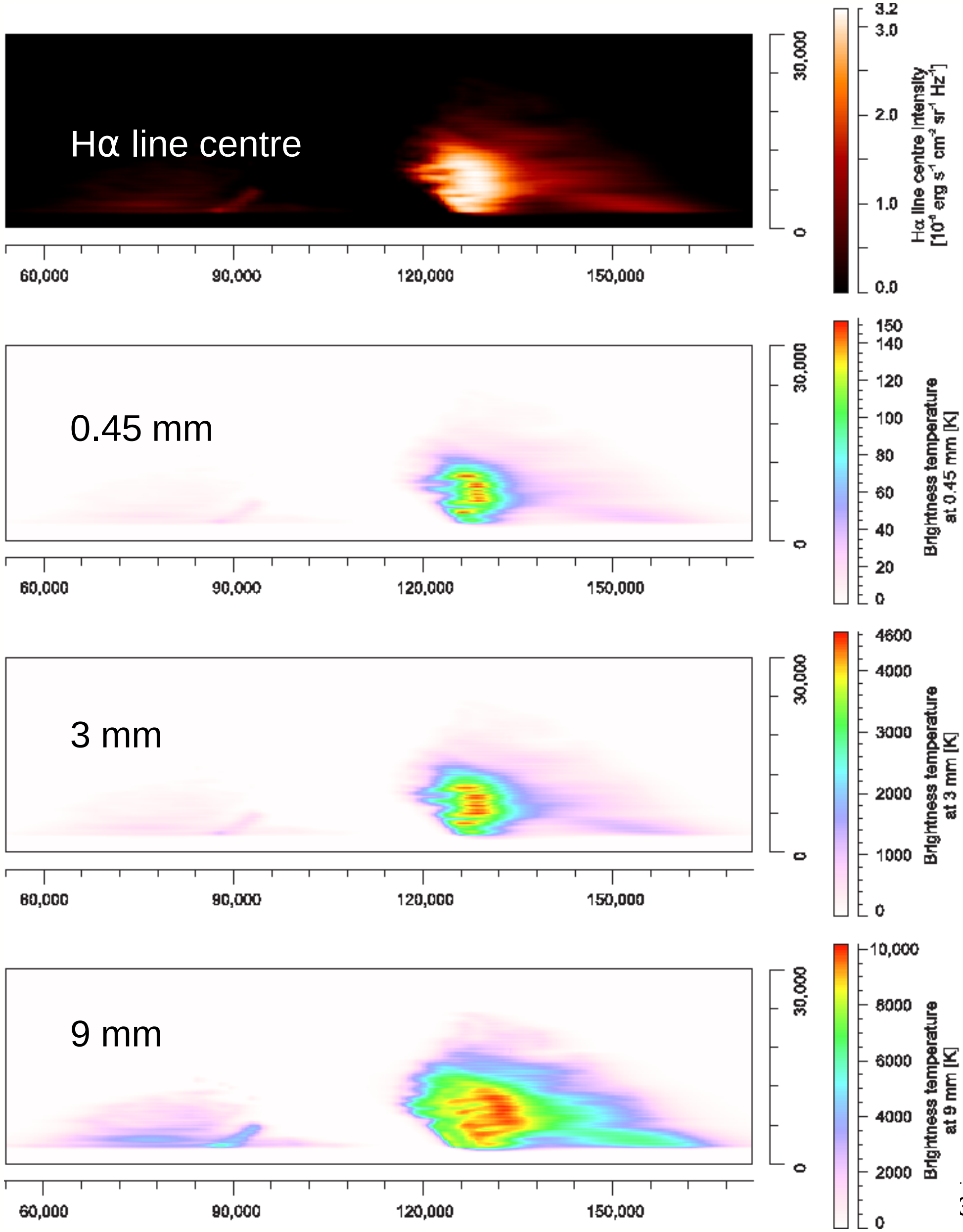
Heinzel et al (2015)





Brightness temp. maps of fine structures

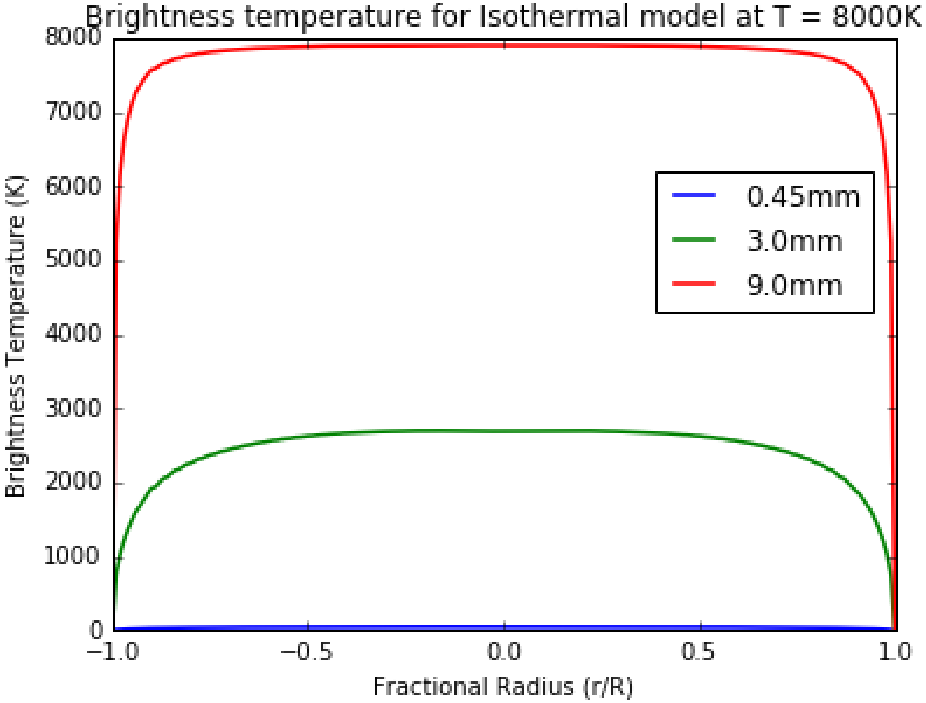


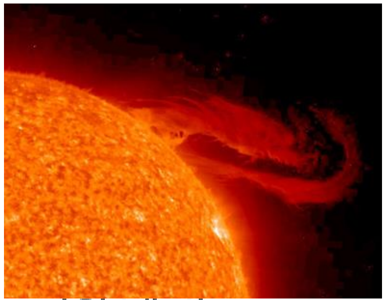


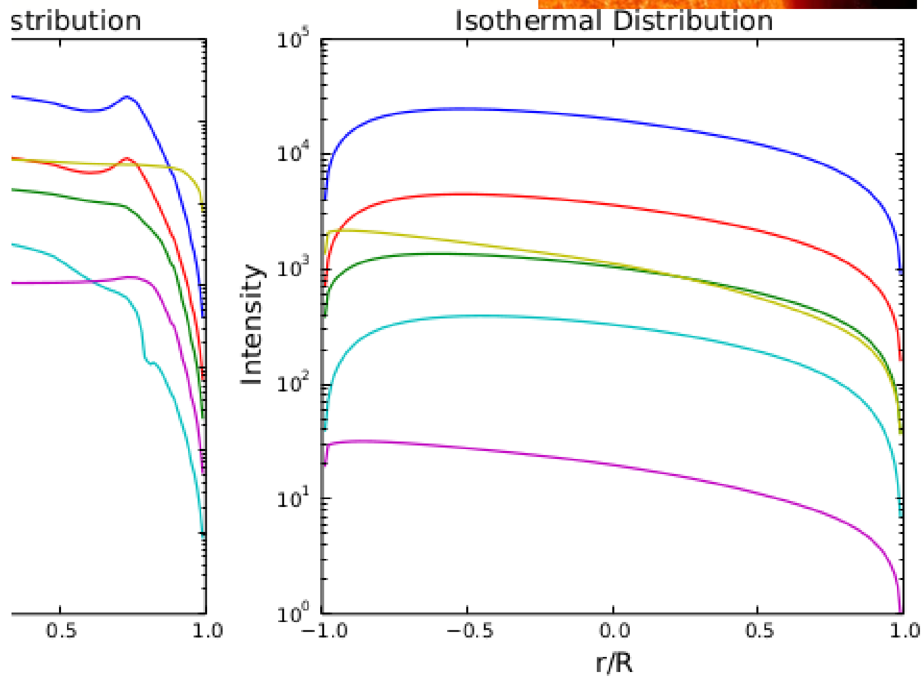
Visualization of the 3D Whole-Prominence Fine Structure (WPFS) model developed by Gunár & Mackay (2015a,b) viewed from the side as a prominence above the solar limb.

The resolution of the displayed synthetic images is 150 km.

Gunár et al. (2016 – *in prep*)







intensity across a section of a cylindrical thread. The frequency-integrated intensity is measured
onal units of the cylinder radius. The horizontal axis represents the position vertically away from
centre. The *left-hand graph* used the *p*4 model, whilst the *right-hand graph* used the isothermal

Gouttebroze & Labrosse (2009)
Labrosse & Rodger (2016)

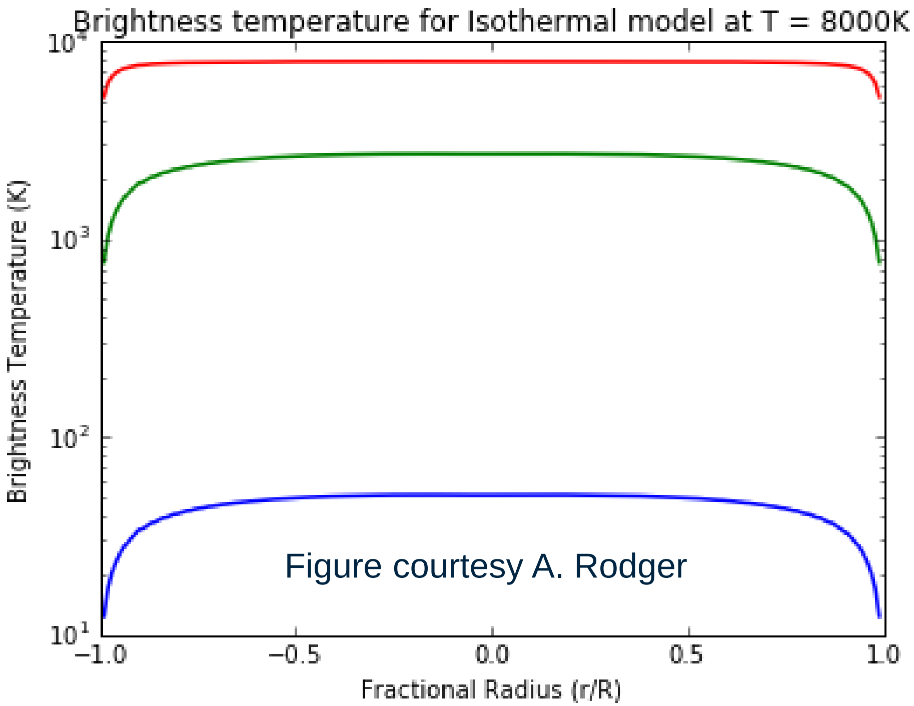
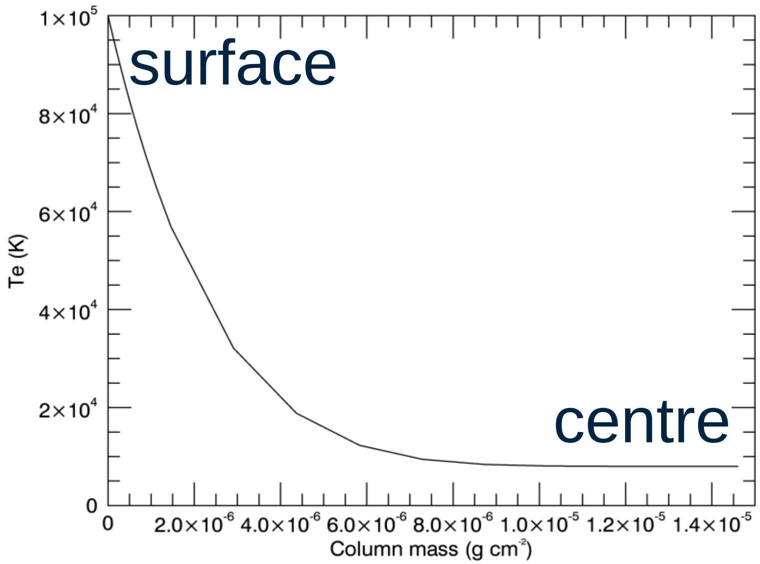
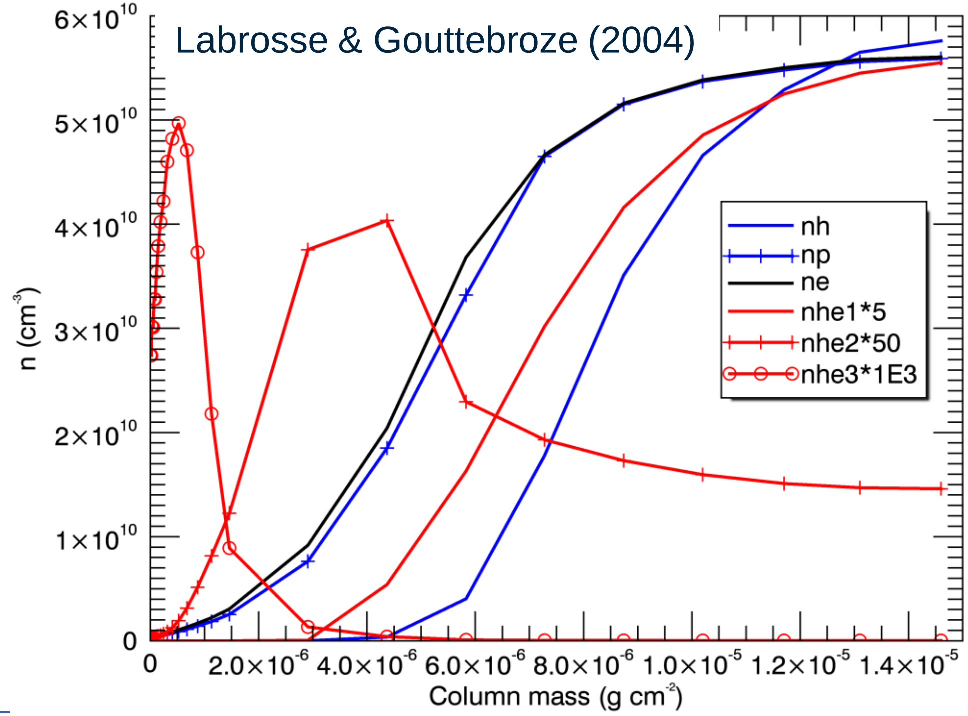
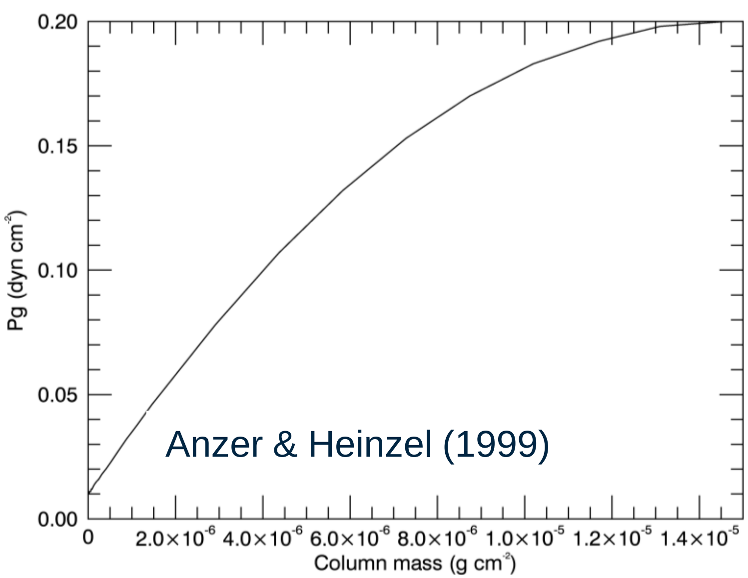


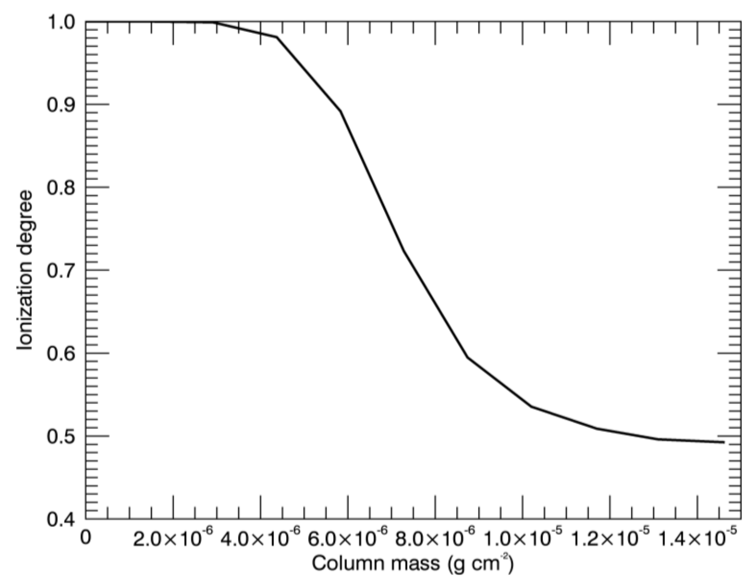
Figure courtesy A. Rodger

1D prominence model

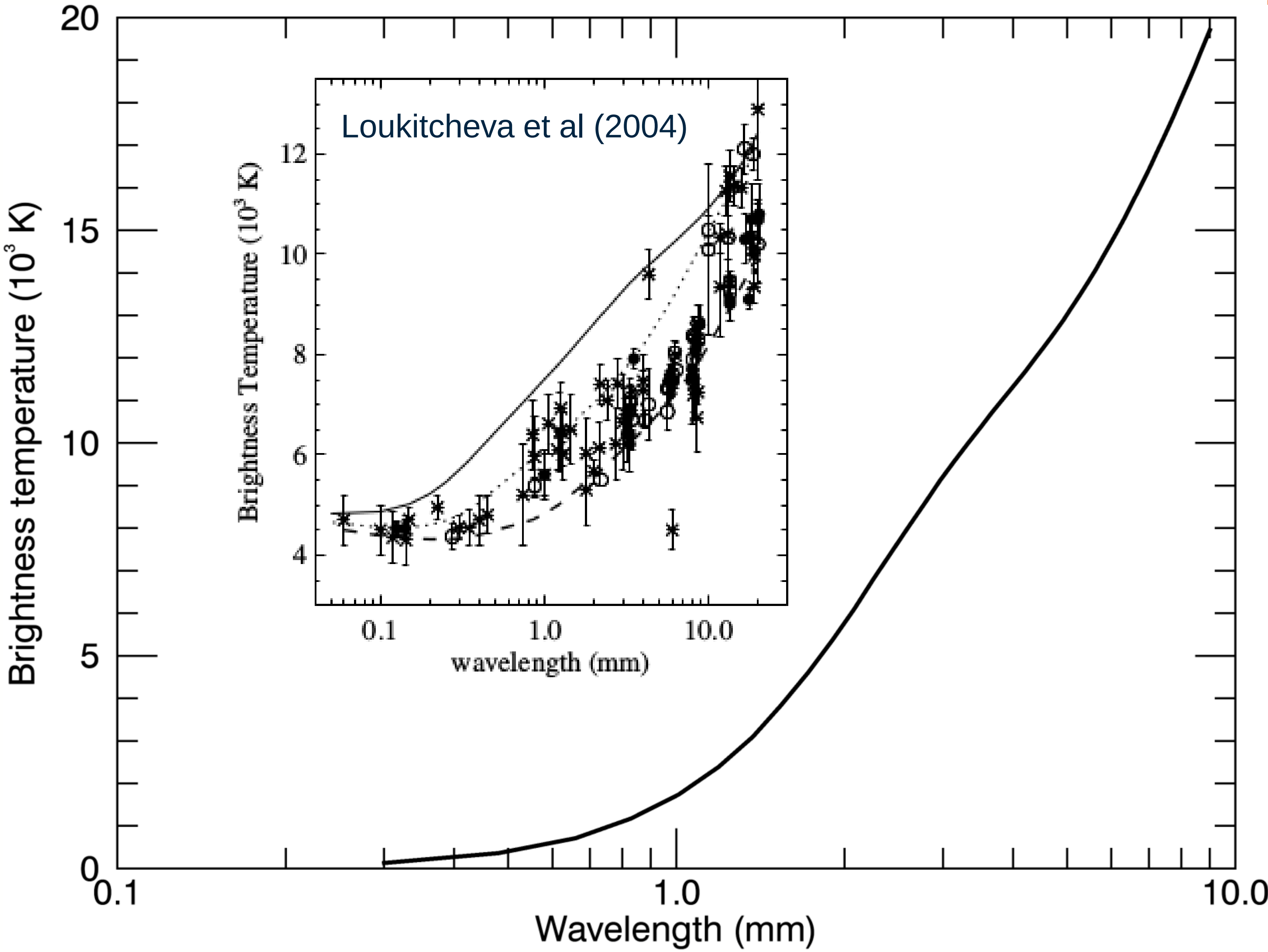


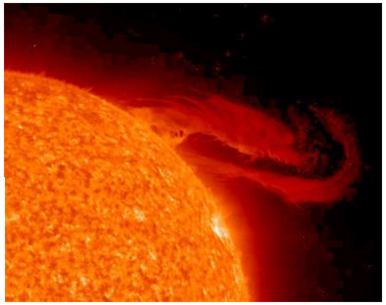






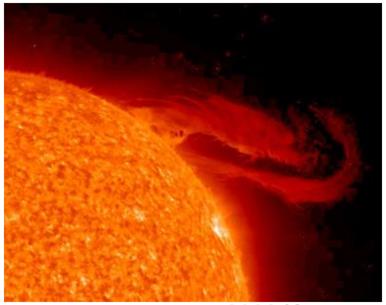
1D prominence model: brightness temp.

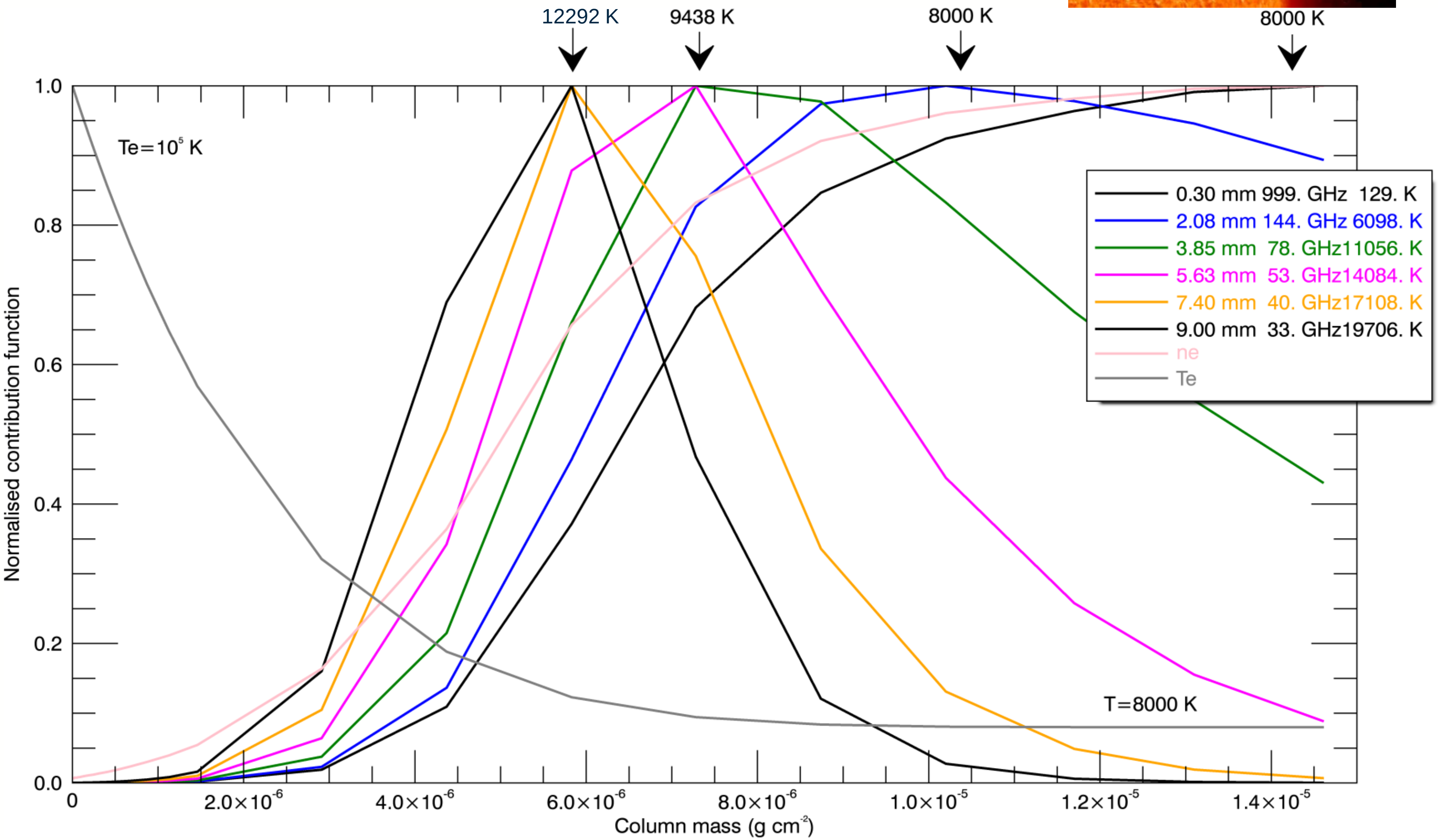




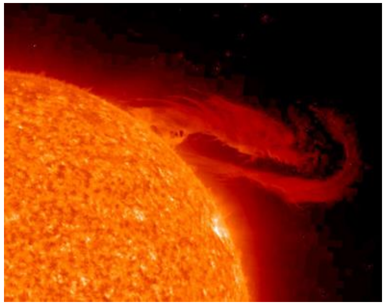
1D contribution functions

Plasma optically thick for λ>2.2mm
⇒ observing in bands 3 and 6 is key (Cycle 4)





Suggested observing sequence for ALMA



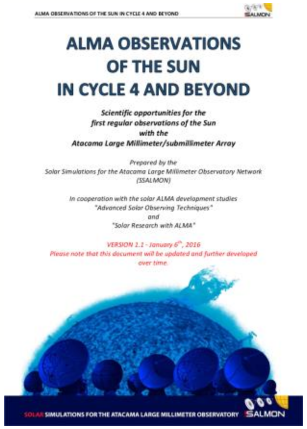
Only band 3 (84 - 116 GHz, 3.6-2.6mm) and band 6 (211 - 275 GHz, 1.4-1.1mm) will be available. Hence, depending on scientific objective:

- Large mosaic, with 150 pointings, at low cadence, in two bands – suitable for large-scale studies of thermal structure and spatial structure
- Small mosaic, with <40 pointings, at moderate cadence – suitable for small-scale studies of dynamical changes in thermal structure and spatial structure (incl. “tornadoes”)
- High-cadence, single point sit-and-stare, with ~2s per map, only one band – suitable for oscillation studies

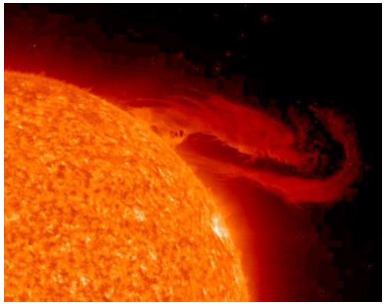
Support from other GBOs (e.g. Hα, D3, Ca II) and from space valuable

- Complementary data, probing different layers
- IHOP campaigns, 1 or 2 weeks long, particularly useful for prominences

See Wedemeyer et al. (2015,2016)



Key points



ALMA will
- provide precise temperature estimates at high cadence
- benefit from the support from other instruments (Hα, HMI, ...)

ALMA can help to answer important open questions about prominences and filaments

- What is their thermal structure?
- What is their spatial fine-structure?
- Can we constrain the magnetic field structure?

Challenges

- When observing at the limb: side lobes of PSF could swamp out off-limb signal with large contributions from solar disk
- Calibration and continuous observing
- Small field-of-view of ALMA requires mosaicking, implying lower cadence