The temperature of the chromosphere seen with ALMA, IRIS and IBIS

Momchil Molnar [1,2]

Kevin Reardon[2], Steven Cranmer[1], Yi Chai[3], Han Uitenbroek[2], Gianna Cauzzi[2,4], Dale Gary[3]

[1]University of Colorado, Boulder

[2]National Solar Observatory, Boulder

[3]New Jersey Institute of Technology, New Jersey

[4]INAF, Arcetri

June 28, 2018

IRIS-9, Göttingen, 25-29 June 2018

Contributed Talk

5. Opportunities and challenges

PROBING THE TURBULENT QUIET CHROMOSPHERE WITH ALMA, IRIS AND IBIS

Momchil Molnar[1,2,5], Kevin Reardon[2,3], Yi Chai[4], Steven Cranmer[1,5]

[1] *University of Colorado, Boulder, CO, USA*
[2] *National Solar Observatory, USA*
[3] *Istituto Nazionale di Astrofisica, Florence, Italy, 50032*
[4] *New Jersey Institute of Technology, Newark, NJ, USA*
[5] *Laboratory for Atmospheric and Space Physics, Boulder, CO, USA*

We present an exploratory study of the dynamics of the quiet solar chromosphere observed simultaneously with the Atacama Large Millimeter/submilimeter Array (ALMA), the Interface Region Imaging Spectrograph (IRIS) and the Interferometric Bidimensional Spectropolarimeter (IBIS) at the Dunn Solar Telescope (DST) in April 2017. This first-of-its-kind dataset comprises high resolution, co-temporal observations of the chromosphere spanning from the far ultraviolet (FUV) with IRIS, through the optical and near infrared parts of the spectrum (IBIS and FIRS at the DST) to the mm-wavelengths with ALMA. Using the high cadence and high angular resolution of ALMA, IRIS and IBIS observations we study the heating mechanisms in the chromosphere, including the role of steepening acoustic waves. We explore the power spectra and phase delay properties of the observed solar regions to study the dynamics of the observed chromospheric structures. Furthermore, our observations of turbulence in the chromosphere extend previous work by Reardon et al. (2008) up to higher temporal frequencies and further consolidate the idea of turbulent dissipation of the wave energy propagating upward from the photosphere as a heating mechanism.

The temperature of the chromosphere seen with ALMA, IRIS and IBIS

Momchil Molnar [1,2]

Kevin Reardon[2], Steven Cranmer[1], Yi Chai[3], Han Uitenbroek[2], Gianna Cauzzi[2,4], Dale Gary[3]

[1]University of Colorado, Boulder

[2]National Solar Observatory, Boulder

[3]New Jersey Institute of Technology, New Jersey

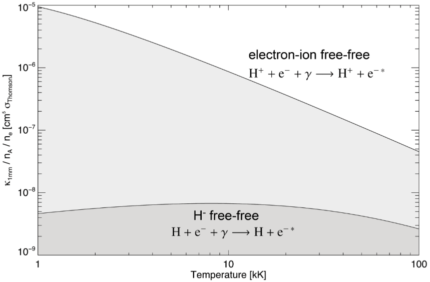
[4]INAF, Arcetri

June 28, 2018

ALMA as a Chromospheric LTE-thermometer

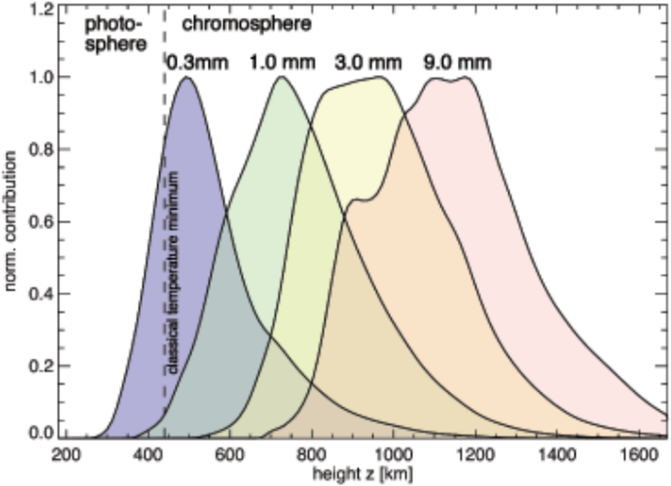
- ALMA Band 3 (3mm), Band 6 (1.25 mm) available for solar observations;
- The mm-radiation is formed under LTE (free-free transitons);
- Under Rayleigh-Jeans limit - linear thermometer!

$$\chi = \xi(T, e)\frac{n_e^2}{n\nu^2 T^{1.5}} \quad (1)$$



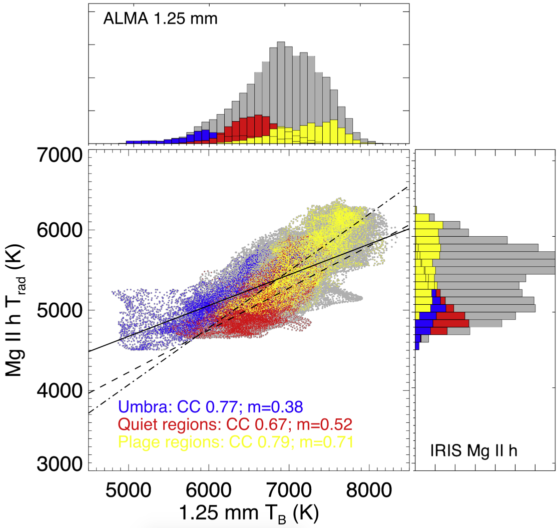
Wedemeyer et al. (2015)

Formation heights of the ALMA radiation



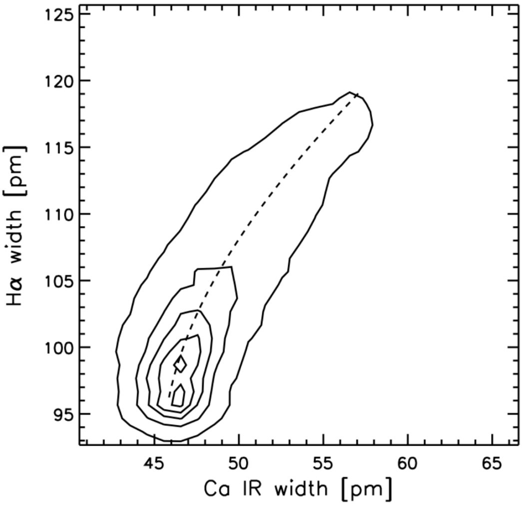
Wedemeyer et al. (2015)

IRIS Mg II h2v radiation temperature - too cold?



Bastian et al. (2017)

IBIS observations of the chromosphere - too hot?



Cauzzi et al. (2009)

- Hα width correlates with CaII 8542 width;
- Thermal Doppler widening reproduces the correlation;
- Temperature range: 5,000-50,000 K.

ALMA Band 3 - just right?

ALMA-DST-IRIS coordinated observations (23-Apr-2017)

DST:

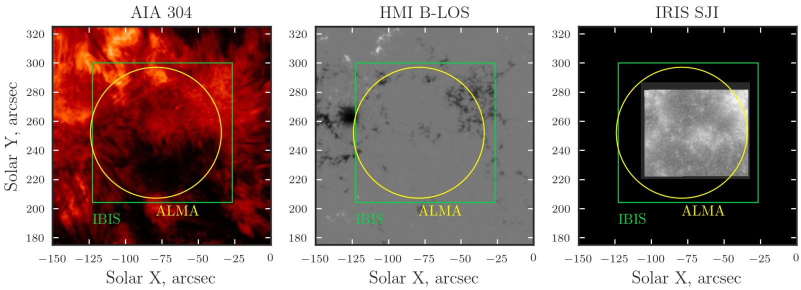
- IBIS: Hα 6563 Å, CaII IR 8542 Å, Na D1 5896 Å;
- FOV: 96"x96"
- Cadence: 16 sec

IRIS:

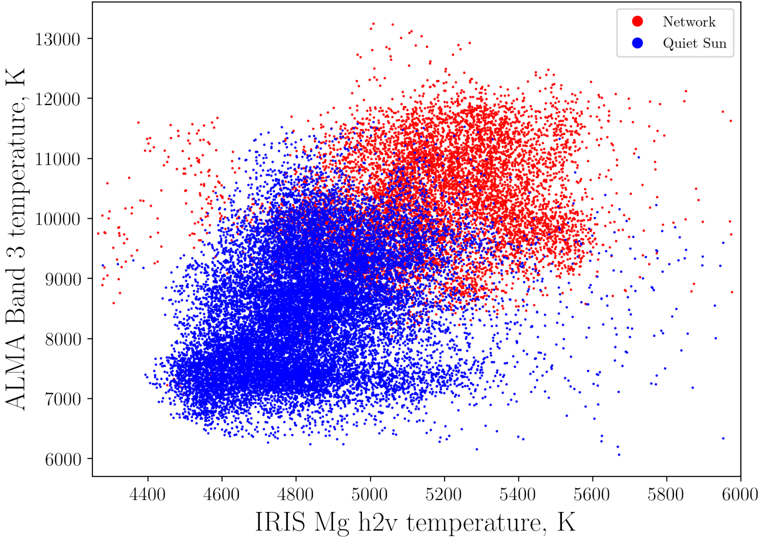
- Medium coarse 8-step raster;

ALMA:

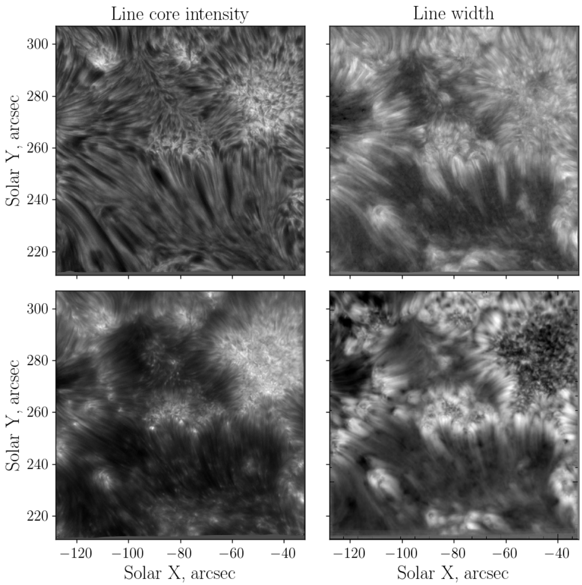
- Band 3 (3 mm) and Band 6 (1.25 mm);
- 10 min continuous observing blocks followed by $\sim$ 2 min calibrations;
- Cadence: 2.02 s.



IRIS Mg h2v T_{rad}- ALMA Band 3 T_B comparison



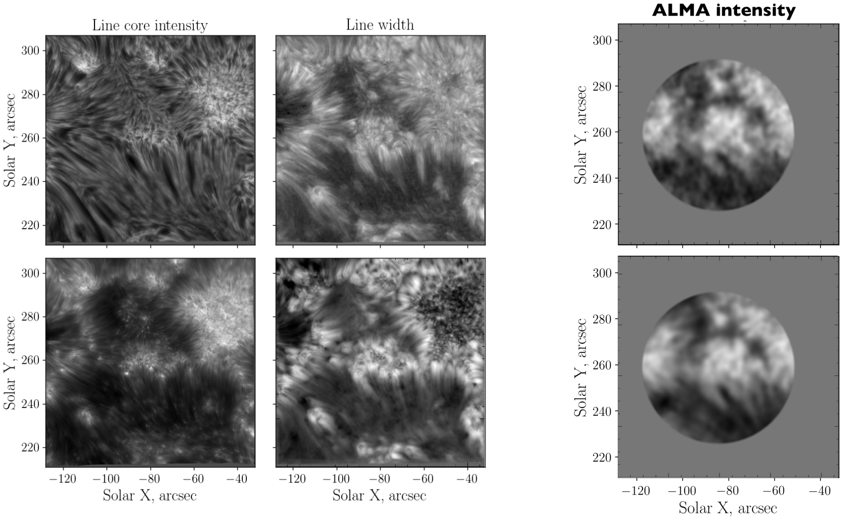
IBS FOV in Hα and CaII 8542



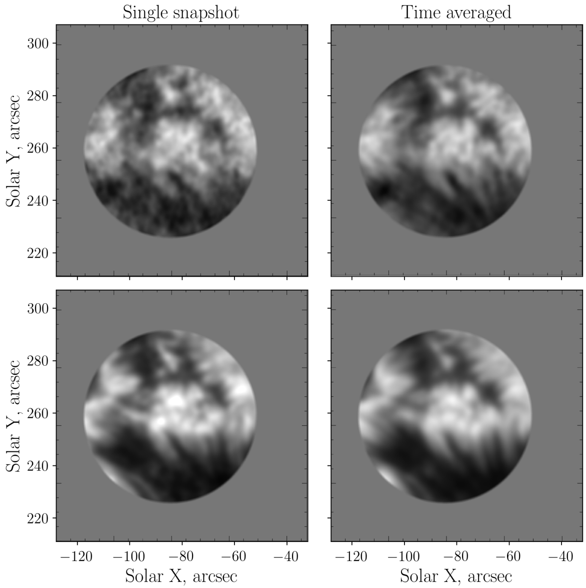
Hα 6563 Å

CaII IR 8542 Å

ALMA-IBIS FOV comparison



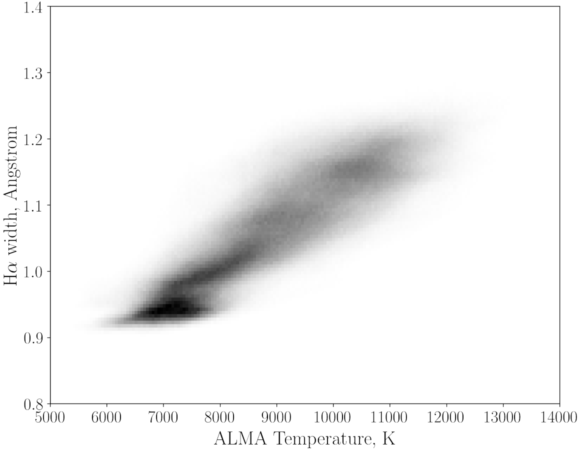
ALMA-IBIS FOV - instantaneous and time-averaged



ALMA Band 3

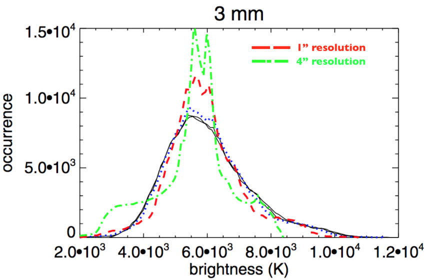
IBIS Hα width
(smoothed with 1.0" Gaussian)

ALMA T_B - Hα width comparison

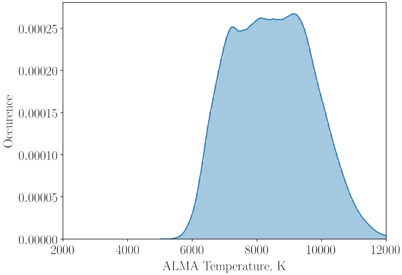


- Hα width correlates with ALMA brightness temperature! (Leenaarts et al. 2012)
- However:
  1. An increase from 9k to 12k Kelvin cannot explain thermal width increase of Hα;
  2. Why Hα width changes that significantly and correlates well with an LTE-diagnostic?

3D MHD Simulations are missing mm-wavelength opacity

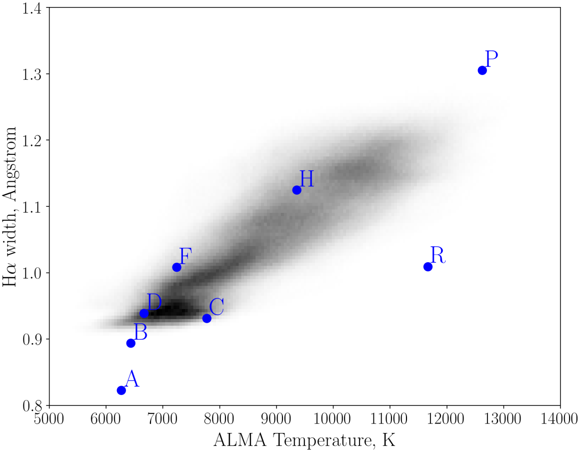


BIFROST NLTE Hydrogen time-dependent ionization Loukitcheva et al. 2015



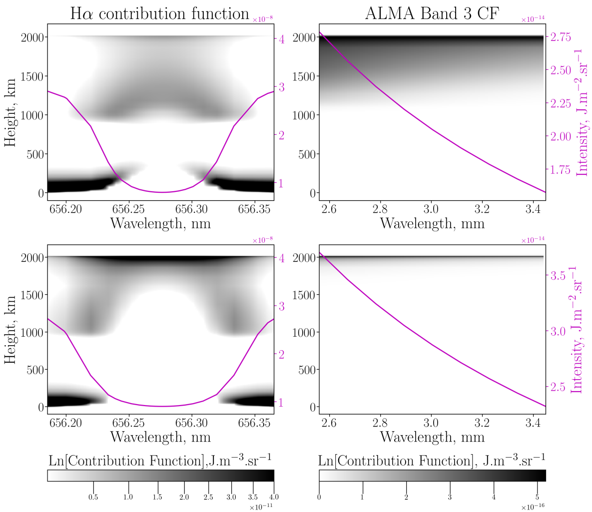
ALMA Band 3 Temperatures

ALMA T_B-Hα width comparison and RH synthesis



- Hα width correlates well with ALMA Band 3 temperature;
- RH + FAL11 synthesis - 1D models reproduce the observed correlation; Why?
- ALMA Band 3 temperatures cannot account for the Hα width range as thermal broadening.

Contribution functions of Hα and ALMA Band 3



- Model D (Cooler)
- Model H (Hotter)

Hydrogen n=2 population dictates the correlation

1. Models with highest n=2 population have the highest ALMA T_B and widest H_α; models with lowest n=2 population have the lowest ALMA T_B and lowest Hα.

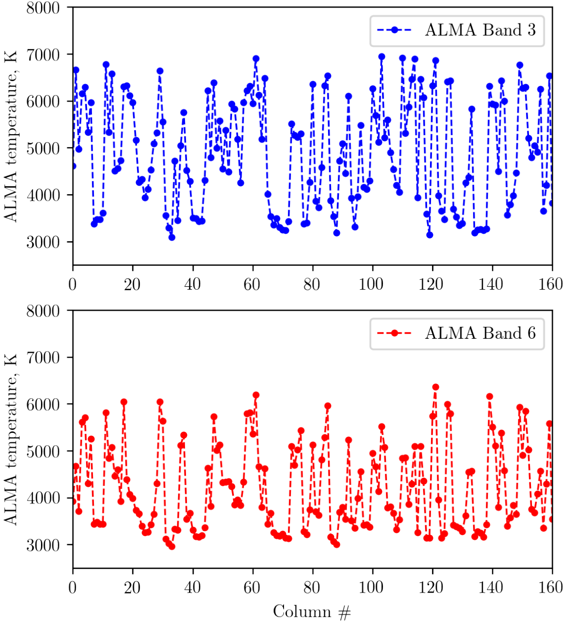
2. ALMA opacity depends strongly on e^- number density (ionization state).
   - Most probable way to get a free electron is to ionize H-atom from n=2 state.
   - The H n=2 population determined by the Lyα flux.

3. Hα is a saturated line (flat bottom).
   - The width of a saturated line is proportional to the opacity.
   - The opacity of the chromosphere in Hα is proportional to the n=2 population;
   - The H n=2 population is determined by the Lyα flux.

Conclusions

- ALMA is a linear thermometer of the plasma at its formation height;
  - But formation height can change dramatically depending on local conditions.
  - Useful for constraining upper chromospheric temperature in inversions (da Silva Santos+ 18, Linsky (private communication)).
- ALMA Band 3 correlates well with Hα width;
  - Hα width is a good proxy for temperature? (Leenaarts et al. 2012)
- The long Hα fibrils are seen in ALMA Band 3 (Rutten 2017);
- Hα width and ALMA radiation are dictated by the Lyα flux?

BIFROST GOL model

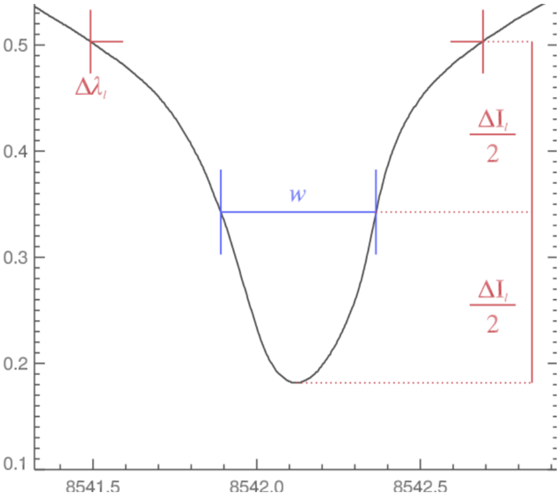


Band 3 temperature average: $\sim$ 4500 K

Band 6 temperature average: $\sim$ 4000 K

Measuring chromospheric line widths

Measuring widths of chromospheric spectral lines



RH synthesis of observables with FAL 11 1D models

1. RH code (Uitenbroek, 2001) for spectral synthesis
2. FAL 11 atmospheres (Fontenla+2011)

Table 1. Solar Features Designation and Corresponding Model Indices

Feature	Description	Photosphere-Chromosphere Model Index	Corona Model Index
A	Dark quiet-Sun inter-network	1000	1010
B	Quiet-Sun inter-network	1001	1011
D	Quiet-Sun network lane	1002	1012
F	Enhanced network	1003	1013
H	Plage (that is not facula)	1004	1014
P	Facula (i.e., very bright plage)	1005	1015
S	Sunspot umbra	1006	1016
R	Sunspot penumbra	1007	1017
Q	Hot facula	1008	1018

Width-Equivalent width correlation for Hα