An archival study of millimeter continuum data shows that **regions of long-lived, cool chromospheric gas appear adjacent to magnetic concentrations**

Supplemental Figures, Data, & more

Studying the Cool Chromosphere with ALMA

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Introduction

- The millimeter continuum is one of the only LTE diagnostics of chromospheric temperature, providing a unique tool to study thermodynamics in this region[1]
- High-resolution maps of the 3 mm [2] and 1 mm [3] brightness temperatures observed by the Atacama Large **M**illimeter **A**rray (ALMA) have revealed regions with unexpectedly cool plasma temperatures, termed "**Ch**romospheric **A**LMA **H**oles" (ChAH's)
  - ChAH's may correspond to the cool regions in the low chromosphere inferred from the IR spectrum of carbon monoxide (CO) at the limb[4] and on disk [5]
- We perform an archival study of CHAH's observed by ALMA [6,7] in the hopes of determining their origins

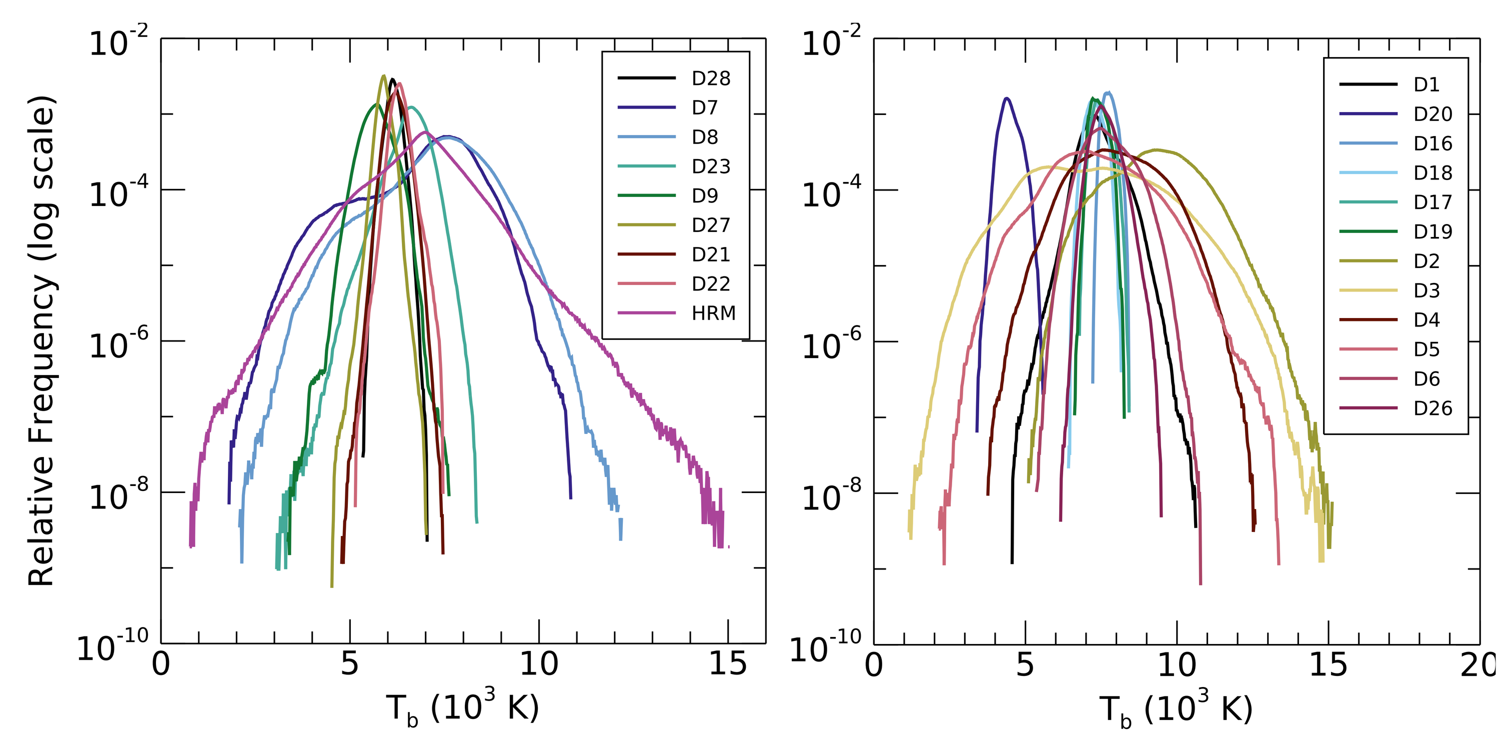

Fig 1. Histograms of the brightness temperatures seen in ALMA Bands 6 (left) and Band 3 (right). For details on the individual observations, see the supplemental materials. Note that the vertical axis is on a logarithmic scale.

Results

- Some datasets show narrow, Gaussian T_b distributions, while others show extended tails at both low and high temperatures (**Fig. 1**)
- Pixels with high T_b correspond to magnetically active regions (e.g. network/plage), while pixels with low T_b are collected in ChAH's in non-magnetic areas (**Fig. 2**)
  - In some cases, ChAH's seen at 1 and 3 mm overlap
  - Ca II 8542 Å and AIA 304 Å show decreased brightness in the 3 mm ChAH's, but no diagnostics show good correspondence with the 1 mm ChAH's (see also [7])
- ChAH's are long-lived, lasting the entire observing sequence (30-45 min)

Discussion

- ChAH's appear exclusively in the vicinity of magnetic network/plage, and sometimes are interspersed by hotter, fibrillar structures at 3mm. This may be because:
  1. low-lying loops originating from the magnetic network may raise cold, electron-dense plasma into the chromosphere [8] (**Fig. 3a**)
  2. the magnetic field extending from the network may alter the propagation and steepening of waves, depressing the acoustic heating of the chromosphere [9] (**Fig. 3b**)
  3. changes in mm opacity may cause the mm formation height to occasionally dip to lower heights [7] (**Fig. 3c**)
- In Cases 1 and 2, ChAH's show the presence of cool gas at chromospheric heights, previously inferred from CO [3,4]
  - Model atmospheres inferred from Mg II k and the 1 mm continuum show pockets of cool gas in the mid-chromosphere which are cool enough to affect CO line core intensities [2]
- In Case 3, ChAH's may not correspond to regions of cold gas in the chromosphere, but instead to areas with low free electron density
  - If this is the case, ChAH's should show no correlation with CO
- In April/May 2022, simultaneous observations of the CO spectrum at 4.7 um and ALMA Band 6 were obtained of two solar targets (**Fig. 4**)
  - ChAH's formed as in Cases 1 & 2 will show increased CO absorption
  - Long (~1.5 hr) and wide-field mosaic ALMA observations in Band 6 will help constrain the size and lifetime of ChAH's
- More numerical studies (e.g. [8,10]) needed to tell Cases 1&2 apart

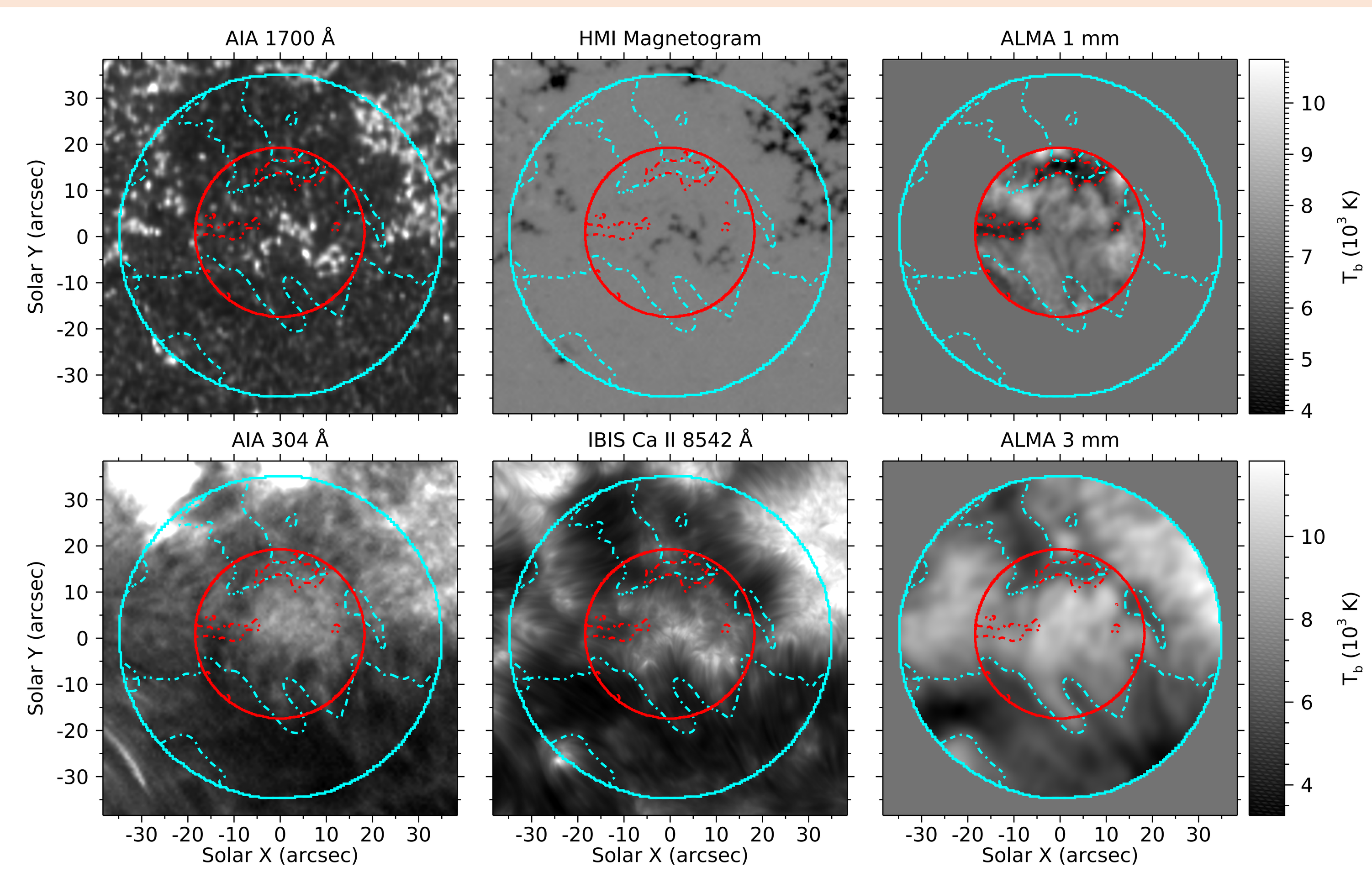

Fig 2. Plots of the time-averaged 1 mm (top right) and 3 mm (bottom right) brightness temperatures for a region of plage observed on 4/23/2017 (datasets HRM and D3). The remaining panels show various coaligned chromospheric observables and the HMI magnetogram, with the circular ALMA FOVs shown in red (1 mm) and blue (3 mm). Regions of cold brightness temperatures shown by the dot-dashed contours.

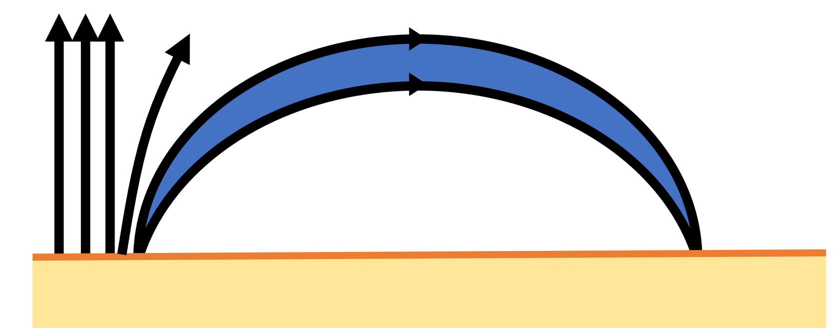

Fig 3a. In Case 1, cool gas is lifted to chromospheric heights by low-lying magnetic loops originating from the magnetic network. If this gas is electron-dense, it will result in a decreased mm brightness temperatures.

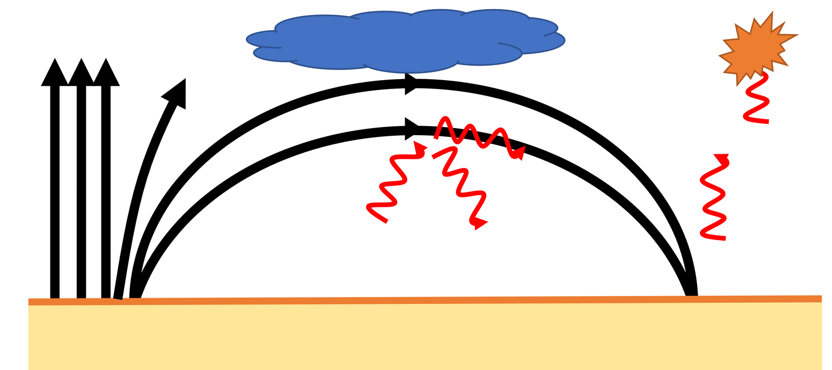

Fig 3b. In Case 2, the inclined canopy field reflects/redirects acoustic waves (red lines) before they can steepen and heat the overlying chromosphere (e.g. through shocks, as in the quiet Sun). The atmosphere above the canopy will radiatively cool while remaining relatively dense, resulting in the low temperatures see in the mm continuum.

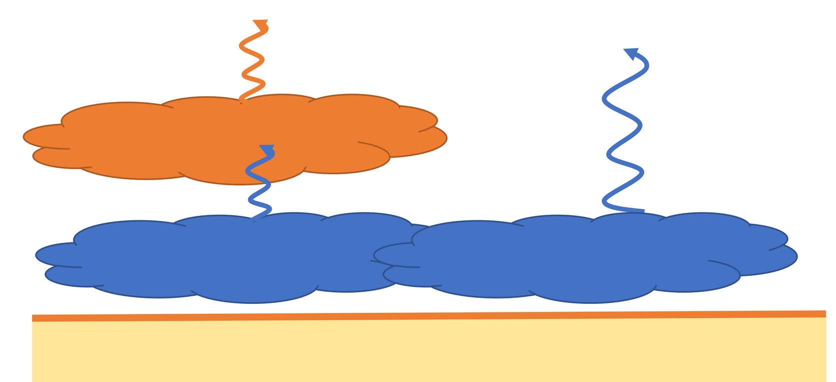

Fig 3c. In Case 3, the chromosphere is usually suffused with hot, electron-dense gas, which blocks mm emission from lower in the atmosphere (e.g. the temperature minimum). In places where the electron density of the chromosphere dips, the mm continuum may show emission from these cooler regions.

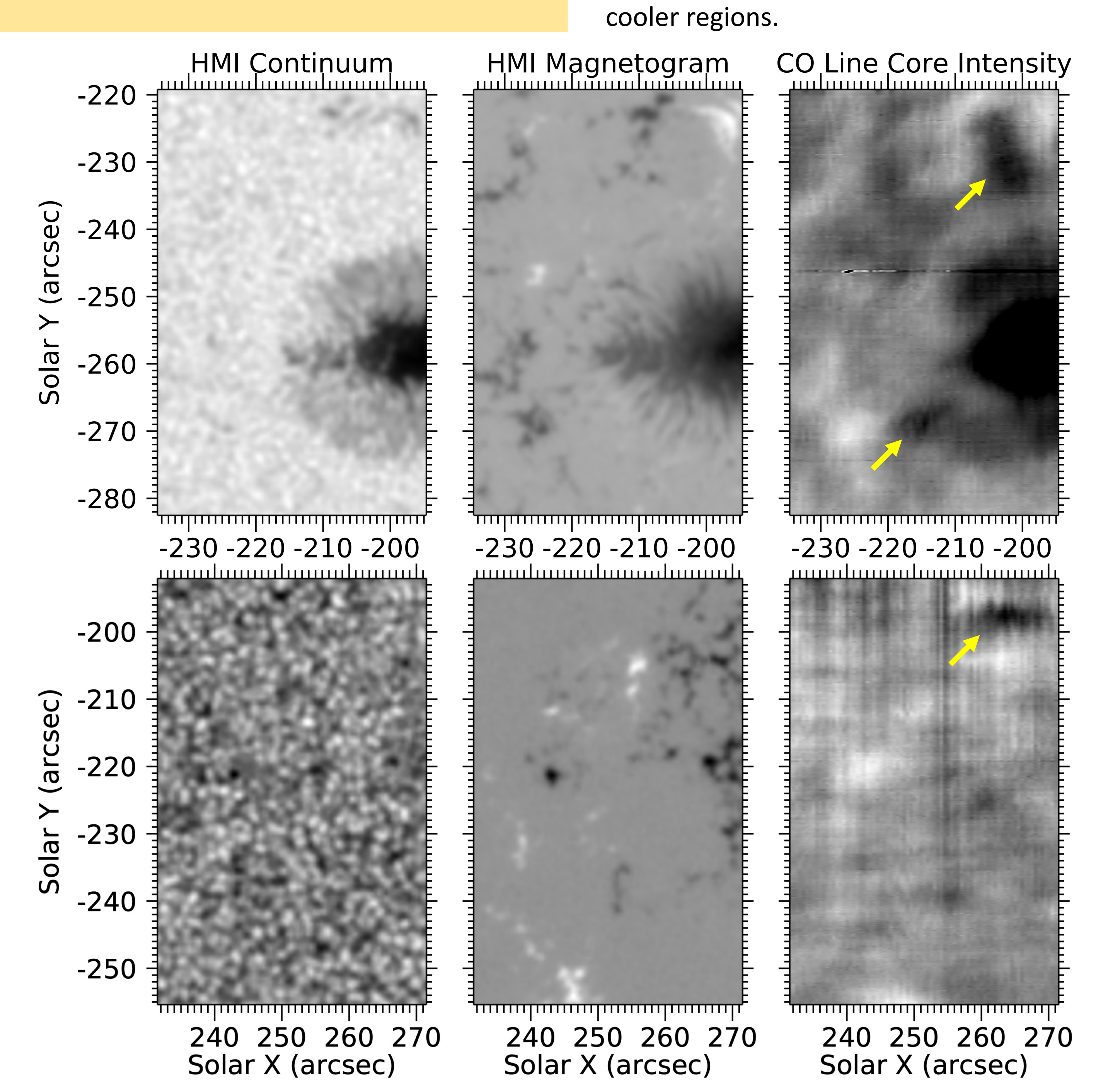

Fig 4. Plots of the visible continuum (left) and line-of-sight magnetic field (middle) observed by HMI and CO line core intensity (right) observed by GST/CYRA in the regions chosen to study the evolution of ChAH's in ALMA cycle 8. The top row shows an active region observed on 4/28/22, while the bottom row shows a relatively quiet region observed on 5/3/22. Note the dark CO absorption features in each plot (yellow arrows). ALMA simultaneously observed these regions at 1.25 mm to see whether these features correspond to ChAH's.

References

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