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

Scan for

Supplemental Materials

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NSO

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]
  - Beginning in 2017, the **A**tacama **L**arge **M**illimeter/submillimeter **A**rray (ALMA) has produced high-resolution images of the Sun at these wavelengths
- Maps of the 3 mm [2] and 1 mm [3] brightness temperatures have revealed unexpected regions of apparently cool plasma, termed "**Ch**romospheric **A**LMA **H**oles" (ChAH's)
  - ChAH's may show the cool chromospheric gas inferred from the IR spectrum of carbon monoxide (CO) observed at the solar limb [4] and in the vicinity of a magnetic pore [5]
- We perform an archival study of CHAH's observed by ALMA in the hopes of determining their origins

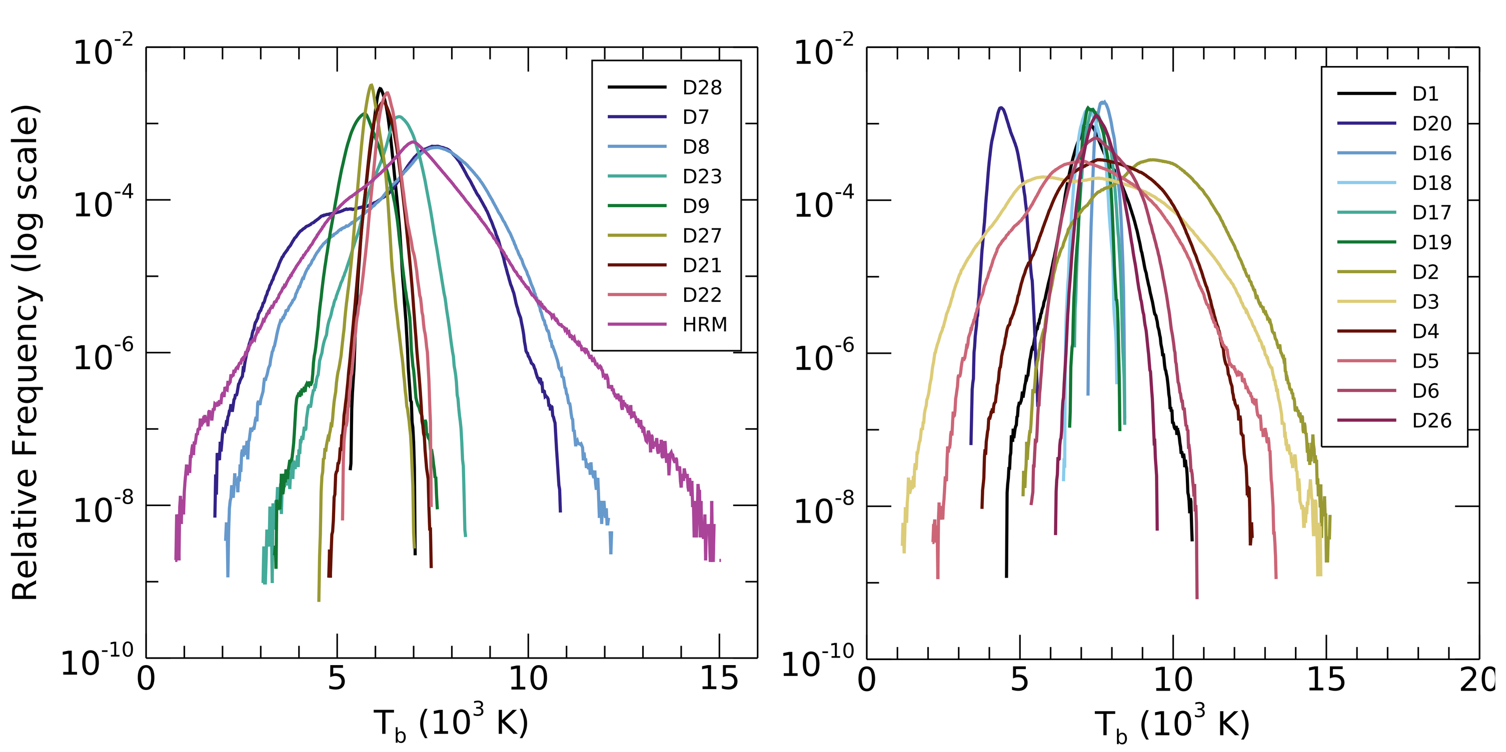


Fig 1. Histograms of the brightness temperatures seen in ALMA Bands 6 (left) and Band 3 (right). For details on the individual observations, see the supplemental materials. Note that the vertical axis is on a logarithmic scale.

Data & Methods

- We use publicly available data from the **S**olar **ALMA** **S**cience **A**rchive (SALSA, [6]) in bands 6 (1.25 mm) and 3 (3 mm)
  - One dataset, HRM, is not available via SALSA and was provided by R. Hofmann [7]
- To identify datasets with potential ChAH's, we plot histograms of the 1 mm and 3 mm brightness temperature in **Fig. 1**
- To study the spatial distribution of ChAH's, we plot regions of cold temperature (4σ below the average quiet-Sun temperature) in the time-averaged data (**Fig. 2**)
- To study their time evolution, we look at the minimum temperatures shown by a ChAH at each wavelength (**Fig. 3**)

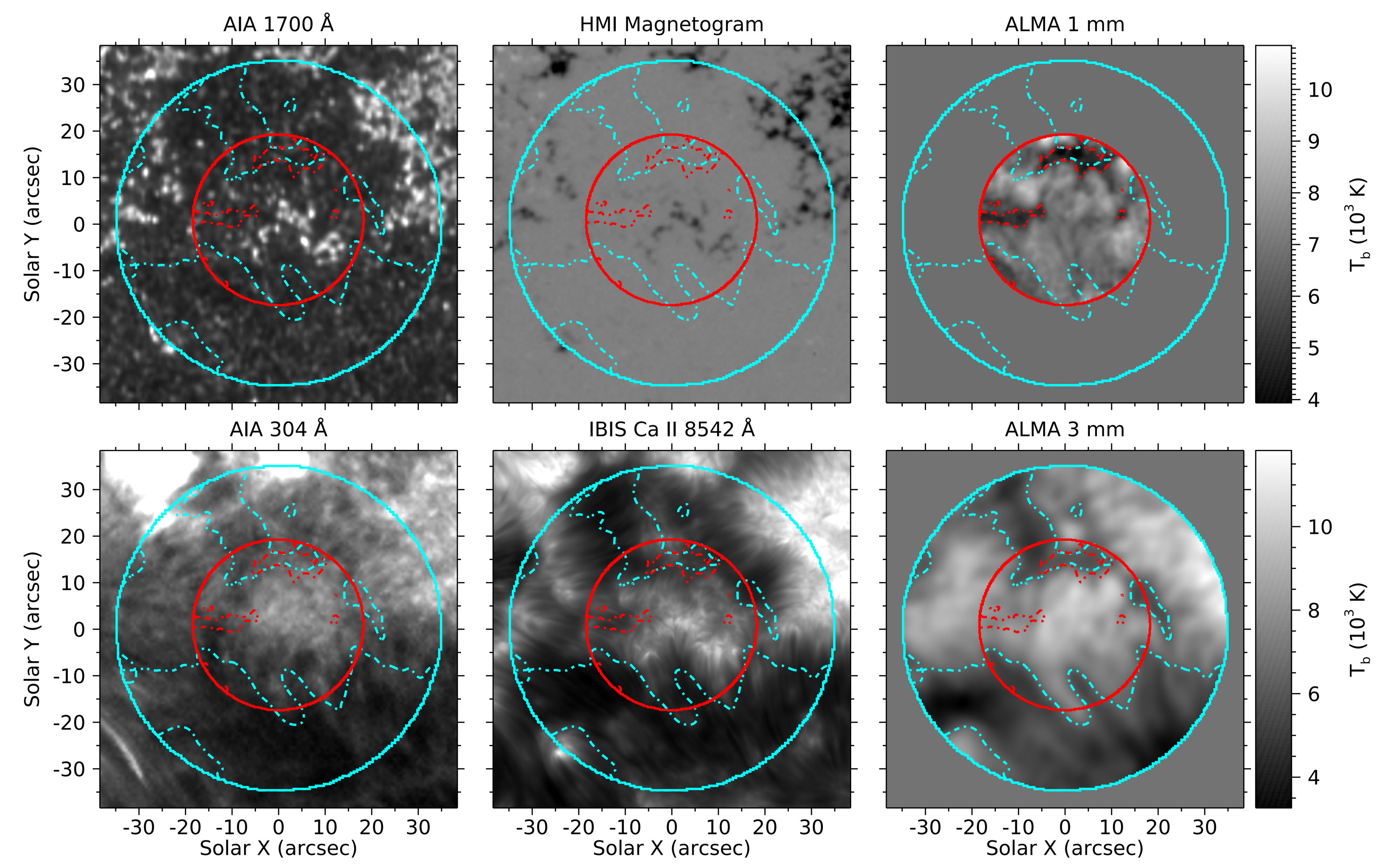


Fig 2. Plots of the time-averaged 1 mm (top right) and 3 mm (bottom right) brightness temperatures for a region of plage observed on 4/23/2017 (datasets HRM and D3). The remaining panels show various coaligned chromospheric observables and the HMI magnetogram, with the circular ALMA FOVs shown in red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

Results

- Some datasets show narrow, Gaussian T_b distributions, while others show extended tails at both low and high temperatures
- 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 at the edges of active regions
  - 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
- ChAH's are long-lived, lasting the entire observing sequence (30-45 min)

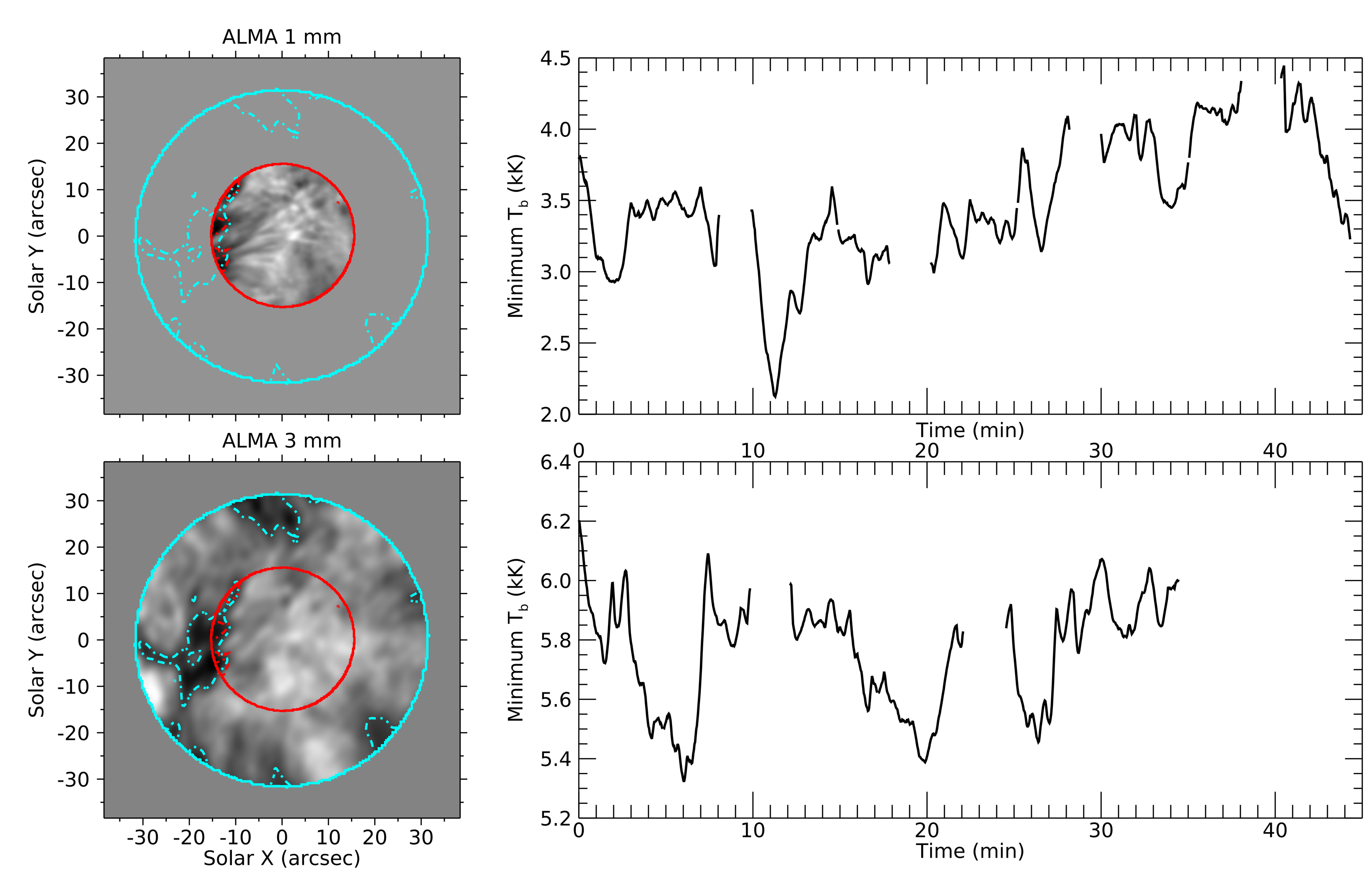
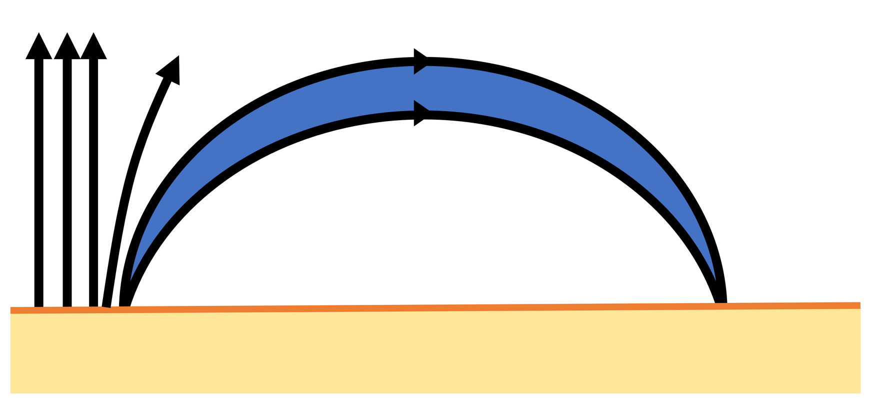


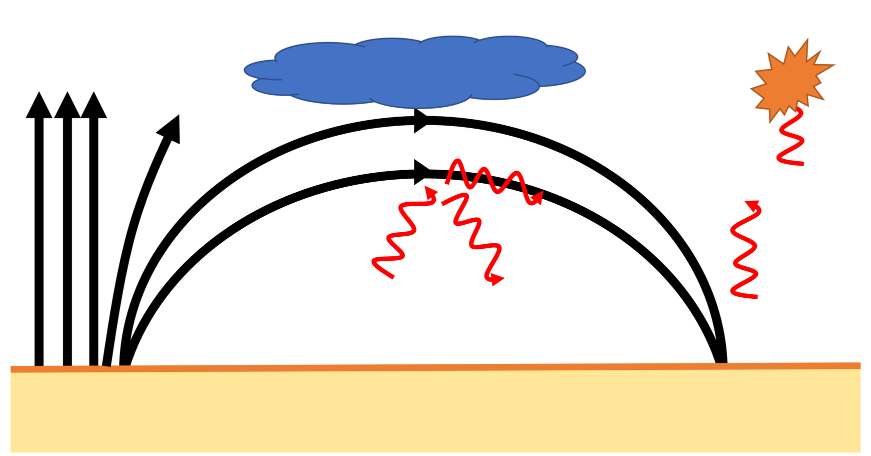
Fig 3. (Left) Time-averaged 1mm temperature for dataset D8 (top) and 3mm temperature for dataset D2 (bottom). ChAH boundaries are shown as in Fig. 2. (Right) The change in temperature over time for the large ChAH at (-20, 0).

Discussion

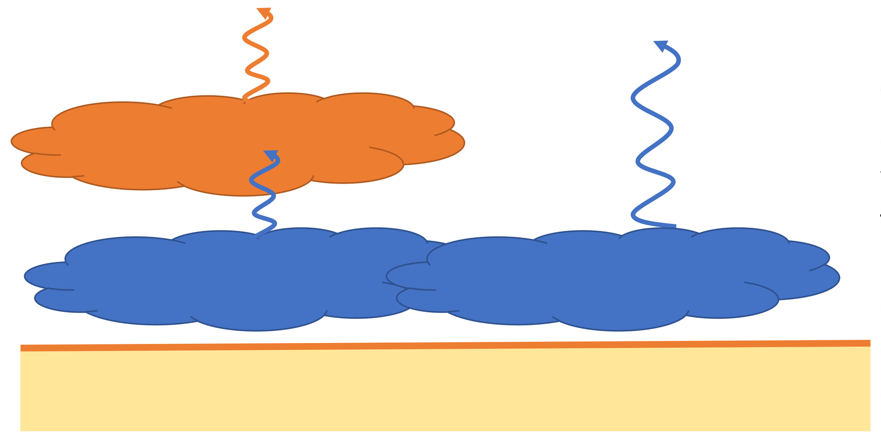
- ChAH's appear exclusively in the vicinity of magnetic network/plage, and show elongated fibrillar structures at 3mm. This may be because:
  1. low-lying loops originating from the magnetic network may loft cold, electron-dense into the chromosphere [8]
  2. the magnetic field extending from the network may alter the propagation and steepening of waves, depressing the acoustic heating of the chromosphere [9]
  3. changes in chromospheric opacity may cause the mm formation height to occasionally dip to lower heights, e.g. the temperature minimum [7]
- 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]
  - Long-lived ChAH's should show an observable signature in CO core intensity or equivalent width
- 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 now correlation with CO core intensity
- Simultaneous CO observations will help rule out Case 3
- Additional observations (especially long-duration) and numerical studies (e.g. [8,10]) of ChAH's needed to distinguish Cases 1 & 2



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.



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.



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.