Millimeter Wavelength Observations of Solar Spicules in a Polar Coronal Hole

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Abstract We report the first observations of solar spicules at 1.25 mm, as well as observations at 3 mm with the Atacama Large Millimeter/submillimeter Array (ALMA). These are supplemented by observations in ultraviolet, extreme ultraviolet and optical wavelengths from the Interface Region Imaging Spectrometer (IRIS), the Solar Dynamics Observatory/Atmospheric Imaging Assembly (SDO/AIA), as well as Hα images from the GONG network. The observations were made on 2018 December 25 in the northern polar coronal hole present at that time. ALMA obtained time-resolved imaging observations at wavelengths of 3 mm (100 GHz; 2 s cadence) and 1.25 mm (239 GHz; ~ 2 min cadence) with an angular resolution of 2.2 x 1.3" and 1.5" x 0.7", respectively. We discuss the numerous challenges to the data reduction and analysis of these observations. We then discuss the structure of the chromosphere at the limb, estimates on the temperature and density of spicules, and their kinematics. The limited angular resolution make it difficult to isolate individual spicules. Nevertheless, examples are shown of spicules that display transverse motions, rising and falling motions, and those which simply fade.

Introduction

Solar spicules are a ubiquitous phenomenon in which multitudes of dynamic, filamentary jets with temperatures of the order of 10^4 K, extending thousands of kilometers from the chromospheric network up into the low solar corona. As in practically all solar phenomena, radio observations are much simpler to interpret in terms of physical conditions than optical or UV data but, in the pre-ALMA era, suffered from insufficient spatial resolution (see review by Alissandrakis et al., 2022). Here we present the first ALMA observations of spicules at 1.25 mm, together with new observations at 3 mm, as well as simultaneous IRIS, SDO and GONG data.

Observations

ALMA observed a region in the north pole coronal hole on December 25, 2018, in Band 3 (100 GHz, 3 mm) from 14:03-14:48 UT and in Band 6 (239 GHz, 1.25 cm) from 16:58-18:19 UT, with a 2 s cadence. A single field of view (fov) of 58.3" was employed for Band 3 and a 14-pointing mosaic for Band 6 (Figure 1). The spatial resolution was 2.2" by 1.3" for 3 mm and 1.5" by 0.7" for 1.25 mm, with a position angle of about 80 deg, measured East from North. Full disk (TP) concurrent Images with a resolution of 58.3" and 24.3" in band 3 and band 6, respectively, were obtained

IRIS provided UV spectral and slit-jaw observations in the 2796 band (Mg II h & k lines) and in the 1400 band (Si IV doublet), with a cadence of 18.73s. SDO/AIA and GONG Hα images provided context information.

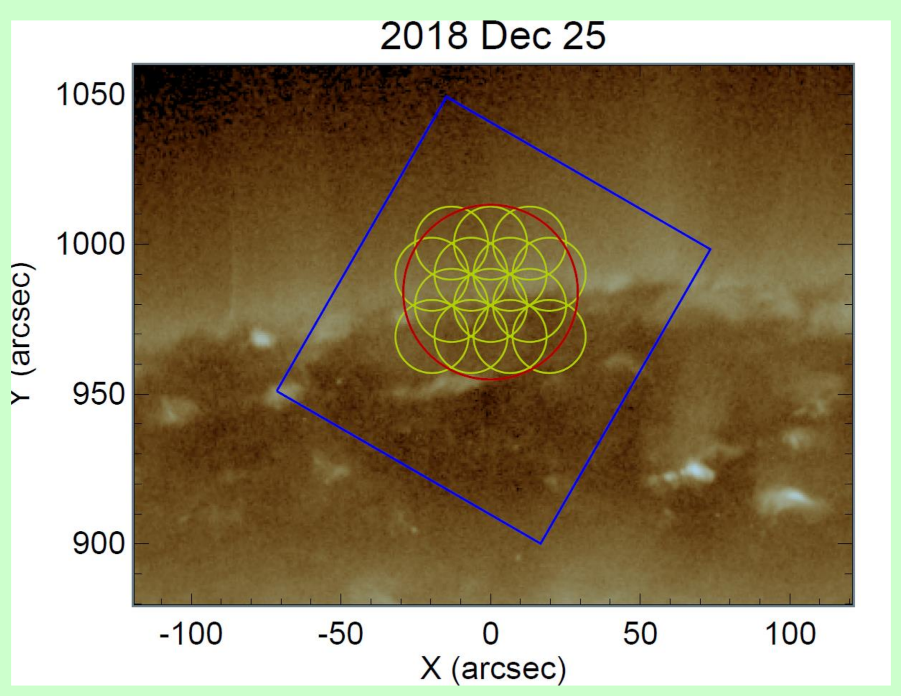

Fig. 1 The target region on top of a 193 Å AIA image. The red circle shows the 100 GHz field of view, the Yellow circles the fov of the 14 mosaic pointings and the blue rectangle the fov of the IRIS SJ images.

Image processing

Image processing, in particular the restoration of the short spacings (large angular scales) missing from the interferometric data, was particularly challenging, due to the sharp drop of brightness at the limb. Regular self-calibration did not give satisfactory results (Figure 2), so we opted for a more elaborate iterative scheme, to be described in detail in a future publication. In short, we measured the radius of the solar disk from the TP images and then we formed a model disk of that radius with a quiet Sun brightness and center-to-limb brightness profile as determined by Alissandrakis et al. (2022). The model TP map was multiplied by the telescope primary beam, centered at the pointing coordinate. The interferometric snapshot maps, uncorrected for primary beam response, were feathered with the model TP data and the result was then corrected for the primary beam response.

We found that the mean limb at 3 mm is 5010 km above the photospheric limb, with a range of 3725-6435 km due to the presence of dynamic structures. The mean limb height at 1.25 mm is 2650 km with a range of 2010-3440 km.

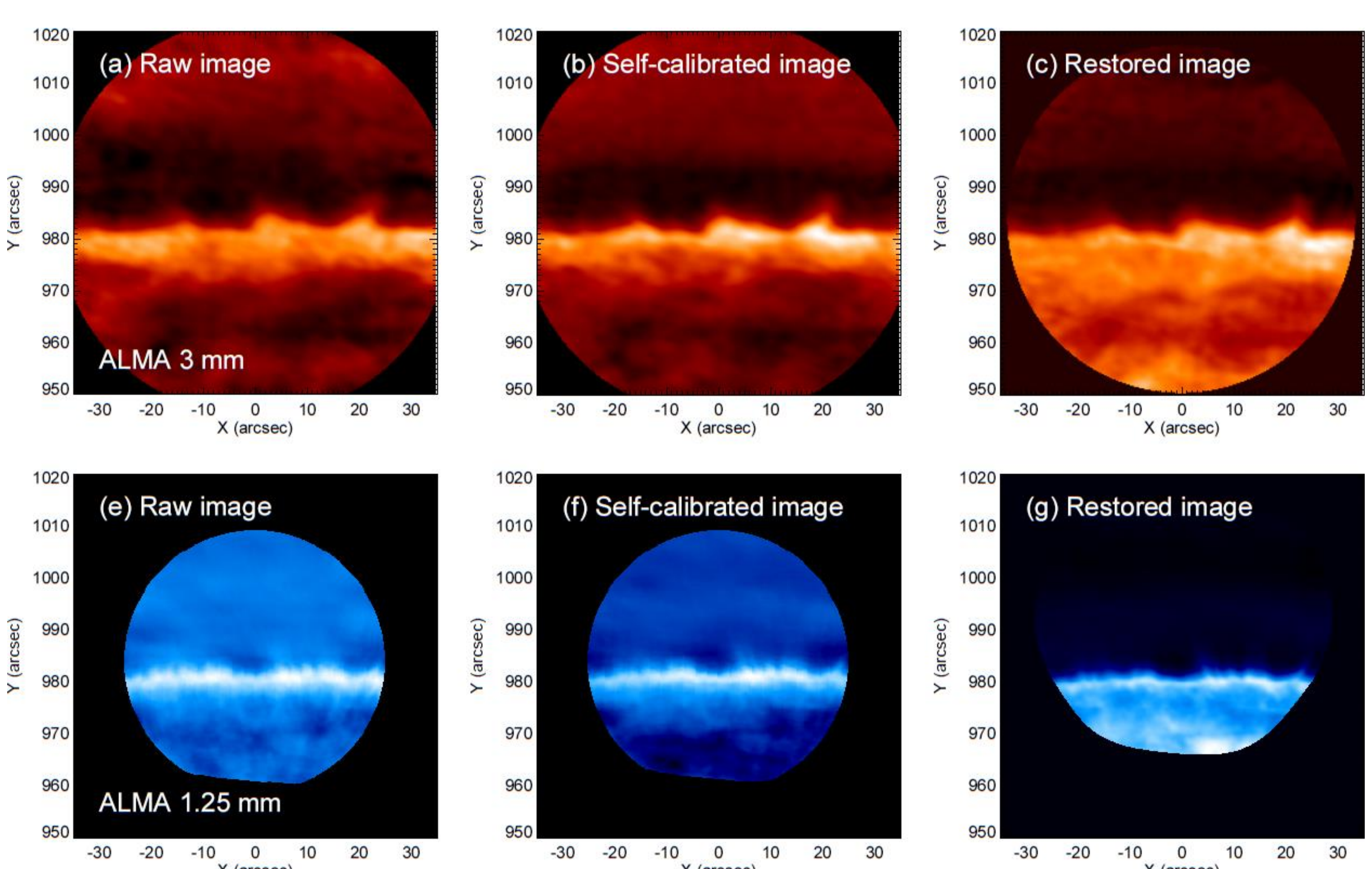

Fig. 2 Raw, self-calibrated and restored ALMA images at 3 mm (top) and 1.25 mm (bottom).

Spicule imaging and comparison with Hα and EUV

Figure 3 shows representative snapshot images at 3 and 1.25 mm, together with images in other spectral regions. All images have been processed to enhance spicule visibility, while AIA images have also been averaged in time to reduce noise.

We note that the GONG Hα images, although of inferior resolution, show a strong similarity with the images in both ALMA bands, as noted by Nindos et al. (2018). Spicules extend higher in the AIA 1600 Å images, so that the mm-λ structures are near their roots. The same is true for the k line SJs and the Si IV SJs (not shown in the figure), where spicules are detected higher up above the limb. In the 171 Å images ALMA spicules appear dark, absorbing the background coronal emission (Yokoyama et al. 2018). This absorption is due to neutral Hydrogen (e.g. Alissandrakis & Valentino, 2019).

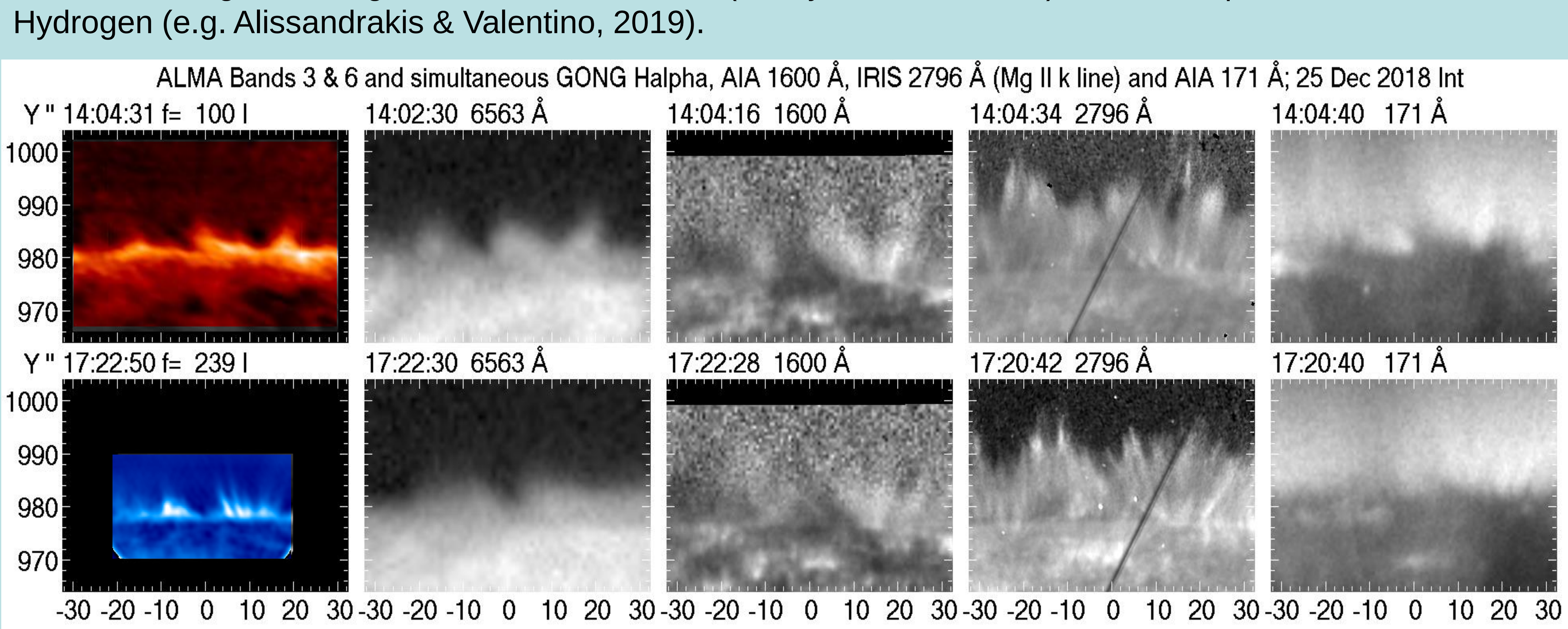

Fig. 3 *Top row:* An ALMA snapshot image at 3 mm, together with a GONG Hα, AIA 1600 Å, IRIS k line SJ and AIA 171 Å images. *Bottom row:* Same for 1.25 mm. The diagonal dark line in the SJ images is the spectrograph slit. The photospheric limb is at Y=975.6".

Physical parameters of spicules

The measurement of the brightness temperature, T_b, of spicules provides information on their temperature, T_e, and density, N_e, as, for the optically thin case, T_b goes like $N_e/\sqrt{T_e}$. Simultaneous measurements in at least two frequencies are required, which are not possible with ALMA for the time being. In order to remedy for that, we computed the N_e from T_b measurements along well-defined spicules, assuming a constant T_b of 10^4 K, in conformity with optical spicule models.

The results are plotted as a function of height in Figure 4, for Band 3 (blue) and Band 6 (red). Interestingly, the curves from the two ALMA frequencies have comparable slopes, indicating that our constant temperature assumption is not too far from reality. Moreover, the ALMA density estimates are systematically lower (by ~30%) than those compiled by Alissandrakis et al. (2018), but display a similar trend with height. Given that two wholly independent techniques were used, the agreement is remarkable. Similar results were obtained under the assumption that the spicule temperature increases with height.

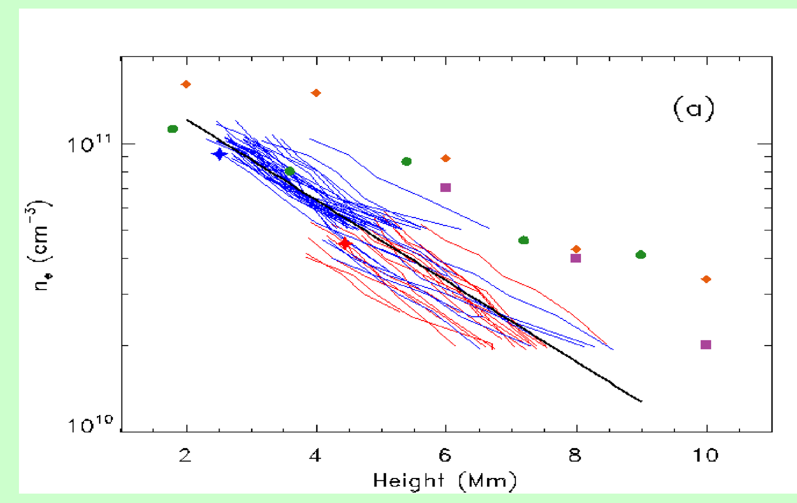

Fig. 4 The electron density inferred from the 1.25 mm (blue) and 3 mm (red) data. Each line is based on the measurement of a single spicule. The spicule temperature is assumed to be constant with height with $T_e = 10^4$ K. The solid black line represents a fit to the joint density measurements. The points are drawn from a compilation of results summarized by Alissandrakis et al. (2018), referenced to a single spicule thickness of 815 km.

Evolution and kinematics

Although the 1.25 mm data are better for studying the spicule kinematics due to their high resolution, their cadence (2 min) is rather low due to the mosaicking; moreover, some mosaics were interrupted by calibration. Still, the full set of images gives an idea of the spicule evolution (Figure 5).

In spite of their lower spatial resolution, the 3 mm images revealed several types of motions: rising and falling, rising and stalling, oscillatory (Figure 6), as well as orientation changes .

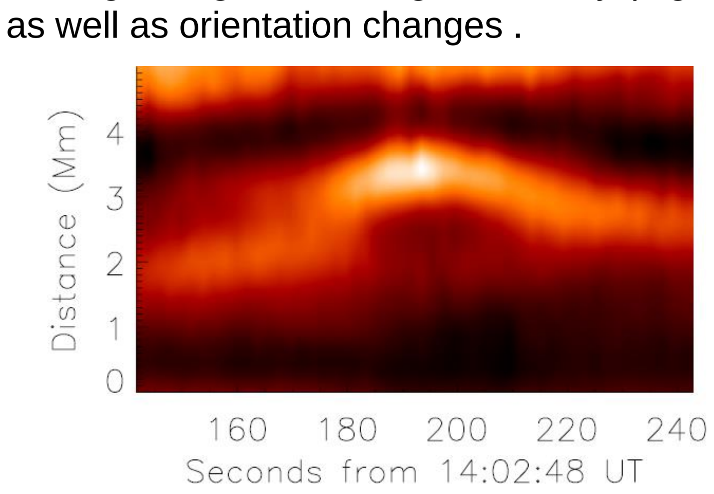

Fig. 6 Intensity along the axis of a spicule as a function of time and position, showing a transverse oscillation.

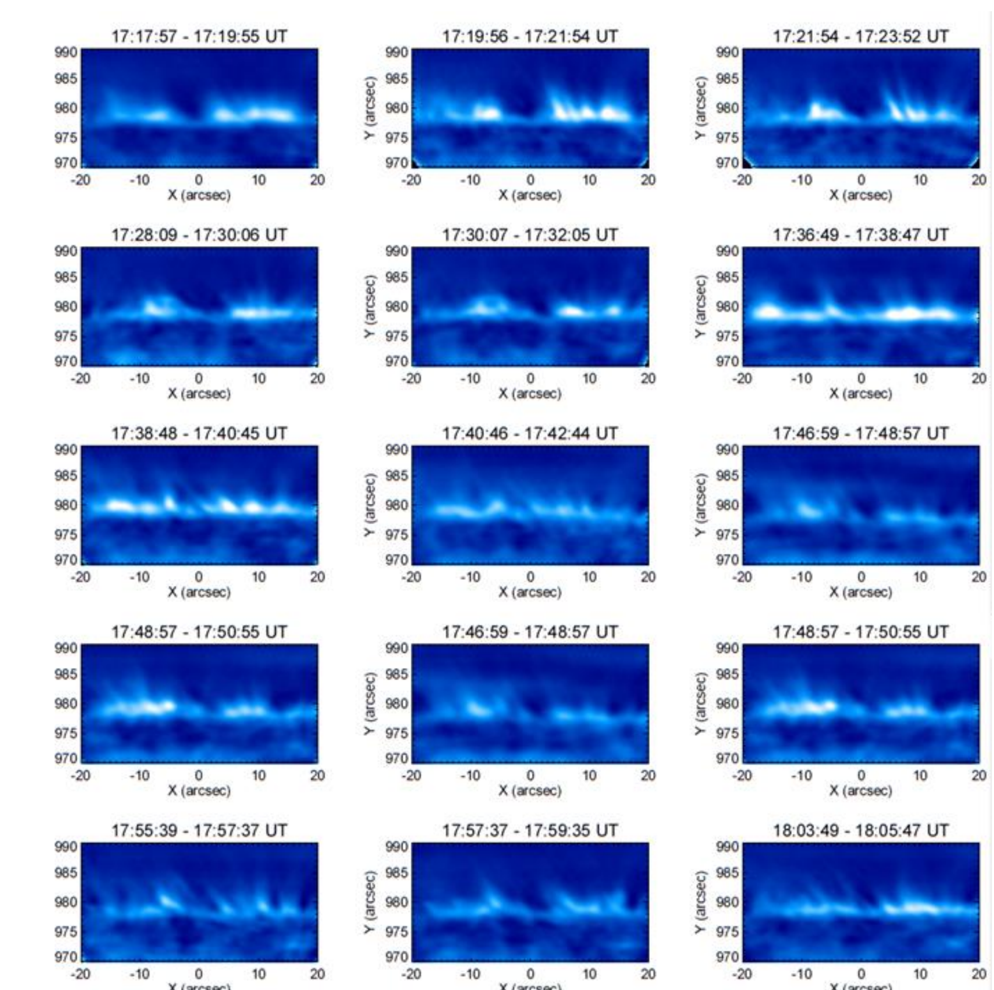

Fig. 5 A time sequence of 1.25 mm ALMA images.

Summary and future prospects

In this work we presented the first ALMA images of spicules at 1.25 mm, as well as high quality 3 mm spicule images, in a coronal hole in the north polar region of the Sun. We have measured a number of properties in each wavelength band and have compared the data with observations made in Hα and at UV and EUV wavelengths. Our main results are summarized below:

- The average limb is 5010 km above the photospheric limb at 3 mm and 2650 km at 1.25 mm
- mm-λ spicules have a similar appearance as spicules in lower resolution Hα GONG images; they correspond to the roots of spicules visible in AIA continuum images at 1600 Å, as well as in IRIS SJs in the Mg II k and the Si IV lines. In the coronal AIA channels spicules appear dark, due to neutral Hydrogen absorption.
- We measured the variation in brightness temperature as a function of height for a sample of spicules at both 3 mm and 1.2 mm. Assuming a constant temperature of 10^4 K, we inferred densities that are consistent with those reported by Alissandrakis et al. (2018) as well as those reported by Beckers (1972).
- From height-time plots constructed for a small number of spicules we inferred speeds consistent with those of type II spicules. In addition, we found at least one example of an oscillating structure and one example for which the structure appears to reorient from a nearly horizontal to a nearly vertical position.

Continuum observations of solar spicules at mm-λ with high angular and high time resolution provide a new suite of diagnostics that are complementary to observations in spectral lines at optical and UV wavelengths. The fact that the source function is Planckian greatly simplifies the radiative transfer and its interpretation. There remain limitations, however. While the time resolution at 3 mm is excellent, the angular resolution available in ALMA Cycle 6 in 2018 was not sufficient to fully resolve spicules. More recently, a larger array configuration has been approved for solar observations in the 3 mm band that provides a nominal resolution of 0.92". While the angular resolution at 1.25 mm was perhaps sufficient, the use of mosaicking limited the cadence to ~2 min, which is not sufficient to adequately resolve spicule kinematics. Another limitation is that it is not yet possible to perform simultaneous multi-band observations of the Sun with ALMA.

Regardless of these limitations, ALMA proved once again to be an invaluable instrument for solar studies.

References

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