ALMA observations of impulsive heating in a solar active region

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ABSTRACT

Aims. We investigate the temperature enhancements and formation heights of impulsive heating phenomena in solar active regions such as Ellerman bombs (EBs), ultraviolet bursts (UVBs), and flaring active-region fibrils (FAFs) using interferometric observations in the millimeter (mm) continuum provided by the Atacama Large Millimeter/submillimeter Array (ALMA). Methods. We examined 3 mm signatures of heating events identified in Solar Dynamics Observatory (SDO) observations of an active region and compare the results with synthetic spectra from a 3D radiative magneto-hydrodynamic simulation. We estimated the contribution from the corona to the mm brightness using differential emission measure analysis. Results. We report the null detection of EBs in the 3 mm continuum at ~1.2″ spatial resolution, which is evidence that they are sub-canopy events that do not significantly contribute to heating the upper chromosphere. In contrast, we find the active region to be populated with multiple compact, bright, flickering mm bursts – reminiscent of UVBs. The high brightness temperatures of up to ~14 200 K in some events have a significant contribution (up to ~7%) from the corona. We also detect FAF-like events in the 3 mm continuum. These events show rapid motions of >10 kK plasma launched with high plane-of-sky velocities ($37 - 340$ km/s$^{-1}$) from nanoflare kernels. The mm FAFs are the brightest class of warm canopy fibrils that connect magnetic regions of opposite polarity. The simulation confirms that ALMA should be able to detect the mm counterparts of UVBs and small flares and thus provide a complementary diagnostic for impulsive heating in the solar chromosphere.

Key words. Sun: atmosphere – Sun: chromosphere – Sun: corona – Sun: UV-radiation – Sun: radio-radiation – Sun: activity

1. Introduction

Solar active regions are sites of small-scale impulsive heating phenomena that are routinely observed in the ultraviolet and visible wavelength range as relatively short-lived, compact brightenings, among them Ellerman bombs (EBs), ultraviolet bursts (UVBs), and flaring active-region fibrils (FAFs), nano/microflares (NFs/MFs), and other explosive events (see reviews by Rutten et al. 2013; Young et al. 2018, and references therein). They are commonly regarded as different manifestations of magnetic reconnection. There is mounting observational evidence that they preferentially occur in regions of magnetic flux emergence and interaction of mixed polarities in a variety of contexts (e.g., Porter et al. 1987; Dere 1994; Innes et al. 1997; Chae et al. 1998; Watanabe et al. 2011; Vissers et al. 2013, 2015; Gupta & Tripathi 2015; Tian et al. 2016; Chitta et al. 2018; Guglielmino et al. 2018; Li et al. 2018).

Numerical simulations have shown that the magnetic topology that determines the height of reconnection along with the line of sight to the reconnection site play a role in the visibility of these small-scale heating events across the wavelength spectrum (Hansteen et al. 2019; Peter et al. 2019; Ortiz et al. 2020; Syntelis & Priest 2020). For example, strong emission in the wings of Hα would imply reconnection in the lower atmosphere, whereas bright Mg II h and k, Si iv 1393.7, 1402.8 Å or even extreme-ultraviolet (EUV) emission would originate in higher layers. Other key signatures such as recurrence, intermittency, and large flow velocities may be caused by the release of fast-moving sequences of magnetic islands (or plasmoids) and jets (e.g., Karpen et al. 1995; Shibata & Tanuma 2001; Bhattacharjee et al. 2009; Watanabe et al. 2011; Innes et al. 2015; Ni et al. 2015; Rouppe van der Voort et al. 2017; Peter et al. 2019), while turbulence has also been shown to play a role in triggering fast reconnection in MFs (e.g., Chitta & Lazarian 2020).

The Atacama Large Millimeter/submillimeter Array (ALMA, Wootten & Thompson 2009) offers a different view into the properties of small-scale heating events by producing high-cadence interferometric maps of the millimeter (mm) continuum at unprecedented spatial resolution at these long wavelengths. The bulk of the solar emission in the mm, and in particular in ALMA Band 3 (3 mm or 100 GHz), comes from the chromosphere from a range of heights between ~1200-2000 km above the average height where the optical depth of the 500 nm continuum ($τ_{500}$) is unity in quiet conditions (e.g., Vernazza et al. 1981; Loukitcheva et al. 2015). The main emission mechanism is thermal bremsstrahlung but non-thermal synchrotron may also be detected in large flares (see review by Wedemeyer et al. 2016). Because the source function of the mm continuum is given by the Planck function, which is nearly linear in temperature in the Rayleigh-Jeans limit, one would expect
ALMA to detect the counterpart of UVBs, FAFs, and similar active region phenomena whenever they cause a significant temperature increase at or above the opaque chromospheric canopy (Rutten 2017). ALMA observations also do not suffer from blurring by scattering that affects the more widely used chromospheric diagnostics such as Hα and Mg II h and k (see review by de la Cruz Rodríguez & van Noort 2017) and can be used to constrain temperature stratifications using inversion codes (da Silva Santos et al. 2018, 2020).

However, recent studies that used some of the first solar ALMA observations brought up the need to better understand the formation heights of the ALMA bands in active regions (Louchicheva et al. 2017; da Silva Santos et al. 2020; Chintzoglou et al. 2020) as they likely differ from the quiet Sun (QS) where the emission is dominated by acoustic shocks (e.g., White et al. 2006; Wedemeyer-Böhm et al. 2007; Patsourakos et al. 2020). Moreover, the contribution functions of the mm continuum may also depend on nonequilibrium ionization/recombination effects in the chromosphere (e.g., Carlsson & Stein 2002; Leenaarts & Wedemeyer-Böhm 2006; Rutten 2017; Martínez-Sykora et al. 2020a). In theory, a contribution from the overlying corona to the mm brightness is also expected but deemed to be small, at least in the QS (e.g., White & Kundu 1992).

Shimojo et al. (2017) reported on the first detection of a localized heating event featuring a plasmoid ejection during the ALMA science verification campaign. In this paper we address in a more systematic way the visibility of different small-scale heating events such as EBs, NFs and FAFs in the mm continuum using recent ALMA observations taken at higher spatial resolution, and we compare them to a snapshot of a 3D radiative magnetohydrodynamic (r-MHD) simulation of magnetic flux emergence. We discuss the importance of understanding the contribution functions of the ALMA bands, in particular the contribution from the transition region (TR) and corona in high density conditions, for interpreting the observations.

2. Observations

2.1. Data reduction and calibration

ALMA was pointed at a group of pores in the periiphery of a large sunspot in NOAA 12738 near disk center ($\mu = 0.98$, where $\mu$ is the cosine of the heliocentric angle) on 13 April 2019. The ALMA Band 3 data were acquired in two execution blocks, each consisting of three 10-minute scans separated by 140-second calibration intervals. Each scan contains 300 2.02-second integrations. The two periods covered by the execution blocks were 18:19:52-18:54:55 and 19:15:32-19:50:31. The array contained 42 antennas contributing to the imaging most of the time (other antennas were also occasionally flagged during individual scans).

The data in each execution block were mapped and self-calibrated in phase with progressively smaller intervals to remove atmospheric effects. The field of view of the 7m antennas is about 100″ at 100 GHz, while that of the 12m antennas is 58″. We made 512x512 pixel maps with a cell size of 0.3″, but quantitative analysis is restricted to the inner 60″ regions of the images. The four sidebands (94, 96, 104, 106 GHz) were included together in the mapping in order to improve instantaneous $u, v$ coverage. The final maps used here were primary-beam corrected and restored with a Gaussian beam of width 1.2″. The maps are converted from flux to brightness temperature. To put them on an absolute temperature scale, we compared the average temperature within the 60″ region of interest in the interferometer maps with the corresponding temperature at that location in a calibrated single-dish image (resolution 60″). This resulted in the addition of 7700 K to the interferometer maps. The typical noise level in the difference map made from consecutive maps is 20 K.

We also use ultraviolet (UV) images taken with the Atmospheric Imaging Assembly (AIA, Lemen et al. 2012) and photospheric magnetograms obtained with the Helioseismic and Magnetic Imager (HMI, Scherrer et al. 2012) aboard the Solar Dynamics Observatory (SDO, Pesnell et al. 2012). As part of the routine AIA data reduction, cosmic rays are removed from the EUV images in a so-called “de-spiking” procedure. While this is desirable for most purposes, it also causes many small-scale, bright events to be erroneously removed. We therefore “respiked” the level-1 AIA data products using the IDL code aia_respike in SolarSoftWare (SSW, Freeland & Handy 1998). The regions of interest were maintained and the image artifacts caused by cosmic rays were, for the most part, replaced by interpolated values using a Gaussian kernel. The AIA and HMI data were further processed with routines provided in the SunPy package (SunPy Community et al. 2015), namely for alignment, scaling, derotation, and resampling. The HMI continuum images and magnetograms were deconvolved and upsampled to 0.3″/pixel using the Enhance deep learning code1 by Díaz Baso & Asensio Ramos (2018) to improve the visibility of small-scale flux emergence in the regions of interest. The AIA EUV data were corrected for instrumental degradation (Boerner et al. 2014) and stray light contamination using the semi-empirical point-spread-functions of Poduval et al. (2013). Finally, the AIA images were rebinned 0.3″ to match the deconvolved HMI and ALMA pixel scale. The cadence of the AIA observations is 12 s and 24 s for the EUV and UV passbands, respectively, while that of the HMI magnetograms is 45 s.

Given the discrepancy between ALMA and SDO coordinates2, the co-alignment was refined by taking advantage of the good correspondence between the mm and EUV bright structures, in particular in the 304 Å passband which overall resembles Band 3 the most in the active region. A particular event at 18:36 UTC (described in Sect. 4.3) was especially useful since it features two compact kernels and one bright arch fibril allowing the offset and angle between the different diagnostics to be better constrained. The accuracy was visually verified by the spatial coincidence of other events at different times. However, we do not expect the mm and EUV brightenings to exactly align at all times. We note that the maximum spatial resolution of these ALMA observations is ~1.2″ and thus similar to AIA.

2.2. Overview

Figure 1 shows an overview of the target at the start of the ALMA Band 3 observations. The right-hand side of the ALMA field-of-view (FOV) captured an area where significant flux emergence was visible at the time in the vicinity of a group of pores and plage region. The area includes bright, thus warm, compact features and long fibrilar structures that appear to be

1 https://github.com/cdiabas/Enhance
2 Recent work has shown that an inappropriate shift to account for gravitational deflection has been applied to ALMA observations of the Sun during recent Cycles (N. Phillips and R. Marston, ALMA ICT ticket 16261). This results in a position error that can be as large as 55″ within 100″ of disk center. For this observation, centered 170″ from apparent disk center, the offset could be of order 10″.
Fig. 1: Overview of the target as seen by SDO and ALMA on 13 April 2019. Clockwise from top left: HMI magnetogram, spectral radiance in AIA 1600 Å and AIA 1700 Å, ALMA 3 mm brightness temperature, and spectral radiance in AIA 193 Å and AIA 304 Å. The dotted circle displays the ALMA field-of-view on the SDO data. The x and y axes are the helioprojective coordinates at approximately 18:20 UTC. The crosses indicate the location of EBs (see Sect. 4.1), and the triangles correspond to NFs (see Sect. 4.2) that we detected in the entire time series.

rooted in the photospheric magnetic elements and connect regions of opposite polarity.

We identified several localized, impulsive events in the AIA images throughout the duration of the ALMA campaign. We plot the location of EBs and NFs on the HMI magnetogram. They predominantly occur between the two pores. The EB detections are presented in Section 4.1 and the NFs are discussed in Section 4.2. We also observe FAF-like events in the EUV and mm (Sect. 4.3).

3. Simulations

We used one snapshot of a 3D r-MHD flux emergence simulation performed with the Bifrost code (Gudiksen et al. 2011) and analyzed by Hansteen et al. (2017) to which we refer for a detailed description of the setup. The box size is 504x504x496 px and the resolution is 48 km per px in the horizontal direction and between 20-100 km per px in the vertical direction from the photosphere to the corona.

We complement the synthetic visible and UV diagnostic images of Hansteen et al. (2017) with 3 mm thermal continua that were computed in non-local thermodynamic equilibrium (NLTE) using the STockholm Inversion Code3 (STIC, de la Cruz Rodríguez et al. 2016, 2019). The calculations are carried out iteratively by solving the statistical equilibrium equations for a six-level hydrogen atom imposing charge conservation so that the electron densities are consistent with the NLTE hydrogen populations. The ionization balance of other atoms is treated in LTE in the equation of state.

We also computed the optically thin emission in the AIA EUV channels using version 8 of the temperature response functions $K_{\alpha}(T)$ (Boerner et al. 2014) that are obtained through the aia_get_response routine in SSW using standard coro-

3 https://github.com/jaimedelacruz/stic
4. Results

4.1. Ellerman bombs as sub-canopy events

In the absence of Hα observations, the 1700 Å continuum can be used as a proxy for EBs (e.g., Vissers et al. 2013; Chen et al. 2017; Danilovic et al. 2017). We searched for EB signatures in AIA 1700 Å using the EBDETECT code (Vissers et al. 2019b). We only consider events that reach a conservative threshold of 9σ above the QS mean. This may sacrifice the recovery of some of the lower energy EBs, but it ensures that a higher fraction of the detections correspond to Hα EBs. We identified a total of 20 EBs within the ALMA FOV during the whole time span of the observations.

Figure 2 shows three examples of EB detections (EB1, EB2, and EB3) in AIA and their corresponding visibility (or lack thereof) in ALMA at different times. The other events are displayed in the supplementary Fig. B.1. The brightest EBs appear as compact (∼3") sources in AIA 1600 Å and 1700 Å with lifetimes ranging from tens of seconds to several minutes, and at least half of the candidates are clearly associated with the interaction of opposite polarities (e.g., EB1, EB2 and EB3) as far as we can tell from the deconvolved HMI magnetograms. They usually have no obvious counterpart in the EUV filters, or the emission seems unrelated to the UV brightenings. Likewise, we find that most EBs (both the 9σ cores and 5σ extended halos) have no clear signature in the 3 mm continuum.

EB2 is a striking example of how Band 3 is not sensing the energy release of the EB but it must be formed much higher in the chromospheric canopy. The panels show a strong enhancement in the UV continuum associated with a flux cancellation site that appears dark at 3 mm with $T_b \sim 7500$ K (similar to QS level), yet right next to it we clearly see a warm loop-like structure connecting the two main polarities patches in the region. Events such as EB3 that occur within an extensive region that is generally enhanced in Band 3 are inconclusive. In this case, the average $T_b$ (and standard deviation) within the EBDETECT 5σ contours is $\approx 8200(\pm 350)$, but the lack of contrast between the EBs and the periphery does not allow us to unambiguously associated the 1700 Å continuum enhancement with the 3 mm brightness.

\[ I_{ch} = \int n_e(z)K_{ch}(T)dz. \]

(1)

\[ https://github.com/grviss/ebdetect \]
We find that brightness temperature of the events located further way from the AR center were lower (down to QS levels) than the EBs occurring near the pores, which strongly suggests that enhanced $T_b$ values are probably the result of the more "space-filling", persistent heating that is found in flux emerging regions (e.g., Leenaarts et al. 2018), rather than a consequence of episodic chromospheric heating by EBs. Overall, the mean and standard deviation of the brightness of the EBs in Band 3 are $T_b \sim 7900(\pm 300)$ K.

Figure 3 shows the light curves for the AIA 1700 Å filter and ALMA Band 3 for EB1, EB2 and EB3 shown in Fig. 2. They confirm that the photospheric 1700 Å continuum enhancements and the overlying chromospheric mm continuum are weakly correlated in the EB candidates. After interpolating the mm observations to the AIA temporal sampling, the Pearson’s linear correlation coefficients are $r=0.28$, $r=0.35$, and $r=-0.08$ for EB1, EB2, and EB3, respectively. We also find no evidence for a lag between the photospheric and chromospheric signals.

4.2. The millimeter counterparts of EUV nanoflares

Contrary to the EB events discussed in the previous section, we find nine impulsive events in the AIA EUV images that have clear counterparts in the ALMA maps. These are also small ($\lesssim 4''$) and short-lived ($\sim 1$–$8$ min), but unlike the EB candidates that do not have a mm analogue, the EUV brightenings are usually accompanied by simultaneous (within the $12$ s cadence of the EUV data) mm continuum enhancement, or at least every time that there is a significant intensity increase in the 304 Å channel. In most cases they have only a relatively weak signature in the 1600 Å filters compared to the plage region and EBs. We note that the ALMA data shows other interesting transients brightenings that do not have a EUV analogue and could possibly be UVBs, but we did not quantify their occurrence in the same systematic way given the lack of context from IRIS.

In this paper we focus on the two most significant events that occurred between 18:24–18:42 UTC and feature three compact EUV kernels associated with bright loops. The kernels are some of the brightest features detected during the whole observation period in all AIA passbands, and we estimated their thermal energies to be similar to typical nanoflares (see Sect. 4.4). Therefore, we labeled them as NF1 (first event) and NF2 and NF3 (second event), and we use the terms nanoflares and EUV brightenings interchangeably in the remainder of the text.

Figure 4 shows the three TR coronal brightenings (NF1, NF2, and NF3) identified by visual inspection of the EUV data and their counterparts in the 3 mm continuum. Other interesting brightenings are displayed in the supplementary Fig. B.2. NF1 appears as roundish bright source in all AIA EUV channels at the same location where we see an enhancement in the 3 mm brightness temperature of several thousand kelvin relative to the background. Interestingly, no significant 1600 Å or 1700 Å emission is detected. NF2 is a different event that occurs at the same location as NF1 approximately 10 min later and near NF3. In the latter there is a strong enhancement in the UV channels. The highest brightness temperature at 3 mm that we observe in the EUV kernels is $T_b=14300$ K. In the three cases there is a remarkable spatial and temporal similarity between the EUV images and Band 3 maps. We present the results of the analysis of the time series in Sect. 4.3.

The insignificant 1700 Å emission in NF1 but weak enhancement in the 1600 Å filter (compared to average plage brightness) is indicative of a contribution from the C iv doublet and other lines that may dominate the passband in flaring conditions (Simões et al. 2019). In the second event, we find a more pronounced brightening in both filters at NF3 which implies a mixed contribution from photospheric continuum and transition region lines and possibly suggests a different formation mechanism in the two events.

We note that the average photospheric magnetic field strength is weak ($\lesssim 100$ G) at the flaring locations, and the association of NFS1-3 with opposite polarities in the photosphere is unclear and definitely not as obvious as in the EBs shown in Fig. 2. We do not find clear evidence for magnetic flux cancellation as the driver of the three NFs.

4.3. Flaring active region fibrils

In this section we analyze the temporal evolution of the two main events that feature the three NFs presented in Sect. 4.2. Inspection of the AIA data shows that NF1, NF2, and NF3 are associated with significant loop brightenings similar to FAF events, which are also clearly visible in the ALMA maps.
Figure 5 shows selected instances of the evolution of the two events. An online movie showing the full temporal evolution is also available. NF1, NF2, and NF3 occur in the vicinity of a particular fibril (e.g., Fig 1 between y = 180°−190°) that is about ~18′′ long and ~1.5″ wide in the 3 mm maps, and it is visible throughout the entire ALMA sequence. The brightness temperatures of the fibril are typically within 8000–9000 K, but reach much higher values (up to ≈12 200 K) in connection with the flare kernels. The fibril is cospatial with a small filament that appears as an absorption feature in the AIA 171 Å, 193 Å and 304 Å channels between the two main opposite polarity patches, although it is not clear whether they are related. A somewhat larger filament is also visible in the AIA images to the North and away from the flux emergence region, but it appears practically indistinguishable from the local background at 3 mm.

In the first event that starts around 18:24 UTC, NF1 intermittently powers a faint EUV loop to which it is connected. The loop is best seen in AIA 171 Å and 304 Å but it is practically undetectable in AIA 94 Å and 131 Å. NF1 eventually releases a fast-moving blob with an average FWHM of 1.9″×2.8″ as measured in the AIA 171 Å, 193 Å and 304 Å filters that have higher signal-to-noise ratio. The same temporal evolution is echoed in the ALMA Band 3 maps. The loop is initially between \( T_b \approx 8000–8500 \) K, but it gradually warms up to \( T_b = 9000–9500 \) K from a stream of plasma that travels with a projected velocity of approximately \( \approx 37 \) km s\(^{-1}\) from the flare kernel as the latter oscillates in brightness (see Fig.6). Analogous flickering intensities and similar velocities were observed in high-resolution SST Ca II K filtergrams of plasmoid-like fine structure in UVBs (Rouppe van der Voort et al. 2017). The blob is also visible in Band 3 and resembles the plasmoid ejection described in Shimojo et al. (2017) but shows higher temperatures \( (T_b \approx 12-400 \) K) and EUV intensities.

The second event starts at around 18:35 UTC in the same area of the first event but it features two different EUV brightenings (NF2 and NF3) and an even more pronounced flaring fibril. This time the loop is partially visible in AIA 94 Å. The loop reaches \( T_b \approx 12\) 200 K at 3 mm more impulsively than in the first event, and we detect a much faster heat front with \( T_b \approx 10\) 000 K and plane-of-sky velocity of \( \approx 340 \) km s\(^{-1}\) (see Fig.6) which is best seen at the high cadence of the ALMA observations.

Interestingly, we do not observe any copatial 1600 Å emission in the hot loops in neither of the events unlike, for example, in the FAFs reported in Vissers et al. (2015) or the transient brightenings in Pariat et al. (2009) and Gupta et al. (2018), which suggests that the bulk of the plasma is not at temperatures between \( \log T \sim 4.2-5.1 \) K to which AIA 1600 Å would be sensitive (Simões et al. 2019).

Figure 7 shows the AIA and ALMA light curves of the three NFs discussed above and the respective cross-correlation obtained for different temporal displacements (or lag) of the ALMA signal relative to AIA. The latter are computed by interpolating the ALMA observations to the AIA cadence. We find that there is not only spatial correspondence but also temporal coherence between the EUV and mm emission since the correlation values approach unity and are maximal or nearly flat-topped at lag zero, which means that the brightenings are nearly simultaneous in all wavelengths or have a relative delay that is of the order of the AIA cadence at most.

Another interesting aspect of the ALMA time series given its very high signal-to-noise ratio and cadence are the rapid variations in \( T_b \) with amplitudes of several hundred kelvin. We investigated if there are any periodic components in the more long-lasting NF signals using wavelet analysis and found statis-
tically significant periodicities in the range \(\sim 25\text{-}140 \text{ s}\) (see Appendix A). Similar time scales were identified in Interface Region Imaging Spectrograph (IRIS, De Pontieu et al. 2014) FUV observations of explosive events and linked to variations in the photospheric magnetic field strength (Gupta & Tripathi 2015). We do not find evidence for the latter in the events presented here, therefore their origin remains unclear.

### 4.4. Differential emission measure analysis

We estimated an order of magnitude for the thermal energy of the EUV kernels (Sect. 4.2) as \(E_{\text{th}} \sim 3n_e k_B T V\) where \(T\) is the electron temperature, \(n_e\) is the electron density, and \(V\) is the volume that is approximated as \(l w^2\) for brightenings with a certain projected length \(l\) and width \(w\) on disk (e.g., Aschwanden 2004). The dimensions are estimated by fitting a 2D Gaussian to the kernels and computing the full-width-at-half maximum (FWHM) along the orthogonal axes, while the depth is assumed to be the same as \(w\). The temperature is obtained from the peak of the differential emission measure (DEM) curve that is inferred from the AIA 94 Å, 131 Å, 171 Å, 193 Å, 211 Å, and 335 Å filters using the regularized DEM inversion code\(^5\) described in Hannah & Kontar (2012). We use time-dependent AIA instrumental responses obtained from SSW with CHIANTI v9 (Dere et al. 1997, 2019) to account for instrumental degradation on the uncorrected count rates, and we include a systematic uncertainty factor of 20% to account for uncertainties in atomic data.

Figure 8 shows examples of the DEM inversions of spatially-averaged intensities (4×4 px, 1.2 arcsec\(^2\)) at the center of NF1, NF2, and NF3 at peak brightness. We note that the inverted DEM curves are only reliable from \(\log T \geq 5.5 \text{ K}\) and some large error-bars are related to sensitivity gaps in the AIA response functions. We find an increase of the DEM at all temperature bins compared to the background. Despite the greatest relative increase being at \(\sim 10^{5.9} \text{ K}\), the highest peak of the DEM curves is at \(\sim 10^{6.6}\pm1.1\) K even after background subtraction. The background intensities are defined as the values just before the onset of the events at the same locations.

Assuming a typical active region coronal density of \(n_e \sim 10^9 \text{ cm}^{-3}\) and an estimated size of \(\approx 1.4\times10^2\) NF1 (1.5\times10\(^2\) (NF2 and NF3) we find \(E_{\text{th}} \approx 2.1(\pm0.5) \times 10^{25}\) erg (NF1) and \(E_{\text{th}} = 2.3(\pm0.5) \times 10^{24}\) erg (NF2 and NF3). If we estimate the electron densities using \(n_e \sim \sqrt{EM/w}\), where \(EM = \int \text{DEM}(T) dT\) is the plasma column emission measure, and a filling factor of one is assumed, we find \(n_e \approx 2\times10^{10}\) cm\(^{-3}\) (NF1) and \(n_e \approx 2.7\times10^{10}\) cm\(^{-3}\) (NF2 and NF3). Therefore, the energies are \(E_{\text{th}} \approx 4(\pm1) \times 10^{25}\) erg (NF1) and \(E_{\text{th}} \approx 6(\pm1) \times 10^{24}\) erg (NF2 and NF3). These estimates are within the typical nanoflare energy range \(10^{24} - 10^{27}\) erg (e.g., Aschwanden 2004).

The spatio-temporal correspondence between the bright EUV kernels and the mm bursts raises the question whether there is a significant contribution from the corona to the brightness temperatures in Band 3. Following the approach of Bastian et al. (2017), the contribution to the mm intensity along the \(z\)-direction on the line of sight from the optically thin corona can be estimated as follows:

\[
\Delta I_v \approx \int_a S_v dz
\]

where \(S_v = B_v(T)\) is the source function that is equal to the Planck function, and \(\alpha_v\) is the free-free absorption coefficient that is given by:

\[
\alpha_v = \frac{4e^6}{3hc} \left( \frac{2\pi}{3km_e^2} \right)^{1/2} \frac{n_e}{T^{1/2} v^3} \sum_i Z_i^2 n_i g_i(v,T)(1 - e^{-hv/kT})
\]

where \(h\) is the Planck constant, \(e\) is the electron charge, \(c\) is the speed of light, \(k\) is Boltzman constant, \(m_e\) is the electron mass, \(v\) is the frequency, \(Z_i\) and \(n_i\) are the charge number and density of the ion species \(i\), \(g_i\) is the Gaunt factor of free-free processes, and the last term between parenthesis is the correction for stimulated emission. In the Rayleigh-Jean’s limit the expression above can be approximated as given by Dulk (1985) in cgs units:

\[
\alpha_v \approx 9.78 \times 10^{-3} \frac{n_e}{v^2 T^{3/2}} \sum_i Z_i^2 n_i (24.5 + \ln T - \ln \nu)
\]

\(^5\) [http://www.astro.gla.ac.uk/~iain/demreg](http://www.astro.gla.ac.uk/~iain/demreg)
Fig. 7: AIA and ALMA light curves. Panels a, b, and c: intensity as function of time in different AIA passbands at the three nanoflares shown in Fig. 4; the shaded areas in the 1600 Å and 1700 Å panels enclose the mean ± 1σ of the (detrended) signal over a longer period of time. Panels d, e, and f: the corresponding mm brightness temperature. Panels g, h and i: cross-correlation functions between ALMA and AIA; one lag unit corresponds to 12 s in the EUV and 24 s in the UV.

for $T > 2 \times 10^5$ K. Substituting Eq. 4 in Eq. 2 and assuming a fully ionized hydrogen plasma, the contribution defined in terms of brightness temperature is given as follows:

$$\Delta T_b \approx 9.78 \times 10^{-3} \nu^{-2} \int (24.5 + \ln T + \ln \nu)T^{-1/2}n_e^2dz$$  \hspace{1cm} (5)

In reality the stratification of electron density with height is not known, but we can use the estimated DEM curves instead from the definition:

$$\text{DEM}(T) = n_e^2 \frac{dz}{dT}$$  \hspace{1cm} (6)

This means one expects a larger contribution from the corona in the heating events where there is a significant enhancement of the plasma emission measure (see Fig. 8). We compute the DEM in each pixel of the FOV, and the integration is carried between $5.5 \leq \log T \leq 7.3$ within the range of sensitivity of the AIA bands.

Figure 9 shows examples of the contribution from the corona to the observed 3 mm brightness temperature for three instances of the main events discussed in this paper. We perform a 10-sec average on the ALMA data to account for the different time sampling of each AIA channel. We find that the contribution from the corona in Band 3 is $\lesssim 1\%$ ($\lesssim 73$ K) in the more quiet areas, but it increases to several hundred kelvin at the NF sites. We find a relative contribution of $\sim 3\%$ in NF1, 4% in NF2, and 7% in NF3. This suggests that a non-negligible contribution from the corona may overlap with the chromospheric signal detected with Band 3 in NF events, or more generally in flaring conditions in high density media. The mm brightness may remain significantly enhanced for several minutes after the strong emission in the hotter AIA channels has vanished as shown on the right panel in Fig. 7, but it still correlates with the intensity enhancements detected in the 304 Å filter. The contributions in the flaring loops are lower (1–2%).
The aforementioned estimates can be considered as lower limits since we did not assess the contribution of the transition region (log $T < 5.5$ K) to the mm brightness, which is in principle more important than the corona given the $T^{-1/2}$ dependence in Eq. 5. We note that these results are subject to the uncertainties in the flux calibration of both instruments and uncertainties inherent to the DEM inversion due to the limited information that can be extracted from the response functions of the EUV channels alone.

4.5. Synthetic mm continuum from a 3D flux emergence simulation

Figure 10 shows synthetic observables computed from a 3D $r$-MHD simulation (see Sect. 3). Synthetic H$\alpha$ and Si iv 1393 Å images are shown for identification of EBs and UVBs that were previously discussed and compared with observations in Hansteen et al. (2017). The average $T_b$ at 3 mm in the whole box is approximately $\approx 6700$ K, which is lower than the observed QS average ($\approx 7300$ K, White et al. 2017). Furthermore, the magnetic topology is not directly comparable to the observed active region. However, from the synthesized mm continua we see that the flux emergence process is able to significantly heat the chromosphere in different reconnection events. We find a good correspondence between $T_b$ at 3 mm and the Si iv brightenings but no counterparts to the brightenings in the wings of H$\alpha$. This is due to the deeper formation of the EBs relative to the UVBs and small flares in the simulation (see below).

For example, the highlighted UVB in Fig. 10 shows a range of brightness temperatures between $\sim 20$–$37$ kK, although the highest values are only reached in a few pixels, so they would not be resolved in our ALMA data. Smearing the data to the spatial resolution of the observations brings the maximum $T_b$ down to $\sim 13$ kK, which agrees with the typical values that we observe at the bright kernels (see Fig. 4). The simulation also produces a FAF-like feature in the mm continuum that is remarkably similar to the observations (see Fig.5), although the maximum synthetic brightness of $\sim 19$ kK at 1.2” resolution is much larger than observed ($\sim 12$ kK).

In this simulation we also find a good correspondence between ALMA and the EUV brightenings, especially with the 304 Å passband as in the observations, which can be understood from the temperature response of this band to relatively cooler ($T < 10^5$ K) plasma. However, detailed optically thick, nonequilibrium radiative transfer is needed to more accurately model the He ii 304 Å line (e.g., Golding et al. 2014, 2017) that dominates this passband.

Figure 11 shows two cuts through the simulation along the horizontal (bottom panels) and vertical (lower panels) lines drawn in panel e in Fig. 10. We plotted the layers where the optical depth of the 3 mm continuum and the wing of H$\alpha$ at 1.5 Å from the line center reach unity. The 3 mm continuum is formed over a broad range of heights that spans several megameters due to the expansion of the chromosphere in this simulation due to the magnetic flux emergence process. At the reconnection sites the $\tau_{3\text{mm}} = 1$ layer drops due to the large temperature increase in the overlying atmosphere ($\alpha_\nu \propto T^{-3/2}$). Figure 11 also shows that the formation height of the EB-like brightening in the wing of H$\alpha$ is much lower than the 3 mm radiation, which is consistent with the observational findings (see Sect. 4.1).

We find that the brightness temperature at 3 mm and the gas temperature at $\tau_{3\text{mm}} = 1$ are well-correlated ($r = 0.92$), but these two quantities may differ by several thousand kelvin at certain locations, particularly in the upflowing jets due to the integration of contributions from different layers including the TR. At the center of the UVB and FAF, as indicated by the vertical dotted lines in Fig. 11, $T_b(3\text{mm})$ provides a good direct estimate of the temperature of the reconnection. In this simulation the contribution from the corona to the mm intensities is negligible as most of it has been pushed away by the emerging magnetic fields. For example, in the flaring fibril the optically thin contribution from plasma at $T \gtrsim 10^5$ K is approximately 1% at 3 mm. This may not be the case in real active regions on the Sun (see Sect. 4.4).

5. Discussion

In the comprehensive study of Georgoulis et al. (2002) EBs were described as bright features in the wings of H$\alpha$ (and often in the 1600 Å continuum) with a typical size of 1.8′′×1.1′′ and occurring at a rate of at least 1.43 min$^{-1}$ in a FOV of 1800 arcsec$^2$, and it is speculated they could be important for chromospheric and even coronal heating. EBs with such properties would readily be detected in our ALMA observations. However, not even the brightest and largest candidates that we found in the 1700 Å continuum images had a mm counterpart, which is in line with the prediction of Rutten (2017). This is consistent with observational and numerical studies that propose low-altitude reconnection as the causing mechanism of EBs (e.g., Georgoulis et al. 2002; Pariat et al. 2007; Matsumoto et al. 2008; Archontis & Hood 2009; Watanabe et al. 2011; Vissers et al. 2013; Danilovic 2017; Hansteen et al. 2017, 2019), and link temperature enhancements around the temperature minimum region with their common spectral signatures (e.g., Fang et al. 2006; Berlicki et al. 2010; Bello González et al. 2013; de la Cruz Rodríguez et al. 2015; Li et al. 2015; Reid et al. 2017; Danilovic et al. 2017; Vissers et al. 2019a). We note that ALMA Band 3 observations might still detect EBs that have an UVB counterpart (e.g., Vissers et al. 2015; Tian et al. 2016; Libbrecht et al. 2017). Future ALMA observa-
In contrast, we identified multiple impulsive, intermittent heating events with brightness temperatures above 9 kK in the ALMA sequence that coincide with bright EUV structures. Their thermal energies of the order of a few $10^{24} - 10^{25}$ erg along with the lack of strong photospheric signal, suggest they are NF events occurring in higher layers of the atmosphere. These mm-bursts could be UVBs, although it is uncommon for the latter to show strong EUV emission (e.g., Young et al. 2018), likely due to absorption by cool gas along the line-of-sight (Hansteen et al. 2019) or because temperatures above ~0.1 MK may not be
We investigated the contribution of the corona to the mm brightenings from DEM analysis using six AIA channels and found that there could be a significant contribution between ~4-7% from plasma at $T > 10^{5.5}$ K in different NF events, although this only explains in part the enhancements of up to ~60% in Band 3 relative to the background. The cooler TR plasma is also expected to contribute to the observed brightness. Therefore, the emission detected by ALMA Band 3 in small (and larger) flares may result from a contribution from a broad distribution of plasma temperatures. The Bfrost simulation shows $T_b$ at 3 mm around 37 kK at spatial scales much smaller than what ALMA can resolve at the moment. Everywhere else in the AR including the bright loops and periphery the contribution is smaller ($\lesssim 2\%$).

Shimojo et al. (2017) interpret a plasmoid ejection from a small flare kernel observed with AIA and ALMA Band 3 (analogous to our first event) as emission from multi-thermal plasma where ALMA could trace a cooler ($10^4$ K) component surrounded by a MK-hot sheet, but they note that optically thin emission could be an alternative explanation. Rodger et al. (2019) analyze the same ALMA dataset and rule out the latter but suggest that the optical depth of the plasmoid is in the transition from optically thin to optically thick regime. Our analysis of the first event shows that the relative contribution from coronal plasma in the plasmoid is only approximately 2% and is thus consistent with those previous observations.

We have also found that the core of the active region consists of long, warm mm fibrils that connect regions in the photosphere with strong opposite polarity field. They seem to be a common occurrence in active regions observed in the mm (see also Molnar et al. 2019; da Silva Santos et al. 2020; Wedemeyer et al. 2020; Chintzoglou et al. 2020). This is in good agreement with synthetic mm maps that were obtained from a 3D r-MHD Bfrost simulation of an enhanced network (Loukitcheva et al. 2015). Even though that simulation is not meant to reproduce a solar active region, it shows the same kind of loop-like structures with $T_e \gtrsim 10$ kK at 3 mm, albeit shorter than the observed ones given the limited size of the computational box. They sample relatively higher layers between ~1500-2000 km compared to the weakly magnetized areas. That simulation was also compared to a small-scale arch-filament system observed with ALMA Band 3 (Wedemeyer et al. 2020).

The 3D r-MHD simulation that we used in this paper does not show the same kind of ubiquitous long mm fibrils (see Fig. 10), likely because it lacks large-scale magnetic connectivity. However, the process of magnetic flux emergence gives rise to localized heating events that resemble UVBs and FAFs. The brightness temperatures of the synthetic UVBs are in good agreement with the observations, whereas the simulated FAF is stronger than the observed. The 3 mm continuum is optically thick at the base of the reconnection sites and traces the warm material in the upflowing high-velocity jets.

We note that our simulation does not include the effects of ambipolar diffusion which has been shown to play an important role in 2.5D flux emergence experiments (e.g., Leake & Arber 2006; Martínez-Sykora et al. 2020b; Nóbrega-Siverio et al. 2020), and it could affect the visibility of different heating events through changes in temperature and density. However, the 2.5D simulation of Martínez-Sykora et al. (2020a) that included the effects of ambipolar diffusion and non-equilibrium ioniza-
tion of helium also suggests that ALMA Band 3 will observe canopy fibrils that originate from strong concentrations of magnetic field, but it predicts low brightness temperatures (∼4500–5000 K) as a consequence of expansion of cool dense plasma to much higher heights than in the 3D case (Loukitcheva et al. 2015) constituting a cool canopy. This is in contrast with our observations that show that the 3 mm canopy within the active region is consistently warmer ($T_b \sim 8000–9000$ K) than the QS ($T_b \sim 7300$ K) and occasionally shows signs of impulsive heating and rapid flows (∼40–340 km s$^{-1}$) of $T_b \gtrsim 10$ K plasma (or heat fronts) along fibrils (see Fig. 5) powered by small flare kernels. Perhaps they are the signatures of precursor heating events of Hz contrail fibrils (Rutten & Rouppe van der Voort 2017; Rutten 2017) caused by dissipation of electrical currents as in our Bifrost simulation.

6. Conclusions

This work reports on the first results of a dedicated ALMA campaign to study the visibility of small-scale heating events in the solar atmosphere using observations in the millimeter wavelength range. We compare SDO and ALMA Band 3 (3 mm) observations of an active region close to disk center and we use a snapshot of a Bifrost 3D r-MHD simulation of flux emergence in order to interpret the results.

We find that not even the brightest EB candidates identified in the AIA 1700 Å continuum have a clear counterpart in Band 3 (3 mm) that was observed at the highest spatial resolution so far (1.2″). This finding is consistent with the large body of evidence that EBs are photospheric reconnection phenomena (e.g., Georgoulis et al. 2002; Watanabe et al. 2011; Rutten et al. 2013; Vissers et al. 2013; Danilovic 2017; Hansteen et al. 2017) and do not contribute significantly to heating the upper chromosphere.

However, throughout the course of approximately one hour we find multiple compact, bright, flickering mm-bursts (by analogy with the UV-bursts), and long fibrils that compose a warm canopy in the flux emergence region. The brightness temperatures of the bright kernels are typically 10 kK, but reach as high as 14 kK in the strongest events, and they last from dozens of seconds to several minutes. Some of them could be UVBs, but IRIS observations would be required to confirm this. Interestingly, the brightest events are the mm counterparts of NFs identified in the AIA hot channels, and the emission in the EUV and mm are well correlated both in space and time. The relatively weaker 1600 Å and 1700 Å emission compared to the plage and EBs suggests that they occur in higher layers of the atmosphere. Wavelet analysis reveals periodicities in the range 25–140 s which is similar to values found in UVBs observed in the FUV with IRIS (Gupta & Tripathi 2015) that are possibly linked to plasmoid-mediated reconnection (Peter et al. 2019). Follow-up observations and modeling are needed to understand the origin of these frequencies.

We also report for the first time on the detection of FAF-like events in the mm continuum. We observe plane-of-sky motions of warm ($T_b \sim 9–12$ kK) plasma with high horizontal velocities (∼37–340 km s$^{-1}$) that originate from NF sites and travel along fibrils. Our simulation indeed shows that ALMA may be able to detect the mm analogues of UVBs and FAFs should they cause a significant temperature increase in the chromosphere. Therefore, it is possible to use mm continuum observations to directly estimate the temperature of the reconnection and constrain their formation heights.

Given the significant increase of the emission measure at the NF kernels a non-negligible contribution of several hundred kelvin (∼4–7%) from the lower corona may overlap with the chromospheric signal the Band 3 as shown by the DEM analysis. The remarkable spatial and temporal correlation between the 3 mm continuum and AIA 304 Å also suggests that Band 3 may be sensitive to transition region temperatures at the sites of strong, small-scale impulsive heating. The Bifrost simulation also predicts that 3 mm brightness temperatures close to 40 kK may be detected at reconnection sites at much shorter time scales than what ALMA can resolve at the moment.

Future work should aim at further investigating the contribution functions of the mm continuum under flaring conditions which are very different from the QS where the 3 mm emission is predominantly chromospheric. Our work shows that ALMA observations can be used to detect impulsive heating phenomena in active regions and possibly constrain magnetic reconnection modeling, while comparisons with other diagnostics provide interesting insight into the thermal structure of the solar atmosphere.

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6 https://astropy.org
7 https://sunpy.org
on the two signals with longest duration (NF1 and NF3, see Fig. 7). The signals are first detrended by removing the approximation coefficients in a five-level decomposition with an orthogonal wavelet which effectively removes the low-frequency component of the signals. The low frequency component in the NF1 shows two peaks separated by 160 s. Then we performed time-frequency analysis using the Python wavelet software\(^8\) based on Torrence & Compo (1998).

The results of the wavelet analysis are shown in Fig. A.1 and Fig. A.2 for NF1 and NF3, respectively. The cone of influence represents the region where boundary effects may affect the wavelet coefficients. We find clear indications of periodicities in the range \(\sim25-140\) s in NF1 and \(\sim50-120\) s in NF3 at a 99% confidence level. In the first case the main peaks of the global wavelet power spectrum (averaging in time) are at 60 s and 110 s, whereas in the second case the main peaks are at 72 s and 99 s. Their location in frequency is confirmed in the Fourier power spectrum. Interestingly, in the first event (Fig. A.1) we find a transition from a lower frequency component to a higher one that appears just before the release of the large plasmoid (see animated Fig. 5). In the second case (Fig. A.2) we also show a reconstructed signal by computing the inverse Fourier transform using the two main frequencies.

Gupta & Tripathi (2015) reports on a similar range of frequencies derived from IRIS observations of UVBs and links them to changes in the emerging photospheric magnetic field. We do not find evidence for the latter. Intensity fluctuations in visible and UV diagnostics have also been associated to plasmoid-mediated reconnection (e.g., Innes et al. 2015; Rouppe van der Voort et al. 2017; Peter et al. 2019). Apart from the intermittency of the mm signals, the release of a fast-moving blob from NF1 in the first event is tentative evidence for such scenario. The lack of a similar feature in the second event may be due to insufficient spatial resolution since plasmoids have been found at scales ten times smaller (Rouppe van der Voort et al. 2017) than what we can resolve with ALMA Band 3. This warrants further investigation.

### Appendix B: Supplementary figures

![Fig. A.1: Time-frequency domain analysis for NF1. The scalogram is shown in inverse color. The hatch is the cone of influence. The 99% confidence regions are shown by the yellow lines. The (normalized) global wavelet power spectrum as well as the Fourier power spectrum of the signal are shown in the right panel.](https://example.com/fig_a1)

![Fig. A.2: Time-frequency domain analysis for NF3. Analogous to Fig. A.1.](https://example.com/fig_a2)

### Appendix A: Brightness oscillations in ALMA

A feature that stands out in the high-cadence ALMA lightcurves in Fig. 7 are the high-frequency oscillations in \(T_b\) with amplitudes of several hundred kelvin. In order to investigate whether there are any periodicities in the brightenings in the two main events (see Fig. 5), we conducted a wavelet analysis. We focus

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8. [https://github.com/chris-torrence/wavelets](https://github.com/chris-torrence/wavelets)
Fig. B.1. EB candidates in SDO and ALMA. All panels show a $10'' \times 10''$ FOV centered on EBs. The contours correspond to $5\sigma$ (thick) and $9\sigma$ (thin) EBDETECT thresholds (see Sect. 4.1). Only the $9\sigma$ events are considered as EBs. The image scale is indicated in the panels in the second column. The dotted lines in the second row delimit the edge of the ALMA field-of-view. The range in the HMI magnetograms is clipped at $\pm 0.3$ kG and the intensities in the AIA 1700 Å, 1600 Å and 304 Å channels are capped at 4000 DN s$^{-1}$, 150 DN s$^{-1}$, and 3000 DN s$^{-1}$ in all panels. The ALMA color-bars are in units of kilokelvin.
Fig. B.1. Continued.

Danilovic, S. 2017, A&A, 601, A122
Danilovic, S., Solanki, S. K., Barthol, P., et al. 2017, ApJS, 229, 5
de la Cruz Rodríguez, J., Hansteen, V., Bellot-Rubio, L., & Ortiz, A. 2015, ApJ, 810, 145
de la Cruz Rodríguez, J., Leenaarts, J., & Asensio Ramos, A. 2016, ApJ, 830, L30
de la Cruz Rodríguez, J., Leenaarts, J., Danilovic, S., & Uitenbroek, H. 2019, A&A, 623, A74
de la Cruz Rodríguez, J. & van Noort, M. 2017, Space Sci. Rev., 210, 109
De Pontieu, B., Title, A. M., Lemen, J. R., et al. 2014, Sol. Phys., 289, 2733
Dere, K. P. 1994, Advances in Space Research, 14, 13
Dere, K. P., Del Zanna, G., Young, P. R., Landi, E., & Sutherland, R. S. 2019, ApJS, 241, 22
Dere, K. P., Landi, E., Monsignori Fossi, B. C., & Schmieder, B. 2002, The Astrophysical Journal, 575, 506
Golding, T. P., Carlsson, M., & Leenaarts, J. 2014, ApJ, 784, 30
Golding, T. P., Leenaarts, J., & Carlsson, M. 2017, A&A, 597, A102
Gudiksen, B. V., Carlsson, M., Hansteen, V. H., et al. 2011, A&A, 531, A154
Guglielmino, S. L., Zuccarello, F., Young, P. R., Murabito, M., & Romano, P. 2018, ApJ, 856, 127
Gupta, G. R., Sarkar, A., & Tripathi, D. 2018, ApJ, 857, 137
Gupta, G. R. & Tripathi, D. 2015, ApJ, 809, 82
Hannah, I. G. & Kontar, E. P. 2012, A&A, 539, A146
Hansteen, V., Ortiz, A., Archontis, V., et al. 2019, A&A, 626, A33
Hansteen, V. H., Archontis, V., Pereira, T. M. D., et al. 2017, A&A, 589, 22
Innes, D. E., Guo, L. J., Huang, Y. M., & Bhattacharjee, A. 2015, ApJ, 813, 86
Innes, D. E., Inhester, B., Axford, W. I., & Wilhelm, K. 1997, Nature, 386, 811
Karpen, J. T., Antičić, N. M., & DeVore, C. R. 1995, ApJ, 450, 422
Leake, J. E. & Arber, T. D. 2006, A&A, 450, 805
Leenaarts, J., de la Cruz Rodríguez, J., Danilovic, S., Scharmer, G., & Carlsson, M. 2018, A&A, 612, A28
Leenaarts, J. & Wedemeyer-Böhm, S. 2006, in Astronomical Society of the Pacific Conference Series, Vol. 354, Solar MHD Theory and Observations: A High Spatial Resolution Perspective, ed. J. Leibacher, R. F. Stein, & H. Uitenbroek, 306
Lemen, J. R., Title, A. M., Akin, D. J., et al. 2012, Sol. Phys., 275, 17
Li, D., Li, L., & Ning, Z. 2018, Monthly Notices of the Royal Astronomical Society, 479, 2382
Li, Z., Fang, C., Guo, Y., et al. 2015, Research in Astronomy and Astrophysics, 15, 1513
Libbrecht, T., Joshi, J., Rodríguez, J. d. l. C., Leenaarts, J., & Ramos, A. A. 2017, A&A, 598, A33
Loukitcheva, M., Solanki, S. K., Carlsson, M., & White, S. M. 2015, A&A, 575, A15
Loukitcheva, M. A., Iwai, K., Solanki, S. K., White, S. M., & Shimojo, M. 2017, ApJ, 850, 35
Martínez-Sykora, J., De Pontieu, B., de la Cruz Rodríguez, J., & Chintzoglou, G. 2020a, ApJ, 891, L8
Martínez-Sykora, J., Leenaarts, J., De Pontieu, B., et al. 2020b, ApJ, 889, 95
Matsumoto, T., Kitai, R., Shibata, K., et al. 2008, PASJ, 60, 95
Mohvr, M. E., Reardon, K. P., Chai, Y., et al. 2019, ApJ, 881, 99
Ni, L., Kliem, B., Lin, J., & Wu, N. 2015, ApJ, 799, 79
Nóbrega-Siverio, D., Moreno-Insertis, F., Martínez-Sykora, J., Carlsson, M., & Szydlarski, M. 2020, A&A, 633, A66
Ortiz, A., Hansteen, V. H., Nóbrega-Siverio, D., & van der Voort, L. R. 2020, A&A, 633, A58
Pariat, E., Masson, S., & Aulanier, G. 2009, ApJ, 701, 1911
Pariat, E., Schmieder, B., Berlicki, A., et al. 2007, A&A, 473, 279
Patsourakos, S., Alissandrakis, C. E., Nindos, A., & Bastian, T. S. 2020, A&A, 634, A86
Pevtsov, W. D., Thompson, B. J., & Chamberlin, P. C. 2012, Sol. Phys., 275, 3
Peter, H., Huang, Y. M., Chitta, L. P., & Young, P. R. 2019, A&A, 628, A8
Peter, H., Tian, H., Cudrit, W., et al. 2014, Science, 346, 1255726
Poduval, B., DeForest, C. E., Schmelz, J. T., & Pathak, S. 2013, ApJ, 765, 144
Porter, J. G., Moore, R. L., Reichmann, E. J., Engvold, O., & Harvey, K. L. 1987, ApJ, 323, 380
Reid, A., Mathioudakis, M., Kowalski, A., Doyle, J. G., & Allred, J. C. 2017, ApJ, 835, L37

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Fig. B.2. Other ALMA Band 3 counterparts of EUV brightenings. From left to right: HMI magnetogram, spectral radiance in AIA 1600 Å, AIA 304 Å, and AIA 171 Å, and ALMA 3 mm brightness temperature. All panels show a 10″×10″ FOV centered on the bright structures. The contours correspond to $T_b(3\text{ mm}) = 9$ kK. The image scale is indicated in the panels in the second column. The range in the HMI magnetograms is clipped at $\pm 0.3$ kG. The EUV images are displayed in logarithmic scale and the colormaps are individually scaled. The ALMA colorbars are in units of kilokelvin.

Rodger, A. S., Labrosse, N., Wedemeyer, S., et al. 2019, ApJ, 875, 163
Rouppe van der Voort, L., De Pontieu, B., Scharmer, G. B., et al. 2017, ApJ, 851, L6
Rutten, R. J. 2017, A&A, 598, A89
Rutten, R. J. & Rouppe van der Voort, L. H. M. 2017, A&A, 597, A138
Rutten, R. J., Vissers, G. J. M., van der Voort, L., H. M. R., Süterlin, P., & Vitas, N. 2013, Journal of Physics: Conference Series, 440, 012007
Scherrer, P. H., Schou, J., Bush, R. I., et al. 2012, Sol. Phys., 275, 207
Shibata, K. & Tanuma, S. 2001, Earth, Planets, and Space, 53, 473
Shimojo, M., Hudson, H. S., White, S. M., Bastian, T. S., & Iwai, K. 2017, ApJ, 841, L5
Simoëns, P. J. A., Reid, H. A. S., Milligan, R. O., & Fletcher, L. 2019, ApJ, 870, 114
SunPy Community, T., Mumford, S. J., Christie, S., et al. 2015, Computational Science and Discovery, 8, 014009
Syntelis, P. & Priest, E. R. 2020, ApJ, 891, 52
Tian, H., Xu, Z., He, J., & Madsen, C. 2016, ApJ, 824, 96
Tian, H., Zha, X., Peter, H., et al. 2018, ApJ, 854, 174
Torrence, C. & Compo, G. P. 1998, Bulletin of the American Meteorological Society, 79, 61
Vernazza, J. E., Avrett, E. H., & Loeser, R. 1981, ApJS, 45, 635
Vissers, G. J. M., de la Cruz Rodríguez, J., Lobjeicht, T., et al. 2019a, A&A, 627, A101
Vissers, G. J. M., Rouppe van der Voort, L. H. M., & Rutten, R. J. 2013, ApJ, 774, 32
Vissers, G. J. M., Rouppe van der Voort, L. H. M., & Rutten, R. J. 2019b, A&A, 626, A4
Vissers, G. J. M., Rouppe van der Voort, L. H. M., Rutten, R. J., Carlsson, M., & De Pontieu, B. 2015, ApJ, 812, 11
Watanabe, H., Vissers, G., Kitai, R., Rouppe van der Voort, L., & Rutten, R. J. 2011, ApJ, 736, 71
Wedemeyer, S., Bastian, T., Brajša, R., et al. 2016, Space Sci. Rev., 200, 1
Wedemeyer, S., Szydlarski, M., Jafarzadeh, S., et al. 2020, A&A, 635, A71
Wedemeyer-Böhm, S., Ludwig, H. G., Steffen, M., Leenaarts, J., & Freytag, B. 2007, A&A, 471, 977

White, S. M., Iwai, K., Phillips, N. M., et al. 2017, Sol. Phys., 292, 88
White, S. M. & Kundu, M. R. 1992, Sol. Phys., 141, 347
White, S. M., Loukitcheva, M., & Solanki, S. K. 2006, A&A, 456, 697
Wootten, A. & Thompson, A. R. 2009, IEEE Proceedings, 97, 1463
Young, P. R., Tian, H., Peter, H., et al. 2018, Space Sci. Rev., 214, 120