AN ERUPTIVE HOT-CHANNEL STRUCTURE OBSERVED AT METRIC WAVELENGTH
AS A MOVING TYPE-IV SOLAR RADIO BURST

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ABSTRACT
Hot-channel (HC) structure, observed in the high-temperature passbands of the Atmospheric Imaging Assembly/Solar Dynamic Observatory, is regarded as one candidate of coronal flux rope that is an essential element of solar eruptions. Here, we present the first radio imaging study of an HC structure in the metric wavelength. The associated radio emission manifests as a moving type-IV (t-IVm) burst. We show that the radio sources co-move outward with the HC, indicating that the t-IV emitting energetic electrons are efficiently trapped within the structure. The t-IV sources at different frequencies present no considerable spatial dispersion during the early stage of the event, while the sources spread gradually along the eruptive HC structure at later stage with significant spatial dispersion. The t-IV bursts are characterized by a relatively high brightness temperature (∼10^6–10^9 K), a moderate polarization, and a spectral shape that evolves considerably with time. This study demonstrates the possibility of imaging the eruptive HC structure at the metric wavelength and provides strong constraints on the t-IV emission mechanism, which, if understood, can be used to diagnose the essential parameters of the eruptive structure.

Key words: Sun: activity – Sun: corona – Sun: coronal mass ejections (CMEs) – Sun: radio radiation
Supporting material: animations

1. INTRODUCTION
Hot-channel (HC) structures, first observed through the high-temperature passbands at 131 and 94 Å of the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on the Solar Dynamic Observatory (SDO; Pesnell et al. 2012), are regarded as one candidate of coronal flux ropes that are the main energy carrier and one of the essential elements of solar eruptions (Cheng et al. 2011; Zhang et al. 2012). It is not or hardly present in cooler passbands of AIA such as the 211 and 171 Å, indicating its temperature is as high as 5–10 MK. The formation process and the associated heating mechanism of HCs, not resolved at this time, are likely related to some slow formation process and the associated heating mechanism of HC, indicating its temperature is as high as 5

Full text of the scientific article.
emission is responsible for the burst. This is based on the observational characteristics such as the relatively low brightness temperature ($T_B < 10^6$ K), the absence of spatial dispersion at different NRH imaging frequencies, and the power-law spectra typical for gyro-synchrotron emission. The radio sources are found to be co-spatial with an eruptive filament that may represent the core of the coronal mass ejection (CME).

Here, we show another moving t-IV burst with properties distinct from those investigated by Tun & Vourlidas (2013) and Bain et al. (2014). The burst is found to be closely associated with an eruptive HC structure, thus establishing the physical connection between the t-IV sources and the HC-flux rope, and demonstrating the possibility of imaging this essential component of solar eruptions at metric wavelength.

2. OVERVIEW OF THE EVENT: THE HC ERUPTION AND THE RADIO BURST

The eruption originated in NOAA AR11429 at the northeastern limb on 2012 March 4. See Figure 1 (and the accompanying animation) for the AIA-observed eruptive process at two hot passbands 131 and 94 Å and one cool passband 171 Å. This AR, well studied by a number of authors (e.g., Harker & Pevtsov 2013; Liu et al. 2014; Colaninno & Vourlidas 2015), is super-active releasing 15 M-class and 3 X-class flares and several CMEs during its transit across the disk from March 2 to 17. The eruption studied here is associated with an M2-class flare located at N16E65 and a halo CME propagating at an average speed of 1306 km s$^{-1}$ according to the Large Angle Spectroscopic Coronagraph (Brueckner et al. 1995) C2 data. According to the GOES SXR light curves (see Figure 2(a)), the flare started at 10:29 UT and peaked at 10:52 UT lasting for nearly two hours.

The pre-eruption structure, clearly visible from the 94 Å image in the upper panels of Figure 1 (pointed at by a pair of red arrows), starts to rise slowly at 10:27 UT, several minutes before the flare start. The structure presents a highly curved morphology writhing around the main bright loops of the AR. It has one root at the northwestern side of the AR, while the other root is unidentifiable and possibly located behind the AR. Along with its slow rise, the structure becomes clearly visible at 131 Å, yet remaining invisible at 171 Å. This indicates that the structure contains high-temperature plasmas.

Panels of Figure 1(b) present the eruptive structure. The original writhed structure evolves into a bright plasmoid connected to a co-moving faint arcade feature on its southern side that is clearly visible from the accompanying animation. The eruptive structure is best seen at 131 Å (and invisible at 171 Å), again indicating its high internal temperature. It represents an eruptive HC structure (Zhang et al. 2012), likely associated with a magnetic flux rope consisting of twisted field lines with free magnetic energy to power the subsequent solar eruption.

During the eruption, the HC gradually fades and becomes invisible around 10:45 UT, while at its northwestern foot there appears an obvious dimming region (see green arrows in Figure 1(c)). This indicates that the dimming is due to an evacuation of plasmas. The dimming region is surrounded by a narrow layer of brightenings that evolves dynamically and expands slowly toward the northwestern direction during the eruption. The brightening layer is likely attributed to the dissipation of currents (or magnetic reconnection) at the interface of the HC and the surrounding magnetic field.

In Figure 2(a), we also present the Fermi Gamma-ray Burst Monitor (GBM; Meegan et al. 2009) data at three energy bands. This is to show the presence of HXR-emitting non-thermal electrons, as well as the timing of the flare. In Figures 2(b)–(c), we show distance–time maps along slice S1 (see Figure 1(b)), which corresponds to the outward moving direction of the plasmoid of the HC. The overlying arcade that has been pushed outward by the HC (see black arrows in Figure 1) is clearly visible in the S1-171 Å map. The motion of the plasmoid can be separated into a slow rise stage at a speed of 72 km s$^{-1}$ and an eruptive stage at 367 km s$^{-1}$, while the overlying 171 Å arcade expands at slightly smaller speeds of 56 and 335 km s$^{-1}$ (along S1), according to the height measurements and linear fittings. This is in line with the suggestion that the eruption is driven by the HC structure.

On the other hand, the accompanying radio burst was recorded by the Artemis radio spectrograph (Kontogeorgos et al. 2006) and imaged by the NRH. From the spectra shown in Figure 3(a), we see a wide-band continuum emission from 200 to 20 MHz (10:38–11:00 UT). The spectra present a trend of downward drift with time. A data gap exists from 110 to 90 MHz. It looks like the radio burst continues after the gap until the frequency reaches the lower spectral end ($\sim$20–30 MHz).

The high-frequency counterpart of the radio burst is not clear possibly due to the low sensitivity of the Artemis instrument as well as the strong radio interference. Yet, according to the much more sensitive measurements of NRH, there exist weaker yet significant emissions from 150 to 445 MHz. From Figure 3, we see that the maximum intensity of these emissions is higher at lower frequencies, reaching 100 sfu at 445 MHz and 1200 sfu at 150 MHz. The burst at 445 MHz, the highest NRH observing frequency, starts around 10:34 UT, and lasts for 15 minutes. At lower NRH frequencies, the starting and peak times are delayed, and the duration becomes longer reaching 25 minutes for 150 MHz. This is in general consistent with the characteristics of a broadband emission that drifts toward lower frequency. Therefore, we conclude that the radio burst, starting from around 10:34 UT (at 445 MHz) and drifting to lower frequencies, represents a t-IVm event.

The temporal evolution of the polarization levels of the t-IVm burst is shown in Figures 3(d) and (e), which are calculated as the ratio of the sum of Stokes-V over the sum of Stokes-I within the region defined by the contour level of 95% of the maximum $T_B$ in each NRH image. We see that the polarization levels vary significantly, being left-handed at earlier stage (before 10:42 UT), becoming right-handed and increasing gradually later, up to values $\sim$10%–20% for 150 MHz and 50% for 327 MHz ($\sim$40% for 445 MHz) at 10:44 UT. The emission spectra given by the total flux intensities at different NRH frequencies are shown in Figure 3(f) during the t-IVm. The spectra are generally power-law like with a spectral index varying from $-1$ to $-3$. The spectral shape varies considerably with time.

The corresponding $T_B$ images can be viewed from Figure 4 and the accompanying animation. The t-IVm sources can be identified through all NRH channels, consistent with the broadband continuum characteristic. The $T_B$ maximum ($T_{B\text{max}}$)
reaches higher values at lower frequencies, being $\sim 10^7$, $10^8$, and $10^9$ K at 432, 360, and 150 MHz, respectively. These high $T_B$ values are important to further infer the emitting mechanism. From 10:39 to 10:43 UT the sources move outward (along with the plasmoid, see below). They disappear earlier and reach lower altitude at higher frequency. In general, lower-frequency sources have higher $T_B$, consistent with the above description of the radio fluxes and the power-law like spectra. The NRH imaging data show a continuous motion and transition of radio sources from high to low frequencies, supporting the above conclusion that the t-IVm burst contains a high-frequency (200–445 MHz) component.

3. CORRELATION OF THE RADIO SOURCES AND THE ERUPTIVE HC STRUCTURE

In this section, we further examine the spatial correlation of the radio burst and the eruptive structure. To do this, in Figure 5, we plot the contour levels at 95% of $T_{B_{\text{max}}}$ at different frequencies of a certain time together and superpose them onto the closest AIA 131 Å images. The sources can be roughly separated into two groups. The first group of sources, at higher NRH frequencies (445–360 MHz), line up together on the northern side of the dimming HC foot region without considerable motion. This group does not belong to the t-IVm burst of study. The other group of sources, observable at

Figure 1. HC eruption recorded by AIA at 131, 94, and 171 Å at (a) 10:33 UT (to show the slowly rising HC; red arrows), (b) 10:40 UT (to show the eruptive plasmoid-HC structure; white arrows), and (c) 10:46 UT (to show the dimming foot region; green arrows). S1 is for the distance maps shown in Figure 2. An accompanying animation of both direct and base difference images is available. (An animation of this figure is available.)
The direction angle of the n2 detector to the Sun is stable and around 60°. The two vertical lines indicate the flare start (10:29) and peak (10:52) time. (b)–(c) Distance–time maps along the slice S1 observed at AIA 131 and 171 Å. The velocities are given by linear fitting. Red vertical lines in panel (b) represent the NRH source positions given by the 95% \( R_{\text{max}} \) contour levels at 228 MHz.

4. DISCUSSION

With the above analysis, we present strong evidence of the HC being the t-IVm emitting structure. According to the GBM data presented in Figure 2(a) at 27.3–50.9 keV, the HXR-emitting nonthermal electrons are present from 10:30 to 10:50 UT. During this interval, the plasmoid forms and erupts, likely a result of the flare reconnection, which may contain the most twisted magnetic field lines within the HC structure. This makes it an efficient trap of flare-injected energetic electrons, as inferred from the t-IVm sources being spatially correlated with the plasmoid at the earlier stage. Along with the upward eruption, the HC plasmoid may get untwisted to gradually release the confinement. This allows the electrons to spread over a larger section of the structure along its side arcade, as has been manifested by the spatially dispersed radio sources in Figure 5(b).

Note that the CME structures have been imaged at the radio wavelength in earlier studies. Bastian et al. (2001) proposed the radio CME concept by investigating one specific event, in which the radio sources present an expanding loop shape. Later studies (Maia et al. 2007; Démoulin et al. 2012) present another event with similar characteristics, and claim that the radio sources correspond to the CME cavity. The sources in these...
two events are co-spatial at different frequencies, with a large spatial extension (several solar radii), a relatively low $T_B$ ($\leq 10^6$ K), and a power-law spectra of radio fluxes. Based on these observations, they suggest that the bursts are given by the incoherent synchrotron emission mechanism. Similar observational characteristics are obtained for the latest imaging studies on a t-IVm burst combining the NRH and AIA data (Tun & Vourlidas 2013; Bain et al. 2014), as introduced earlier. They conclude that the t-IVm burst is given by the gyro-synchrotron emission.

Here, we find very different characteristics. First, the radio sources at different frequencies are initially co-spatial with each other, yet later they spread across the emitting structure and get spatially dispersed with an organized pattern. Each source occupies a relatively small part, and together they delineate a larger section of the structure. The $T_B$ is much higher than reported by those studies (consistent with some other earlier observations on the t-IVm radio bursts; Stewart et al. 1978; Duncan et al. 1980). Therefore, we suggest that our event points to a different emitting mechanism, possibly a coherent one to account for the high $T_B$. Since the radio bursts here are constrained to certain specific part of the HC, they should be attributed to energetic electrons trapped therein. This means that the classical plasma emission mechanism induced by fast electron beams propagating in background plasmas may not play a role here.

Another coherent emission mechanism that is associated with trapped electrons is the electron maser cyclotron emission, developed when electrons are lost from the trap to form a positive gradient of the velocity distribution function along the perpendicular direction in the velocity phase space (Wu & Lee 1979). Earlier studies have used this mechanism to explain continuum radio bursts such as the t-IV burst (Lakhina & Buti 1985; Winglee & Dulk 1986). Yet, further studies are required to check whether this mechanism can properly account for the radio characteristics reported here.

Our study presents that the t-IVm sources are carried by the plasmoid-HC structure. Such structure is of high temperature, and not observable with earlier solar imaging instruments. It is therefore not known whether such structure is present in those earlier events.
The polarization data in our event present a change of handed sense. Since the polarization levels are strongly affected by the angle between the magnetic field and the wave vector, we tentatively attribute this observation to the presumed untwisting motion of the HC, which likely results in some rotation of the magnetic structure.

The last point of discussion is relevant to the ionospheric effect on source positions. First, the significance of this effect declines with increasing frequency (Wild et al. 1959; Bougeret 1981). At frequencies above 150 MHz the effect is generally small. Second, from the NRH animation accompanying Figure 4, the positional fluctuation of radio sources is not important in comparison to the overall motion of the sources, indicating that the effect of ionospheric irregularities is relatively weak. Finally, in this event, the radio sources, with an overall outward propagation, first concentrate around the plasmoid and then get scattered gradually along the HC side structure. This pattern is consistent with the eruption of the HC and not likely caused by the ionospheric effect, which tends to result in systematic position shift of sources at different frequencies. We therefore suggest that the ionospheric effect does not affect the result of this study.

Figure 4. NRH images at different frequencies at 10:40 UT. The contour levels represent 85%, 90%, and 95% of $T_{\text{Bmax}}$. The location of the HC plasmoid observed by AIA at the same time is denoted with a red ellipse. (An animation of this figure is available.)
5. SUMMARY

This study demonstrates that the AIA-observed eruptive HC structure can be imaged with the NRH at various metric wavelengths in the form of a t-IVm burst. The radio sources at different frequencies are found to be co-spatial with the moving HC structure. Initially, the sources are constrained at the plasmoid that is at the top front of the HC. Then, the sources at different frequencies spread across the structure to a larger region and line up across the HC side arcade. Other characteristics include a relatively high brightness temperature (∼10^7–10^9 K), a moderate polarization with a change of the handed sense, and a power-law-like spectral shape that evolves considerably with time. Preliminary discussion on the possible emitting mechanism has been presented, and more studies are required to further explore the diagnostic potential of this kind of event to infer the critical parameters/conditions of the eruptive structure.

We thank the Artemis, NRH, STEREO, SDO, and SOHO teams for providing the data. We also thank Dr. Koval and Dr. Hillaris for their help in plotting the dynamic spectrum. This work was supported by grants NNSFC 41274175, 41331068, and U1431103, and NSBRSF 2012CB825601.
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