Identification of a peculiar radio source in the aftermath of large coronal mass ejection events.

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ABSTRACT

We report the discovery of a new radio feature associated with coronal mass ejection (CME) events. The feature is a low frequency (< 1 MHz), relatively wide (~ 300 kHz) continuum that appears just after the main phase of the eruptive event, lasts for several hours, and exhibits a slow negative frequency drift. So far, we have identified this radio signature in a handful of CME events and suspect it might be a common occurrence. The radio continuum starts almost simultaneously with the commonly observed decimetric type-IV stationary continuum (also called flare-continuum) but the two seem unrelated. The emission mechanism, whether plasma emission or gyroresonance, is unclear at the moment. Based on our preliminary analysis, we interpret this radio continuum as the lateral interaction of the CME with magnetic structures. Another possibility is that this continuum traces the reconfiguration of large-scale loop systems, such as streamers. In other words, it could be the large-scale counterpart of the post-CME arcades seen over active region neutral lines after big CME events. This letter aims to bring attention to this feature and attract more research into its nature.

Subject headings: Sun: activity – Sun: corona – Sun: coronal mass ejections – Sun: radio radiation

1. Introduction

One of the first applications of radio astronomy have been observations of emissions from solar eruptive phenomena in the late 1940s using spectral receivers. Due to the Sun's strong radio signal and the relative simplicity of the receivers, many solar radio spectrographs have been built around the world since. These instruments have accumulated a large body of observations on solar emissions which are commonly categorized within a small set of burst types based on their spectral morphology (Kundu 1965). Some of the bursts are usually associated with electrons escaping the Sun (e.g., type II and III bursts) while other bursts are stationary, usually appearing above active regions (e.g., type I) or more often above flaring sites where reconnection might be taking place (e.g., type-IV bursts). After the flare episode has taken place, energetic electrons produce type IV radio bursts which are usually intense broadband continua, last several hours and follow an evolution similar to the soft X-ray flare. Traditionally, these radio emissions have been called stationary type IV bursts (or *storm continua*). These emissions are associated with eruptive, long duration flares which, in turn, are almost exclusively associated with CMEs. Radio imaging reveals that the sources of these continua are located above the post-CME loops seen in the EUV or soft X-ray observations and therefore appear in the aftermath of CMEs. These emissions do not usually attract particular attention since they tend to arise after the main phase of the eruption, they are relatively stable and their origin seems to be well-understood. However, in some events there is a similar but previously unnoticed low frequency continuum, which is the focus of this paper.

Here, we report the observation of an unsual pair of long duration (several hours long) radio emissions that occurred on 24 September 2001 during a CME event, and despite being separated by widely different frequencies, they have very similar temporal and spectral profiles. To the best of our knowledge, it is the first time that this type of radio emission is reported. We believe that such emission might be common during the post-CME phase of strong radio events and it might reveal important information about the reconfiguration of the corona after a CME. We use the radio data from the Nançay decameter (DAM) array (Lecacheux 2000) and the WAVES radio instrument aboard the Wind spacecraft (Bougeret et al. 1995) stationed at the time in the solar wind. So far, we have indications that this phenomenon is present during large and fast CME events associated with particle events.

This letter aims to make the community aware of this radio phenomenon in the hope that it encourages further research in the area. The paper gives a description of the observations for the 24 September 2001 event and ends with a discussion about the possible origin of this emission. A brief analysis of this event was reported by Lario & Pick (2006) with focus on the associated SEP event.

2. Observations

The activity was associated with an X2.6 flare at S16E23 starting at 09:32 UT, peaking at 10:38 UT and ending at 11:09 UT. Figure 1 shows a combined plot of the radio spectra obtained by DAM and WIND/WAVES. This plot shows two successive groups of bursts followed by a pair of long duration continua which occur in two discrete frequency ranges: the first one is a broad frequency radio continuum, extending from frequencies > 70 MHz (observed by the Nançay radioheliograph, NRH (Kerdraon & Delouis 1997)) to about 10 MHz; the second one is a weak continuum which is detected in the range 1-0.1 MHz and drifts slowly toward lower frequencies down to below 100 kHz lasting for more than a day. This feature has a bandwidth of about 300 kHz. There is a definitive gap between the two continua which are separated by a factor ≈ 80 in frequency that makes it clear that the WAVES continuum emission is not the low frequency extension of the high frequency continuum.

The first group of bursts, mainly type III emission, corresponds to the precursor phase. During the same period a considerable outflow was detected above the active region by both EIT and LASCO instruments on SOHO. Transient EUV brightenings were also observed in the locations labelled A and B. This is illustrated in the top panel of Figure 2. The main event started at about 10:13 UT as a rapid enhancement of the radio emission and displayed all the characteristics of an intense complex type III-like emission as defined by Reiner & Kaiser (1999). This outburst was associated with a type II burst (seen between 10 and 1 MHz in Figure 1 from $\sim 10:30$ to 12:00 UT) and with a major flare/CME event, as usually for this class of events. The CME front first appeared at a height of 3.3 R_{odot} in the LASCO images at 10:33 UT and the last measurement was taken at a height of 25.4 R_{odot} at 12:18 UT. The estimated projected speed of the CME was 2400 km/sec. The flanks of the CME expanded rapidly in longitude and in latitude, and towards the North disturbed a bright streamer at about 30° from solar North (Figure 3).

To investigate the origin of the pair of long duration continua, we used the imaging data from the NRH in combination with the direction-finding capabilities on the WAVES radio instrument (Hoang et al. 1998) in the range below 1MHz. In Figure 4, we plot the results for three frequencies (740, 624, and 428 kHz) within the passband of the low frequency continuum. The figure includes the full history of the event, from the precursor phase (starting around 9:30 UT) extending to several hours in the post-CME phase, as can be seen in the flux history (upper panel). The other two panels show the azimuth (relative to the Sun-spacecraft line) and elevation (relative to the ecliptic plane) of the centroid of the emission at each observed frequency.

From the onset of the event up to about 10:30 UT, the emission (predominantly type III

bursts) comes from the ecliptic plane and from the East (see left upper panel). Then after that time, the type III bursts and the low frequency continuum originate from close to the Sun center (see azimuth plots). The onset of the continuum is masked by the predominant type III burst emission. The continuum is first stationary in position and then shows a strong northward drift that reaches 20-40 degrees above the ecliptic by 15:00 UT. Figure 4 shows that the onset of this drift appears progressively later with decreasing frequencies. At the same time, radio imaging from the NRH shows that the higher frequency continuum is associated with a stationary source above the post-eruptive loops in the active region as expected for this type of emission. This difference in location is another evidence that the two continua are distinct. The northward motion seen in the low frequency continuum suggests that its source was located somewhere to the north of the active region and is undergoing evolution over several hours. If the emission mechanism of the low frequency continuum is plasma emission then the source should have a lower density than the continuum source detected at higher frequency.

3. Origin of the low-frequency continuum emission

To understand the origin of the low frequency continuum we need to locate its solar source region and identify the emission mechanism. The location cannot be pinpointed with accuracy because imaging observations below about 100 MHz are nonexistent. But we can make some inferences about it using other means.

Figure 2 (bottom panel) displays the magnetic field configuration derived by applying a potential field source surface (PFSS) extrapolation to magnetograph measurements of the photospheric field (Schrijver & Derosa 2003). The extrapolation reveals large transequatorial loop systems linking the flaring active region to regions in the north which are likely associated with the CME and its aftermath as most of the EUV activity is located under them (e.g., sources A and B in Figure 2, top panel). These loop systems are the most probable site of the radio emission because: (i) they are the dominant connection between the flaring region in the south and the northern active latitudes, (ii) the loops have a similar orientation to the northward positional drift of the low frequency continuum source and, (iii) correspond to the same range of longitude.

Finally, the frequency drift towards lower frequencies is an important piece of information but we first need to know the emission mechanism to make use of it. If we assume a plasma emission, which is the mechanism regularly invoked for the higher frequency continua, the emission arises at the local plasma frequency f_p of a given layer of the atmosphere which relates to the local electron density, n_e, as $f_p \approx 9n_e^{1/2}$ with f_p(kHz) and n_e (cm^{-3}).

The negative frequency drift of the source spectrum (Figure 1) implies that the density in the source is decreasing with time. In other words, the emission should originate in larger loops with time, plausibly expanding loops. To estimate the height of the radio emission, we have to adopt a coronal density model. In this case, the model of Leblanc, Dulk, and Bougeret (1998) is the most appropriate because it was derived from Waves observations of type III bursts covering the same frequency range as our event. By assuming that the emission is at the first harmonic, we derive an altitude of ~ 6.3 $R_\odot$ for the emission at 1 MHz, near its onset (10:50 UT) which is close to the (albeit projected) CME front (7 R_{odot}) at that height, and 13.4 $R_\odot$ when the emission drifted down to 400 kHz at 16:00 UT. The implied expansion speed is about 390 km/s. Since we do not know how well the density model affects our estimates, we repeat these calculations for a 0.5x and 2x model cases. The derived heights are then 5 and 8 R_{odot} (1 MHz) and, 10 and 18.6 R_{odot} (400 MHz), respectively. The expansion speeds become 242 and 512 km/s for these model choices. In all cases, the drifting of the radio emission is slower than typical type-II speeds and much slower than the CME itself (2400 km/s). It is clear that the radio emission is occuring at the aftermath of the main event. We emphasize that these values should be taken with caution as it is very unlikely that stable closed loops can exist at these heights. The density model, which corresponds to a stable corona, is approximative in the context of a CME.

From the above, several scenarios can be envisioned, and we propose two below. A first one is the lateral interaction of the CME with the northward loops (Figure 2), as well as, at larger altitude, with the streamer which overlies above them. We know from the coronagraph measurements (Figure 3) that most, if not all, of the CME material escapes along the southeast direction and only the CME wave is propagating along the northern direction. Then, in its initial stages, the CME would first interact with the open field lines shown in the extrapolation and possibly cause the early type-III bursts. The continuing lateral expansion of the CME wave would then lead to compression of the northward magnetic structures which in turn could launch a magnetosonic wave along their overlying streamer. This wave could be the source of the low frequency continuum and could explain its relatively low speed ($\approx$ 390 km/s), and its presence to large distances. The northward drift of the continuum would occur as a projection effect since the interacting structures are northward of the CME.

The second scenario takes into account the similarities between the two continua, so the low frequency continuum can also be interpreted as radio emission in relaxing post-CME loops. Initially, the large transequatorial loop system is destabilized by the CME passage, say, by magnetic interaction between the expanding CME and these neighbouring loops. The activity in source B (Figure 2) might be evidence of that. Such destabilization of transequatorial loops has been proposed also by Delannée & Aulanier (1999) to explain the

appearance of a large transequatorial dimming in another event. After the passage of the CME, the transequatorial system returns to its original configuration by slowly reforming its loops. In other words, we suggest that while the high-frequency source is originating over the "active region-scale" post-CME loops, the low-frequency source is occurring over a similar post-CME loop system which is forming over a much larger transequatorial-scale area. Since the latter post-CME loops are much longer than those over the active region, they should also have lower densities (hence the low-frequency source); and because the candidate loops system connects the flaring active region to northern latitudes, we expect a northward location for the radio source (as observed).

We believe that this is not an unlikely scenario. The large amount of CME research over the last 10 years has shown that the CME is not simply a local eruption over an active region but it involves the opening of the magnetic field over a considerable part of the solar corona (Maia et al. 2001). Streamer blowout events, where the whole streamer disappears during the eruption and reappears within a few hours, are an extreme example of this large scale coronal reconfiguration (Vourlidas et al. 2001). It is natural to expect that post-CME loops will form not only over the source active region but also over any other preexisting loop system which is destabilized by the CME. It may, therefore, be that our detection of these low frequency continua is the first observation of this process. The main difficulty with this scenario is the large distances ($\geq 6-19$ $R_\odot$) estimated above with the plasma frequency (this applies also for gyrosynchroton emission since the emission should be above the local plasma frequency. However the static density model used above is questionable in a CME region. Indeed, during a CME, coronal plasma is launched away, creating a time-dependent underdense region behind. It is not unreasonable to expect depletions of a factor of 10 or more compared to the quiet corona. Then it is plausible that the low frequency continuum originates from lower altitudes than derived above.

Finally, it is worth mentioning that the signature of the low frequency continuum is especially clear in the September 24, 2001 event. In most of the other events we have examined, the continuum is masked by successive type IIIs and other activity (as in the case of the October 28, 2003 which we do not report here). This might be the reason it was noticed earlier. Also, we cannot exclude the possibility that the emission mechanism of the low-frequency source is not plasma emission, but gyrosynchrontron from nonthermal electrons.

Our intent with this Letter, is to bring attention to the low frequency radio feature and its relation with large CME events. Although, we present only one example in detail due to space considerations, we plan to analyse several other events to establish how common is this radio source. The Waves event catalogue (lep694.gsfc.nasa.gov/waves/waves.html) is a

good starting point as it includes many examples of such drifting continuua. We also plan to use extrapolations of the large scale magnetic field and direction-finding techniques to see whether large-scale loops exist at the proper locations to account for the observed source centroid location and drift. We underline that, for many events, it is difficult to follow the evolution of the low frequency continuum because of the superposition in the spectrum of other types of emission.

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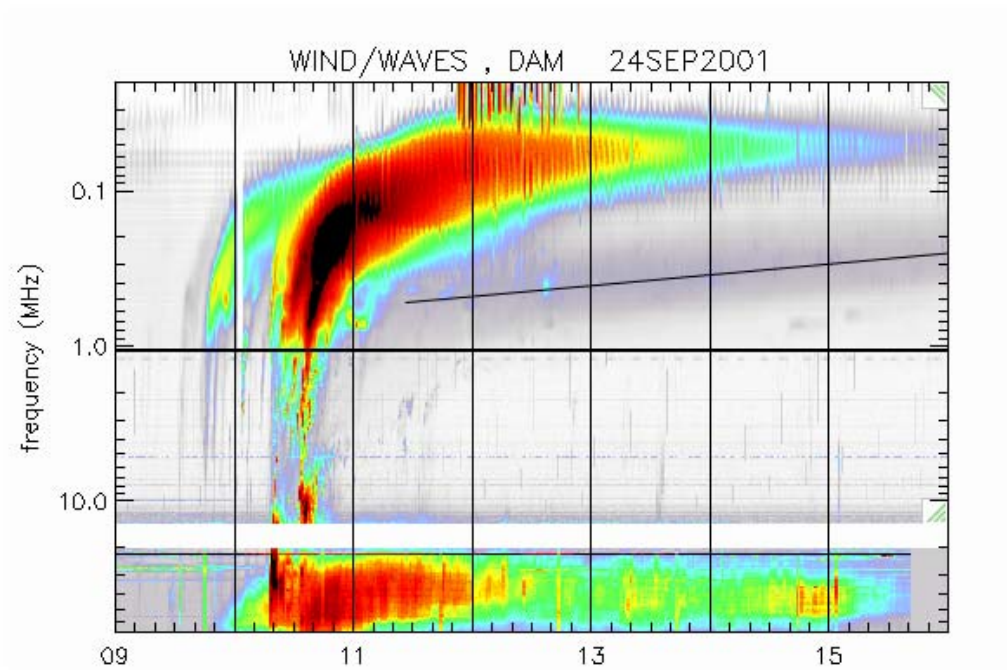

Fig. 1.— Combined radio spectrum of the Sep 24, 2001 event using DAM (between 20-70 MHz) and WAVES (<14 MHz). Both the high and low frequency continua are clearly visible on this plot. The black line is hand-drawn to approximately indicate the frequency drift of the low frequency continuum.

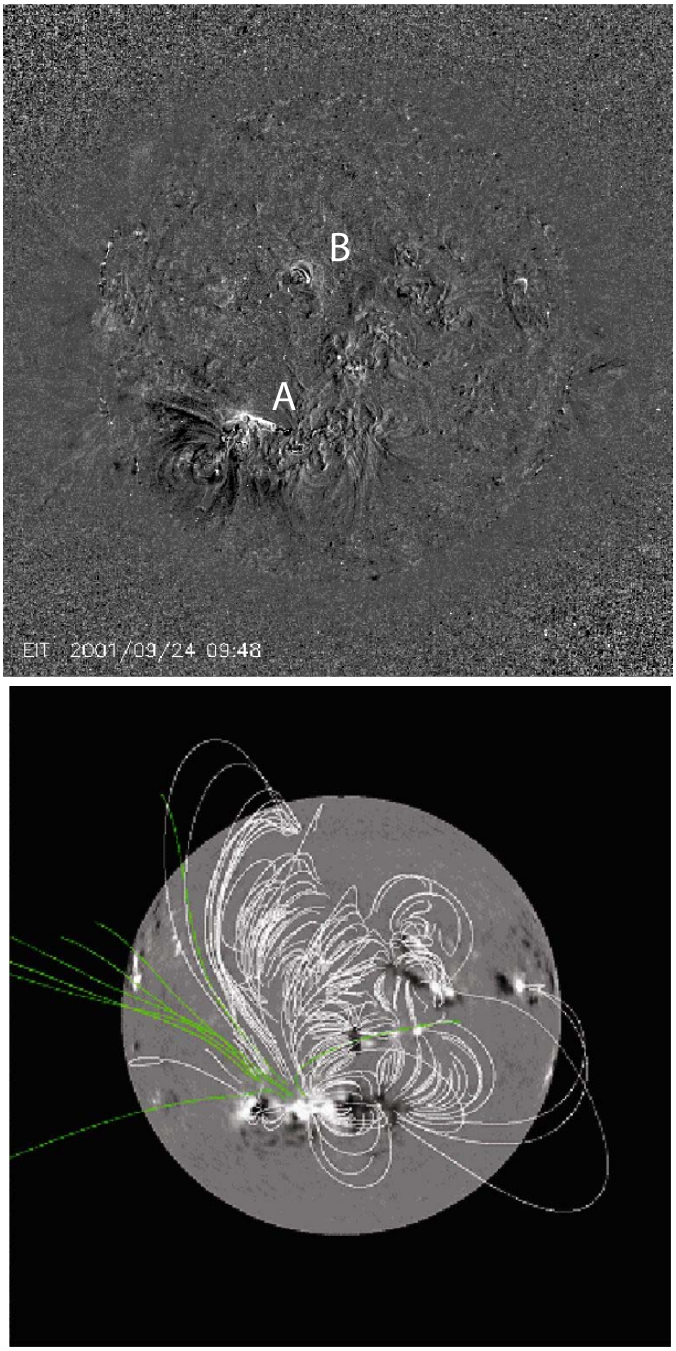

Fig. 2.— The upper panel displays an EIT difference image during the precursor phase of the September 24, 2001 event; the letters A and B indicate the location of the brightenings. The lower panel shows the magnetic field configuration above the active region derived by applying a potential source-surface extrapolation to magnetograph measurements of the photospheric field.

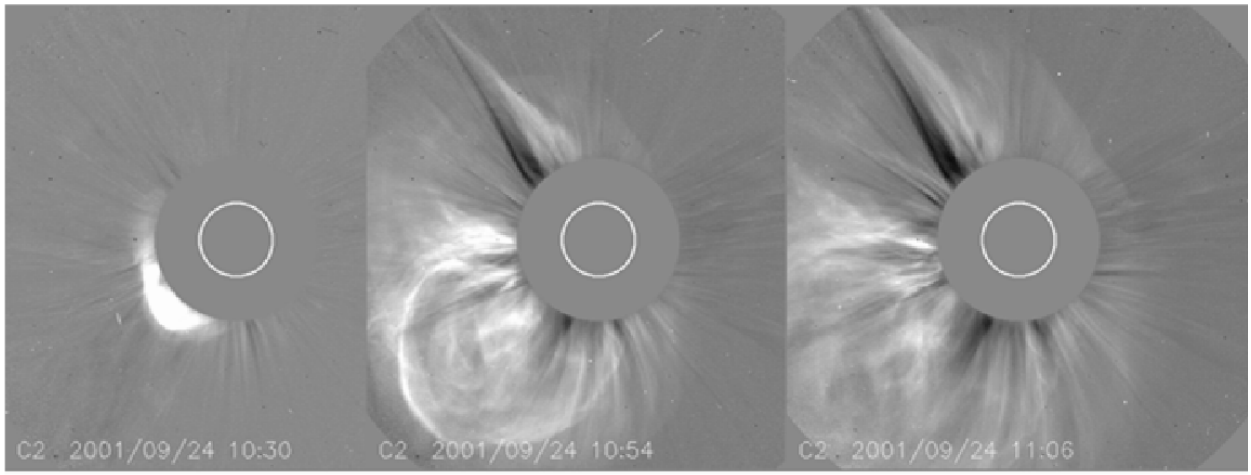

Fig. 3.— LASCO C2 observations of the September 24, 2001 CME.

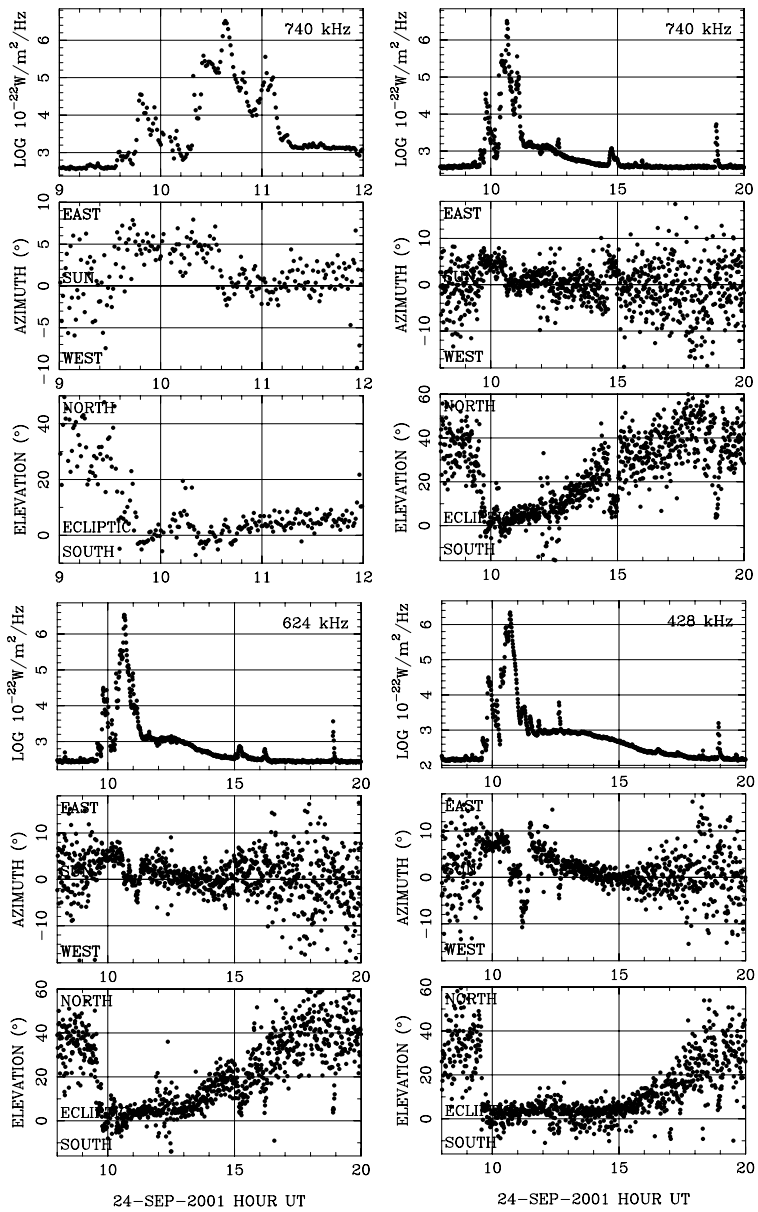

Fig. 4.— WAVES direction-finding for the event on September 24, 2001. The plots show the flux density, azimuth and elevation of the radio source for three frequencies; 740 kHz (top, with two time scales), 624 kHz (bottom left) and 428 kHz (bottom right). The data suggest that the continuum source drifts from the equator towards higher elevation, reaching almost 40° North within 3 hours from the CME onset. These data illustrate the evolution with frequency of the continuum onset time. The few bursts which appear during the progression of the continuum originate from a different direction and are unrelated.