A Solar Stationary Type IV Radio Burst and Its Radiation Mechanism

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Abstract A stationary Type IV (IVs) radio burst was observed on September 24, 2011. Observations from the Nançay RadioHeliograph (NRH) show that the brightness temperature ($T_B$) of this burst is extremely high, over $10^{11}$ K at 150 MHz and over $10^8$ K in general. The degree of circular polarization ($q$) is between $-60\% \sim -100\%$, which means that it is highly left-handed circularly polarized. The flux–frequency spectrum follows a power-law distribution, and the spectral index is considered to be roughly $-3 \sim -4$ throughout the IVs. Radio sources of this event are located in the wake of the coronal mass ejection and are spatially dispersed. They line up to present a formation in which lower-frequency sources are higher. Based on these observations, it is suggested that the IVs was generated through electron cyclotron maser emission.

Keywords Radio bursts, Type IV · Radio emission, theory

1. Introduction

Solar radio bursts represent the phenomenon of temporary and intense increases of emissivity in the solar radio dynamic spectrum. They are categorized into five main types according to their spectral appearances: Type I, Type II, Type III, Type IV, and Type V radio bursts. Most of them are closely related to solar eruptions such as coronal mass ejections (CMEs)
and solar flares (McLean, 1985; Cho et al., 2011; Reid and Kontar, 2013; Chen et al., 2014; Feng et al., 2015). Of the five types of solar radio bursts, a Type IV radio burst is the broadband continuum emission in metric wavelength that usually lasts for a relatively long time (> 10 minutes) (Pick, 1963). Type IV radio bursts can be divided into two sub-categories: moving Type IV bursts (IVm), and stationary Type IV bursts (IVs) (Kundu, 1965). The difference between IVm and IVs is that IVm shows an obvious frequency drift, while IVs does not, which means that the radio source of IVm moves outward from the Sun, while IVs is stationary (Pick, 1986). The source region of IVs usually coincides with the top of solar flare loops or the lower part of open field lines (Robinson 1985; Figure 15.10). In the former case, energetic particles trapped in high magnetic arches emit radiation, and in the latter case, energetic particles propagating along open or large-scale closed field lines dominate (Robinson, 1985).

Until now, four types of radiation mechanisms have been proposed to interpret Type IV radio bursts. These are synchrotron emission (Boischot, 1957), gyrosynchrotron emission (Kai, 1969; Carley et al., 2017), plasma emission (Duncan, 1981; Hariharan et al., 2016), and electron cyclotron maser (ECM) emission or ECM instability (Melrose and Dulk, 1982; Chernov et al., 1998). Of these mechanisms, gyrosynchrotron and synchrotron radiations are incoherent emission mechanisms, while plasma radiation and ECM emission are coherent mechanisms.

It has been highly debated whether IVm is generated by gyrosynchrotron radiation, plasma emission, or the ECM emission. For example, based on observations made with the Nançay RadioHeliograph (NRH), Vasanth et al. (2016) tentatively suggested that the ECM mechanism may account for the IVm. However, Carley et al. (2017) examined another event and proposed that gyrosynchrotron emission might be responsible for IVm. IVm has a large range of brightness temperatures, from as low as 10^6 K to as high as 10^{13} K (Duncan, Stewart, and Nelson, 1980). The degree of circular polarization (q) can be any value (0% ~ ±100%). In contrast, the brightness temperature of IVs is usually higher than or near 10^9 K, and it is highly polarized with |q| near ±100% (Dulk, 1985). Therefore, IVs events are usually thought to be generated by a fundamental plasma emission process (Melrose, 1975). Twiss (1958) was the first to suggest a possible ECM process to directly amplify the EM waves near the electron cyclotron frequency. Later on, Wu and Lee (1979) made significant contributions by assuming a loss-cone distribution of energetic electrons with ∂f/∂v⊥ > 0, and by considering the relativistic effect on the instability, which made it physically possible to interpret solar radio bursts. We note that ECM emission has been proposed to explain IVs, in other words, the long-duration Type IV continuum (Winglee and Dulk, 1986).

Although IVm has recently been studied by numerous authors (Tun and Vourlidas, 2013; Bain et al., 2014; Vasanth et al., 2016; Carley et al., 2017), IVs has rarely been reported. Koval et al. (2016) observed a IVs with a brightness temperature (TB) near 10^9 K. The source region was claimed to be a “single high-lying loop” with one foot located near the active region from which the CME appeared. The detailed radiation mechanism was not analyzed. Our study here is distinct from that of Koval et al. (2016). A IVs on September 24, 2011 is studied here. The observational data are presented in Section 2. From the NRH and SDO/AIA overplotted images, we report that the IVs is generated in the wake of a CME. In Section 3, we focus on physical parameters of the IVs event, including TB, the degree of circular polarization (q), and spectral index (α). In the final section, we briefly review all possible radiation mechanisms and suggest that the IVs is generated through ECM emission.
2. Observations and Data Analysis

A stationary Type IV radio burst appeared at 12:40 UT on September 24, 2011. We retrieved data from Bleien Observatory (BLEN7M) and from Sagamore Hill Observatory (SGMR) from 12:15 UT to 14:30 UT and plotted them together, as shown in Figure 1. The frequency of the Type IV burst spans from 25 MHz to 450 MHz. Before the IVs, an M7.1 class flare occurs in Active Region 11302 at 12:33 UT, and the flare peaks at 13:17 UT. A CME was observed in LASCO-C2 images at 12:48 UT (Figure 2). From the solar radio spectrum, a decimetric flare continuum is visible, which appeared around 13:00 UT. In order to reduce the influence of the decimetric flare continuum on the Type IV study in our work, only the data recorded before 13:05 UT are analyzed.

Figure 1 shows that the frequency drift is not obvious in the spectrum. It is thus hard to tell whether this Type IV is IVs or IVm. This is also partly due to the interference from the flare continuum. Such a long duration and the relatively weak frequency drift seem to favor a burst of IVs. In order to make it clearer and to have a general understanding of the source region, we resort to data from the Nançay RadioHeliograph (NRH).\(^1\) NRH consists of a T-shaped array of antennas. It can provide brightness temperature, Stokes V and I, and flux

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\(^1\) Sources at [http://secchirh.obspm.fr/nrh_data.php](http://secchirh.obspm.fr/nrh_data.php).
data of up to ten frequencies within the range of 150 MHz \sim 445 MHz. The time cadence is 5 ms, and the spatial resolution is 0.3 \sim 6 \text{ arcmin}, depending on the observing frequency (Kerdraon and Delouis, 1997). We only used integrated 1 s data.

We carefully examined the images of several SDO/AIA wavelengths and multi-frequency NRH radio sources from 12:30 UT to 13:10 UT. A contour of 95\% of the maximum intensity is drawn for NRH sources. After checking all data, we present NRH and AIA 131 Å overplotted images in Figure 3. From an animation of the data, it is noted that the radio sources remain stationary throughout the Type IV radio burst, making it a IVs. The radio sources of all ten NRH frequencies line up very well, stretching from the lower flaring site to the higher corona. As we have stated in the introduction, earlier studies have shown that there are two main types of source regions of IVs; one is the top of solar flare loops, and the other is the lower part of open field lines (Robinson 1985; Figure 15.10). After we compared the observed radio sources with Figure 15.10 presented by Robinson (1985), it seems likely that the field line carrying the radio sources is an open or a section of a large-scale closed loop-like structure. We checked all relevant AIA data and did not observe a clear loop structure cospatial with the radio sources. It should be noted that some coronal loops are too weak in emissivity to be observable.

3. Properties of the IVs Burst

The maximum $T_B$s observed at NRH frequencies and their time dependencies are plotted in Figure 4(a). An average $T_B$ of all pixels within the 95\% maximum contour is presented.
Figure 4  (a) Brightness temperatures of NRH frequencies from 12:35 UT to 13:05 UT on September 24, 2011.  (b) Degrees of circular polarization ($q$) of NRH frequencies from 12:35 UT to 13:05 UT. The starting time of the Type IV (12:40 UT) and the starting time of the flare continuum (13:00 UT) are shown as dashed lines. To minimize errors, we use an average value of all pixels within the 95% maximum contour shown in Figure 3. GOES X-ray data are also plotted in the lower panels to compare changes of the parameters and X-ray flare flux profile.

here. The maximum $T_B$s at all frequencies are above $10^8$ K. The maximum $T_B$ at 150 MHz even exceeds $10^{11}$ K for several minutes. We also note that the higher the frequency, the lower the $T_B$. From around 12:58 UT, $T_B$s at high frequencies start to rise to higher values. A rise of high-frequency (445 MHz, 360 MHz) $T_B$s at 12:58 UT marks the appearance of the decimetric flare continuum.

The degree of circular polarization ($q$) is defined by the Stokes $V$ component over the Stokes $I$ component as follows:

$$q = \frac{V}{I}. \quad (1)$$

The time dependence of the degree of circular polarization is plotted in Figure 4(b). We also use the average $q$ of all pixels within the 95% maximum contour. Throughout the Type IV radio burst, $|q|$ remains steady at a very high value of 60% $\sim$ 100% for all frequencies, as shown in Figure 4(b). At the same time, $q$ is negative, which means left-handed circular polarization. This high degree of circular polarization matches the common features of IVs, but gives more constraints on the radiation mechanism of this event.

Using NRH data, we also plotted the flux–frequency spectrum for every minute from 12:40 UT until 13:00 UT, as shown in Figure 5. The spectral index is given by the slope of the flux intensity (in units of solar flux) in log scale. From 12:42 UT to 12:58 UT, the spectrum can be well fitted by a power-law distribution. During the IVs, the spectral index ranges from $-3$ to $-4$, as shown in Figure 6. From around 12:58 UT, the spectral index starts to change considerably, which indicates the appearance of the decimetric flare continuum. There are outliers at the beginning of the event (from 12:40 UT to 12:42 UT). We do not consider them in the following analysis since the IVs has just started and has not been fully developed. We conclude that the flux during the IVs is well fit by a power-law spectrum.
4. Radiation Mechanism

As mentioned in the introduction, four different types of radiation mechanisms have been proposed to interpret Type IV solar radio bursts. To determine the appropriate mechanism,
we resort to the main observational characteristics of the IVs burst. Dulk (1985) summarized the observational characteristics of different types of solar radio burst and their underlying radiation mechanisms. Here we recall this, focusing on these radiation mechanisms in the case of several important physical parameters: brightness temperature, degree of circular polarization, flux–frequency spectrum, and spectral index (see Table 1).

We list these physical parameters of the September 24, 2011 event separately. First, an important characteristic is the extremely high brightness temperature ($\sim 10^{11}$ K). This means that it has to be either the coherent plasma radiation or ECM emission. Second, the polarization degree is near 100%, which precludes that this originate from the second harmonic plasma radiation. Third, the spectrum here represents a power law. In this event, the $T_B$ is so high that there should be a considerable relativistic effect. For relativistic electrons, the spectral index ($\alpha$) is proportional to the exponent of the energy distribution ($\delta$), if we assume it to be plasma radiation (Kaplan and Tsytovich, 1969). The brightness temperature of fundamental plasma radiation barely reaches up to $10^{10}$ K for the power-law spectrum (Robinson, 1978b; Wentzel, 1985). This is not consistent with our observations. If the spectrum were not represented by a power law, this event could have been well explained by fundamental plasma radiation.

Taking into account the high $T_B$, high $|q|$, and the power-law flux–frequency spectrum, the only feasible mechanism is the ECM emission. This is consistent with the earlier theoretical study by Winglee and Dulk (1986).

### 5. Conclusions and Discussions

A Type IV radio burst on September 24, 2011, was studied in this work. The radio sources of various NRH frequencies remain stationary instead of propagating. It is thus a stationary Type IV burst (IVs). From the NRH and SDO/AIA overplotted images, we note that the NRH sources of different frequency line up very well. We then focused on the physical parameters of the IVs. The brightness temperatures of different frequencies are extremely high. They all exceed $10^8$ K, while the $T_B$ at 150 MHz even exceeds $10^{11}$ K. Higher frequency has lower $T_B$ in general. The degree of circular polarization ($q$) is between $-60\%$ and $-100\%$.

### Table 1

Characteristics of various radiation mechanisms and our observation. $T_B$ stands for brightness temperature, $q$ stands for degree of circular polarization, $\alpha$ refers to the spectral index, and $\delta$ is the particle energy distribution power-law slope. We also list the observational parameters of the IVs on September 24, 2011, for comparison.

| Mechanism               | $T_B$  | Polarization ($|q|$) | Spectral index          | Reference         |
|-------------------------|--------|---------------------|-------------------------|-------------------|
| Cyclotron               | $< 10^9$ K | Any                | $\alpha \neq f(\delta)$ | Dulk (1985)       |
| Synchrotron             | $< 10^9$ K | 0% (Linear)        | Power law, $\alpha \propto \delta$ | Dulk (1985)       |
| Gyrosynchrotron         | $< 10^9$ K | Any                | $\alpha \neq f(\delta)$ | Robinson (1978a)  |
| Fundamental plasma      | $\geq 10^9$ K | $\sim 100\% \sim 0\%$ | $\alpha \neq f(\delta)$ or $\alpha \propto \delta^a$ | Robinson (1978b)  |
| 2nd harmonic plasma     | $\leq 10^{13}$ K | $< 10\%$           |                         | Melrose (1975)    |
| ECM emission            | $\geq 10^{10}$ K | $\sim 100\%$       | Power law                | Winglee (1985)    |

Our observation

| IVs of 20110924 | $10^{11}$ K | $60 \sim 100\%$ | Power law |

*a*For relativistic electrons, the brightness temperature barely reaches $10^{10}$ K.
which is highly left-handed circularly polarized. Meanwhile, the flux–frequency spectrum follows a power-law distribution very well, and the spectral index is between $-3$ and $-4$ throughout the IVs.

We have also summarized possible radiation mechanisms and their predictions of physical parameters. Based on the high $T_B$, high $|q|$, and the power-law flux–frequency spectra, we conclude that this IV is generated through electron cyclotron maser (ECM) emission. To our knowledge, this is the first reported observational evidence to support ECM emission as the mechanism of stationary Type IV radio burst (IVs).

One possible argument against the ECM mechanism is that ECM emission usually exhibits short spikes that are shorter than 0.1 s (Aschwanden, 2004). However, we reiterate that the long-duration continuum has also been explained by ECM emission (Winglee and Dulk, 1986). Moreover, Zhao et al. (2013) have developed a theory to explain the Type I radio burst with the ECM mechanism, which is also a long-duration continuum. In addition, Morosan et al. (2016) showed that close to active regions, the ECM emission mechanism might dominate the plasma emission. This supports our conclusion. ECM emission occurs as a result of the loss-cone instability, which occurs in converging magnetic fields at the loop footpoint, or simply in a magnetic bottle (Melrose, 1986). In Section 2, we have claimed that the radio sources of this IVs lie at the bottom of an open or large-scale closed magnetic field line. Since energetic electrons cannot become trapped in an open field line, only a large-scale closed magnetic field line can account for the ECM emission here.

We conducted this study using imaging data at metric wavelengths from the NRH. According to Benz and Tarnstrom (1976), spectral indices usually require fitting in a wider frequency range to be more accurate. However, the NRH only provides observations between 150 MHz and 445 MHz. It is unfortunate that the Ukrainian T-shaped Radio Telescope (UTR-2), working at lower frequencies (8~33 MHz), has no radioheliographic data for this event (Konovalenko et al., 2012). If more similar events can be observed from the Low-Frequency Array (LOFAR) (de Vos, Gunst, and Nijboer, 2009) or the Mingantu Ultra-wide SpEctral Radioheliograph (MUSER, renamed from CSRH) (Yan et al., 2009; 2015), our understanding of IVs can be further improved.

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