A Weak Coronal Heating Event Associated with Periodic Particle Acceleration Episodes

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Abstract

Weak heating events are frequent and ubiquitous in the solar corona. They derive their energy from the local magnetic field and form a major source of local heating, signatures of which are seen in EUV and X-ray bands. Their radio emission arises from various plasma instabilities that lead to coherent radiation, making even a weak flare appear very bright. Hence, the radio observations probe nonequilibrium dynamics, providing complementary information on plasma evolution. However, a robust study of radio emission from a weak event among many simultaneous events requires high dynamic range imaging at subsecond and sub-MHz resolutions owing to its high spectrotemporal variability. Such observations were not possible until recently. This is among the first spatially resolved multiwaveband studies of active region loops hosting transient brightenings (ARTBs) and is dynamically linked to meter-wave type I noise storms. Observations at meter-wave, EUV, and X-ray bands are used, along with magnetogram data. We believe that this is the first spectroscopic radio imaging study of a type I source, the data for which were obtained using the Murchison Widefield Array. We report the discovery of 30’s quasi-periodic oscillations (QPOs) in the radio light curve riding on a coherent baseline flux. The strength of the QPOs and the baseline flux were enhanced during a microflare associated with the ARTB. Our observations suggest a scenario where magnetic stress builds up over an Alfven timescale (30 s) across the typical magnetic field braiding scale and then dissipates via a cascade of weak reconnection events.

Unified Astronomy Thesaurus concepts: Solar coronal heating (1989); Radio spectroscopy (1359); Solar active region magnetic fields (1975); Active solar corona (1988); Solar coronal transients (312); Sunspots (1653); Solar radio flares (1342); Solar oscillations (1515); Solar coronal loops (1485)

1. Introduction

The solar corona is teeming with weak particle acceleration events. These events derive their energy from the local magnetic fields and eventually dissipate as heat. There is a large body of observational evidence to substantiate that the number of weaker events is much larger than those with higher energy (e.g., Drake 1971; Lu & Hamilton 1991; Crosby et al. 1993). This can easily be seen in the full-Sun integrated X-ray light curves. Of the 338,661 X-ray flares recorded by the Geostationary Operational Environmental Satellite (GOES) over a period of 37 yr, Aschwanden & Freeland (2012) showed that about 90% of the flares belonged to classes with energy less than a C-class flare (<10^{-5} W m^{-2}), and only 0.07% flares belonged to the strongest GOES category (>10^{-4} W m^{-2}). While not responsible for the steady heating of the quiet corona, these weak flaring events form a significant source of heat flux in their vicinity. From the brightest to the faintest, the flare energies are known to vary by at least 9 orders of magnitude. Our ability to detect weaker flares is constrained by instrumental limitations. Studying these weak flares is essential for understanding the processes that convert magnetic energy to thermal in the solar atmosphere. There is also the interesting possibility that these flares are higher-energy analogs of those that give rise to the steady coronal heating.

Meter waves provide a very interesting and complementary observational window for studying such weak flares. The electron beams accelerated by these weak flares eventually radiate via resonant wave–particle and wave–wave interactions, leading to coherent plasma emission at \(\omega_p\) or its harmonic (Ginzburg & Zhelezniakov 1958; Tsyтович & Kaplan 1969; Melrose & Sy 1972). Hence, even energetically weaker flares tend to give rise to very high brightness temperatures, making it easier to probe a much weaker population of flares than is currently feasible at EUV and X-rays (Crosby et al. 1997; Ramesh et al. 2013; Alissandrakis et al. 2015). The \(\omega_p\) in the low coronal regions lies in the meter-wave band (Newkirk 1961; Zucca et al. 2014). As the plasma emission is believed to be at \(\omega_p\) (or its harmonic), the frequency of emission can be mapped directly to the local plasma density. In the corona, \(\omega_p\) is a function of height, so the observation frequency can be used to infer an approximate height of the emission and probe coronal heights inaccessible to observations at high energies. These observations of nonthermal emissions probe independent aspects of evolution of the flare plasma, in contrast to the observations at high-energy bands, which are sensitive to signatures of thermal emission. Together, they help build a more complete picture. Another aspect of these coherent emissions is their rapid temporal and spectral variability, as evidenced by numerous prior observations (e.g., Wild 1957; Ellis 1969; de La Noe 1975; Mugundhan et al. 2017; Suresh et al. 2017; Sharykin et al. 2018). However, for a source like the Sun, which has a wide variety of structures spanning a large range in angular size and intrinsic brightness, high-fidelity imaging with sufficient time and frequency resolution has traditionally remained challenging.

Snapshot spectroscopic imaging with subsecond, sub-MHz resolutions at meter wavelengths has now become possible with the advent of new-generation low-frequency radio interferometric arrays. These include the Murchison Widefield Array (MWA; Lonsdale et al. 2009; Tingay et al. 2013), the LOw Frequency ARray (LOFAR; van Haarlem et al. 2013), and the Long Wavelength Array (LWA; Kassim et al. 2010). The MWA can provide images with resolutions down to 0.5 s

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and 40 kHz. The design of the MWA is especially well suited for high dynamic range (DR) imaging. Using an unsupervised imaging pipeline, it has recently been demonstrated that the DRs of MWA solar images typically exceed $10^3$ for high dynamic range and 40 kHz. The design of the MWA is especially well suited to studying the dominant emission feature on the Sun. Until recently, most solar radio studies were largely limited to studying the dominant emission feature on the Sun. This study is an example of the kind of novel explorations enabled by the availability of these high-DR images. Until recently, most solar radio studies were largely limited to studying the dominant emission feature on the Sun. The high DRs of these radio images now allow us to effectively isolate the emissions from different features simultaneously present on the Sun of potentially very different strengths and carry out detailed studies of weak emission features. Mohan et al. (2019) provided a recent example of such studies that combines snapshot spectroscopic imaging with high-energy observations and magnetic field modeling to investigate the dynamics of a weak active region jet associated with groups of type III radio bursts.

Here we present the first spectroscopic radio imaging study of a type I noise storm associated with a weak active region transient brightening (ARTB). Simultaneous observations from the meter-wave, EUV, and X-ray bands are used alongside concurrent vector magnetogram data. A salient feature of this work is that it used multiwaveband light curves constructed using images of the regions of interest. Earlier studies of ARTBs were mainly restricted to high-energy bands that demonstrated the link between these events and microflares (e.g., Shimizu et al. 1992; Berghmans & Clette 1999; Warren et al. 2007). Using imaging observations from the 1–18 GHz band, a link between microwave bursts and ARTBs has also been demonstrated (Gopalswamy et al. 1994; White et al. 1995; Nindos et al. 1999). In meter-wave bands, some studies have shown that the transient EUV brightening events could produce accelerated particle beams that caused impulsive metric type III radio bursts (Kundu et al. 1986; Alissandrakis et al. 2015). For metric type I noise storms, the higher-energy EUV and X-ray have remained elusive, and their physical drivers are also not well understood (Elgarøy 1977; White 2007). However, they have been long associated with active region magnetic field structures and sunspot groups (Wild & Zirin 1956; Wild 1970). Most of the noise storms were associated with flaring events and interpreted as nonthermal emission triggered by flare-accelerated electrons (e.g., Dodson 1958; Le Squeren 1964; Willson et al. 1998; Kathiravan et al. 2007; Iwai et al. 2011). Some of these bursts also show quasi-periodic brightness fluctuations ranging from a few seconds to minutes in their light curves (e.g., Wild 1951; Sastry 1969; Sundaram & Subramanian 2004), the origins of which and possible links to high-energy sources are not well understood. Occasionally, these sources are observed associated with nonflaring active regions (Smith & McIntosh 1962), implying that flaring is not a necessary condition for the existence of these events. In a case study, Iwai et al. (2012) demonstrated a temporal correlation between the onset of such type I bursts in the full-Sun integrated dynamic spectrum and small-scale EUV and magnetic field activities at a nonflaring active region. However, the dynamical/causal link between the type I burst and small-scale EUV and magnetic activities still remained unclear until Li et al. (2017) demonstrated a good correlation between spatially resolved light curves of type I burst sources at three frequencies and the co-spatial EUV and magnetic activities. This work presents a detailed investigation of an ARTB--type I system with the aim of understanding the nature of emission at high-energy and meter-wave bands, the dynamical correlations that exist between them, and their implications for the physical mechanism involved.

The radio data used in this study come from the MWA, the EUV data from the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO), the X-ray data from RHESSI (Lin et al. 2002), and the vector magnetogram data used for magnetic field modeling from the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) on board the SDO. The analysis of these spatially resolved light curves led to interesting insights about the evolution of the physical parameters of the system during the ARTB-driven microflare as it progressed from its pre-flare state to the heating phase followed by the cooling phase. In particular, the ability to detect fine emission features in SПatially RESolved Dynamic Spectra3 (SPREDs; Mohan & Oberoi 2017) allowed us to detect quasi-periodic oscillations (QPOs) in the radio emission associated with the type I source. We also suggest a physical scenario to explain these observations.

The organization of the paper is as follows. The event and multiwaveband observations are described in Section 2. The radio, X-ray, EUV, and HMI data analyses are described in Section 3. Section 4 presents a discussion of the observations and the inferences that can be drawn from them, with their implications and likely interpretations. Section 5 presents the conclusions.

2. Observations

The radio data were gathered using the MWA on 2014 November 3 between 06:08:02 and 06:20:02 UT under the observing code G0002. The observations were made across a bandwidth of 15.36 MHz with a time and frequency resolution of 0.5 s and 40 kHz, respectively. The data comprise three contiguous observations of 4 minutes duration with neighboring central frequencies. The first (06:08:02–06:12:02 UT) and last (06:16:02–06:20:02 UT) observations were centered at 199 MHz. The intervening observation (06:12:02–06:16:02 UT) was centered at 229 MHz.

The day was characterized as a period of medium activity, with 10 type III radio bursts, eight type IV radio bursts, and a GOES class C1.4 flare.4 The Space Weather Prediction Center (SWPC) reported groups of type III bursts from 06:02 to 07:22 UT, which includes the period of MWA observations.5 The 1–8 Å GOES band shows evidence for a B6-class flare. The X-ray light curves from RHESSI show signatures of a weak flare in the 3–12 keV bands. This event was not reported in the SWPC event list, likely because its flux did not sufficiently exceed the background. Figure 1 shows the MWA dynamic spectra for the three observations. The bottom right panel of the figure shows the GOES and RHESSI X-ray light curves for the different energy bands during the observation period.

The top panels of Figure 2 show AIA 131 Å images before (left) and during (right) the type III bursts. Overlaying on each of

3. Analogous to a dynamic spectrum, SPREDs is the dynamic spectrum of the emission arising from a specific region on the Sun.
4. http://www.solarmonitor.org
5. ftp.swpc.noaa.gov/pub/indices/events/README
them are the MWA 229 MHz contours at the respective times. The bright radio source in the northwest part of the visible solar disk is a persistent source present throughout the observation. The image in the top right panel shows a brighter radio source located in the eastern half of the disk. This source consistently appears during every type III burst with high brightness temperatures \( T_B \approx 10^8-10^9 \) K. The darker \( T_B \) contours signify the enhanced brightness of this source relative to the persistent radio source. Six groups of type III bursts took place during the observation period and were spatially and temporally associated with a weak active region jet seen in all observing bands of the AIA. A detailed study of the type III bursts and the associated jet is presented in Mohan et al. (2019). Here we focus on the persistent radio source. The bottom left panel of the figure shows a RHESSI image made by averaging the data over 3–12 keV and 120 s (06:13:16–06:15:16 UT). We find a bright compact X-ray source centered at \((150^\prime, 135^\prime)\), close to the location of the persistent radio source. An X-ray source of similar (flux) strength was found to be associated with the type III burst sources as well. So, the X-ray flare seen in GOES and RHESSI data (Figure 1) has contributions from both these sources. The bottom right panel zooms into the northwest region of the AIA 131 Å map corresponding to the location of the persistent radio source. Overlaid are the MWA 229 MHz \( T_B \) contours. The location of the associated RHESSI source is marked by an arrow. An EUV-bright active region loop is associated with the radio and X-ray sources. This loop was persistently bright during the observation period. It belonged to an active region numbered AR 12203 by the National Oceanic and Atmospheric Administration (NOAA). No flares were recorded by NOAA from this active region on this day. But this region had the largest number of sunspots (nine) and sunspot area (150 millionths) among all 10 active regions recorded on that day.

We note that the radio source is offset from the location of the bright EUV loop. This is expected, as the radio source is located much higher up in the corona, and its location is determined by magnetic and density fields in the region. The meter-wave radiation from the burst source is also subject to propagation effects like scattering, refraction, and ducting due to coronal plasma structures and turbulence in the medium (e.g., Steinberg et al. 1971; Arzner & Magun 1999; Kontar et al. 2017; Mohan et al. 2019). Simulations have shown that these effects can shift the location of the radio source by a few arcminutes (Robinson 1983; Wu et al. 2002). The bright active region loop is the only EUV and X-ray source seen in the vicinity of the radio source. Hence, despite the offset, it is reasonable to associate the radio source with it. This system is the focus of the present study.

3. Analysis

As mentioned in Section 2, the meter-wave radio emission is generated at a much greater height in the corona as compared to the bright active region loop. To get an estimate for the radio
source height, we use the fact that the coronal plasma frequencies fall in meter wavelengths. Being proportional to the square root of local density that falls monotonically with heliocentric distance, the local plasma frequency in the corona decreases with height in the corona. Since any radiation produced at a frequency less than the local plasma frequency gets efficiently absorbed, the observed frequency of radiation must be generated at a height greater than the region where the local plasma frequency equals the observation frequency. This provides a straightforward way to estimate a lower limit to the height of the radio emission using a coronal electron density model. Using the model provided by Zucca et al. (2014; hereafter the Z model), we estimate the source height limit to be $1.14 \ R_\odot$. Assuming a semicircular geometry for the bright AIA loop and using the observed separation of foot points as its diameter, we estimate a height of $\approx 1.02 \ R_\odot$ for this loop. The radio and EUV emission thus comes from regions well separated in height.

This section is divided into four subsections, describing the analysis of EUV images from the AIA, radio observations from the MWA, the RHESSI imaging data, and the vector magnetogram from the HMI, respectively.

3.1. AIA Data Analysis

The bright active region loops seen in the coronal EUV bands of the AIA, namely 94, 131, 171, 193, 211, and 335 Å, were analyzed using routines in the SolarSoft Ware (SSW; Freeland & Handy 1998) package. Level 1 data were obtained
from the Virtual Solar Observatory (VSO) and coaligned using the SSW routine \texttt{aia\_prep}. The left panel of Figure 3 shows a 94 Å image of the active region containing the bright loop. The black boundary around the loop defines the region used for further analysis. This boundary was defined by thresholding the image above 40 times the mean value and slightly dilating the resulting mask to fully encompass the region that underwent significant brightening during the event. The light curves in the right panel of Figure 3 span the duration of MWA observations and correspond to the average value within this boundary, normalized by the intensity at the beginning of the time series, before the onset of the event. A clear rise in the normalized intensity is observed starting around 06:11:40 UT. The intensity in different bands peaks at different times, with the 94 Å light curve peaking after 06:14:00 UT. It is difficult to conclude anything about the evolution of physical fields at the loop region by just examining these light curves. This is for two reasons: the observed intensity is a function of temperature and density, and the AIA bands have very broad and overlapping temperature response functions. To study the evolution of temperature and density, we use a technique based on differential emission measure (DEM; Withbroe 1975) by combining light curves from all of the AIA bands.

3.1.1. DEM(T)

The observed intensity in the various AIA bands is the sum of emission from multithermal plasma components along the line of sight (LOS). The DEM(T) is a quantity that characterizes the individual contributions from these different temperature (T) components. By estimating the DEM(T) at various instances of time during our observation, we can detect signatures of heating by looking for a rise in the high-temperature component. Using the DEM(T) function, we can obtain the total emission measure (EM) by simply integrating over DEM(T). Assuming that the number densities of electrons \(n_e\) and protons \(n_H\) are the same, the observed intensities at a wavelength \(\lambda\), \(I_\lambda\), EM, and DEM(T), are related as

\[
I_\lambda = \int \left( n_e^2 \frac{dz}{dT} \right) \Delta(T, n_e, \lambda, \chi) R_\lambda dT, \tag{1}
\]

\[
\text{DEM}(T) = n_e^2 \frac{dz}{dT}, \tag{2}
\]

\[
\text{EM} = \int \text{DEM}(T) dT = \int n_e^2 dz, \tag{3}
\]

where \(dz\) is a height segment present along the LOS at a particular temperature, \(R_\lambda\) is the known instrumental response.
function, and $\Lambda$ is the contribution function that gives the emissivity of the plasma at a given $T$, $n_e$, and wavelength assuming a typical ion abundance of $\chi$ in the corona. Here $\Lambda$ can be computed for any $n_e$ and $T$ using the CHIANTI database of atomic spectral lines (Dere et al. 1997; Landi et al. 1999), and $I_\lambda$ is the observable in different AIA bands. Thus, each AIA band contributes one equation corresponding to Equation (1), giving rise to a system of equations that can be solved to obtain DEM($T$).

We integrate the DEM($T$) to obtain the total EM and DEM-weighted average temperature $\langle T \rangle$ along the LOS. By assuming an LOS depth $D$, we can then estimate the mean electron density $\langle n_e \rangle$ and mean thermal energy $\langle E \rangle$ for the emission region,

$$\langle T \rangle = \frac{\int_0^T \text{DEM}(T) T dT}{\text{EM}},$$

$$\langle n_e \rangle = \frac{\text{EM}}{\Lambda},$$

$$\langle E \rangle = 3 \langle n_e \rangle k_B \langle T \rangle V,$$

where $k_B$ is the Boltzmann constant and $V$ is the volume of the loop. For the chosen loop region, we estimated DEM($T$) at each 12 s time step between 06:08:00 and 06:20:00 UT.

To estimate DEM($T$), we used the `xrt_dem_iterative2` algorithm available in SSW (Golub et al. 2004; Weber et al. 2004). The code was designed for the X-ray Telescope (XRT) on board the Hinode satellite and later adapted for AIA data (e.g., Schmelz et al. 2011; Cheng et al. 2012). The approach is to forward-fit DEM($T$) by predicting the observed count rates from an initial guess and iteratively modifying the solution to minimize the $\chi^2$ between the observed and predicted fluxes. Iterative Levenberg–Marquardt least-squares minimization is used, DEM($T$) is interpolated between the available points using spline knots, and this method has been shown to reproduce model DEMs of active regions using simulated AIA data (Cheng et al. 2012). Uncertainties are obtained from 100 Monte Carlo runs, for which the data are randomly varied within their uncertainties prior to each pass through the algorithm. We obtained date-dependent AIA response functions from the SSW routine `aia_get_response` using the “chiantifx,” “evenorm,” and “noblend” keywords. Our implementation is adopted from Reeves et al. (2015), but we compute DEM($T$) over a narrower temperature range of log ($T$) = 5.8–7.3. This range spans the breadth of the AIA’s temperature response peaks, and although there is some sensitivity at higher and lower temperatures, the data are not well constrained beyond this range. Incorporating higher-temperature soft X-ray observations would improve the DEM estimation, but those data are not available for this event. Figure 4 shows the DEM($T$) distribution derived at three epochs: before, during the peak, and after the brightening event (left to right). The DEM distributions before and after the loop brightening event look very similar, with a peak temperature of $\approx 3$ MK. The DEM($T$) obtained during the middle of the period when various AIA bands attain their peak intensity (06:13:31 UT) shows a significant rise in the high-temperature component.

Estimations of $\langle n_e \rangle$ and $\langle E \rangle$ require the depth and volume of the loop, respectively. The loop was assumed to be a cylinder with a diameter equal to its observed thickness. This gives it a radius of 7 AIA pixels ($\approx 3$ Mm). The length of the loop segment is about 22 Mm. The volume of the loop then turns out to be about $1.58 \times 10^{26}$ cm$^3$. Note that the loop segment length is a projected value, but it was estimated by taking care of the curved structure rather than just the foot-point separation. If one assumes the loop to be semicircular and the foot-point separation to be its diameter, then the loop length comes to around 32 Mm. This will not cause large differences to the $\langle E \rangle$ estimates. Figure 5 shows the evolution of $\langle T \rangle$, $\langle n_e \rangle$, and $\langle E \rangle$. The error bars on each quantity are estimated as its standard deviation across the set of solutions obtained from the 100 Monte Carlo runs. The impulsive rise in all of these quantities is evident. This evolution is primarily due to the evolution of the high-temperature components in the DEM($T$). Hereafter, this period of evolution of the thermal properties of the loop plasma will be referred to as the “flare.” The physical size of the bright loop region, the estimated range of the variation of thermal properties, and the flare duration during the period of transient EUV brightening all lie within the typical ranges for an ARTB (Shimizu 1996).

### 3.2. Radio Analysis

The MWA data were imaged at a time cadence of 0.5 s and a spectral resolution of 160 kHz. Imaging was done using an automated radio interferometric imaging pipeline called the Automated Imaging Routine for Compact Arrays for Radio Sun (AIRCARS; Mondal et al. 2019), which is optimized for arrays having a dense central core of collecting area, like the MWA. AIRCARS uses imaging and calibration routines from the Common Astronomy Software Applications (CASA; McMullin et al. 2007) and relies on the technique of self-
The images used had DRs varying from \( \approx 250 \) to 6900, depending on the solar activity level. The highest DRs were obtained during the times of high integrated flux density. During the type III event, we obtained DRs well exceeding 1000. The \( T_B \) of the intermittent type III source varied between \( \approx 10^8 \) and \( 10^9 \) K, while that of the persistent radio emission source ranged from \( \approx 5 \times 10^7 \) to \( 10^8 \) K, with a mean \( T_B \) well above \( 10^8 \) K. The high \( T_B \) implies a nonthermal emission mechanism. The high DRs in these images allowed us to isolate the emission from the persistent radio source across the entire time and frequency span of our observations, even in the presence of the significantly more intense intermittent burst source. The location of the persistent radio source in the snapshot spectroscopic images was always close to the bright loop, as seen in the example image in Figure 2. However, its precise sky location fluctuated over the duration and across the spectral band of observation. To quantify this fluctuation, a 2D Gaussian function was fitted to each image of the radio source across frequency and time, and the sky location of the best-fit Gaussian was recorded. Good-quality fits were obtained for about 99.5% of the snapshot spectroscopic images, with a mean uncertainty of about 0.01 in the R.A. and decl. estimates. Figure 6 shows 2D histograms of the shift in the source sky location from its mean during the first 8 minutes of observations. The distribution is clearly asymmetric about the mean location, though the magnitudes of these shifts are typically less than \( \pm 1\). This is less than 25% of the typical FWHM of the synthesized beams at the respective observation frequencies. The FWHMs of the synthesized beams at 199 and 229 MHz are \((4/4, 3/5)\) and \((4', 3')\), respectively.

### 3.2.1. SPREDS

The SPREDS were obtained by recording the flux density of the radio source across frequency and time, as observed in the snapshot spectroscopic images. The top left panel of Figure 7 shows a sample \( T_B \) map at 229 MHz, and the region used for obtaining the SPREDS is marked with a black dashed ellipse. This region was centered at the persistent source and defined to have a mean length of the point-spread function (PSF). The SPREDS for this region for each of the 4 minute observations are shown in the remaining panels. We will use flux density instead of \( T_B \) in further discussions, as it is a physically more meaningful quantity in the case of nonthermal emission. Numerous bright emission features of flux density \( >200 \) solar flux units (SFUs; 1 SFU = \( 10^{-22} \) W m\(^{-2}\) Hz\(^{-1}\)) are seen in the SPREDS with a typical extent of \( \approx 0.5\)–2 s in time and \( \approx 10\)–13 MHz in frequency during the flare period. The source flux density varies between \( \approx 20 \) and \( 525 \) SFU (\( \approx 5 \times 10^7\)–\( 10^9 \) K in \( T_B \)) during the observation. The observed emission properties are typical of a type I noise storm, which comprises numerous fine bursts riding over a nonthermal background emission (e.g., Elgaroy & Ugland 1970; McLean 1981).

The left panel of Figure 8 shows a superposition of \( \langle E \rangle \) and the radio light curve for the persistent source. The radio light curve was obtained by averaging the SPREDS for every 4 minute observation across the frequency axis. The light curve shows a large number of short-lived impulsive features. It is also evident that the baseline flux density of the light curve is elevated during the flare period. This is likely due to the blending of numerous episodes of impulsive emissions that remain unresolved in these observations. For a more robust study of the nature of variations in radio emission, we examined the mean filtered radio light curve using a window length of 10 s (left panel). This revealed the presence of QPOs in the light curve. These oscillations are of larger amplitude during the flare as compared to the pre-flare and decline phases. The right panel shows the running median filtered radio light curve obtained using a 36 s wide window. As this window is much larger than the period of the QPOs but much smaller than the timescale of the flare itself, it is a good choice for estimating the evolution of the baseline radio flux density and comparing it to the \( \langle E \rangle \) light curve. The very similar temporal evolution of these two physically very different quantities provides strong evidence that the sites of the type I noise storm emission and the ARTB associated with loop heating are being powered by the same underlying source.

Note that the data used to generate the radio light curve are centered at different but nearby frequencies. Using the Z density model chosen for this work, the difference in the coronal heights corresponding to the two central frequencies used is 0.03 \( R_\odot \) (\( \approx 20 \) Mm), i.e., less than 10% of the pressure scale height in the region. Therefore, these observation bands probe practically the same coronal region. This is also evident in the continuity of the radio flux density light curve across observation boundaries.

![Figure 6](image_url)

**Figure 6.** The 2D histogram of the relative sky location of the radio source with respect to its mean for the first two sets of observations. The observations are centered at 199 MHz (left) and 229 MHz (right).
3.3. X-Ray Analysis

As discussed in Section 2, the flare time is marked by a rise in the low-energy X-ray bands of RHESSI (3–6 and 6–12 keV; Figure 1). The observed rise in emission has contributions from two sources of comparable flux, one associated with the bright loop of interest and the other with a weak active region jet associated with the type III bursts. In order to unambiguously obtain the light curve for the X-ray source associated with the bright loop, we imaged this source. The imaging analysis combined the RHESSI channels from 3 to 12 keV. Based on the detector performance during the observation period, only the data from the 3F, 6F, 8F, and 9F detectors were used. Imaging was done using the CLEAN algorithm. While imaging, we attempted to obtain the finest time resolution possible while maintaining a reasonable signal-to-noise ratio (S/N). We could attain S/N > 10 with time averaging as low as 5 s during the peak time of the flare. Attempts to image this region before the...
start and after the end of the RHESSI flare did not lead to a source detection, even with several minutes of averaging. The left panel of Figure 9 shows a superposition of the X-ray source contours from the time it was at its peak brightness on an AIA 94 Å image around the same time. This clearly establishes the cospatial nature of the soft X-ray source with the bright EUV loop. Immediately after the start of the rise phase of \( (E) \), the soft X-ray source appeared on the bright loop centered at \((150^\circ, 136^\circ)\). The right panel shows the evolution of the total flux enclosed within the 60% contour in the RHESSI images, along with the evolution of \( (E) \). The first and last points in the RHESSI light curve are obtained for the cases of nondetection, where the X-ray maps remained noisy even after averaging the data over 4 minutes. Hence, these estimates provide an upper limit for the X-ray flux in the region in the pre- and post-flare periods. The bright RHESSI source that appeared close to 06:12:00 UT attained its peak flux about 50 s before the observed \( (E) \) peak and faded away rapidly, falling below the detection threshold about 2 minutes beyond the \( (E) \) peak. The cotemporal nature of \( (E) \) and the X-ray flux evolution is self-evident.

3.4. HMI Data Analysis

We use the HMI vector magnetogram data to reconstruct the coronal magnetic field. The values of the magnetic field components at the photosphere provided by HMI are used as the boundary conditions, and the magnetic field is assumed to be force-free. The relevant HMI magnetogram data are given by the Space weather HMI Active Region Patch (SHARP) for AR 12203, 2014 November 3, 06:12 UT. The SHARP patch is 608 × 309 pixels in size, where each pixel is 0\(^{\prime}\)5 across, and the highest value of the radial field component at the photosphere is 2.48 × 10\(^{13}\) G. The nonlinear force-free field (NLFFF) code CFIT was used to solve the NLFFF equations using the Grad–Rubin iteration (Wheatland 2007). As CFIT works in a Cartesian geometry, we approximate the SHARP field strength data, given in a Lambert cylindrical equal-area projection, as field values on a Cartesian grid and solve for the magnetic field in a Cartesian box, where the photosphere is located on the \( x-y \) plane at \( z = 0 \) and the positive \( z \)-direction is the radial direction away from the Sun (in other words, we take \( B_\theta = B_x \), \( B_\phi = -B_y \), and \( B_z = B_z \)).

The Grad–Rubin method solves for the magnetic field and force-free parameter \( \alpha \) iteratively, using the value of the normal component of the magnetic field and the value of \( \alpha \) at the photosphere as boundary conditions. The other boundary conditions we impose on the solution box are that the field decays to zero as \( z \to \infty \) and is periodic at the sides of the box. Open field lines, i.e., those that cross the boundaries of the box either at the sides or the top, are assigned \( \alpha = 0 \). Values of \( \alpha \) on the photosphere are obtained from the local vertical components of the current density, which are calculated from the derivatives of the horizontal components of the magnetic field. In general, HMI magnetogram data overprescribe the problem by giving values of \( \alpha \) over both positive and negative polarities of the active region. Therefore, two solutions can be constructed, depending on which \( \alpha \) values are used as boundary conditions: those from the positive (P solution) or negative (N solution) magnetic polarity regions.

In practice, P and N solutions can be very different, because the vector magnetogram data are inconsistent with the force-free assumption (De Rosa et al. 2009). To address this problem, Wheatland & Régnier (2009) proposed the “self-consistency procedure.” The P and N solutions are separately calculated, then the values of \( \alpha \) from the two solutions are averaged, weighted by the associated uncertainties. At the end of one such self-consistency “cycle,” we arrive at a new set of boundary conditions for \( \alpha \). The P and N solutions are then calculated again from the new set of boundary conditions. The process is repeated until the P and N solutions agree and we arrive at a self-consistent NLFFF model.

Initially, we applied CFIT with the self-consistency procedure implemented to the active region containing the bright loop (AR 12203), 2014 November 3, 06:12 UT SHARP magnetogram. However, we were unable to reconstruct the large loop structure, clearly visible in the EUV, from this SHARP patch alone. We extended the magnetogram to include the neighboring active region, AR 12202. The magnetogram, now 1367 × 600 pixels in size (each 0\(^{\prime}\)5 across), was rebinned by a factor of 2 to speed up calculations, so that our solution box size is 683 × 300 × 300 pixels, with each pixel being 1\(^{\prime}\)005. The top of the solution box is, therefore, at 1.314 \( R_\odot \). In addition, to deal with noise in the data, we censor currents on the boundary surface with \( S/Ns \) less than 1; i.e., we set \( \alpha = 0 \).
Figure 10. Top left: HMI magnetogram showing the sunspot group associated with the bright loop visible to the left. A large loop structure bridges this sunspot group with another sunspot group to its right. Top right: same region as in the AIA 171 Å map. The bright loop region centered around (150”, 130”) is relatively dim in this AIA band, which is primarily sensitive to plasma at 0.65 MK. The small square marked at (185”, 155”) marks the apex of the large loop. Bottom: extrapolated magnetic field structures overlaid on the HMI (left) and AIA 171 Å map (right). The field lines are shown in different colors to highlight the difference in their topology and foot-point connectivity.

4. Discussion

The previous section presented a multiwavelength imaging analysis of a bright loop region using EUV, X-ray, and meter-wave observations. The coronal magnetic field extrapolation done using the NLFFF technique on the vector magnetogram data was also presented. The EUV and X-ray analysis revealed an ARB event during our observations. The emission features in the SPREDs for the associated persistent meter-wave source were typical of a type I noise storm. The ARB was associated with a microflare. The rise in $\langle E \rangle$ of the bright loop region during the flare is accompanied by an enhancement in the average radio flux density, and as $\langle E \rangle$ falls to its pre-flare value, the radio flux density also drops (Figure 8). These observations show that the radio and high-energy events are cotemporal. There is also clear evidence for the spatial association of the sources. The noise storm source is seen slightly shifted by $\approx 1\arcmin$ to the right of the bright loop region, and it overlaps the large loop structure connecting AR 12203 and AR 12202. Though the sky location of the radio source is observed to fluctuate around its mean, the vast majority of these fluctuations are below 25% of the FWHM of synthesized beams at the respective observation frequencies. Such fluctuations in the observed source location are expected to arise due to radio-wave scattering (e.g., Steinberg et al. 1971; Kontar et al. 2017; McCauley et al. 2018; Mohan et al. 2019). The observed asymmetry in the distribution of the location of the compact radio source (Figure 6) is likely due to the anisotropy in the distribution of coronal density inhomogeneities encountered by the rays as they traverse out of the corona (Robinson 1983). The magnetic field extrapolation (Section 3.4) revealed that the peak of the large loop structure extends to the height from which the radio emission is expected to arise and shares a photospheric foot point with the bright loop region. Together, these analyses establish the spatiotemporal association and the dynamical link between the emission regions seen in the multiwaveband images.

This section examines the coevolution of the observed emissions at different wave bands to put together a physical picture for the mechanism driving them. We start by noting that flares are inherently nonequilibrium processes, while the thermodynamic quantities determined using the DEM analysis rely on thermal equilibrium physics. These quantities (Equations (4)–(6)) therefore cannot generally be interpreted in their usual thermodynamic sense but should rather be regarded as equivalent thermodynamic quantities, which are proxies for various properties of the nonequilibrium particle energy/velocity distribution. For instance, a rise in the local average temperature and energy represent an increase in the average velocity dispersion and free energy, respectively, due to the introduction of suprathermal electrons in the region.

Starting around 06:11:40 UT, the quantities determined using the DEM analysis, $\langle T \rangle$, $\langle E \rangle$, and $\langle n_e \rangle$, show a rapid rise wherever $S/N(J_e) < 1$. We also censor out weak field regions; i.e., we set $\alpha = 0$ where $|B| < 0.05 \max(|B|)$.

The resulting coronal field extrapolation is presented in Figure 10. The large loop structure connecting AR 12203 to AR 12202 is well replicated by the model (yellow field lines). The apex of the large loop connecting the two regions is at $\approx 1.14 R_\odot$, and the magnetic field strength at this height is about 5 G. The available free energy in the magnetic field close to the bright loop region was estimated from the difference between the total magnetic energy in the region and the energy of the potential field. This value turned out to be $\approx 5.1 \times 10^{25}$ erg, which is about 2 orders of magnitude larger than the thermal energy in the region.
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from their pre-flare equilibrium values of 4 MK, $2 \times 10^{27}$ erg, and $8 \times 10^{3}$ cm$^{-3}$ to attain the respective peak values of about 6 MK, $5.2 \times 10^{27}$ erg, and $1.4 \times 10^{10}$ cm$^{-3}$. This rapid-rise phase ends at 06:13:19 UT, and beyond this, these quantities slowly relax to their pre-flare values. The rising phase coincides exactly with the presence of a cospatial RHESSI source (Figure 9). The appearance of this source at the start of the heating phase and its dramatic decline below the detection threshold past this phase imply that some heating mechanism was active for this duration, of which the RHESSI source was a consequence. The energy required for the loop heating likely came from the local magnetic field. As mentioned in Section 3.4, the magnetic free energy in the region, being 2 orders of magnitude larger than the generated heat energy, is capable of powering the heating.

4.1. Estimating the Heating Rate

The quantity $\delta E = \langle E_{\text{peak-flare}} \rangle - \langle E_{\text{pre-flare}} \rangle$ provides an estimate of the excess free energy that was deposited in the loop during this flare. It is estimated to be $\approx 3.2 \times 10^{27}$ erg and is consistent with the typical energy budget of a microflare (Aschwanden et al. 2000; Aschwanden 2006). It is useful to check if this excess free energy can indeed heat the loop plasma to a kinetic temperature of 6 MK within the observed period of about 100 s. For this, we use the model proposed by Rosner et al. (1978; hereafter the RTV model), which describes the thermal energy balance in the corona, assuming an equilibrium between heating and cooling rates. This model accounts for conductive and radiative heat losses using approximate power-law models. It neglects the spatial variation in the heating scale height and gravitational stratification of the loop, though these effects become important when the length of the loop strands exceeds the respective scale heights. Under these conditions, the RTV model provides an expression for the equilibrium heating rate, $E_H$, required to maintain a steady temperature profile across a coronal loop segment of length $L$ and volume $V$, with a maximum temperature of $T$ at the loop top:

$$E_H = 0.95 \times 10^{-6} L^{-2} T^{7/2} V \text{ erg s}^{-1}. \quad (7)$$

The segment length $L$ is taken as the half length of the loop for symmetric loops. The RTV model assumes the equilibrium heating/cooling rate to be uniform along the loop. The scaling law (Equation (7)) derived using the model, referred to as the RTV scaling law, can be used to get a zeroth-order estimate for the equilibrium heating/cooling rate. It is evident that in the pre-flare phase, the loop was being maintained at an equilibrium temperature of 4 MK (Figure 5). At the start of the flare, the heating rate suddenly increased to a larger value, leading to the observed rise in X-ray flux from the loop region and a rise in $T$ deduced from the DEM analysis. The peak value of $T$ is determined to be 6 MK. The simplest model for a heating source that one can envisage is that of a source whose heating rate suddenly increased to a value that remained steady throughout the heating phase. For such a model, the minimum value of the enhanced heating rate required has to be sufficient to raise the temperature of the loop to 6 MK. Using a loop length of 22 Mm and $V \approx 1.58 \times 10^{26}$ cm$^{3}$ (Section 3.1.1) and assuming that the RTV scaling law provides approximate estimates under these conditions, we estimate this enhanced heating rate, $E_H$, to be $6.35 \times 10^{25}$ erg s$^{-1}$. We assume that the cooling efficiency remained at the pre-flare value, resulting in a sudden dumping of excess thermal energy in the loop. Considering the pre-flare equilibrium temperature of 4 MK as $T$, assuming that the spatial variation of the temperature is negligible, we estimate the typical cooling rate using Equation (7), invoking the fact that there was an equilibrium between heating and cooling rates in the pre-flare phase. The cooling rate $E_C = 1.59 \times 10^{25}$ erg s$^{-1}$. Then the typical heating time, $t_{\text{heat}}$, required to heat the plasma to 6 MK by the enhanced heating source would be $\approx \delta E/(E_H - E_C)$, which is about 67 s. Since this estimate is a strong function of loop length, to get a rough upper limit of the heating time, the loop length of 32 Mm, which was obtained by assuming a semicircular loop geometry, can be used. This results in $t_{\text{heat}} \approx 142$ s. For further analysis, a typical value of 25 Mm will be used for the loop length. The estimate of $E_C$ for this loop length is about $1.2 \times 10^{25}$ erg s$^{-1}$, and $t_{\text{heat}}$ evaluates to around 86 s. In reality, $E_C$ depends on the instantaneous effective temperature. So, as the loop gets heated up, its cooling efficiency should also increase. Hence, the timescales computed above are lower limits to $t_{\text{heat}}$ for different loop lengths. The observed $t_{\text{heat}}$ of 100 s lies within the estimated range of lower limits ($\approx 67$–142 s). Note that the $E_H$ computed using $T = 6$ MK is a lower limit for any given loop length. In reality, the enhanced heating power could be much higher, resulting in a lower $t_{\text{heat}}$ estimate. Given the uncertainty associated with the loop length estimate, $E_H$; the approximate nature of the RTV scaling laws; and that these estimates represent lower limits, the agreement with the observation suggests that it is plausible for such a heating source to raise the temperature of this loop to 6 MK within the observed duration. Alternatively, an effective cooling rate was estimated using the observed duration of the heating phase of the flare ($t_{\text{heat}} = 100$ s), the $\delta E$ estimated using DEM analysis, and assuming the $E_H$ value for $T = 6$ MK used above. As $t_{\text{heat}} = \delta E/(E_H - E_C)$, the only unknown in this expression is now $E_C$, which evaluates to $1.7 \times 10^{24}$ erg s$^{-1}$, assuming a loop length of 25 Mm. Interestingly, this value of $E_C$ is close to that obtained for this loop length in the pre-flare case ($1.2 \times 10^{25}$ erg s$^{-1}$). It also corresponds to an effective temperature of 4.4 MK, which is not far from the equilibrium pre-flare value. This suggests that the assumption in the heating model that the cooling rate remained steady at the pre-flare value during the heating phase is not unreasonable.

4.2. Estimating the Cooling Time

As seen in the right panel of Figure 9, the soft X-ray source suddenly drops below the detection threshold very close to when $\langle E \rangle$ peaks. We regard this as an evidence for the switching off of the enhanced heating rate responsible for the temperature rise and assume the heating rate to have dropped to the pre-flare level at this point in time. By this time, as we computed in the previous subsection, the cooling rate would have risen by a small amount from the pre-flare value. The loop then goes through a nonequilibrium phase where the rate of heat loss via radiative and conductive pathways is larger than the heating rate, and the temperature of the loop begins to drop. Here we estimate the cooling time, $t_{\text{cool}}$, required for the loop to release the excess heat energy $\delta E$ deposited in it and relax to its
pre-flare equilibrium. This timescale is given by $t_{\text{cool}} = \delta E / (E_C - E_H)$, where $E_H$ and $E_C$ now correspond to the cooling phase of the flare. Based on the assumption of the sudden switching off of the heating source beyond the peak time of the flare, and the loop relaxing to its pre-flare state, the $E_H$ in this regime corresponds to that required to maintain the plasma at 4 MK. Assuming to zeroth order that $E_C$ remains a constant during the cooling phase, we use the estimate of the slightly enhanced effective cooling rate at the end of the previous subsection. Using these estimates of $\delta E$, $E_H$ and $E_C$, we estimated the cooling time $t_{\text{cool}} = \delta E / (E_C - E_H)$ to be 655 s. Our observation window extends to only 400 s beyond the peak in $(E)$, and all three quantities, $(T)$, $(E)$, and $(n_e)$, approach their pre-flare levels by the end of the observing duration. This is consistent with the expectation based on the $t_{\text{cool}}$ estimate. This demonstrates that both the heating and cooling timescales are consistent with the abrupt switching on and off of a heating source, as suggested by the synchronized appearance of the soft X-ray source at the loop location.

4.3. Implications of the Nonthermal Radio Emissions

As mentioned at the beginning of Section 3, the minimum coronal height of the radio source is 1.14 $R_\odot$, and the typical magnetic field at these heights was found to be around 5 G. This leads to a gyrofrequency, $\omega_p$, of 15 MHz, which is much smaller than $\omega_p = 229$ MHz. As height increases in the corona, both $\omega_p$ and $\omega_p$ fall. The former always remains lower than the latter, as it decreases relatively faster (Morosan et al. 2016). However, for gyrosynchrotron emission to be observed and the electron cyclotron maser instability (ECMI) to operate, it is essential to have $\omega_p > \omega_p$ (Melrose & Dulk 1982; Gary & Hurford 2004). This rules out these emission mechanisms. The only remaining possibility for the origin of these bright fine features is plasma emission mechanisms. These mechanisms are triggered by the two-stream instability and lead to coherent radio emission. This emission, produced by the passage of accelerated electron beams, is known to be generated at the local $\omega_p$ and its harmonic (Ginzburg & Zhelezniakov 1958; Tsytovich & Kaplan 1969; Melrose & Sy 1972). For further analysis, it is assumed that the observed emission is at the local $\omega_p$. Note that the following analysis also holds if the emission is assumed to be harmonic instead.

The SPREDS for the radio source show numerous bright but short-lived and narrow-band emission features, reminiscent of type I bursts (Figure 7). In the following, we refer to these features as bright fine features, which typically last for 0.5–2 s and span about 10–13 MHz. These are likely to be coherent plasma radiation triggered by electron beams propagating outward along the magnetic fields. The radio emission is then expected to drift to lower frequencies as a consequence of the radially decreasing coronal electron density and hence $\omega_p$. In the SPREDS, however, we do not find evidence for frequency drifts in these bright fine features. This could simply be a consequence of the 0.5 s time resolution being too coarse to be able to detect these spectral drifts.

Consider the observations centered at 229 MHz, which overlap with the period when the X-ray source was seen in the 3–12 keV images. The local plasma density corresponding to $\omega_p = 229$ MHz is $6.5 \times 10^{8} \text{ cm}^{-3}$. Figure 11 illustrates the physical scenario emergent from the interpretation of the observations and the coronal magnetic field structure extrapolated using the NLFFF technique. The bright loop extends to a height of around 1.02 $R_\odot$, while the radio source is located at a height of around 1.14 $R_\odot$. The radio source is associated with the large loop connecting the active regions AR 12203 and AR 12202. We note that the EUV-bright loop and the loop hosting the radio source share a common foot point. The observation bandwidth of 15 MHz corresponds to a very narrow height range of $\approx0.014 R_\odot$, according to the Z model. The magnetic field strength of 5 G estimated in the radio source region leads to a local Alfvén speed of 0.4 $\text{ Mm s}^{-1}$. The left panel of Figure 12 shows the SPREDS during the period of interest. The typical spectral extent of the bright fine features (10–13 MHz) corresponds to a distance range of $\approx7$–8.5 $\text{ Mm}$ using the Z model. The lack of a discernible spectral drift within the imaging time resolution of 0.5 s provides lower limits for the speeds of electron beams, i.e., $14$–$17 \text{ Mm s}^{-1}$. The observed lifetime of these bright fine features ($\approx0.5$–2 s) compares well with the ion–electron collision timescale, $\tau_{\text{col}}$. The $\tau_{\text{col}}$ is estimated to be about 1.0–1.8 s for a plasma with a density corresponding to $\omega_p = 229$ MHz at a temperature of 4–6 MK. This estimate is based on the assumption that the local temperature at the radio source is close to the effective temperature of the bright loop and was computed using the
Lorentz collision model (Krall & Trivelpiece 1973),

$$\tau_{\text{col}} = \frac{4\pi n_e \lambda_D^3}{\omega_p \ln(12\pi n_e \lambda_D^3)} \approx \frac{3 \times 10^5 \lambda^3/2}{n_e \ln(12\pi n_e \lambda_D^3)},$$  

(8)

where $\lambda_D$ is the Debye length. The close match between the observed lifetime of the particle jets and the $\tau_{\text{col}}$ estimate suggests that these jets dissipate via collisions in the local plasma. The overall physical picture that emerges is that of the presence of numerous particle beams radiating via plasma emission mechanisms at a height of $\approx 1.14 R_\odot$. These particle beams damp on length scales of $7–8.5$ Mm within timescales of $0.5–2$ s. A consequence is that these beams must arise locally, implying that the magnetic reconnections giving rise to them must take place at these coronal heights. The emissions from the stronger of these particle beams are seen as individual bright fine features in the SPREDS.

The strength of the radio emission is found to be larger during the flare (Figure 8). This increase in emission is attributed to an enhanced presence of the bright fine features. The strength of these features is expected to follow a distribution. In the instances where attempts have been made to study the occurrence frequency distribution of their energies, several authors have found power-law distributions with steep negative slopes, often lower than $-2$, suggesting the presence of a large number of weak fine features (e.g., Mercier & Trottet 1997; Iwai et al. 2014; Mugundhan et al. 2016; Suresh et al. 2017). A similar situation is likely to prevail here. This would, in turn, imply the presence of a large number of fine features too faint to be observed individually and too numerous to be resolved and form the baseline coherent radio flux density. During the flare, their strength and occurrence rates increased, causing the observed raise in baseline flux density.

An implication of the above scenario is that particle beams arising from the reconnection sites should be bidirectional and must propagate both upward and downward. This should lead to short-lived emission features drifting to both higher and lower frequencies from their point of origin, corresponding to the beams propagating downward and upward, respectively (Aschwanden et al. 1993; Meléndez et al. 1999). While the time resolution of these data is insufficient to be able to see these drifts, they have a sufficient frequency resolution to be able to test a different prediction of this scenario. In addition to the drift, the intensity of the coherent emission observed should drop as these beams propagate due to collisional damping of these beams. Hence, the spectrum of these bright fine features should have a central peak at the frequency corresponding to the $\omega_p$ of the location of the acceleration event, with intensities falling as one moves farther from this spectral peak. The left panel of Figure 12 shows the SPREDS during the X-ray flare with some bright fine features numbered. These features were selected to span a range of flux densities, and their spectra are shown in the right panel. For the features that are largely confined to the observing bandwidth, a close examination of the SPREDS shows that their spectra indeed rise, reach a maximum, and then fall as the frequency increases. This is seen much more clearly in the spectra shown in the right panel. The small fluctuations seen in the spectra are noteworthy. Similar behavior has been observed for type IIIb solar bursts and interpreted as arising due to the presence of density inhomogeneities in the medium (Ellis 1969; de La Noe 1975; Loi et al. 2014; Kontar et al. 2017; Mugundhan et al. 2017). In the radio images used for this study, the typical rms of the flux densities in a blank sky region far from the Sun is $\approx 0.015$ SFU. The value was arrived at by estimating this rms value for all of the images used in the analysis and finding their median. We use this value as a representative estimate of the ($\sigma$) uncertainty in our flux densities. The fact that the observed fluctuations are orders of magnitude larger than the flux density uncertainty implies that they are significant.

As is evident from the panels in the right column of Figure 7, the bright fine features are seen during the entire observation period, though their occurrence frequency is comparatively very high during the heating phase of the flare. The observations in the pre-flare and flare decline phases happen to be centered at a frequency of 199 MHz, but they effectively probe the same region of the corona as inferred in Section 3.2. Hence, physical parameters like $\omega_p$ and $\tau_{\text{col}}$ are not remarkably different between these observing frequencies, making the analysis and conclusions drawn earlier in this section equally applicable to these observations too. Though the observations presented here are confined to a 15 MHz band ($\approx 10$ Mm in height range) at any given time, the similarities between the observations centered at 199 and 229 MHz suggest that a similar situation prevails across the combined observation band.
4.4. QPOs in Radio Flux Density

The top left panel of Figure 13 shows the SPREDS corresponding to the central MWA observation, which starts close to the initiation of the heating phase and continues well into the cooling phase. The vertical white dashed lines are drawn at intervals of 30 s. One of these lines was drawn next to a prominent fine feature, and it is evident that practically all of them are next to such one episode of emission. This periodicity is seen more clearly in the bottom panel of this figure. It shows the band-averaged radio light curve for all three SPREDS data smoothed by a running mean filter of 10 s temporal width, similar to the black curve in the left panel of Figure 8. The vertical green dashed lines are drawn at 30 s intervals, and the shaded area marks the period when the X-ray source was detectable in the 3–12 keV RHESSI channels (Figure 9). These panels demonstrate that there is an intrinsic preferred timescale of about 30 s at which a large number of bright fine features tend to bunch. The amplitudes of these oscillations are larger, and they are more regular when the heating is in progress (i.e., when the soft X-ray source is seen). Though they lose their regularity and are not as well formed, their presence is evident even during the nonheating phase. This suggests that the mechanism driving these QPOs can operate independently of the heating process, though they become more regular and prominent during the heating phase. As discussed in Section 4.3, the bright fine features are believed to be signatures of the presence of particle jets. Hence, their quasi-periodic bunching implies a similar bunching in the excitation of these particle jets.

It is widely believed that the magnetic foot-point motions due to random convective flows at the base of the photosphere lead to a buildup of magnetic stress (e.g., Parker 1972, 1983b, 1983a, 1988; Longcope & Tarr 2015). Tenerani et al. (2016) demonstrated that the tearing mode instabilities set up in such a system can give rise to reconnections at a rate fast enough to steadily heat the local corona. The 30 s period of the observed QPOs can be interpreted as the timescale at which the magnetic stress is built up and then relieved via fast reconnection events at the radio source height. Using the local Alfvén speed of $0.4 \text{ Mm s}^{-1}$ at the radio source region, the length scale corresponding to a duration of 30 s is $12 \text{ Mm}$. Interestingly, this length scale is very close to the twisting/braiding scale seen in the AIA 94 Å image of the bright loop region (Figure 13, top right panel). Since the magnetic fields threading the radio source region and the bright loop share a common magnetic foot point, they are subject to the same convective motions. Hence, it is reasonable to expect twisting or braiding in the various loops originating from the foot point to occur at similar spatial scales ($12 \text{ Mm}$, in our case). The timescale for a disturbance to travel across these braided structures would depend on the local Alfvén speed, which leads to a timescale of 30 s at the radio source region. The Alfvén speed in the regions

Figure 13. Top left: SPREDS during the X-ray flare. Vertical dotted lines in the SPREDS plot are drawn at 30 s intervals. Top right: zoomed AIA 94 Å image of the bright loop region obtained by averaging four images centered around 06:13:12 UT. Two overlapping loop strands are seen with a brightening close to the crossover location. Bottom: radio flux density light curve obtained by averaging all three SPREDS data over the 15 MHz observing band after they have been smoothed by a running mean filter of 10 s width. The shaded area is the period during which the X-ray source was detected, and the vertical lines are marked at 30 s intervals.
where EUV and X-ray emissions originate is close to 10 Mm s\(^{-1}\), leading to an Alfvén travel time across a braided structure of about 1 s. Therefore, while periodicity is evident in the radio data, we do not expect to see periodic behavior in the EUV observations because the Alfvén travel time in the bright loop region is too short compared to the current instrumental cadence. Our model suggests that such periodicity should exist and could become observable in the future as instrumentation providing finer time resolution becomes available.

The microflare must be driven by a significant enhancement in the rate of magnetic stress being built up in the magnetic loops involved. This, in turn, would lead to enhanced local heating and particle acceleration via reconnection events. The signatures of the former would be seen in X-ray (and EUV) emissions as ARTBs, and those for the latter would be seen in radio emissions as enhanced type I noise storm emission. If this is indeed true, as the magnetic disturbance must travel across the loops at Alfvén speed, there must be a lag between the appearance of these signatures in the X-ray and radio bands. It is therefore interesting to look for this lag and compare it with an estimate of Alfvén travel time based on NLFFF reconstruction and the Z model. The time difference between the epochs when the X-ray and radio sources attain their respective peak flux densities is about 50 s. The former peaks around 06:12:30 UT (Figure 9), close to the start of the heating event, while the latter attains the peak flux density around 06:13:20 UT (Figure 8). The Alfvén travel time, \(t_A\), from the common foot-point region to the height of the radio source, \(h\), was computed as \(\int_0^h dz/v_A(z)\), where \(v_A\) is the spatially varying Alfvén speed. Here \(t_A\) was estimated to be 60 s and is in remarkable agreement with the observed value.

The bright loop region is associated with active region AR 12203. It has been shown to be at a temperature higher than the ambient coronal temperature (Figure 5) and is also associated with a coherent nonthermal radio source (Figure 7). These imply that there is some mechanism in operation that is steadily maintaining it at a higher temperature and also powering the coherent radio emission. The presence of 30 s QPOs even before the X-ray flare implies that this too is a part of the ambient behavior, which does not owe its existence to the flare. Nonetheless, whatever disturbances gave rise to the flare also lead to these QPOs becoming more energetic and regular. In addition, the baseline coherent flux density, interpreted as arising from the superposition of numerous weak coherent emissions each arising from a weak electron jet, also shows a simultaneous systematic rise.

However, even if each of the relaxing braids was to conform to a periodicity of 30 s, a large number of such braids relaxing independently of one another would wipe out the signature of any periodicity in our data product. Hence, the clear presence of QPOs requires the existence of a network of braided magnetic strands that relax in unison. A promising possibility is a cascade-like process, where the relaxation of one particular braid in a magnetic loop sets off an avalanche of relaxation of braids in the interconnected strands, which are already in a near-critical stressed state (van Ballegooijen 1986; Wilmoth-Smith et al. 2011). Once this system relaxes, it takes about an Alfvén timescale to build up near-critical levels of magnetic stress, and the process continues. This interpretation suggests that the observed emission is dominated by the contribution from a prominent braided network that relaxes via a cascade-like process, giving rise to the quasi-periodic bundling of bright fine features in the SPREDS. This bundling of coherent fine features at a 30 s timescale manifested as the QPOs in the band-averaged radio light curve. Contributions from a large number of magnetic strands relaxing asynchronously give rise to the enhanced radio baseline flux density. This physical picture lends support in favor of the idea of small-scale magnetic rearrangements in the vicinity of sunspots powering radio noise storms suggested by Bentley et al. (2000).

5. Conclusion

In this work, we present a multiwaveband imaging study of an ARTB event using simultaneous imaging observations in meter-wave, EUV, and X-ray bands. A bright coronal loop was seen at the EUV coronal bands of the AIA. The evolution of the local temperature, density, and thermal energy obtained from DEM analysis shows a fast-rising phase in all of these quantities leading to a peak, which slowly relaxes back close to pre-flare levels by the end of the observations. For the duration of the heating phase, a transient X-ray source appeared in 3–12 keV low-energy RHESSI bands. The wave-band snapshot spectroscopic images showed this region to be associated with a persistent bright radio source with a mean \(T_R \approx 10^8\) K located at a height of around 1.14 \(R_s\). The SPREDS for the source bear a striking resemblance to the dynamic spectra of a type I noise storm. The radio flux density light curve for this source varied in consonance with the local thermodynamic properties estimated via DEM analysis. The spatial and temporal correlations between these disparate emissions establish that the high-energy and radio sources are a part of a single system powered by a common underlying mechanism. Magnetic field NLFFF extrapolations based on HMI vector magnetograms show large loop structures that share foot points with the bright EUV loop region and extend to the heights from where radio emission is expected to originate, providing independent evidence for the X-ray, EUV, and meter-wave sources being parts of a single system.

The energy deposited in the corona during the event was consistent with the energy budget for a typical microflare (3.2 \(\times\) \(10^{39}\) erg). The energy requirement for heating the plasma in the magnetic loop was estimated to be only about 5% of the magnetic free energy content in the region. Our rough estimates using the RTV scaling law suggest that it is indeed feasible for the plasma in the EUV loop to be heated from a pre-flare equilibrium value of 4 MK to a peak value of 6 MK over the observed duration. Similarly, the observed cooling time is also consistent with rough expectations based on the RTV scaling law. The SPREDS for the associated radio source show numerous short-lived (0.5–2 s) narrow-band (10–13 MHz) nonthermal slivers of emission (“bright fine features”). Our analysis suggests plasma emission as the only plausible emission mechanism for these bright fine features and rules out gyrosynchrotron and ECMI mechanisms. Each of these features, hence, must arise from an electron beam born at these coronal heights. The durations of the bright fine features are comparable to the ion–electron collision timescale at these heights. Their observed bandwidths lead to a coronal height range of 7–8.5 Mm, using a reasonable coronal electron density model. No spectral drifts were discernible in these features, perhaps due to the 0.5 s time resolution of these data. However, the observed spectral profiles were consistent with expectations for beams propagating both toward and away from the Sun. The band-averaged radio light curve showed that the
occurrence rate of these impulsive features increased and the observed baseline radio flux density rose while the flare was in progress. We interpret the latter to be due to the blending in of the numerous instances of weak emissions that are present simultaneously and are too faint to be resolved individually.

Very interestingly, the radio flux density light curve shows clear QPOs with a 30 s period. They are very well formed and regular during the phase when heating is underway. Though a little less regular, they are clearly seen in the pre-flare phase, implying that they must arise from a mechanism independent of the flare. Curiously, the Alfvén length scale corresponding to the QPO period at the height of the radio source is comparable to the braiding or twisting scale seen in the EUV images of the bright loop, despite their separation of ≈0.1 R⊙ in coronal height. We suggest that braiding/twisting occurs at the same spatial scale across this vast distance because the magnetic fields in these regions arise from a common foot point and are hence subject to similar convective motions. We find evidence for the disturbance responsible for the flare to be traveling at the spatially varying Alfvén speed to the height of the radio-emitting region. Overall, this suggests a physical picture where a large number of coronal reconnection events happen over a variety of spatial and energy scales asynchronously with respect to one another, forming the floor of the radio light curve. Superposed on this are the emissions from a dominant braided magnetic loop that quasi-periodically relaxes at the local Alfvén timescale via a cascade of reconnection events, giving rise to the periodic bunching of bright fine features in the SPREDS and the observed QPOs in the band-averaged radio flux density light curve.

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Software: CASA, SolarSoft Ware, Python 2.7,8 NumPy,7 Astropy,8 Matplotlib.8

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