

## LOW-FREQUENCY OBSERVATIONS OF TRANSIENT QUASI-PERIODIC RADIO EMISSION FROM THE SOLAR ATMOSPHERE

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### ABSTRACT

We report low-frequency observations of quasi-periodic, circularly polarized, harmonic type III radio bursts whose associated sunspot active regions were located close to the solar limb. The measured periodicity of the bursts at 80 MHz was  $\approx 5.2$  s, and their average degree of circular polarization (dcp) was  $\approx 0.12$ . We calculated the associated magnetic field  $B$  (1) using the empirical relationship between the dcp and  $B$  for the harmonic type III emission, and (2) from the observed quasi-periodicity of the bursts. Both the methods result in  $B \approx 4.2$  G at the location of the 80 MHz plasma level (radial distance  $r \approx 1.3 R_{\odot}$ ) in the active region corona.

*Key words:* Sun: corona – Sun: magnetic fields – Sun: oscillations – Sun: radio radiation

### 1. INTRODUCTION

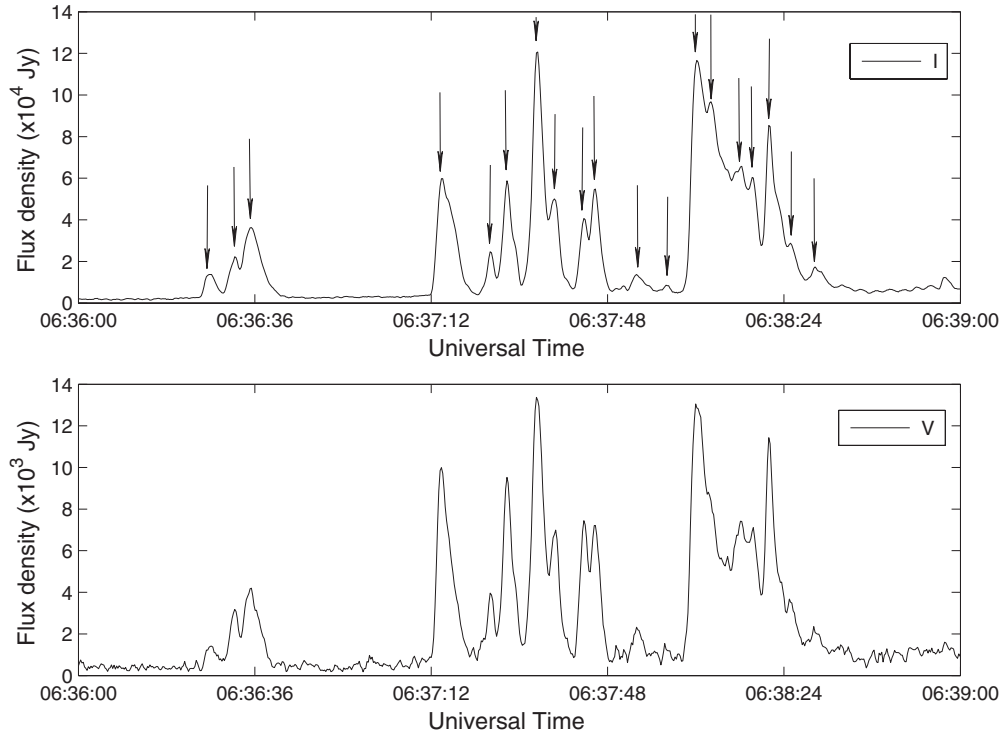
Type III solar radio bursts are the signatures of accelerated electrons streaming outward through the corona and the interplanetary medium in the aftermath of flares and weak chromospheric brightenings. The electrons stream at speeds  $\approx c/3$  along the open field magnetic field lines. The radio emission is widely accepted to be because of the following two-step process: (1) the excitation of high levels of plasma oscillations (Langmuir waves) by the propagating electron streams/beams and (2) subsequent conversion of these Langmuir waves into electromagnetic waves at the fundamental (F) and second harmonic (H) of the local plasma frequency. The H emission results from the coalescence of two Langmuir waves. The type III bursts are best identified on the dynamic spectra obtained using radio spectrographs. They appear as intense emission, drifting from high to low frequencies at  $\approx 100$  MHz  $s^{-1}$ . The above frequency drift results from the decrease of electron density, and hence the plasma frequency, with distance in the solar atmosphere. The bursts occur over the frequency range from  $\approx 1$  GHz to 10 kHz, corresponding to a distance range extending from the low corona to beyond the orbit of the Earth. The bursts occur either isolated or in groups. While the former has a lifetime of about few seconds at any given frequency, the groups of bursts last for  $\approx 5$  m (Suzuki & Dulk 1985). Groups of type III bursts are generally associated with flares observed in X-rays and/or  $H\alpha$ . They are a classic signature of the impulsive phase of flares in which the radiation is primarily non-thermal. It is believed that each individual burst is due to radiation associated with electron streams moving outward through the corona along large-scale diverging magnetic field lines connected to a common acceleration/injection site (Mercier 1975; Pick & Ji 1986). The occurrence of non-thermal bursts is a clear indication of particle acceleration during an event. Note that the generation of radio emission by non-thermal electron beams is very efficient due to the coherent nature of the emission mechanism. Most of the type III bursts are weakly, circularly polarized with degree of circular polarization (dcp)  $< 0.15$ . However, some bursts, those identified as due to fundamental plasma emission, have dcp  $\approx 0.5$  (Suzuki & Sheridan 1978; Dulk & Suzuki 1980). Harmonic emission is observed mainly at low frequencies. Note that the presence of the background magnetic field at the source region of type III radio bursts can give rise to a net dcp in the ordinary (“o”) mode for the escaping radiation (Melrose & Sy 1972; Melrose et al.

1978, 1980; Zlotnik 1981; Willes & Melrose 1997). The polarization observations of the H component of type III radio bursts are considered to be a better diagnostic tool to estimate the solar coronal magnetic field since the polarization of the F component is affected by propagation effects (Dulk & McLean 1978). In this paper, we report observations of quasi-periodic, harmonic type III bursts (Wild et al. 1963; Janssens et al. 1973; Mangeney & Pick 1989; Zhao et al. 1991; Aschwanden et al. 1994; Ramesh et al. 2003, 2005) and estimate the coronal magnetic field using the empirical relationship between the magnetic field and the dcp for the harmonic plasma emission (Melrose et al. 1978). We verified the results by independently estimating the magnetic field from the periodicity of the observed type III radio bursts. Interestingly both methods give consistent results, indicating the usefulness of ground-based low-frequency radio observations to estimate the coronal magnetic field, particularly over the range  $1.2 R_{\odot} \lesssim r \lesssim 2 R_{\odot}$ , where measurements at other wavelength bands in the electromagnetic spectrum are currently difficult.

### 2. OBSERVATIONS

The radio data reported in the present work were obtained at 80 MHz on 2012 September 20, 2013 January 18, and 2013 March 11 with the heliograph (Ramesh et al. 1998, 1999b, 2006a), the polarimeter (Ramesh et al. 2008), and the spectrograph (Ebenezer et al. 2001, 2007) at the Gauribidanur Observatory,<sup>1</sup> about 100 km north of Bangalore in India (Ramesh 2011). The coordinates of the array are longitude =  $77^{\circ}27'07''$  east and latitude =  $13^{\circ}36'12''$  north. The heliograph (Gauribidanur RAdio heliograPH, GRAPH) is a T-shaped radio interferometer array that produces two-dimensional images of the solar corona with an angular resolution of  $\approx 5' \times 7'$  (R.A.  $\times$  decl.) at the above frequency. The integration time is  $\approx 250$  ms and the observing bandwidth is  $\approx 2$  MHz. The polarimeter (Gauribidanur Radio Interference Polarimeter, GRIP) is an east–west one-dimensional array operating in the interferometer mode, and it responds to the integrated and polarized flux densities from the “whole” Sun. The half-power width of the response function (“beam”) of the GRIP is broad (compared to the Sun) in both right ascension/east–west direction ( $\approx 2^{\circ}$  at 80 MHz) and declination/north–south direction ( $\approx 90^{\circ}$ ). This implies that a plot of the GRIP data (i.e., the

<sup>1</sup> <http://www.iiap.res.in/centers/radio>



**Figure 1.** GRIP observations of group of type III solar radio bursts on 2012 September 20 at 80 MHz in Stokes  $I$  (upper panel) and Stokes  $V$  (lower panel). The arrow marks indicate the individual bursts.

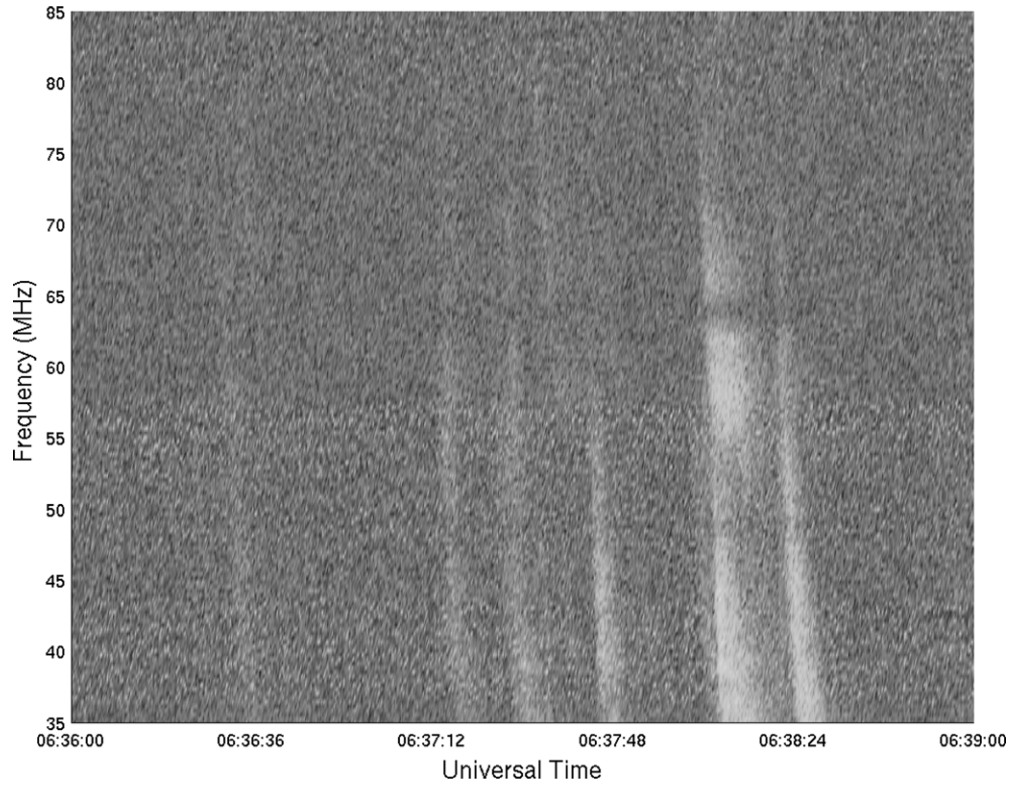
time profile) for observations in the transit mode is essentially the “east–west beam” of the array with an amplitude proportional to the strength of the emission from the “whole” Sun at the observing frequency, weighted by the antenna gain in that direction. The integration time is  $\approx 250$  ms, and the observing bandwidth is  $\approx 2$  MHz. The radio source(s) responsible for the circularly polarized emission observed with the GRIP are identified using the two-dimensional radioheliograms obtained with the GRAPH around the same time. Note that linear polarization, if present at the coronal source region, tends to be obliterated at low radio frequencies because of the differential Faraday rotation of the plane of polarization within the observing bandwidth (Grogard & McLean 1973). The spectrograph antenna system (Gauribidanur LOW-frequency Solar Spectrograph, GLOSS) is a total power instrument, and the half-power width of its antenna response of GLOSS is  $\approx 90^\circ \times 6^\circ$  (R.A.  $\times$  decl.) at 80 MHz. The integration time is  $\approx 100$  ms and the observing bandwidth is  $\approx 300$  kHz at each frequency. The width of the response of GLOSS in hour angle is nearly independent of frequency. The Sun is a point source for both the GRIP and the GLOSS. All three of the above instruments observe the Sun everyday during the interval 4–9 UT. The minimum detectable flux densities of the GRAPH, GRIP, and GLOSS are  $\approx 20$  Jy, 200 Jy, and 3000 Jy, respectively ( $1 \text{ Jy} = 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$ ).

Figure 1 shows the temporal evolution of the Stokes  $I$  and  $V$  radio emission from the solar corona at 80 MHz as observed with the GRIP on 2012 December 20 during the interval 06:36–06:39 UT, i.e., around the transit of the Sun over Gauribidanur. One can notice the presence of intense quasi-periodic emission in both the Stokes  $I$  and  $V$  time profiles. This is the characteristic signature of groups of type III solar radio bursts from the Sun (Suzuki & Dulk 1985). We verified the same from the dynamic spectra (85–35 MHz) obtained with GLOSS during the above interval (Figure 2). The peak Stokes  $I$  and  $V$  flux densities in Figure 1 are  $\approx 1.2 \times 10^5$  Jy and  $1.6 \times 10^4$  Jy,

respectively. The corresponding  $\text{dcp} = (|V\text{flux}|/I\text{flux})$  is  $\approx 0.11$ . Note the average flux density of the type III solar radio bursts reported in the literature is typically  $\approx 10^7$  Jy (Suzuki & Dulk 1985). This is about two orders of magnitude higher than the peak flux density of the type III burst of 2012 December 20, indicating that the latter is a weak event. The non-observations of the burst at high frequencies with the e-CALLISTO radio spectrometer at the Gauribidanur observatory support the above (Benz et al. 2009). The estimated average periodicity of the radio emission in Figure 1 is  $\approx 4.5$  s in both Stokes  $I$  and  $V$ . The source region of the bursts was identified from the radioheliogram obtained with the GRAPH around the same time (Figures 3 and 4). We note that the bursts originated close to the solar limb. They were associated with an SF class H $\alpha$  flare from AR 11574<sup>2</sup> located at S25W69.<sup>3</sup> A shift in the solar radio source position due to ionospheric effects is expected to be  $\lesssim 0.1 R_\odot$  at 80 MHz in the hour angle range  $\pm 2$  hr (Stewart & McLean 1982). The present observations were carried out close to the transit of the Sun over the local meridian at Gauribidanur. Similarly, the effects of scattering (irregular refraction due to density inhomogeneities in the solar corona) on the observed source position are also considered to be small at 80 MHz compared to lower frequencies (Aubier et al. 1971; Bastian 2004; Ramesh et al. 2006b). The positional shift of discrete solar radio sources due to scattering is expected to be  $\lesssim 0.2 R_\odot$  at 80 MHz (Riddle 1974; Robinson 1983; Thejappa et al. 2007). Ray-tracing calculations employing realistic coronal electron density models and density fluctuations show that the turning points of the rays that undergo irregular refraction almost coincide with the location of the plasma (“critical”) layer in the non-scattering case even at 73.8 MHz (Thejappa & MacDowall 2008). Obviously, the situation should be better at 80 MHz. Note

<sup>2</sup> <http://www.swpc.noaa.gov/>

<sup>3</sup> [http://www.lmsal.com/solarsoft/latest\\_events/](http://www.lmsal.com/solarsoft/latest_events/)



**Figure 2.** GLOSS dynamic spectra (85–35 MHz) of the group of type III solar radio bursts in Figure 1.

**Table 1**  
Parameters Related to the Group of Type III Radio Bursts Observed with the Gauribidanur Facilities

S. No.	Date	Time (UT)	Period $p$ (s)	Alfvén Speed $v_A$ ( $\text{km s}^{-1}$ )	Sunspot Heliographic Co-ordinates	Viewing Angle $\theta$ (deg)	dcp	Magnetic Field $B$ (G)	
								Harmonic Emission <sup>a</sup>	Quasi-periodic Emission <sup>b</sup>
1	2012 Sep 20	06:35–06:38	4.5	2222	S25W69	71	0.13	$4.7 \pm 1$	$4.8 \pm 0.3$
2	2013 Jan 18	06:51–06:57	6.4	1562	N18W88	88	0.08	$2.9 \pm 1$	$3.4 \pm 0.3$
3	2013 Mar 11	07:00–07:03	4.8	2083	N10E88	88	0.14	$5.0 \pm 1$	$4.5 \pm 0.3$

**Notes.**

<sup>a</sup> See Section 3.1 for details.

<sup>b</sup> See Section 3.2 for details.

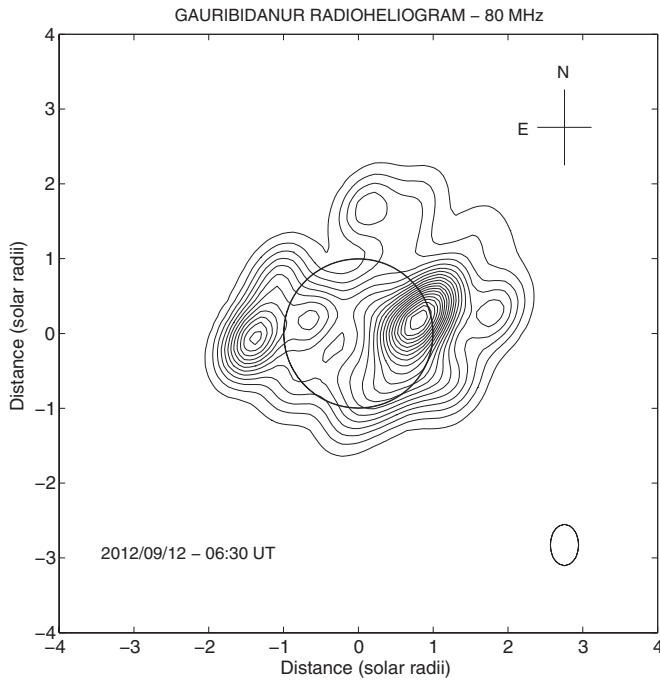
that high angular resolution observations of the solar corona indicate that discrete radio sources of angular size  $\approx 1'$  are present in the solar atmosphere from where low-frequency radio radiation originates (Kerdraon 1979; Lang & Willson 1987; Willson et al. 1998; Ramesh et al. 1999a; Ramesh & Sastry 2000; Ramesh & Ebenezer 2001; Mercier et al. 2006; Kathiravan et al. 2011; Ramesh et al. 2012). The projection effects are also expected to be minimal since we have used only the limb events for the present work (see, e.g., Figure 4). The details related to the type III radio burst 2012 December 20 described above and the other two events (2013 January 18 and 2013 March 11) are listed in Table 1.

### 3. ANALYSIS AND RESULTS

#### 3.1. Estimate of $B$ from the Estimated dcp of the Type III Radio Bursts

Wild et al. (1959) pointed out that both the fundamental (F) and the harmonic (H) type III solar radio burst emission should generally be observable only for events near the center of the solar disk. Elsewhere, it should be purely harmonic emission.

This is because the F emission is more directive compared to the H emission. According to Caroubalos & Steinberg (1974), the ground-based observations of type III radio bursts associated with sunspot regions located  $\gtrsim 70^\circ$  to either the east or west of the central meridian on the Sun are primarily H emission. The F component has a limiting directivity of  $\pm 65^\circ$  (from the central meridian on the Sun) at 80 MHz (Suzuki & Sheridan 1982). A similar result was recently reported by Thejappa et al. (2012) for the very low frequency solar type III radio bursts observed in the interplanetary medium. Note that the heliographic longitudes of the sunspot regions associated with the type III radio bursts in the present case are all  $\gtrsim 70^\circ$  (see Table 1). The estimated values of dcp for all three events in the present case are close to the average dcp ( $\approx 0.11$ ) reported for the circularly polarized H component of the type III bursts (see Table 1). For the F component, the reported average dcp  $\approx 0.35$  (Dulk & Suzuki 1980). The above arguments on the directivity and the dcp indicate that the type III bursts observed in the present case are due to H emission. Under such circumstances, the magnetic field ( $B$ ) near the source region of the bursts can be calculated using the following relationship (Suzuki & Sheridan 1978; Dulk & Suzuki 1980; Mercier 1990;



**Figure 3.** GRAPH radioheliogram obtained on 2012 September 20 around 06:30 UT, prior to the quasi-periodic type III burst emission in Figure 1. The open circle at the center represents the solar limb. The size of the GRAPH beam at 80 MHz is shown near the lower right. The intense discrete source close to the west limb is the source region of the type III bursts in Figures 1 and 2.

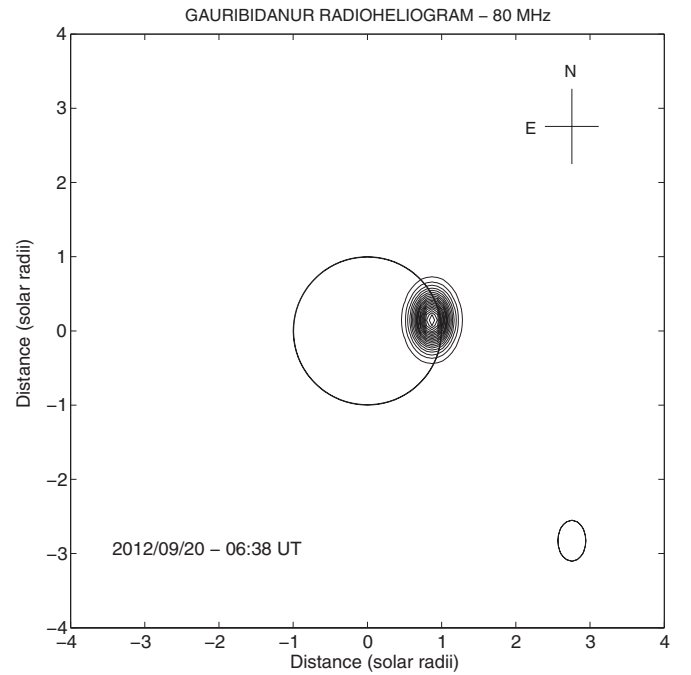
Reiner et al. 2007; Melrose et al. 1978; Zlotnik 1981; Ramesh et al. 2010a):

$$B = \frac{f_p \times dcp}{2.8a(\theta, \theta_0)}, \quad (1)$$

where  $f_p$  is the plasma frequency in MHz and  $B$  is in Gauss.  $a(\theta, \theta_0)$  is a slowly varying function that depends on the viewing angle  $\theta$  between the magnetic field component and the line of sight, and the angular distribution  $\theta_0$  of the Langmuir waves. In the present case,  $\theta \approx 70^\circ$ – $90^\circ$  (see Table 1). We assumed  $f_p = 40$  MHz since the observed emission at 80 MHz is most likely the H component. The Langmuir waves are considered to be confined to a small range of angles, i.e., a cone of opening angle  $\theta_0 \approx 10^\circ$ – $30^\circ$  in the magnetic field direction for harmonic type III emission in the “o” mode (Melrose et al. 1978; Dulk & Suzuki 1980; Willes & Melrose 1997; Benz 2002). Assuming the average value, i.e.,  $\theta_0 \approx 20^\circ$ , we find that  $a(\theta, \theta_0) \approx 0.4$  in the aforementioned range of  $\theta$  (Melrose et al. 1980; Gary 1982; Suzuki & Dulk 1985). The estimated magnetic field values using Equation (1) for the type III events reported in the present work are listed in Table 1. Figure 5 shows the  $B$  values corresponding to the individual bursts in the quasi-periodic type III burst emission observed on 2012 September 20 (Figure 1). They remain approximately constant, within the error limits. We found that the  $B$  values corresponding to the bursts observed on 2013 January 18 and 2013 March 11 also exhibit a similar trend.

### 3.2. Estimate of $B$ from the Observed Quasi-periodicity of the Type III Radio Bursts

The term quasi-periodicity or pulsations in solar radio physics refers to the quasi-periodic amplitude variations in the time profile of the observed radio flux at any particular observing frequency. The associated physical mechanisms have been

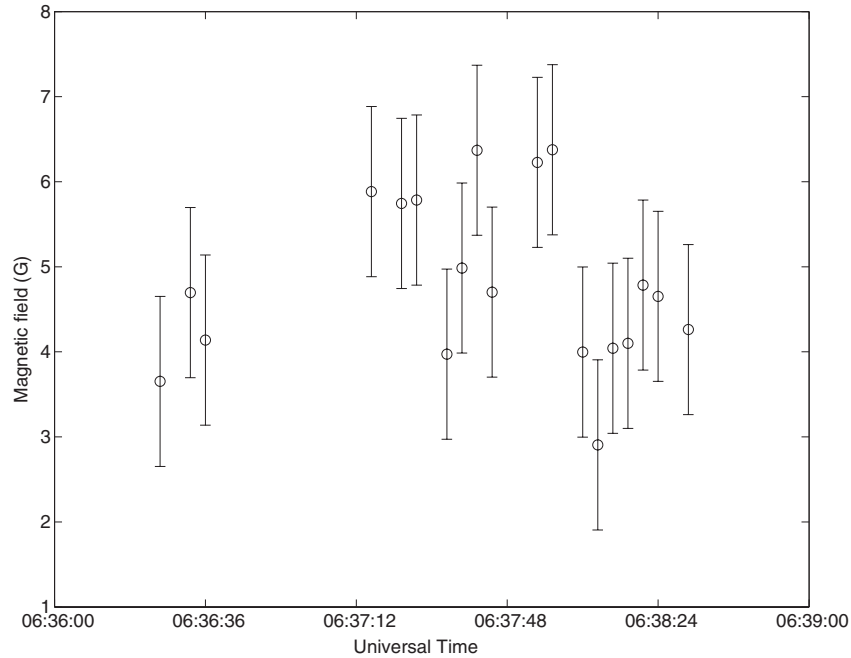


**Figure 4.** Same as Figure 3 but obtained during the peak phase of the burst in Figure 1 at  $\approx 06:38$  UT.

classified into three categories to date: (1) modulation of the emission by coronal loop oscillations, (2) intrinsic oscillations of the emission created by oscillatory wave–wave interactions and wave–particle interactions, and (3) modulation of the electron acceleration/injection process responsible for the emission (Aschwanden 1987; Nindos & Aurass 2007). Out of this, category (2) can be ruled out in the present case since they apply primarily to the fundamental “o” mode and harmonic extra-ordinary mode (“e” mode), whereas the type III bursts reported in the present work correspond to the harmonic “o” mode as mentioned in Section 3.1 (Aschwanden & Benz 1988). In view of this, we have carried out the calculations for categories (1) and (3) in the remainder of this section. Laboratory experiments and numerical simulations have shown that the release of magnetic energy by reconnection must be considered as a highly time-dependent process (see, e.g., Pick & van den Oord 1990). According to Kliem et al. (2000), the temporal variations in the radio burst flux are caused by modulations of the particle acceleration in a highly dynamic reconnection process. A similar model, i.e., quasi-periodic reconnection and particle injection, was also reported by Zlotnik et al. (2003). The authors had noted that even a very small ( $\approx 2\%$ ) quasi-periodic modulation of the magnetic field is sufficient for periodic electron acceleration. Both of these models belong to the category (3) mentioned above and were successful in explaining the associated observations. The modulation is likely to be communicated on a magnetohydrodynamic (MHD) timescale in the acceleration region (Tajima et al. 1987; Aschwanden et al. 1994; Kliem et al. 2000; Asai et al. 2001). In such a case, the corresponding Alfvén speed ( $v_A$ ) can be estimated as

$$v_A \approx l/p, \quad (2)$$

where  $p$  is the period of the quasi-periodic emission in seconds (s) and  $l \approx 10,000$  km is the typical dimension of the region over which the type III radio-burst-producing electrons are injected (Lantos et al. 1984; Aschwanden 2002). It is possible that the



**Figure 5.**  $B$  values corresponding to the individual type III bursts in the quasi-periodic emission in Figure 1, based on the relationship between  $B$  and  $dcp$ .

individual bursts that are temporally separated in a type III group are also spatially fragmented within the same acceleration region (Pick & van den Oord 1990; Vlahos & Raoult 1995; Isliker et al. 1998). Considering category (1) where the observed quasi-periodicities are caused by the MHD oscillations of the associated coronal loop(s), the corresponding relationship for the Alfvén speed is (Roberts et al. 1984)

$$v_A = 2.6a/p, \quad (3)$$

where  $a \approx 3500$  km is the width of the coronal loop. According to Aschwanden (1987), the quasi-periodic emission observed in the upper part of the corona from where the meter–decameter wave radio emission originates, particularly that due to plasma processes as in the present case, is best described by the above model. Asai et al. (2001) showed that the quasi-periodic pulsation observed by them in the microwave range is due to the modulation of the acceleration/injection rate of the non-thermal electrons by the oscillations in the associated coronal loop(s). Once  $v_A$  is known in either category (1) or (3), the associated magnetic field ( $B$ ) can be calculated from the definition of the former:

$$v_A = 2.05 \times 10^6 B N_e^{-1/2}. \quad (4)$$

$N_e$  is the electron density in units of  $\text{cm}^{-3}$  and can be estimated using the relationship  $f_p = 9 \times 10^{-3} N_e^{1/2}$ . Note that  $v_A$  in Equation (3) is in units of  $\text{km s}^{-1}$ . The  $v_A$  and  $B$  values estimated using Equations (2) and (4) for the type III events reported in the present work are listed in Table 1. Equations (3) and (4) result in nearly the same values for  $v_A$  and  $B$ .

#### 4. SUMMARY

We have reported estimates of the coronal magnetic field using low-frequency (80 MHz) radio observations of quasi-periodic harmonic type III burst emission associated with sunspot regions close to the solar limb. The data were obtained with the heliograph, the polarimeter, and the spectrograph at

the Gauribidanur observatory. Though several type III bursts are observed everyday with the aforementioned suite of instruments, we selected only those events with  $dcp \lesssim 0.15$  and whose associated source region is close to the limb of the Sun. The above are the criteria to identify a harmonic type III burst as mentioned earlier. Also, we limited ourselves to data obtained close to the transit of the Sun over the local meridian at Gauribidanur in order to minimize errors in the source position due to propagation effects. We adopted two independent approaches to estimate the magnetic field: (1) based on the relationship between the  $dcp$  and the  $B$  for harmonic type III radio burst emission, and (2) using the quasi-periodicity in the observed type III radio burst emission. Both methods give the same result, i.e., the average  $B \approx 4.2$  G. We would like to note here that the often referred empirical relationship for the coronal magnetic field (Dulk & McLean 1978) predicts  $B \approx 3$  G at 80 MHz. We had assumed the 80 MHz plasma level to be located at radial distance  $r \approx 1.3 R_\odot$  in the solar atmosphere for the above calculation (Ramesh et al. 2011). Note that Lin et al. (2004) had measured  $B \approx 4$  G at  $r \approx 1.1 R_\odot$  using Zeeman splitting observations of the Fe XIII 1075 nm coronal emission line from an active region close to the solar limb. Assuming that  $B \propto r^{-1.5}$  (Dulk & McLean 1978), we find that the above measurement indicates  $B \approx 3.1$  G at  $r \approx 1.3 R_\odot$ . The present estimates are also in reasonable agreement with that of Ramesh et al. (2010b), who had reported  $B \approx 5 \pm 1$  G at 77 MHz for radio sources associated with the coronal streamers at  $r \approx 1.5 R_\odot$ . Note that the type III radio bursts are considered to be closely associated with the coronal streamers (Kundu et al. 1983). We would like to add here that the estimated  $v_A$  in the present case (see Table 1) are consistent with the corresponding values reported by Gopalswamy et al. (2001) and Vrřnak et al. (2002) for the active region solar corona.

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