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Coronal Magnetic Field Lines and Electrons Associated with Type III–V Radio Bursts in a Solar Flare

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Abstract. We recently investigated some of the hitherto unreported observational characteristics of the low frequency (85–35 MHz) type III–V bursts from the Sun using radio spectropolarimeter observations. The quantitative estimates of the velocities of the electron streams associated with the above two types of bursts indicate that they are in the range $\gtrsim 0.13c$–$0.02c$ for the type V bursts, and nearly constant ($\approx 0.4c$) for the type III bursts. We also find that the degree of circular polarization of the type V bursts vary gradually with frequency/heliocentric distance as compared to the relatively steeper variation exhibited by the preceding type III bursts. These imply that the longer duration of the type V bursts at any given frequency (as compared to the preceding type III bursts) which is its defining feature, is due to the combined effect of the lower velocities of the electron streams that generate type V bursts, spread in the velocity spectrum, and the curvature of the magnetic field lines along which they travel.

Keywords. Sun—corona—magnetic field—flares—radio bursts—polarization.

1. Introduction

Type V bursts are relatively unusual solar radio transients. They appear as diffuse continuum following some of the type III bursts, and are usually observed in the frequency range ≈120–1 MHz. The emission is due to plasma processes similar to the type III bursts excited by energetic electrons that propagate outwards through the solar atmosphere from the flaring region. The electrons generate Langmuir waves at the local plasma frequency f_p along their path. Some of the energy of the Langmuir waves are converted into electromagnetic radiation either at the fundamental frequency ($f = f_\mathrm{p}$), or the second harmonic frequency ($f = 2f_\mathrm{p}$), or both. The main difference between the two types of bursts is in their respective durations at any given frequency. The duration is shorter for the type III bursts and longer for the type V bursts. The primary motive of the present work is to understand the reasons for this. Moving further, we find that the geometry of the field lines along which the type V burst electrons propagate is also yet to be established. Observations of polarized radio emission is a potential tool to verify this. Note that plasma emission in the presence of a magnetic field is split into ordinary (O) and the extraordinary (X) modes. Due to the differential absorption of the above two modes in a medium like the solar corona, a net degree of circular polarization (dcp) can be observed (Hariharan *et al.* 2014, 2016a; Melrose & Sy 1972; Sasikumar Raja & Ramesh 2013). This indicates that by carrying out observations of a type III–V event simultaneously at different frequencies in both Stokes I and V, the variation of the dcp of the aforementioned two bursts with the heliocentric distance (r) can be independently estimated. The results are expected to be useful to infer whether the electron streams corresponding to the type III and type V bursts in a type III–V event propagate along the same set of field lines or not. Ground-based radio spectropolarimeter observations at low radio frequencies (<100 MHz) are particularly useful in this regard since the velocities of the electron streams associated with the above bursts, and the variation of the dcp of the bursts with r can be obtained in a relatively straight forward manner. Note that emission in the above frequency range originates typically in the near-Sun corona ($r \approx 1.1-2.0R_\odot$) which is currently difficult to observe in whitelight. The radio observations have the unique advantage of simultaneously observing emission from the corona above the solar disk as well as off its limb (see for example, Kathiravan *et al.* 2002; Kathiravan & Ramesh 2004). Further, they are sensitive to weak energy releases since the associated non-thermal radio emission generally have high brightness temperatures due to the coherent nature of the plasma emission mechanism (Hariharan *et al.* 2016b; Mugundhan *et al.* 2016; Ramesh *et al.* 2010, 2013a).

2. Observations

The radio observations were carried out during 2014 July–2015 May with the Gauribidanur RAdio SpectroPolarimeter (GRASP; Kishore *et al.* 2015). The frequency range of observations is 85–35 MHz. The antenna and the receiver systems were calibrated by carrying out observations in the direction of the Galactic Center as described in Kishore *et al.* (2015). Figure 1 shows the Stokes I and Stokes V spectrum of the type III and type V solar radio bursts obtained from the GRASP observations on 2014 December 14 in the interval 04:27–04:30 UT. The onset of the type III burst (immediately preceding the type V burst) at 85/35 MHz is ≈04:28:31/04:28:34 UT, and that of the type V burst at 85/35 MHz is ≈04:28:40/04:28:49 UT. The aforementioned bursts were also present in the Gauribidanur LOw-frequency Solar Spectrometer (GLOSS; Ebenezer *et al.* 2001, 2007; Kishore *et al.* 2014) observations (in total intensity) during the same epoch. This helped to independently verify their spectral type. The Geostationary Operational Environmental Satellite (GOES) recorded a C8.6 class soft X-ray flare from AR12241 located at the heliographic coordinates S10E73 on the Sun[1] around the same time as the radio bursts in Figure 1. So the latter are most likely due to activity in the above sunspot region. The above details for the bursts reported in the present work are listed in Table 1 (see columns 2–4). Note that we specifically selected only those bursts whose associated sunspot regions were located at heliographic longitudes >70° so that the projection effects are minimal. Further, we imposed the condition that the bursts should have been observed elsewhere[2] also during the same epoch as the GRASP observations. Though six limb type V bursts were reported (from Stokes I observations at other observatories) during our observing period (≈2–9 UT everyday), we found from the GRASP observations that only three of them had measurable circular polarization. The sense of polarization for all the three type V bursts reported in the present work are same as that of the preceding type III bursts. Figure 2 shows the average half-power duration (d) of the type V bursts estimated from the GRASP observations. At a typical frequency like 80 MHz, the values are 10× larger than that of the type III bursts which precede them (see for example, Figure 1).

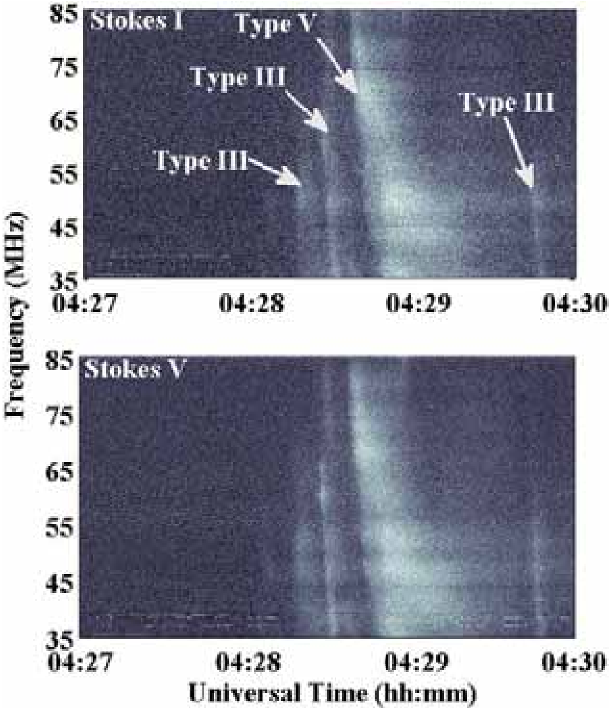

Figure 1. Stokes I and Stokes V dynamic spectra of the type III and type V bursts observed with the GRASP on 2014 December 14.

Table 1. Details related to the bursts observed with GRASP.

Date	Burst time (UT)	Sunspot region	Soft X-ray flare flux (W/m^2)
1	2	3	4
2014/07/09	04:38	N13W71	1.7e-6
2014/12/14	04:29	S10E73	8.6e-6
2015/05/08	07:39	N16E79	8.0e-7

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[1] www.lmsal.com/solarsoft/latest_events

[2] ftp://ftp.swpc.noaa.gov/pub/warehouse

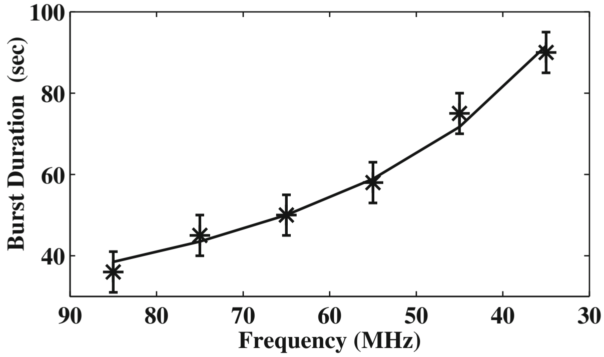

Figure 2. Estimated durations of the type V bursts at different frequencies for the events reported in Table 1. The asterisks indicate the average value at each frequency. The solid line is the power-law fit to the latter. The fit equation is $d = 2969 f^{-0.9782}$.

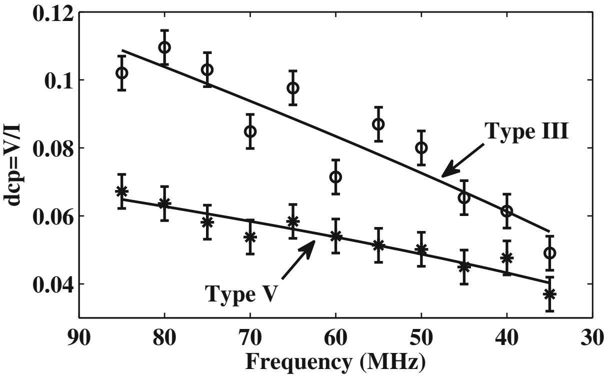

Figure 3. Variation of the estimated dcp with frequency for the type III and V bursts reported in the present work. The circle (type III burst) and asterisk (type V burst) symbols indicate the average value at each frequency. The solid lines are the power-law fits to the estimates. The fit equations are $\mathrm{dcp} = 0.003699 f^{0.761}$ for the type III bursts and $\mathrm{dcp} = 0.005962 f^{0.5372}$ for the type V bursts.

3. Analysis and results

Figure 3 shows the estimated average dcp at different frequencies for the type III–V bursts reported in the present work. The power-law fit to the estimates indicate that $\mathrm{dcp} \propto f^{0.54}$ for the type V bursts, and $\mathrm{dcp} \propto f^{0.76}$ for the type III bursts. Since the frequency range (and hence the heliocentric distance range) of both the above types of bursts are the same, the most plausible explanation for the comparatively gradual variation of the dcp with r in the case of type V bursts reported in the present work is that the associated electron streams travel along magnetic field lines with larger curvature compared to the type III bursts. In this regard we find that (1) the sign of the Stokes V emission remained unchanged in each of the type V bursts during their entire duration, similar to the preceding type III bursts (see for example, Fig. 1). Note that Stokes V emission with positive/negative sign will have brighter/darker shade in the spectra; (2) the type V bursts drifted towards the lower frequencies (i.e. forward drift) as a function of time, similar to the preceding type III bursts (see for example, Fig. 1). Since the type III bursts are known to be generated by energetic electrons that travel outward along open magnetic field lines through the corona, the above findings imply that the type V burst electrons also propagate along similar open field lines. Note that in the case of closed loop geometry the aforementioned drift should turn around (continuously in frequency) after a while, and then progress towards the higher frequencies (i.e. reverse drift) with time (Suzuki & Dulk 1985). Moreover, at any given frequency, the sense of polarization should be different for emission observed during the forward and reverse drifts of the burst. We did not observe the above signatures in the events reported in the present work (see for example, Fig. 1). These facts reinforce our above arguments related to propagation of type V burst electron streams along open field lines.

We calculated the velocities of the electron streams responsible for the type III and type V bursts in Fig. 1 from the difference between their respective onset times at 85 MHz and 35 MHz (see section 2), and the distance between the plasma layers corresponding to the above two frequencies. We used the coronal electron density model proposed by Vršnak et al. (2004) for the latter since the scale height in the above model ($\approx 2.7 \times 10^5$ km) is consistent with that of the active regions (Aschwanden & Acton 2001). The heliocentric distances of the 85 MHz and 35 MHz plasma layers are $\approx 1.36 R_\odot$ and $\approx 1.88 R_\odot$, respectively, in the above model. This implies that the separation between them is $\approx 0.52 R_\odot$. The estimated velocities using the corresponding time and distance details are $v \approx 0.4c$ for the type III bursts, and $v \approx 0.13c$ for the type V bursts. We would like to point out here that the 'true' velocity in the case of the type V bursts will be still lower (i.e. $\lesssim 0.13c$) since the associated electron streams travel along field lines whose length between the 85 MHz and 35 MHz plasma layers is expected to be $\gtrsim 0.52 \mathrm{R}_\odot$ because of the larger curvature (see previous paragraph). We also estimated the velocities of type III and type V burst electron streams in Fig. 1 around the time at which the burst intensity was the maximum, and the end time of the bursts. In the case of the type III burst, the velocities at all the above three epochs are nearly the same. But for the type V burst, they are different. The velocities are $v \gtrsim 0.05c$ during the maximum phase of the burst, and $\gtrsim 0.02c$ close to the end phase of the burst. The above results indicate that the electrons responsible for the type V burst in Fig. 1 have a spread in their velocities, i.e. $v \gtrsim 0.13c{-}0.02c$. We found that the other events in Table 1 also exhibit a similar trend. This implies that the longer lifetime of a type V burst at any given frequency is due to the presence of slower electrons with a range of velocities. The lifetime can be further longer, if the type V electron streams happen to travel along field lines with larger curvature as in the present case. Note that all the type III bursts are not followed by type V bursts. It depends on the velocity distribution of the electrons with positive slope in the associated flaring region (Lin *et al.* 1981; Raoult *et al.* 1990).

We find that the number of electrons (N) associated with the burst can be calculated as $N \approx n_{\mathrm{n}} A \overline{v} d$, where n_n is the non-thermal electron density, A is the area of the source, and $\overline{v}$ is the average velocity of the electrons responsible for the burst. Typical source sizes at 80 MHz are $\approx 10^{20}$ cm^2 (Gopalswamy & Kundu 1987). In the present case $d \approx 40$ s at 80 MHz (see Fig. 2) and $\overline{v} \approx 0.08c$. From the above values we obtain $N \approx 9.6 \times 10^{30} n_{\mathrm{n}}$. The electron density ($n_{\mathrm{e}}$) corresponding to 40 MHz (fundamental plasma frequency) is 2×10^{7} cm^{-3}. The ratio of the non-thermal electron density to ambient density ($n_{\mathrm{n}}/n_{\mathrm{e}}$) is typically $\sim 10^{-6}$ (Melrose 1980). Therefore we get $N \approx 1.9 \times 10^{32}$. This is nearly equal to the number of electrons associated with the type III radio bursts ($\approx 7.2 \times 10^{31}$) that preceded the type V bursts in the present work. Note that we assumed $d \approx 3$ s (see Fig. 1), $\overline{v} \approx 0.4c$, and the type III burst source size at 80 MHz to be the same as the type V burst for the above calculation (Gopalswamy & Kundu 1987). These results suggest that the electrons leading to the type V bursts and the preceding type III bursts are accelerated in the same region.

4. Summary

We carried out analysis of the type III–V solar radio bursts observed with the radio spectropolarimeter in the Gauribidanur Observatory. Our results indicate that the longer duration of the type V burst as compared to the preceding type III burst in the type III–V events at any given frequency is due to the presence of slower electrons with a range of velocities (i.e. electrons with low energies) in the acceleration region, and their propagation along open field lines with larger curvature compared to the type III bursts. It is hoped that 2D imaging observations of type III bursts and type V bursts (simultaneously in both Stokes I and V) with an upgraded facility like Gauribidanur RAdioheliograPH (GRAPH, Ramesh *et al.* 1998, 2006; Ramesh 2011), combined with white light observations using Variable Emission Line Coronagraph (VELC) onboard the upcoming space mission like ADITYA-1 (Singh *et al.* 2011) over $r \approx 1.1{-}3.0 R_{\odot}$ will help to identify the associated coronal structures and their magnetic topology (Pick *et al.* 1979; Trottet *et al.* 1982). Note that it might also be possible to estimate the field strength of the latter using the radio observations under favourable conditions (see for example, Ramesh *et al.* 2003, 2011, 2013b).

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