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LOW-FREQUENCY OBSERVATIONS OF POLARIZED EMISSION FROM LONG-LIVED NON-THERMAL RADIO SOURCES IN THE SOLAR CORONA

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ABSTRACT

We report observations of circularly polarized emission from the solar corona at 77 MHz during the periods 2006 August 11–18, 2006 August 23–29, and 2007 May 16–22 in the minimum phase between the sunspot cycles 23 and 24. The observations were carried out with the east–west one-dimensional radio polarimeter at the Gauribidanur observatory located about 100 km north of Bangalore. Two-dimensional imaging observations at 77 MHz during the same period with the radioheliograph at the same observatory revealed that the emission region co-rotated with the Sun during the three aforementioned periods. Their rotation rates, close to the central meridian on the Sun, are $4\farcm6$, $5\farcm2$, and $4\farcm9 \pm 0\farcm5$ per day, respectively. We derived the radial distance of the region from the above observed rotation rates and the corresponding values are $\approx 1.24 \pm 0.03\,R_\odot$ (2006 August 11–18), $\approx 1.40 \pm 0.03\,R_\odot$ (2006 August 23–29), and $\approx 1.32 \pm 0.03\,R_\odot$ (2007 May 16–22). The estimated lower limit for the magnetic field strength at the above radial distances and periods are $\approx$1.1, 0.6, and 0.9 G, respectively.

Key words: Sun: activity – Sun: corona – Sun: magnetic topology – Sun: radio radiation – Sun: rotation – sunspots

1. INTRODUCTION

The magnetic field dominates most of the solar corona, playing a crucial role in the formation and evolution of the structures there. Despite its fundamental importance, only a few direct measurements of the coronal magnetic field are available (see Lin 2005 for a review on the topic). Extrapolation of the observed solar surface magnetic field distribution under the assumption that it is potential or force-free is the most widely used technique (Schatten et al. 1969; Schrijver & Derosa 2003). In the radio domain, high-resolution circular polarization observations at microwave frequencies (~GHz) have been used to measure the field strengths at a radial distance $r \simeq 1.05\,R_\odot$ above sunspot regions (see reviews by Gelfreikh 2004; White & Kundu 2007). Moving to larger r, it is possible to obtain information on coronal magnetic fields through: (1) Faraday rotation observations (at $r \gtrsim 5\,R_\odot$) of microwave signals emitted by transmitters on board artificial satellites and distant background cosmic sources that pass through the solar corona (Pätzold et al. 1987; Spangler 2005) and (2) low-frequency observations of circularly polarized radio emission from transient burst emission of various types in the middle corona, i.e., $1.2\,R_\odot < r < 3\,R_\odot$ (see, e.g., Dulk & McLean 1978). Recently, Sastry (2009) and Ramesh et al. (2010) showed that radio emission from the "undisturbed" solar corona in the presence of a magnetic field also gives rise to observable circular polarization at low frequencies. 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 (Grognard & McLean 1973). Among the different coronal structures observed at low radio frequencies, the noise storm continuum sources are one of the potential candidates for the estimation of the magnetic field, particularly in the middle corona, since they are usually circularly polarized and constitute the most frequently observed type of solar activity. Unlike the transient radio bursts which relate to solar flares, the noise storms primarily relate to non-flaring sunspot active regions and last much longer than flares. The emission consists of occasional short-lived (<1s) narrowband radio enhancements (type I or noise storm bursts), often superimposed on continuous, slowly varying, long-lasting (for hours to days) broadband background emission called type I or noise storm continuum (see reviews by Elgarøy 1977; Kai et al. 1985). It is now generally accepted that the radiation is due to fundamental (F) plasma emission and the observed circular polarization results from propagation effects in the presence of a magnetic field. The radio polarization is of the ordinary "*o*" mode and corresponds to the magnetic polarity of the leading spot (Kai et al. 1985; Benz 1993). We show in this paper that it is possible to determine the magnetic field in the non-flaring corona from observations of circularly polarized emission from the noise storm continuum source when the associated degree of circular polarization (dcp) is $\lesssim$1 during the central meridian passage (CMP) of the source.

2. OBSERVATIONS

As mentioned in the abstract, the radio data reported were obtained at 77 MHz with the east–west one-dimensional polarimeter at the Gauribidanur observatory (Ramesh et al. 2008) and at 77 MHz with the Gauribidanur radioheliograph (GRH; Ramesh et al. 1998) during the following periods: 2006 August 11–18, 2006 August 23–29, and 2007 May 16–22. For information on the photospheric magnetic field, we used data obtained with the Michelson Doppler Imager (MDI; Scherrer et al. 1995) on board the *Solar and Heliospheric Observatory* (*SOHO*). The antennas in the polarimeter array are non-steerable and fixed vertically pointing toward the zenith. The response function (beam) of the array is broad (compared to the Sun) in both right ascension/east–west direction ($\approx 2°$) and declination/north–south direction ($\approx 90°$). This implies that a plot of the output data is essentially the "east–west beam" of the array with amplitude proportional to the strength of the emission from the "whole" Sun at the observing frequency. The radio source(s) responsible for the circularly polarized emission observed with the polarimeter are identified using the two-dimensional radioheliograms obtained with the GRH at 77 MHz around the same time with an angular resolution of $\approx 10'$. Though polarized emission from the Sun is often

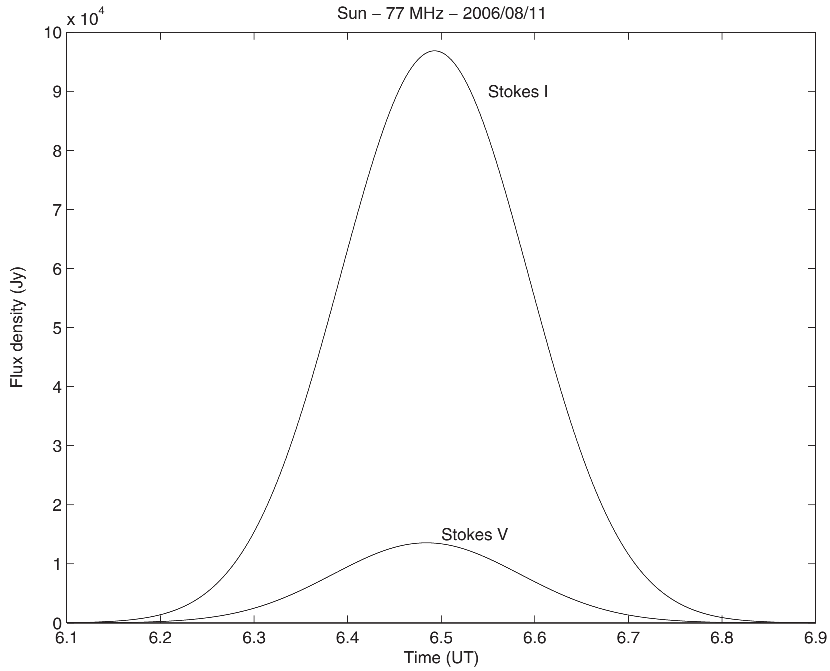

Figure 1. "CLEANed" east–west one-dimensional Stokes I and $|V|$ observations of the Sun at 77 MHz around its transit over the local meridian at Gauribidanur on 2006 August 11.

observed with the Gauribidanur radio polarimeter, we specifically selected the three aforementioned periods for the present work because (1) they were during the minimum between the sunspot cycles 23 and 24. This reduces the confusion that often arises due to the presence of more than one center of activity on the solar surface during comparatively active periods. (2) Observations with the GRH during the same time interval revealed that only a single intense discrete source of emission was present during each of the above periods. This way, we were able to relate the radioheliograph and the polarimeter observations in a straightforward manner and infer the radio source responsible for the observed circular polarization. (3) The discrete source present in the GRH images co-rotated with the Sun and we were able to unambiguously follow the same source continuously for seven days during each of the aforementioned three periods. This regular rotation is required to derive the altitude of the radio source corresponding to the observed circular polarization. (4) Sun was very close to the zenith ($\delta = 14\overset{\circ}{.}1$ north) at the Gauribidanur observatory, the advantages of which are pointed out in Section 4.

2.1. 2006 August 11–18

Figure 1 shows the Stokes I and $|V|$ emission from the solar corona at 77 MHz, observed on 2006 August 11. Note the Stokes V flux can in general be either positive or negative depending on whether the incident radiation is right or left circularly polarized. In the present case, the flux values are obtained from the amplitude of the complex visibilities observed with the polarimeter. Because of this the sign of the Stokes V flux is not there, and we have used $|V|$ instead of V. The observed Stokes I and $|V|$ fluxes from the Sun were calibrated using observations of standard calibrator sources with the polarimeter array (see Ramesh et al. 2008 for details on the calibration). The calibrated fluxes of Stokes I and $|V|$ peak emission at 77 MHz in Figure 1 are $\approx 9.65 \pm 0.02$ and 1.23 ± 0.02 sfu (1 sfu (solar flux unit) $= 10^{-22}\,\mathrm{Wm^{-2}Hz^{-1}}$), respectively (Table 1). Similar emission was observed on the following days until 2006 August 18. An inspection of the GRH images revealed that there was an isolated discrete source of intense emission with brightness temperature $T_b \approx 6.3 \times 10^7$ K close to the east limb of the Sun on 2006 August 11 (left panel of Figure 2). The above emission region persisted for the next few days and co-rotated with the Sun. It was located close to the west limb on 2006 August 18 (right panel of Figure 2). The peak T_b on this day was $\approx 7.1 \times 10^7$ K (see Table 1 for details on the polarimeter and heliograph observations during 2006 August 11–18). No similar intense discrete source was present in the GRH images obtained on 2006 August 10 and 19 (left and right panels of Figure 3, respectively). The peak T_b observed with the GRH on 2006 August 10 and 19 was also comparatively lower by about two orders of magnitude, viz., 5.1 and 6.3×10^5 K, respectively. These values are close to the T_b values for "undisturbed" solar corona at 77 MHz reported in the literature (see Sheridan & McLean 1985 and the references therein). The observations with the polarimeter also followed a similar pattern. No circularly polarized emission was observed for a few days outside the period 2006 August 11–18. We found no transient non-thermal burst emission in our records during the above period. We also verified this from the Solar Geophysical Data.[1]

2.2. 2006 August 23–29

Similar to the period 2006 August 11–18 described in Section 2.1, the Gauribidanur radio polarimeter observed circularly polarized radio emission from the solar corona at 77 MHz for a continuous period of seven days during the interval 2006 August 23–29. The Stokes I and $|V|$ outputs, being essentially the east–west "beam" of the polarimeter as mentioned in Section 2, were identical to the deflections in Figure 1. But the calibrated peak flux values were different. On 2006 August 23, they were $\approx 15.95 \pm 0.02$ sfu (Stokes I) and

[1] http://sgd.ngdc.noaa.gov/sgd/solarindex.jsp

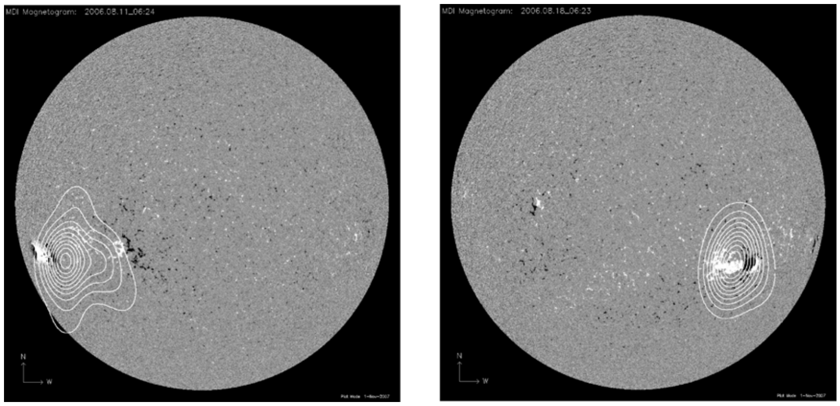

Figure 2. Left panel: composite of the radioheliogram observed with the GRH at 77 MHz on 2006 August 11 around 06:30 UT and *SOHO*-MDI magnetogram obtained during the same period. The peak radio T_b is $\approx 6.3 \times 10^7$ K corresponding to the discrete source near the east limb of the Sun. The contour interval is 0.8×10^7 K. AR 10904 discussed in the text is the bright active region located to the east of the centroid of the aforementioned radio source. The extended nature of the radio source is likely due to contribution from AR 10903 located to the west of AR 10904. Right panel: same as the image in the left panel, but on 2006 August 18. The peak radio T_b is $\approx 7.1 \times 10^7$ K and the contour interval is 0.6×10^7 K. AR 10904 had rotated close to the west limb in this image.

Table 1
Details of Gauribidanur Radio Polarimeter and Heliograph Observations During 2006 August 11–18, 2006 August 23–29, and 2007[a] May 16–22

Date	Stokes I Flux (sfu)	Stokes $\lvert V \rvert$ Flux (sfu)	dcp ($\lvert V \rvert / I$)	GRH Peak T_b ($\times 10^8$ K)	Solar Longitude (deg)	Radial[b] Distance $r(R_\odot)$	Magnetic[b] Field B_c(G)
2006 Aug 11	9.65	1.23	0.13	0.63	61 E		
2006 Aug 12	11.03	3.31	0.30	0.72	47 E		
2006 Aug 13	12.21	7.33	0.60	0.79	34 E		
2006 Aug 14	14.03	10.38	0.74	0.91	21 E		
2006 Aug 15	17.10	14.36	0.84	1.11	8 E	1.24	>1.1
2006 Aug 16	15.23	11.12	0.73	0.99	6 W		
2006 Aug 17	13.64	6.55	0.48	0.89	20 W		
2006 Aug 18	10.93	4.15	0.38	0.71	34 W		
2006 Aug 23	15.95	2.07	0.13	1.04	57 E		
2006 Aug 24	17.22	4.99	0.29	1.11	43 E		
2006 Aug 25	21.22	10.82	0.51	1.38	28 E		
2006 Aug 26	26.67	19.47	0.73	1.73	15 E		
2006 Aug 27	31.26	28.45	0.91	2.03	1 E	1.40	>0.6
2006 Aug 28	27.36	21.07	0.77	1.78	14 W		
2006 Aug 29	24.92	14.46	0.58	1.62	27 W		
2007 May 16	11.50	2.18	0.19	0.75	45 E		
2007 May 17	14.98	5.99	0.4	0.97	31 E		
2007 May 18	19.75	12.24	0.62	1.28	17 E		
2007 May 19	21.37	18.59	0.87	1.39	3 E	1.32	>0.9
2007 May 20	18.56	12.43	0.67	1.21	11 W		
2007 May 21	15.54	6.53	0.42	1.01	24 W		
2007 May 22	12.48	2.87	0.23	0.81	38 W		

Notes.
[a] Refer the text for the errors in the tabulated quantities.
[b] Value derived from observations close to CMP.

2.07 ± 0.02 sfu (Stokes $|V|$) at 77 MHz (Table 1). The GRH image obtained on 2006 August 23 revealed the presence of an isolated discrete source of intense emission with brightness temperature $T_b \approx 10.4 \times 10^7$ K close to the east limb of the Sun (left panel of Figure 4). The above emission region was present for the next few days and co-rotated with the Sun. It was close to the west limb on 2006 August 29 (right panel of Figure 4). The peak T_b on this day was $\approx 16.2 \times 10^7$ K (see Table 1 for details on the heliograph and polarimeter observations during 2009 August 23–29). The discrete source was not noticeable in the GRH images obtained on 2006 August 22 and 30. The polarimeter records also did not show any circularly polarized emission on 2006 August 22 and 30.

2.3. 2007 May 16–22

The characteristics of the polarimeter and the radioheliograph observations during this period were almost identical to our descriptions in Sections 2.1 and 2.2. The Gauribidanur radio polarimeter outputs showed the presence of circularly polarized emission for a continuous period of seven days during 2007 May 16–22. The calibrated fluxes of Stokes I and $|V|$ peak emission at 77 MHz on 2007 May 16 were $\approx 11.5 \pm 0.02$ and 2.18 ± 0.02 sfu, respectively (Table 1). Similar emission was observed on the following days also, until 2007 May 22. But there was no circularly polarized emission for a few days before 2007 May 16 and after 2007 May 22. An inspection of the GRH

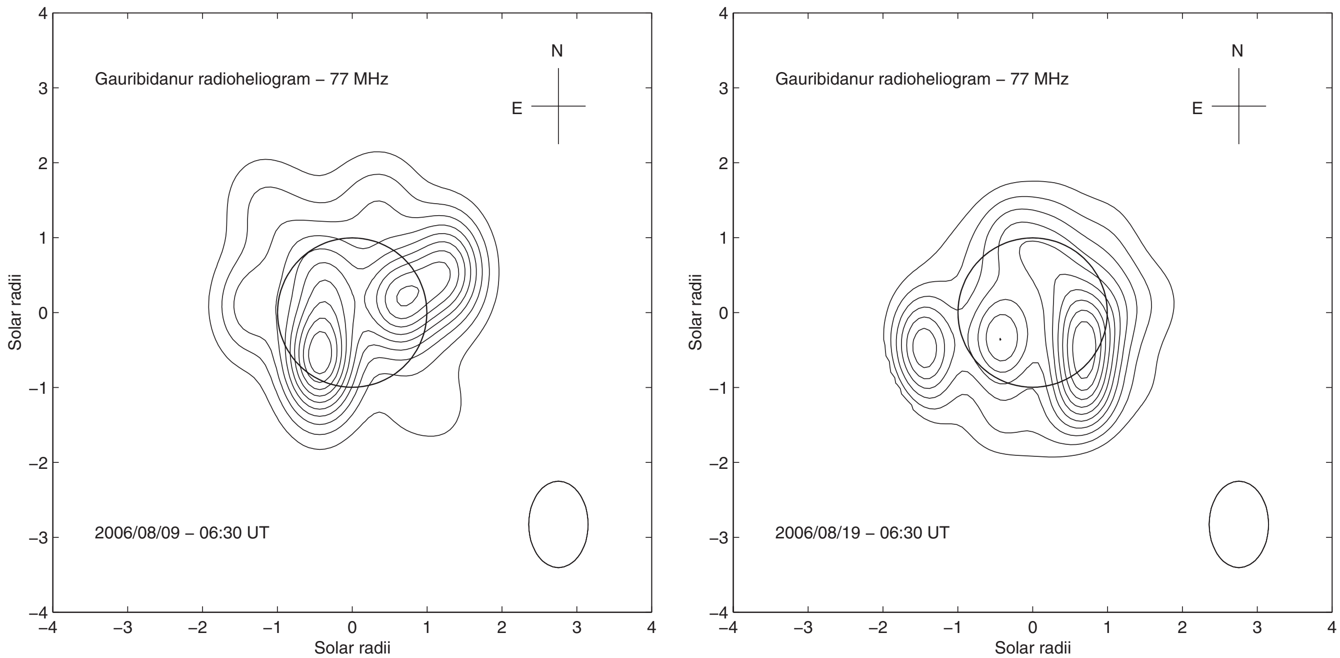

Figure 3. Left panel: GRH observations of 2006 August 10. The open circle at the center represents the solar limb. The ellipse near the lower right corner indicates the GRH "beam" size at 77 MHz. The peak T_b is $\approx 5.1 \times 10^5$ K corresponding to the discrete source near the solar limb in the southeast quadrant. The contour interval is 0.5×10^5 K. Right panel: same as the image in the left panel, but on 2006 August 19. The peak T_b is $\approx 6.3 \times 10^5$ K corresponding to the discrete source near the solar limb in the southwest quadrant. The contour interval is 0.6×10^5 K.

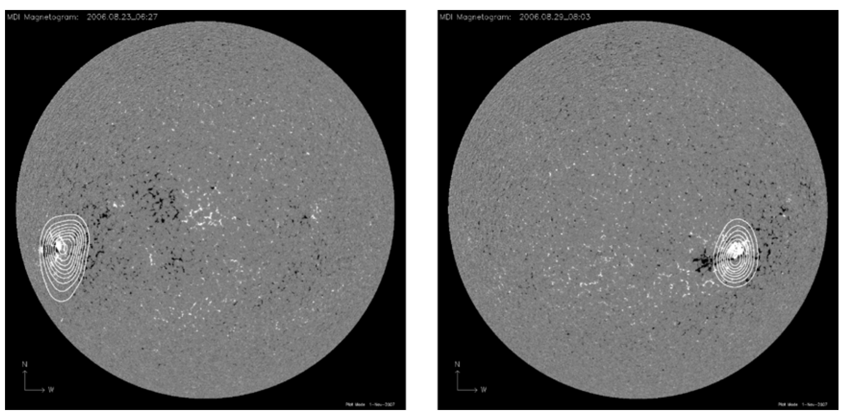

Figure 4. Left panel: composite of the radioheliogram observed with the GRH at 77 MHz on 2006 August 23 around 06:30 UT and *SOHO*-MDI magnetogram obtained during the same period. The peak radio T_b is $\approx 10.4 \times 10^7$ K corresponding to the discrete source close to the east limb of the Sun. The contour interval is 0.4×10^7 K. AR 10905 described in the text is the bright active region underlying the aforementioned discrete radio source. Right panel: same as the image in the left panel, but on 2006 August 29. The peak radio T_b is $\approx 16.2 \times 10^7$ K and the contour interval is 0.4×10^7 K. AR 10905 had crossed over to the western hemisphere of the Sun in this image.

images revealed that there was an isolated discrete source of intense emission with brightness temperature $T_b \approx 7.5 \times 10^7$ K close to the east limb of the Sun on 2007 May 16 (left panel of Figure 5). The above emission region persisted for the next few days also and co-rotated with the Sun. It was located close to the west limb on 2007 May 22 (right panel of Figure 5). The peak T_b on this day was $\approx 8.1 \times 10^7$ K (see Table 1 for details on the heliograph and polarimeter observations during 2007 May 16–22). The discrete source was not noticeable in the GRH images obtained on both 2007 May 15 and 23 as well as for a few days, respectively, before and after the above two days.

3. THE SOURCE OF THE OBSERVED CIRCULAR POLARIZATION

The electron temperature (T_e) of the background solar corona is $\sim 10^6$ K. In the present case, the peak T_b of the discrete radio sources in Figures 2, 4, and 5 are $\sim 10^8$ K. This indicates that the observed emission must be non-thermal in nature. Since the metric radio noise storm continuum is the only long-lasting event in the solar atmosphere that belong to this category (Kai et al. 1985), the circularly polarized emission observed with the Gauribidanur radio polarimeter during 2006 August 11–18, 2006 August 23–29, and 2007 May 16–22 must be due to such sources. The estimated dcp from the Stokes $|V|$ emission during the aforementioned periods varied with the position of the intense discrete source in the corresponding GRH images: it increased as the source moved across the solar disk from the east limb toward the meridian of the Sun, reached a maximum ($\approx 0.84 \pm 0.1$ on 2006 August 15 during the period 2006 August 11–18, $\approx 0.91 \pm 0.1$ on 2006 August 27 during the period 2006 August 23–29, and $\approx 0.87 \pm 0.1$ on 2007 May 19 during the period 2007 May 16–22) when the source was close to the central meridian, and then started decreasing as the source

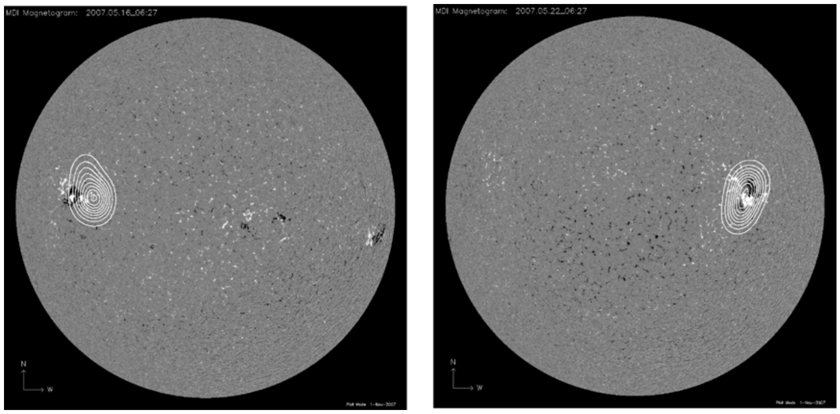

Figure 5. Left panel: composite of the radioheliogram observed with the GRH at 77 MHz on 2007 May 16 around 06:30 UT and *SOHO*-MDI magnetogram obtained during the same period. The peak radio T_b is $\approx 7.5 \times 10^7$ K corresponding to the discrete source near the east limb of the Sun. The contour interval is 0.4×10^7 K. The bright active region located close to the aforementioned discrete source is AR 10956 described in the text. Right panel: same as the image in the left panel, but on 2007 May 22. The peak radio T_b is $\approx 8.1 \times 10^7$ K and the contour interval is 0.4×10^7 K. AR 10956 is located to the west of the central meridian of the Sun in this image.

moved away toward the west limb (see Figures 2, 4, 5 and Table 1). This variation in the observed dcp with the location of the emission region on the solar disk is typical of noise storm emission (see, e.g., Kai 1962).

Generally, any transient or long-duration activity observed in the solar corona should have their "origin" at the underlying layers in the atmosphere. In the case of radio noise storms, it is well established that they are associated with the sunspot regions at the photosphere (Elgarøy 1977; Ramesh & Sundaram 2000). So, we inspected the photospheric magnetogram obtained with *SOHO*-MDI to identify the counterpart of the observed circularly polarized emission at 77 MHz. Figures 2, 4, and 5 show the composite of the MDI and GRH images obtained on 2006 August 11 and 18; 2006 August 23 and 29; and 2007 May 16 and 22, respectively. The images indicate that the sunspot group AR 10904 (S14 E63) located close to the east limb on 2006 August 11 must have been primarily responsible for the radio noise storm and the associated circularly polarized emission observed during the period 2006 August 11–18. Likewise, it must be AR 10905 located at S07 E57 on 2006 August 22 and AR 10956 at N01 E45 on 2007 May 16 for the circularly polarized emission observed during 2006 August 23–29 and 2007 May 16–22, respectively. The sunspot region AR 10903 (S12 E26) located to the west of AR 10904 (left panel of Figure 2) as the cause for the observed radio activity during 2006 August 11–18 can be ruled out because (1) AR 10903 was on the visible solar hemisphere even prior to the appearance of AR 10904 at the east limb, whereas no detectable noise storm emission or circularly polarized emission was observed and (2) the maximum in the observed dcp occurred around the same day (2009 August 15) as the CMP of AR 10904. There is no such confusion as regards to the noise storm emission observed during the periods 2006 August 23–29 and 2007 May 16–22 since AR 10905 and AR 10956 were the only dominant active regions on the solar surface during the corresponding periods (see Figures 4 and 5). Also the estimated dcp values showed a maximum on the same day as the CMP of the associated active regions. The CMP of AR 10905 was on 2006 August 27 during the period 2006 August 23–29, and that of AR 10956 was on 2007 May 19 during the period 2007 May 16–22 (see Table 1 for details). In Figure 6, we have plotted the variation in the Stokes *I* flux, and the dcp for the observed noise continuum sources against the longitude of the associated sunspot region during the three aforementioned periods. In all the cases we find that

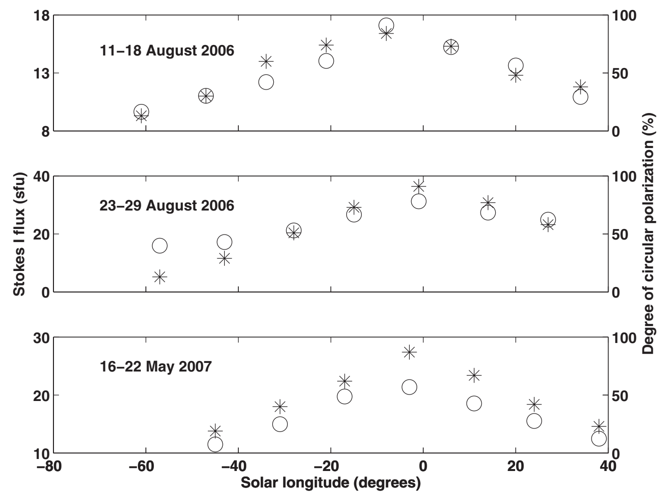

Figure 6. Variation of the Stokes *I* flux (circles) and the dcp (asterisks) of the radio noise storm continuum sources with the solar longitude.

(1) both Stokes *I* flux and dcp peak during the CMP and decrease with increasing central meridian distance as reported (see, e.g., Elgarøy 1977); (2) the polarized noise storms seem to have a preference for the eastern hemisphere compared to the western hemisphere of the Sun (see, e.g., Zlobec et al. 1982); and (3) the estimated dcp is >60% only for ±1 day around the CMP. This could probably be due to the narrowness of the cone of fundamental emission (see, e.g., Thejappa & MacDowall 2010). However, detailed calculations are required to verify this.

4. THE HEIGHT OF THE ASSOCIATED RADIO SOURCES IN THE SOLAR CORONA

It was pointed out earlier in Sections 2.1, 2.2, and 2.3 that the daily GRH images at 77 MHz revealed a regular shift in the position of the noise storm source from the east to the west limb of the Sun starting from 2006 August 11 during 2006 August 11–18 (Figure 2), 2006 August 23 during 2006 August 23–29 (Figure 4), and 2007 May 16 during 2007 May 16–22 (Figure 5). We calculated the rotation rate (β) of the radio sources close to their CMP from our observations, and the values are $\approx 4'.6$, $5'.2$, and $4'.9 \pm 0'.5$ per day, respectively, during 2006 August 11–18, 2006 August 23–29, and 2007 May 16–22. We then estimated the radial distance (r) of the corresponding plasma level in the solar atmosphere using the relation $r\phi = D\beta$, where $\phi \approx 13^\circ\!.3$ is the angular displacement of the associated sunspot region per day on the solar surface and $D \approx 215\,R_\odot$ is the Sun–Earth distance. Substituting for the different values in the above relation, we get $r \approx 1.24$, 1.40, and $1.32 \pm 0.03\,R_\odot$ during the above three periods, respectively. Any error in the above estimate due to possible refraction effects in the Earth's ionosphere is considered to be minimal since the observations were carried out during the local noon. The declination of the Sun was also almost equal to the latitude of GRH ($\delta = 14^\circ\!.1$ N) during each of the above three periods, i.e., the Sun was close to the instrument zenith. This further minimizes the influence of the ionosphere on the observed source position (see Stewart & McLean 1982; Jacobson et al. 1991; Mercier 1996 for details). Effects of scattering on the observed source position/height is also considered to be less at 77 MHz compared to lower frequencies (Aubier et al. 1971). Ray-tracing calculations at 73.8 MHz employing realistic coronal electron density models and density fluctuations also show that the turning points of the rays that undergo irregular refraction due to density inhomogeneities in the solar corona almost coincide with the location of the plasma (critical) layer in the non-scattering case (Thejappa & MacDowall 2008).

5. ESTIMATE OF THE CORONAL MAGNETIC FIELD (B_C)

The characteristic parameters in a magnetoionic medium like the solar coronal plasma are $X = f_p^2/f^2$ and $Y = f_h/f$, where $f_p(= 9 \times 10^{-3}\sqrt{N_e})$ is the electron plasma frequency, $f_h(= 2.8B_c)$ is the electron–cyclotron or gyrofrequency, and f is the observing frequency. In such a medium, the radio waves propagate in two modes—the ordinary (o) and extraordinary (e) mode. Their optical depths differ from each other and the "zero" of the radio wave refractive index (μ) occur at different heights (radial distances) in the solar atmosphere, i.e., at $X = 1$ and $X = 1 - Y$ (located above the $X = 1$ level in the direction of the observer) for the "o" and "e" modes, respectively. If the radio radiation is generated between the above two levels, only the "o" mode can escape toward the observer since the "e" mode cannot penetrate the $X = 1 - Y$ level. This implies that for cases where the observed polarization is due to only a differential absorption of the "o" and "e" modes, the dcp $= \frac{T_b^o - T_b^e}{T_b^o + T_b^e} = 1$. Here, T_b^o and T_b^e are the brightness temperature of the "o" and "e" modes. Strong circular polarization (dcp ~ 1) in the "o" mode is one of the distinguishing characteristics of the noise storm emission when the associated source is close to the central meridian on the Sun (Elgarøy 1977). The occurrence of partially polarized noise storm source there is rare (see, e.g., Zlobec et al. 1982). In the present case, we find that the dcp of the noise storm sources during their CMP is in the range ≈0.8–0.9 during all the three periods mentioned above (see Table 1). One possible scenario for this could be that the source is located between the $X = 1$ and $X = 1 - Y$ levels (Wentzel 1997), and the radiation is depolarized during propagation as mentioned in Wentzel et al. (1986), Gopalswamy et al. (1994), Bastian (1995), and Melrose (2006). This leads to the condition $Y > 1 - X$ near the emission region. Substituting for X and Y, we find that

$$B_c > \frac{f^2 - f_p^2}{2.8f}, \tag{1}$$

where B_c is in units of Gauss (G) and f, f_p are in units of MHz. Plasma waves generated by electrons with typical velocity v_b have a frequency (see, e.g., White et al. 1992),

$$f \approx f_p + \frac{3v_t^2}{2v_b^2} f_p. \tag{2}$$

Here, $v_t = \sqrt{2kT_e/m}$ is the most probable thermal speed of electrons in the ambient plasma. Considering the average T_e to be $\sim 1.5 \times 10^6$ K (see, e.g., Aschwanden 2004), we find that $v_t \approx 6741$ km s^{-1}. Assuming that the T_b of the escaping noise storm radiation cannot exceed that of the Langmuir waves (T^L) which is limited by the energy in the fast electrons, i.e., $T^L \leqslant 0.5 m_e v_b^2/k$, (see, e.g., Melrose 1985; Habbal et al. 1989), we find that the v_b corresponding to the observed peak T_b of the noise storms around their CMP during 2006 August 11–18, 2006 August 23–29, and 2007 May 16–22 (see Table 1) are ≈5.8, 7.8, and 6.5 $\times 10^4$ km s^{-1}, respectively. Using the above values of v_t, v_b, and $f = 77$ MHz in Equation (2), we obtain $f_p \approx 75.5$, 76.1, and 75.8 MHz. Substituting these in Equation (1), we get the lower limit for the corresponding field strengths as $B_c > 1.1, 0.6$, and 0.9 G at $r = 1.24$, 1.40, and 1.32 $R_\odot$, during the above periods. Note that the measured T_b values listed in Table 1 are based on observed source sizes, which are an upper limit to the true source sizes due to finite angular resolution of the GRH. Greater T_b would imply lower B_c values.

6. SUMMARY

We have reported radio observations at 77 MHz of long-lasting (∼ days) solar coronal noise storm continuum sources that co-rotated with the Sun, during three different periods. The observations were in both total and circularly polarized intensity. The observed rotation rates, close to the CMP of the radio sources, are in the range of $\approx 4'\!.6$–$5'\!.2 \pm 0'\!.5$ per day. From this we estimated the radial distance(s) corresponding to the location of the sources in the solar atmosphere during each of the three periods. They are in the range of $r \approx 1.24$–$1.40 \pm 0.03\,R_\odot$. Presuming that polarized noise storm sources should have dcp ≈1 close to their CMP, and taking our measured T_b values at face value, we calculated the lower limit for the coronal magnetic field near their source region using magnetoionic theory to be $\approx 0.6-1.1$G. The corresponding radial variation is $\propto (r-1)^{-1.2}$. These are consistent with the values obtained earlier by other authors using radio burst observations (Dulk & McLean 1978; Gopalswamy et al. 1986; Vrŝnak et al. 2002; Mancuso et al. 2003). We approached the Community Coordinated Modelling Centre at GSFC, NASA[2] to infer the field strength in the corona above the sunspot regions mentioned in Section 3. The results, based on potential extrapolation of the observed solar surface magnetic field distribution, indicate that the average $B_c \approx 0.3$ G corresponding to the periods and radial distances mentioned in Table 1. Since noise storms are the most frequent radio activity particularly in the $r = 1$–$2\,R_\odot$ range, similar observations might allow us to constrain the coronal magnetic field strength there along with the extrapolation techniques. Although the average extrapolated field strength is somewhat lower than those we derived, the possibility that our measured T_b could be underestimated due to finite angular resolution of the GRH may make the two roughly consistent.

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[2] http://ccmc.gsfc.nasa.gov

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