Asian Journal of Physics Vol 13, Nos 3 & 4 (2004) 277 - 284

Seismology of the solar corona through observations of metric type IV radio burst emission

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We present metric radio observations of a transient, quasi-periodic type IV burst emission from the solar corona following the hard X-ray/Hα flare of November 23, 2000. The radio event lasted for about 121 s, and the measured mean period was 14.7 $\pm$ 2.5 s. The source region of the observed radio emission was found to be located at a height of 0.18 $\pm$ 0.03 $R_{\odot}$ above the solar photosphere. The Alfvén speed (v_A) at that location was estimated to be 1185 $\pm$ 181 km s^{-1}. Combined with the plasma density corresponding to the observing frequency (109 MHz), this gives a magnetic field (B) of 7.2 $\pm$ 1.1 G for the above region We also estimated the speed of the disturbance propagating through the solar atmosphere in the aftermath of the flare, and is $\leq$ 755 km s^{-1}.

1. Introduction

The fundamental plasma parameters in the solar corona are relevant to the understanding of solar flares, acceleration of solar wind and coronal mass ejection (CME), and, ultimately, the Sun-Earth connection. The recent observations of oscillations in coronal loops [1] has now raised the feasibility of the development of *coronal seismology*, analogus to helioseismology which provides us with powerful results concerning the interior of the Sun. The seismic information offers the means of determining the local conditions, particularly the coronal magnetic field, a task that has not hitherto proved possible. It is inferred usually from an extrapolation of measurements of the line-of-sight component of the photospheric magnetic field. The observations of transient, pulsating radio emission from the solar corona is a potential diagnostic tool in this connection since radio data can be obtained with a high temporal and spectral resolution [2]. According to Aschwanden [3], the favourable conditions for MHD oscillations occur mainly in the upper part of the corona, i e from where the meter wavelength radio emission orignate. In this situation, we present here metric radio observations of a transient, quasi-periodic type IV burst emission from the solar corona in close temporal and spatial association with a hard X-ray/Hα flare and derive the coronal plasma parameters (notably the Alfvén speed and through this the magnetic field strength).

2. Observations

The radio data were obtained with the Gauribidanur radioheliograph (GRH) operating near Bangalore in India [4] on November 23, 2000. The observing frequency was 109 MHz. The time resolution and bandwidth used were 128 ms and 1 MHz, respectively. Figure 1 shows the temporal evolution of the whole Sun flux observed with the GRH during the interval 05:33 - 05:43 UT on that day. One can clearly notice two phases of strong emission above the background in Figure 1: (i) a couple of bursts during the period 05:35:52 - 05:36.30 UT, and (ii) quasi-periodic emission in the interval 05:38:37 - 05:40:37 UT. We estimated the period of the latter from the time interval between the adjacent peaks and the average value is 14.7 $\pm$ 2 5 s. The observed peak flux density was $\approx$ 3.3 SFU (SFU = solar flux unit = 10^{-22} W m^{-2} Hz^{-1}). The above radio events were closely associated with a 1F class Hα flare (05 36 - 06:15 UT with peak at 05:48 UT) from AR 9238 located at S26W40, and

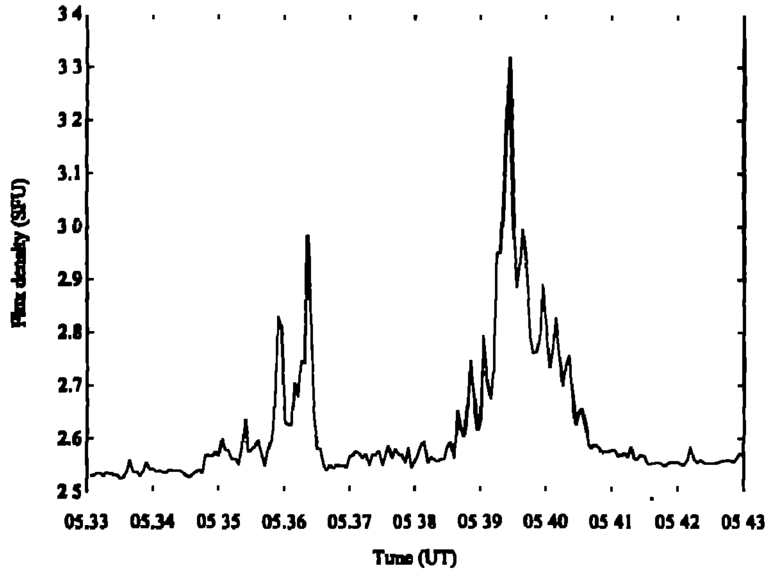

Figure 1: Time profile of the radio emission from the solar corona observed with the GRH at 109 MHz on November 23, 2000 during the time interval 05:33-05:43 UT. The transient emission in the interval 05:35:52 - 05:36:30 UT is a type III burst. The quasi-periodic emission during the period 05:38:37-05:40:37 UT is a stationary type IV burst and is the event under study.

a GOES C5.4 class X-ray flare (05:34 - 06:17 UT with peak at 05:47 UT, Solar Geophysical Data, May [6]). There was also a YOHKOH hard X-ray flare [5] in the 14 - 23 keV energy band around the same time (Figure 2). The latter was observed in the interval 05:35:51 - 05:39:45 UT with peak at 05:37:19 UT. Figure 3 shows an EIT 195 Å running difference image [7] obtained on November 23, 2000 at 05:47 UT, by subtracting the previous image (05:35 UT). The bright emission in the south-west quadrant corresponds to the aforementioned flaring region. The half-power contours of the radioheliogram obtained with the GRH during various stages of the quasi-periodic emission described above are shown in Figure 4. One can notice that their centroids are distributed in the close vicinity of the flare site. Figure 5 shows the dynamic spectrum of the radio emission from the solar corona obtained with the Hiraiso radiospectrograph (HiRAS[8]) on November 23, 2000 in the time interval 05:15 - 06:00 UT. One can notice fast drifting band of burst emission in the interval 05:36 - 05:40 UT. The event was classified as a type III group [9] A comparison with the GRH observations indicate that the first transient event around 05:36 UT in the latter (Figure 1) corresponds to the above burst. The diffuse emission towards the end of the type III event (Figure 5; see Figure 6 for a close view) is most likely a stationary type IV burst (K.Hori, personal communication) and the quasi-periodic emission in the second phase of the GRH observations (Figure 1) corresponds to it.

3. Analysis and results

The metric type IV radio burst emission from the solar corona sometimes show periodic or quasi-periodic fluctuations superimposed on a background continuum [10]. The periodicity is considered to be because of a modulation of the radio emissivity of the electrons trapped inside the associated

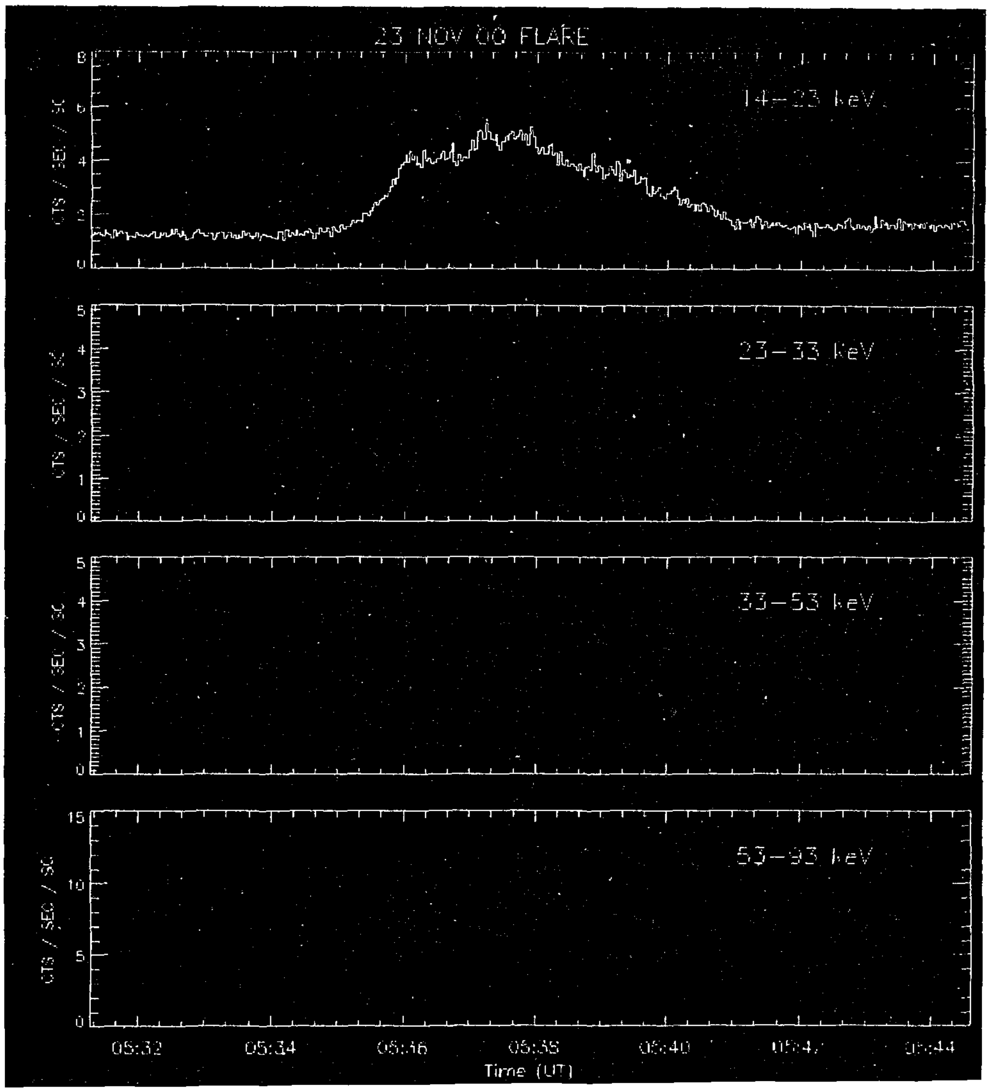

Figure 2: The counts in different energy bands observed with the hard X-ray telescope onboard YOHKOH on November 23, 2000 during the time interval 05:31-05:45 UT. One can clearly notice the flare in the 14-23 keV band in the time interval 05:35:51-05:39:45 UT with peak at 05:37:19 UT.

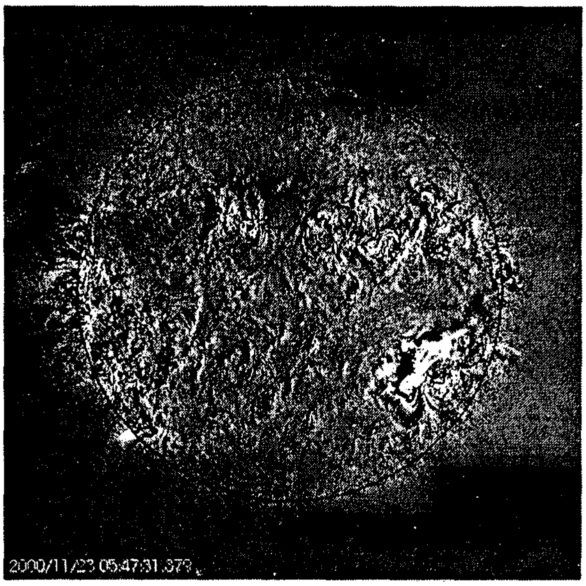

Figure 3: SOHO-EIT 195 Å running difference image obtained on November 23, 2000 at 05:47 UT by subtracting the previous (05:35 UT) image. Solar north is straight up and east is to the left. The dark open circle indicates the solar limb. The bright emission in the south-west quadrant is the flaring region.

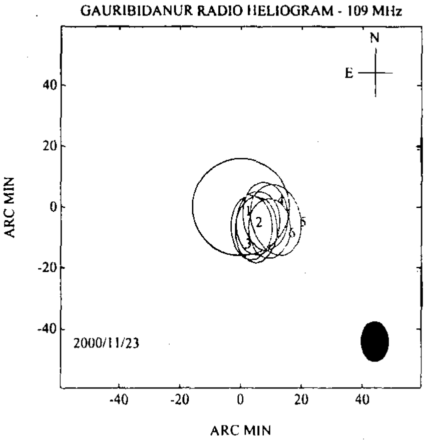

Figure 4: Radioheliogram obtained with the GRH at 05:38:47 (1), 05:39:07 (2), 05:39:27 (3), 05:39:47 (4), 05:40:07 (5) & 05:40:27 UT (6), on November 23, 2000. Note that only the half-power contours are shown here for a better visualisation of the event and to establish the spatial correspondence with the associated activity at other wavelengths. A comparison with Figure 3 indicates that the radio sources are located in the close vicinity of the flare site. The estimated peak radio brightness temperature is $\approx 1.57 \times 10^7$ K and it corresponds to the image obtained at 05:39:27 UT. The open circle at the center is the solar limb. The size of the GRH beam at 109 MHz is indicated at the lower right corner.

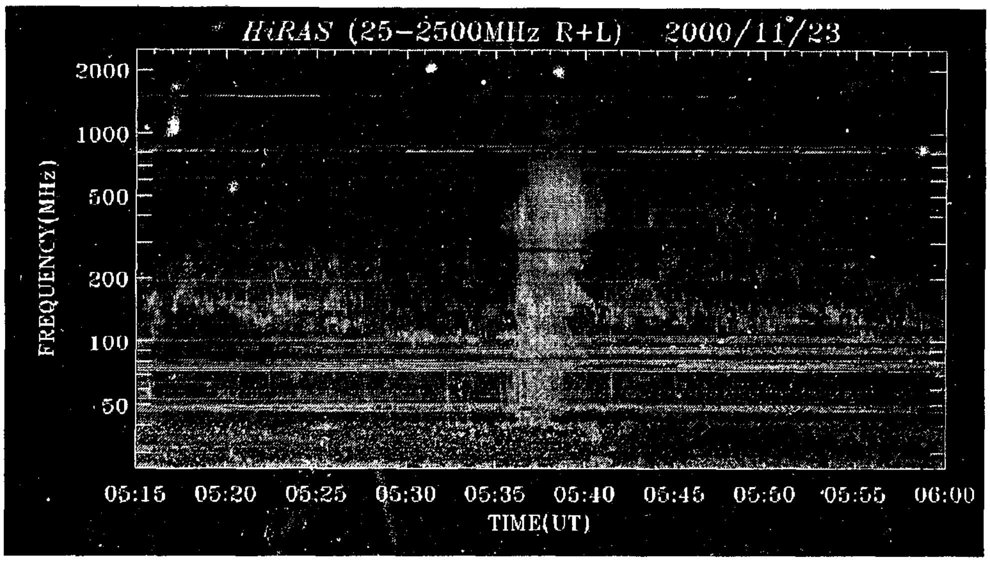

Figure 5: Dynamic spectrum of the radio emission from the solar corona obtained with the Hiraiso radio spectrograph on November 23, 2000 during the period 05:15 - 06:00 UT. The fast drifting bursts in the interval 05:36 - 05:40 UT correspond to a type III group. The diffuse emission towards the end of the above event (see Figure 6 for a close view) is the event under study. Its spectral nature indicates that it is a stationary type IV burst.

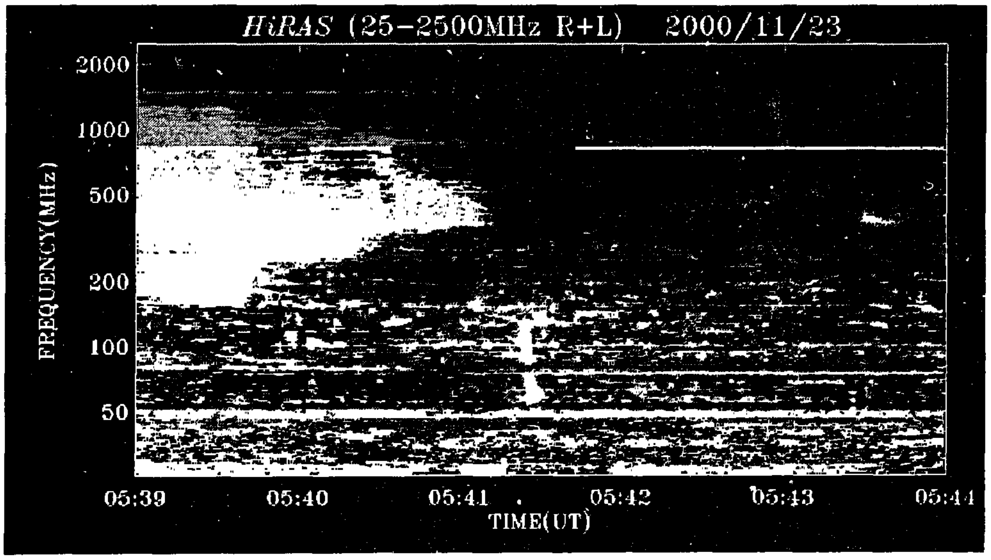

Figure 6: Same as in Figure 5, but for the time interval 05:39 - 05:44 UT. The weak emission during 05:39 - 05:41 UT is the event under study. One can notice that the emission is devoid of both fine structures as well as any noticeable drift.

coronal loop structure by sausage oscillations (symmetric oscillations of a coronal loop with its central axis remaining undisturbed) of the latter, which in turn is due to a disturbance propagating through the solar atmosphere in the aftermath of a flare [2]. A periodic injection of fast electron beams into the coronal loop as the cause for the oscillations can be ruled out in the present case since the dynamic spectrum of the type IV burst emission in Figure 5 & 6 doesn't show any fine structure as is expected [11,12] . Note that when oscillations develop in a coronal loop, the magnitude of the magnetic field strength and the mirror ratio in the trap are modulated. This in turn changes both the energy spectrum and the number of trapped particles. Therefore for any generation mechanism, the radio emission flux density will be modulated with the period (p) of the oscillations. The latter has been calculated by Aschwanden et al. [1],

$$p = 2 \times 10^{-11} \frac{a\sqrt{N_e}}{B} \quad \mathrm{s} \tag{1}$$

where a (cm) is the radius of the coronal loop, B (G) is the associated coronal magnetic field and N_e (cm^{-3}) is the plasma density corresponding to the observing frequency.

The present observations were carried out at a frequency of 109 MHz and therefore $N_e = 1.47 \times 10^8$ cm^{-3}. Ofman and Aschwanden [13] recently reported the parameters of coronal loops in extreme ultraviolet using the data obtained with the TRACE instrument [14]. According to them, the average width of the oscillating loops is 8.7 ± 2.8 Mm. Based on their results, we assumed $a = 4350$ km in the present case. Substituting for the various values in equation (1), we get $B = 7.2 \pm 1.1$ G. Having known B and N_e, one can now calculate the Alfvén speed (v_A) at the location from where the observed radio emission originated. From definition, we have,

$$v_A = \frac{B}{\sqrt{4\pi M N_e}} \quad \mathrm{cm\ s^{-1}} \tag{2}$$

where $M = 2 \times 10^{-24}$ g is the mass ascribed to each electron in the coronal plasma (includes 10% He).

The different values in equation (2) yield $v_A = 1185 \pm 181$ km s^{-1}. Assuming that the disturbance responsible for the triggering of the oscillations was generated at the same time as the onset of the hard X-ray flare (i.e. at 05:35:51 UT), we calculated the altitude of the plasma level from where the observed 109 MHz radio emission orginated (using the relationship between the radius of the coronal loop, duration of the quasi-periodic radio emission, and the delay in the onset of the latter from that of the hard X-ray flare [10]) and the value is 0.18 ± 0.03 $R_\odot$.

It is interesting to note that though the quasi-periodic type IV emission under study was preceded by a group of type III bursts, the latter did not exhibit a similar phenomenon. The quasi-periodicity in some of the type III radio burst groups [15] is due to a modulation of the acceleration of the electrons released during the associated flare by a disturbance propagating through the solar atmosphere in the aftermath of the latter [16,17]. An absence of the above phenomenon in the present case suggests that the disturbance might have been weak to modulate the electron acceleration process. The low value of the flux density of the observed type III burst (Figure 1 of [18] characteristics of type II bursts) and the strength of the associated X-ray & Hα flare (the latter in particular) also indicates the same. The absence of type II radio bursts, which are due to plasma emission from the electrons accelerated by a magneto-hydrodynamic (MHD) shock in the solar corona, strengthens the above view. Note that for the development of the latter, the speed of the disturbance must be greater than the characteristic Alfv́en speed in the medium. In order to establish the above scenario, we verified the kinematics of the flare generated disturbance in the present case in the following manner:

Since metric type II radio bursts are usually observed inbetween the type III and IV emission [19], the disturbance must have travelled a distance of $\leq$ 0.18 $R_\odot$ (the altitude of the source region of the quasi-periodic type IV burst in the present case) in the time interval between the onset of the hard X-ray flare and the quasi-periodic emission ($\approx$ 166 s). This implies that its speed must have definitely been $\leq$ 755 km s^{-1}. This is well below the Alfvén speed inside the coronal loop, derived earlier. Let us now infer the conditions outside the loop. Note that the dynamic spectra of the type IV burst under discussion does not reveal any noticeable drift (Figure 6). This indicates that the quasi-peridiocity in the single frequency radio data presented (Figure 1) is most likely due to a simultaneous (global) oscillation of the whole loop, as pointed out by Roberts et al [10]. Since global sausage-type oscillations are expected only in dense loops [20], the density of the medium external to the coronal loop must be smaller than that inside. In the low-β corona, the thermal pressure is much smaller than the magnetic pressure. So we can assume almost identical magnetic field strengths both inside and outside of the loop. These imply that the Alfvén speed outside the loop must be comparitively greater (refer equation 2). But the estimated speed of the flare generated disturbance in the present case is sub-Alfvénic even inside the loop. Hence the absence of type II burst. According to Smerd [21], though a type II burst requires a fewer electrons compared to a type IV burst, [17]they should be of higher energy. The absence of hard X-ray burst at energies $> 14-23$ keV in Figure 2 is consistent with the above. This clearly indicates that the flare generated disturbance in the present case was weak. Note that when a quasi-periodic type IV burst is preceded by a type II emission, the amplitude of fluctuations in the former is generally large [22]. Finally, Ramesh et al. [17] recently showed quantitatively that both the metric type II and quasi-periodic type III radio burst emission are driven by the same disturbance generated in the aftermath of a flare. This particular last observational evidence, together with the above arguments, clearly explain the reason for the absence of quasi-periodicity in the type III radio burst group in the present case.

4. Conclusions

We estimated the plasma parameters in the solar corona through the transient, quasi-periodic type IV radio burst emisison observed with the GRH at 109 MHz on November 23, 2000 around 05:40 UT. Our findings are:

1. the radio event lasted for about 121 s, and 9 distinct peaks were observed during the above interval.
2. the measured mean periodicity of the observed radio emission is 14.7 ± 2.5 s.
3. the speed of the flare generated disturbance is $\leq$ 755 km s^{-1}.
4. the altitude of the plasma level from where the observed 109 MHz radiation originated is 0.18 ± 0.03 $R_\odot$ above the solar photosphere.
5. the Alfvén speed at the above location is 1185 ± 181 km s^{-1}.
6. the associated magnetic field is 7.2 ± 1.1 G.

5. Acknowledgements

The staff members of the Gauribidanur radio observatory are thanked for their help in data collection and maintenance of the antenna and receiver systems. We thank M.Akioka san, K.Hori san and Y.Kubo san for providing the Hiraiso radio spectrograph data. The hard X-ray light curve and EIT image presented are due to the kind courtesy of S.Yashiro and B.J.Thompson, respectively. The solar X-ray data is from the YOHKOH mission of ISAS, Japan. The X-ray telescope was prepared by the Lockheed Palo Alto Research Laboratory, the National Astronomical Observatory of Japan, and the University of Tokyo with the support of NASA and ISAS. The SOHO data are produced by a consortium of the Naval Research Laboratory (USA), Max-Planck-Institut fuer Aeronomie (Germany), Laboratoire d'Astronomie (France), and University of Birmingham (UK). SOHO is a project of international cooperation between ESA and NASA.

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Received : October 15, 2004 *Revised : November 30,2004* *Accepted : December 07, 2004*