HIGH-FREQUENCY RADIO SIGNATURES OF SOLAR ERUPTIVE FLARES

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Abstract. Several examples of the radio emission of eruptive solar flares with high-frequency slowly drifting structures and type II bursts are presented. Relationships of these radio bursts with eruptive phenomena such as soft X-ray plasmoid ejection and shock formation are shown. Possible underlying physical processes are discussed in the framework of the plasmoid ejection model of eruptive solar flares. On the other hand, it is shown that these radio bursts can be considered as radio signatures of eruptive solar flares and thus used for the prediction of heliospheric effects.

Key words: radio radiation, solar flares

1. Introduction

Eruptive (dynamic) solar flares are connected with the filament eruption and coronal mass ejection (Švestka *et al.*, 1992). On radio waves, in the frequency range below 300 MHz, these flares are usually associated with type II radio bursts indicating shocks driven by coronal mass ejection (Reiner and Kaiser, 1999). The frequency of type II bursts corresponds to the electron plasma frequency in the radio source and an upwards motion of the shock is expressed on radio spectrum by the slow negative frequency drift (~ -1 MHz s^{-1} at 200 MHz) corresponding to the vertical decrease of the atmospheric density. On the other hand, using specific models of the solar atmosphere shock velocities are determined from the frequency drift and used for the prediction of heliospheric disturbances (e.g. Dryer *et al.*, 1998). It is believed that these shocks are formed from rapid plasma motions evolving into MHD shocks. This idea was confirmed by various radio precursors of type II bursts. For example, in the 0.4–1.0 GHz frequency range a negatively drifting group of type U bursts (Karlický, 1992) and faint radio sources (Klassen *et al.*, 1999a) were found before the type II radio bursts.

Recently a new type of slowly drifting emission was recognized at frequencies above 1 GHz (Karlický and Odstrčil, 1994; Karlický, 1998; Hori, 1999): drifting pulsation structure (DPS). It is usually observed at the very beginning of eruptive solar flares (Karlický *et al.*, 2001). The radio observations of the October 5, 1992 flare reveal that the DPS was generated at times of a plasmoid ejection (Ohyama and Shibata, 1998; Kliem *et al.*, 2000). New positional measurements of the DPS

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by the Nancay Radioheliograph (Khan *et al.*, 2002) confirmed this relationship. Based on the MHD numerical simulations, Kliem *et al.* (2000) suggested that every individual burst in the DPS is generated by superthermal electrons, accelerated at a maximum of the electric field in the quasi-periodic regime of the magnetic field reconnection. On the other hand, the global slow negative frequency drift of the DPS was explained by a plasmoid propagation upwards in the solar corona towards lower plasma densities. Furthermore, Hudson *et al.* (2001) identified a rapidly moving hard X-ray source, observed by the *Yohkoh*/HXT, associated with the moving microwave source and the plasmoid ejection seen in the *Yohkoh*/SXT images. The association with the high-frequency slowly drifting continuum was also reported. Therefore, it looks that not only the DPS but also the high-frequency drifting continua or other slowly drifting structures can indicate the plasmoid ejection.

In the present paper, first, examples of flares with slowly drifting structures are presented and their basic characteristics are summarized. The relationship of the drifting structure and the metric type II burst is elucidated in the case of the April 12, 2001 flare. Finally, the bursts under study are discussed using the model of solar eruptive flares (e.g. Yokoyama and Shibata, 2001).

2. Observations and Their Analysis

The August 18, 1998, ~08:20 UT solar flare classified as X2.8/1B occurred at the east limb in NOAA AR8307 (N32E90) and was accompanied by an eruptive prominence, according to the Solar Geophysical Data event list. The hard X-ray emission as seen by the Hard X-ray Telescope (HXT) on board *Yohkoh* began as a gradual rise at ~08:18 UT in all four energy bands of the instrument. An impulsive rise occurred at 08:19:30 UT in the M2 (33–53 keV) and H (53–93 keV) energy bands, followed by a series of pulses which lasted ~2 min in total. The HXT images show a loop-shaped source in the M2 band (33–53 keV) with an indication of a loop-top source component; this loop-top source is indicated even in the H band image (53–93 keV). The *Yohkoh* Soft X-ray Telescope (SXT) took image series of the flare with different resolutions and filters, which reveal an ascending motion of blob structure (plasmoid) at times 08:19:54 to 08:21:32 UT. The blob had an average projected velocity along its upwards path $\sim 490\,\mathrm{km\,s^{-1}}$.

At radio waves, in the 0.8–2.0 GHz frequency range, this flare commenced with a DPS at 08:18:30–08:20:46 UT (its most interesting part is shown in Figure 1). This time interval nearly coincides with the rise of the hard X-rays from onset to peak and includes the formation and initial acceleration of the ascending emission blob in the soft X-ray images. Remarkably, this DPS was well limited in frequency extent at both sides, most pulses were even amplified at the low- and high-frequency edges. Using the Fourier method the characteristic periods of the DPS at the frequency of 1.15 GHz were determined as: 24.0 s (the statistical probability of the period is 77.7%), and 8.8 s (72.5%) (Table I).

TABLE I
The basic characteristics of some drifting structures.

	Aug. 18, 1998	Apr. 12, 2001	Apr. 15, 2001
Start (UT)	8:18:30	10:17:20	13:37:27
Duration (s)	136	280	43
Global freq. drift (MHz s^{-1})	−4.4	−1.6	−4.7
Instantaneous bandwidth (MHz)	400	200−800	300
Period (s) (probability)	24.0 (77.7%) 8.6 (72.5%)	75.0 (87.0%) 25.0 (98.9%) 13.6 (85.4%) 9.4 (92.4%)	12.0 (89.3%) 2.5 (80.7%) 1.5 (79.1%)
Drift of pulses (MHz s^{-1})	Infinite	Infinite	−270
Accompanied bursts	dm-Continuum	Type II burst	–
Cross-Correl. Coeff.	0.3		0.6
Delay of hard X-rays (s)	−4		5−15

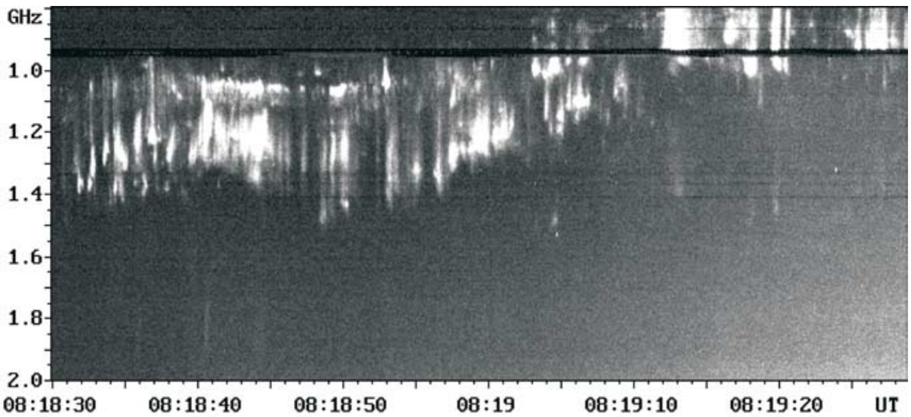

Figure 1. The 0.8−2 GHz radio spectrum observed by the Ondřejov radiospectrograph in August 18, 1998.

The April 15, 2001 flare belongs to the most intense flares in the present solar cycle. According to the GOES observations this flare started at 13:19 UT, reached maximum in soft X-rays at 13:50 UT, and ended at about 15:30 UT; its importance reached X14.4. Simultaneously, the Hα flare of the importance 2B was reported in the NOAA AR 9415 (at the position S20W85) at 13:36 UT, with maximum at 13:49 UT and ending at 15:35 UT. At the very beginning of the hard X-rays

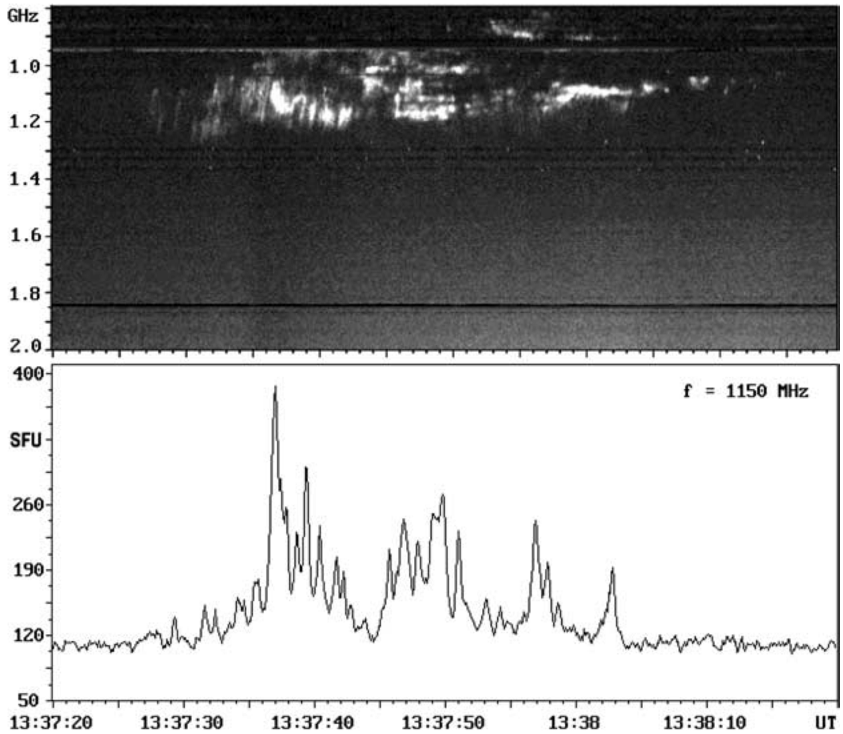

Figure 2. The 0.8−2.0 GHz radio spectrum showing the drifting structure at the very beginning of the April 15, 2001 flare (top) and the radio flux plot at the frequency of 1150 MHz (bottom) observed by the Ondřejov radiospectrograph.

(above 24 keV) of this flare, in the 0.8−1.3 GHz range the slowly drifting structure (DS) with the global negative frequency drift of -4.7 MHz s^{-1} was observed between 13:37:27 and 13:38:10 UT (Figure 2, Table I). Contrary to DPSs, in which pulses have infinite frequency drifts (see Kliem *et al.*, 2000, Karlický *et al.*, 2001), the individual bursts in this DS have the negative frequency drifts of about of -270 MHz s^{-1} (mainly at the beginning part of the DS). At the time of the DS the simultaneous TRACE observations (171 Å line, Fe IX, 0.9 MK) show the plasmoid ejection (Figure 3, left part). The position of this plasmoid in comparison with the *Yohkoh*/SXT bright loops is shown in Figure 3 (right part) by white contours. The speed of the plasmoid ejection in projection in the image plane was estimated to be 60 km s^{-1} in the upwards direction.

On April 12, 2001 a flare of the X2.0 importance (according to the GOES classification) was observed in the NOAA AR 9415 at 09:39 UT, with maximum at 10:28 UT, ending at 10:49 UT (NOAA Solar Events Report). The radio emission of this flare in the 40−4500 MHz range is shown in Figure 4. Here, not only type II burst bands can be seen in the 40−700 MHz range between 10:15 and 10:23 UT, but also the drifting pulsation-continuum structure in the frequency

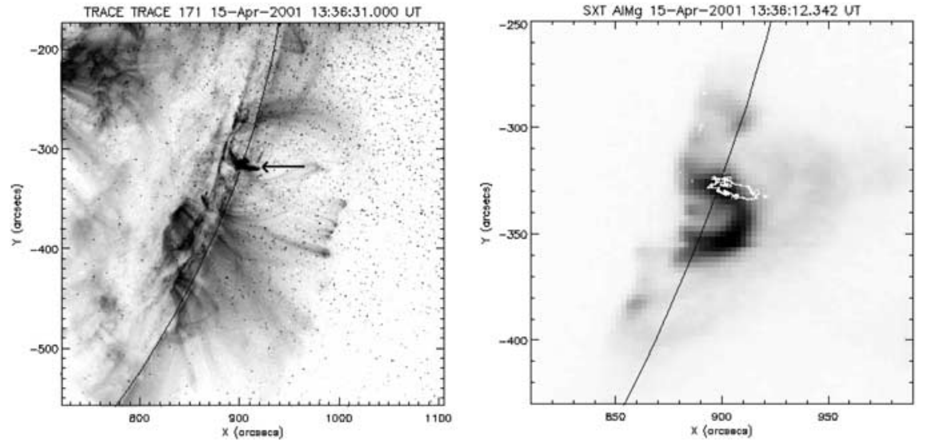

Figure 3. Left: TRACE 171 Å image of a plasmoid ejection (see the arrow) at the very beginning of the April 15, 2001 flare, at 13:36:41 UT, i.e. just before the DS observation. Right: *Yohkoh*/SXT image at 13:36:12 UT; the white contours show the position of the plasmoid observed by TRACE 171 Å at 13:38:36 UT.

range of 450–1500 MHz between 10:17:20 and 10:22:00 UT. The drift rate of the DS was -1.6 MHz s^{-1}. For basic characteristics of this DS, see Table I. In this flare the drifting structure is generated simultaneously with the type II radio burst, but in a different frequency range. Note also their similar frequency drift. At even higher frequencies these radio bursts are accompanied by fast drift bursts (electron beams?) at 10:18:40–10:21:00 UT in the 1.3–3.0 GHz range and by continuum in the 2.0–4.5 GHz range (low-frequency boundary of gyro-synchrotron emission).

For the drifting structures at the very beginning of flares (August 18, 1998 and April 15, 2001), where the radio emission is a relatively simple, their cross-correlations with the hard X-rays (35–57 keV) were made. While in the August 18, 1998 event no significant correlation was found, in the April 15, 2001 the correlation coefficient was 0.6 for the hard X-rays delayed of 5–15 s (Table I).

3. Discussion and Conclusions

Three typical examples of drifting structures (DSs) were presented. It looks that shorter DSs have higher absolute value of the frequency drifts, narrower bandwidths and shorter periods (Table I). It can be connected with the stability of the plasmoid.

In the model of solar eruptive flares with the plasmoid ejection (e.g. Yokoyama and Shibata, 2001), the magnetic field reconnection and plasma reconnection outflows form one self-consistent process, in which the current sheet is formed below the ejected plasmoid, the reconnection takes place between the slow mode shocks, and the plasmoid is simultaneously pushed upwards by the plasma reconnection

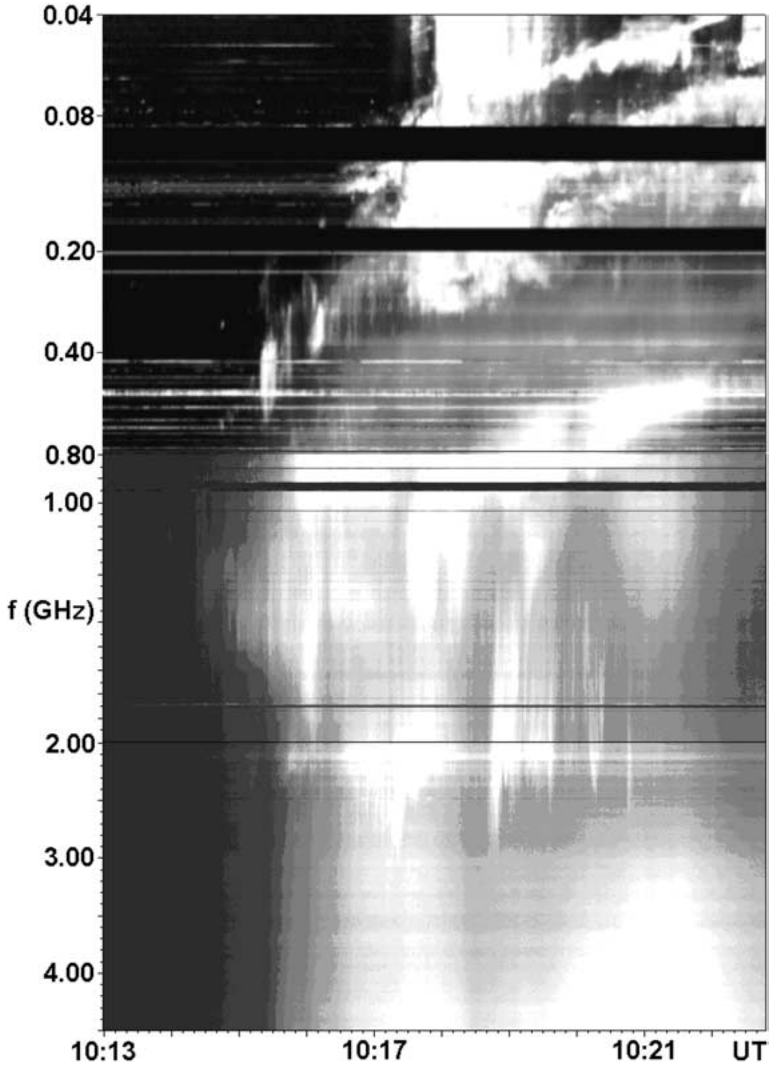

Figure 4. Potsdam radio spectrum in the 40–800 MHz band (courtesy Dr. A. Klassen) and Ondřejov radio spectrum in the 0.8–4.5 GHz band observed during the April 12, 2001 event. The drifting pulsation-continuum structure between 10:17:20 and 10:22:00 UT in the 0.45–1.5 GHz as well as the type II burst observed simultaneously in the metric frequency range are shown.

outflows. The bottom part of the plasmoid and the upper part of the lower-lying loops are obstacles for fast plasma reconnection outflows and thus there the fast mode (termination) shocks are formed. From the point of view of DSs and associated radio bursts the most important regions in the model are those where superthermal electrons are accelerated and trapped, i.e. the fast mode shocks, the MHD turbulence in the plasma reconnection outflows, the magnetically isolated plasmoid and the space limited by the slow and fast mode shocks. Further candidate for the radio emission is the fast mode shock which can be generated at the upper boundary of a rapidly ejected plasmoid. Accepting these ideas the electron density in the plasmoid is in the interval $2 \times 10^9 - 2 \times 10^{10}$ cm^{-3}. The cross-correlation of the DPS with hard X-rays indicate that the plasmoid is fully (August 18, 1998) or partially (April 15, 2001) magnetically closed. Very important observations were made during the April 12, 2001 flare where both the DS and the metric type II burst were observed simultaneously but in different frequency ranges. It indicates that the DS is not formed by large-scale travelling coronal shock front. Using all above mentioned ideas we propose that the DS of the April 12, 2001 flare was generated in the plasmoid and the type II burst in the shock above the plasmoid structure. This suggestion can be supported by a similar frequency drift of both the radio bursts (similar speed of a whole plasmoid structure). In the case of the DS at the very beginning of the X14.4 April 15, 2001 flare we found a clear association of this DS with the ejected plasmoid. The frequency drifts of individual bursts in this DS indicate density gradients inside the plasmoid.

We can see that not only the metric type II radio bursts, but also these new radio phenomena, especially the drifting structures at higher frequencies, indicate eruptive flare processes. Similarly as in the case of type II bursts we interpret their negative frequency drift as caused by a disturbance motion oriented upwards into higher solar atmospheric heights, i.e. towards lower plasma densities. Their frequency drifts express directly flare explosive motions and that is why these radio bursts are considered as radio signatures of the eruptive solar flares and can be used for the prediction of heliospheric effects.

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References

Dryer, M., Andrews M. D., Aurass, H. and 21 coauthors: 1998, 'The Solar Minimum Active Region 7978, its X2.6/1B Flare, CME, and Interplanetary Shock Propagation of 9 July 1996', *Solar Physics* **181**, 159–183.

Hori, K.: 1999, Study of Solar Decimetric Bursts with a Pair of Cutoff Frequencies, in *Proceedings of the Nobeyama Symposium, NRO Report*, **479**, 267–271.

Hudson, H. S., Kosugi, T., Nitta, N. and Shimojo, M.: 2001, 'Hard X-Radiation from a Fast Coronal Ejection', *Astrophys. J.* **561**, L211–L214.

Karlický, M.: 1992, Radio Emission of Eruptive Flares, in Z. Švestka, B.V. Jackson, and M.E. Machado (eds), Eruptive Solar Flares, Lecture Notes in Physics **399**, pp. 171–176.

Karlický, M.: 1998, 'Chromospheric Evaporation Shock and Reduced Optical Thickness Drifting in the 1–4.5 GHz Range', *Astron. Astrophysics* **338**, 1084–1088.

Karlický, M. and Odstrčil, D.: 1994, 'The Generation of MHD Shock Waves during the Impulsive Phase of the February 27, 1992 Flare', *Solar Physics* **155**, 171–184.

Karlický, M., Yan, Y., Fu, Q. *et al.*: 2001, 'Drifting Radio Bursts and Fine Structures in the 0.8–7.6 GHz Frequency Range observed in the NOAA 9077 AR (July 10–14, 2000) Solar Flares', *Astron. Astrophysics* **369**, 1104–1111.

Khan, J. I., Vilmer, N., Saint-Hilaire, P. and Benz, A. O.:2002, 'The Solar Coronal Origin of a Slowly Drifting Decimetric-Metric Pulsation Structure', *Astron. Astrophysics* **388**, 363–372.

Klassen, A., Aurass, H., Klein, K. L. *et al.*: 1999, 'Radio Evidence of Shock Wave Formation in the Solar Corona', *Astron. Astrophysics* **343**, 287–296.

Kliem, B., Karlický, M. and Benz, A. O.: 2000, Solar Flare Radio Pulsations as a Signature of Dynamic Magnetic Reconnection. *Astron. Astrophysics* **360**, 715–728.

Reiner, M.J. and Kaiser, M. L.: 1999, 'High-frequency type II Radio Emissions Associated with Shocks driven by Coronal Mass Ejection', *JGR* **104**, 16979–16992.

Ohyama, M. and Shibata, K.: 1998, 'X-ray Plasma Ejection Associated with an Impulsive Flare on 1992 October 5; Physical Conditions of X-ray Plasma Ejection', *Astrophys. J.* **499**, 934–944.

Švestka, Z., Jackson, B. V. and Machado, M. E.: 1992, Eruptive Solar Flares. *Lecture Notes in Physics* **399**. Springer-Verlag, Berlin, Heidelberg.

Yokoyama, T. and Shibata, K.: 2001, 'Magnetohydrodynamic Simulation of a Solar Flare with Chromospheric Evaporation Effect based on the Magnetic Reconnection Model', *Astrophys. J.* **549**, 1160–1174.