A&A 375, 638–642 (2001)
DOI: 10.1051/0004-6361:20010888

Astronomy & Astrophysics

Radio bursts with rapid frequency variations – Lace bursts

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Received 19 March 2001 / Accepted 8 June 2001

Abstract. The Ondřejov radiospectrograph operating in the 0.8–2.0 GHz frequency range recorded in recent years (1998–2000), three (August 10, 1998; August 17, 1999; June 27, 2000) unique bursts with rapid frequency variations (lace bursts) lasting for several minutes. On August 17, 1999, the same burst was recorded simultaneously by the Brazilian Solar Spectroscope in the 1.0–2.5 GHz frequency range. The frequency variations of these bursts in four time intervals were analyzed by the Fourier method and power-law spectra with power-law indices close to –2 were found. The Fourier spectra show the presence of frequency variations in the 0.01–3.0 Hz interval which indicate fast changes of plasma parameters in the radio source. Due to the similarities in the line features of these bursts with zebra pattern lines, a model similar to that of the zebra pattern was suggested. The model radio spectra, computed using this model with a turbulent state of the solar flare atmosphere, are similar to those observed by the radiospectrographs.

Key words. Sun: activity – Sun: flares – Sun: radio radiation

1. Introduction

The radio bursts above 1 GHz were considered as featureless bursts (without any fine structures) generated by the gyro-synchrotron emission mechanism (Kundu 1965; Krüger 1979). But the new generation of radiospectrographs with higher time resolutions changed this conception and the various observed fine structures are now interpreted as being due to the plasma emission mechanism (e.g. review of Bastian et al. 1998). Moreover, the X-ray observations indicate flare processes at plasma densities of 10^9-10^{11} cm^{-3} (Ohyama & Shibata 1998). Therefore the observations in the decimetric range of wavelengths become very important, especially because of the expected radio emission from the flare primary energy-release sites.

Examples of bursts with rapid frequency variations (because of their appearances we call them also "lace bursts" – see Jiřička et al. 2001) in the range above 1 GHz were shown in the catalogue of the Brazilian Solar Spectroscope (BSS) (Fernandes et al. 2001). Similar fine structures can be recognized in Figs. 26 and 29 of the 1–3 GHz catalogue of Isliker & Benz (1994). From 1992 to 2000 the radiospectrograph at the Ondřejov Observatory (Jiřička et al. 1993) recorded 681 radio events in the frequency range of 0.8–2.0 GHz exhibiting various fine structures. In three cases only (August 10, 1998; August 17, 1999; and June 27, 2000), radio bursts with rapid frequency variations (the changes are of the order of fractions of seconds) were observed. In one case (August 17, 1999) the burst was observed also by the BSS, but the others could not be confirmed due to lack of observations on the respective dates. In the following, these unique bursts are presented and analyzed by the Fourier method. Finally, a phenomenological model is suggested and their artificial spectra computed.

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2. Observations

An example of a burst with rapid frequency variations (lace burst), observed on August 17, 1999, is shown in Fig. 1. The observation made by the Ondřejov radiospectrograph was confirmed by the Brazilian Solar Spectroscope (Sawant et al. 2001), shown at the bottom of Fig. 1. The burst sometimes appears as a very narrowband (about 50 MHz) line with strongly variable frequency and intensity (see e.g. Fig. 1, bottom part, 16:51:06–16:51:12 UT). These lines are sometimes, especially at their low-frequency ends, mutually superimposed and accompanied by continua, forming thus a lace burst in the radio spectrum. The frequencies and intensities change in fractions of second – see Fig. 2, where the time and frequency profiles of one burst line are shown (compare with the radio spectrum – Fig. 1).

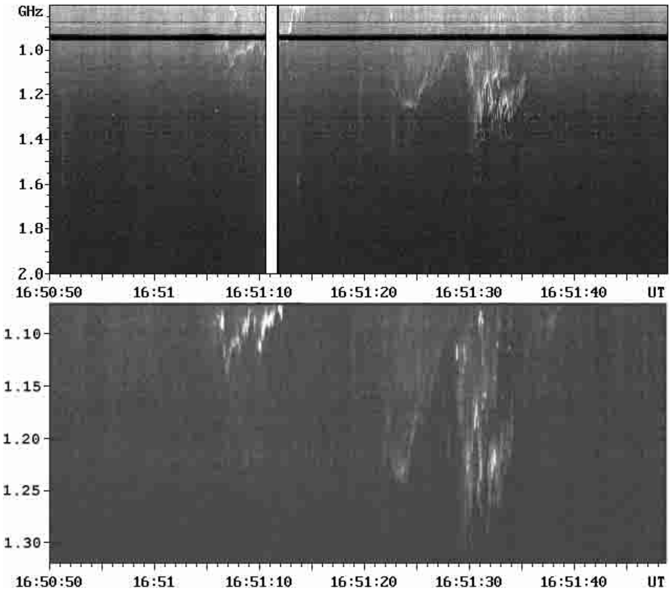

Fig. 1. The burst with rapid frequency variations observed on August 17, 1999 at 16:50:50–16:51:50 UT by the 0.8–2.0 GHz Ondřejov radiospectrograph (top) and for comparison the spectrum observed at the same time by the Brazilian Solar Spectroscope (bottom).

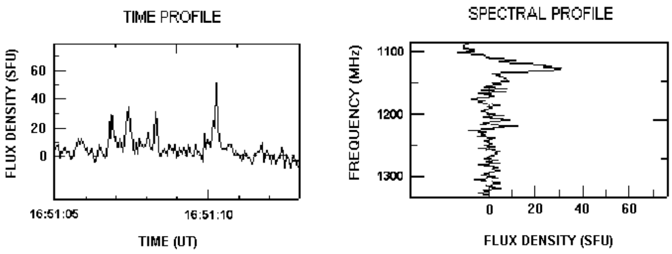

Fig. 2. The time and frequency profiles on 1.11 GHz and 16:51:07 UT obtained by the Brazilian Solar Spectroscope (the background flux density of 110 SFU is subtracted).

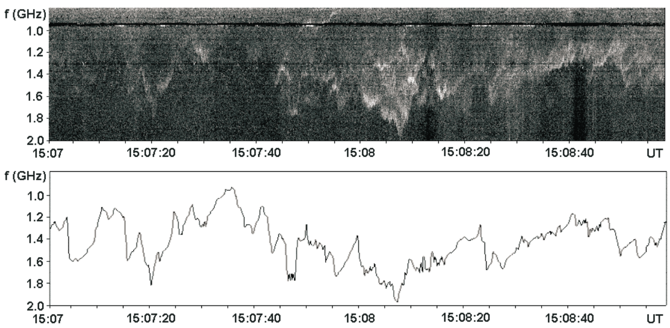

Fig. 3. The burst with rapid frequency variations observed on August 17, 1999 at 15:07–15:09 UT by the 0.8–2.0 GHz Ondřejov radiospectrograph (top) and the corresponding high-frequency burst boundary outline (bottom).

In other cases, especially in those lasting longer, these bursts are even more complex, with lines and continua mutually superimposed, giving thus the impression that they correspond to different radio sources (Fig. 3, upper part). These complex structures can also be seen in Fig. 4,

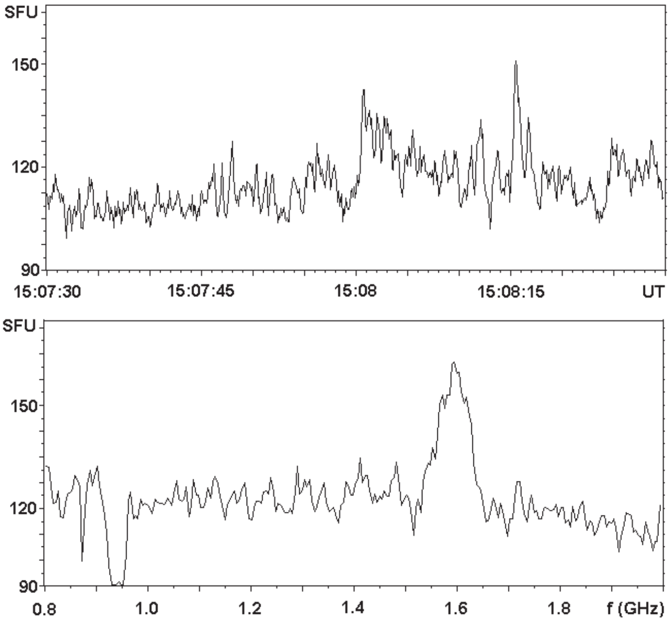

Fig. 4. The time and frequency profiles on 1.6 GHz and 15:08:15.5 UT for the burst from Fig. 3 showing the complex structure of the burst.

where the time (1 minute interval) and frequency profiles of the radio spectrum (see also Fig. 3, upper part) are depicted. For example, the simple peak at 15:08:15.5 UT lasts about 1.3 s and its bandwidth is about 140 MHz. On the other hand, the time profiles of other peaks are more complex, e.g. at 15:08:00–15:08:04 UT.

In all the three observed events these bursts are part of long lasting pulsations in the 0.8–2 GHz frequency range. The flare activity associated with these bursts is summarized in Table 1.

3. Data analysis

From the three observed bursts, four long-lasting (several minutes) time intervals (see Table 2) were selected for analysis. The example of one selected part (August 17, 1999, 15:07–15:09 UT) is shown in Fig. 3, where in its bottom part the line corresponding to the high-frequency boundary of the burst, formed by several lace lines, is drawn. This line shows frequency variations which are then analyzed by the Fourier method. The results for the four selected intervals from Table 2 are shown in Fig. 5. For comparison, straight lines expressing slopes corresponding to the best fitted power-law indices (see Table 2) are added. All the found power-law indices are close to –2. Moreover, the Fourier spectra show the presence of frequency variations in the interval of about 0.01–3.0 Hz. We suppose that these variations correspond to changes of plasma parameters in the radio source.

4. Model radio spectrum

Because the studied lace bursts and the zebra pattern lines show similarities, we use for the interpretation of lace

Table 1. The basic characteristics of flares during which the bursts with rapid frequency variations were observed (all times are in UT).

		Aug. 10, 1998	Aug. 17, 1999	Jun. 27, 2000
GOES	Start	8:35	14:28	12:40
	Max	8:40	16:02	12:55
	End	8:42	17:54	13:21
	Class	B7.6	C5.9	C9.3
H-alpha	Start	8:35	15:05	12:49
	Max	8:40	15:22	12:54
	End	8:54	16:34	13:42
	Importance	SF	SF	2N
	Position	S23W18	N24E37	S17E48
	NOAA AR	8293	8668	9062
radio (1–2 GHz)	Start	8:45	14:47	12:52
	End	9:19	17:04	13:04

Table 2. The list of the analyzed parts of the bursts with rapid frequency variations, Fourier frequency ranges, and Fourier power-law indices.

Part	Date	Start [UT]	Duration [s]	Freq. Range [Hz]	Power-law Index
a	Aug. 10, 1998	08:51:59	120	0.008–5	-2.00 ± 0.04
b	Aug. 10, 1998	08:59:50	120	0.008–5	-1.91 ± 0.04
c	Aug. 17, 1999	15:01:00	300	0.003–5	-1.88 ± 0.03
d	Aug. 17, 1999	15:07:00	120	0.008–5	-2.13 ± 0.04

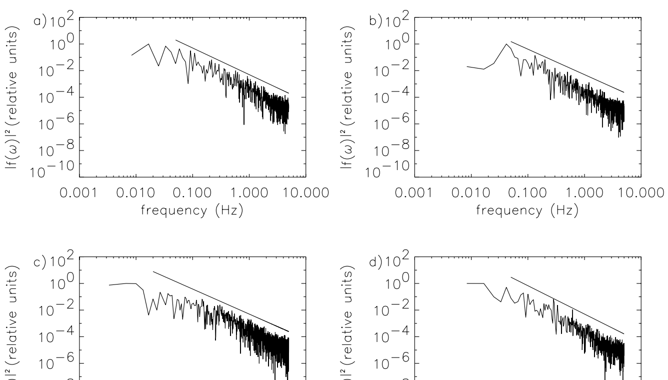

Fig. 5. Fourier spectra of the four selected intervals (see Table 2) from the bursts with rapid frequency variations.

bursts a concept similar to that used for zebra patterns (e.g. Zheleznyakov & Zlotnik 1975; Ledenev et al. 2001). However, here we suggest that the radio emission is generated in plasma with rapidly changing plasma parameters (density or/and magnetic field). Thus we assume that the lines of lace bursts are generated in the solar atmosphere at positions where the following resonance condition is fulfilled:

$$\omega_{\rm UH} = (\omega_{\rm pe}^2 + \omega_{\rm Be}^2)^{1/2} = s\ \omega_{\rm Be}, \tag{1}$$

where $\omega_{\rm UH}$, $\omega_{\rm pe}$, and $\omega_{\rm Be}$ are the upper hybrid, electron plasma and cyclotron frequencies, and s is the integer harmonic number. The source of the energy can be the loss-cone distribution function of superthermal electrons (Zheleznyakov & Zlotnik 1975) or an electron beam anisotropic in temperature with $T_\perp > T_\parallel$, where $T_\perp$ and $T_\parallel$ are the temperatures of energetic electrons across and along the magnetic field, respectively (Mikhailovsky 1975; Ledenev et al. 2001). The anisotropic temperature beam can be formed by the expansion of the hot plasma into the cold plasma along magnetic field lines. The generated upper hybrid waves are then transformed into observable electromagnetic waves. The accompanying continua can be a superposition of many weak lace lines generated in the neighboring flux tubes or they can be generated by some additional instabilities in the disturbed flare plasma.

Based on this idea, we built the following phenomenological model: Let us suppose that the instability leading to the radio emission can be described as two oscillators with frequencies $\omega_{\rm UH}$ and $s \cdot \omega_{\rm Be}$, coupled by positive feedback. Then, the electric field $\boldsymbol{E}$ of the upper hybrid oscillations can be written as

$$\frac{{\rm d}^2\boldsymbol{E}}{{\rm d}t^2} + \nu\frac{{\rm d}\boldsymbol{E}}{{\rm d}t} + \omega_{\rm UH}^2\boldsymbol{E} = C\cos(s\cdot\omega_{\rm Be}t), \tag{2}$$

where the coefficient C expresses the measure of the coupling between the oscillators and ν is the damping of the upper hybrid waves. Solving this equation for $\boldsymbol{E}$ in the form $\boldsymbol{E}(t) = \boldsymbol{E}_0 \cdot \exp(i \cdot s\omega_{\rm Be}t)$, the resulting radio flux F can be written as

$$F \propto \frac{1}{(\omega_{\rm UH}^2 - s^2\omega_{\rm Be}^2)^2 + \nu^2 s^2 \omega_{\rm Be}^2}, \tag{3}$$

where it is assumed that the radio flux is proportional to the square of modulus of the complex amplitude $\boldsymbol{E}_0$ of the upper hybrid waves. From this formula, it follows that the radio flux has a maximum at the place where the resonance condition (1) is fulfilled and strongly decreases elsewhere.

The processes are considered in a 1-D source model with the stationary mean electron density decreasing slowly in space as

$$n(x) = n_0 \left(1 - \frac{x}{L}\right), \qquad x \in (0; L) \tag{4}$$

and the magnetic field in a solitary magnetic flux tube as

$$B(x) = B_0 \left(1 - \frac{x}{\sqrt{x^2 + b^2}}\right) \cdot \tag{5}$$

Here the parameters L and b with dimensions of length represent typical scales on which the magnetic field B and the electron density n vary. Then, on this stationary mean density profile, chaotically varying (in space and time) density and magnetic field perturbations are superimposed. Perturbed frequencies $\omega_{\rm UH}$ and $\omega_{\rm Be}$ are computed at each point x of the source at fixed time t and using the formula (3) contributions of the radio flux in relative units are also determined. Contributions to the flux from each element of the source are divided into frequency channels according to radiation frequency ω. This frequency is given by the forcing frequency, i.e. $\omega = s \cdot \omega_{\rm Be}$. Contributions of the radio flux belonging to an appropriate channel are integrated over the source length. Thus, the spectrum at fixed time is obtained. Using this algorithm repeatedly for subsequent times, at which the plasma parameters are changed, the whole artificial dynamic spectrum can be computed.

One example of such a spectrum is shown in Fig. 6, where the following parameters for the initial flare atmosphere are used: $n_0 = 3 \times 10^{10}$ cm^{-3}, $B_0 = 200$ G, $L = 4 \times 10^9$ cm, $b = 5 \times 10^7$ cm. The radio emission is considered on the $s = 4$ harmonic. The magnetic field variations are set to zero. On the other hand, the density variations have the following spatial characteristics: a) the spectrum is a power-law function with the power-law index –2 for the wave numbers greater than 2×10^{-8} cm^{-1}, b) the rms of the density perturbation is 0.1 n_0, and c) the phases are random. In the flare atmosphere, these density variations propagate with the speed of sound corresponding to the temperature 1.5×10^6 K. Comparing this modelled radio spectrum with the lace burst of August 17, 1999 at 16:51:06–16:51:12 UT (Fig. 1, bottom part), similarities between the two spectra are evident.

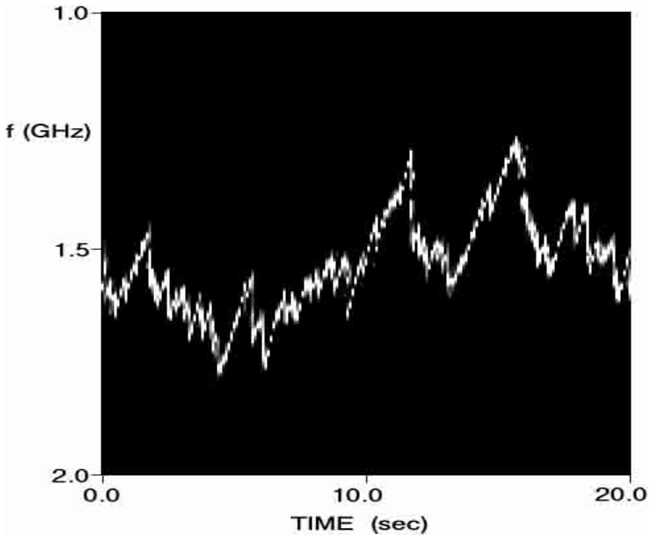

Fig. 6. The modelled 1–2 GHz spectrum of the burst with rapid frequency variation.

5. Conclusions

The bursts with rapid frequency variations (lace bursts) are very rare. During the nine years of observations (1992–2000), among the 681 events observed by the 0.8–2.0 GHz Ondřejov radiospectrograph, only three cases of such bursts were recorded. In longer events these bursts appear to be mutually superimposed, forming complex structures with a relatively well defined high-frequency boundary. Time variations of these boundaries have been analyzed by the Fourier method and power-law spectra with power-law indices close to –2 were found. Moreover, the Fourier spectra show the presence of frequency variations in the interval of 0.01–3.0 Hz. We think that these variations correspond to changes in the plasma parameters within the radio source.

A model of lace bursts, similar to that of zebra patterns, was suggested. The most important aspect of this model is that the flare plasma in the radio source is considered to be in a turbulent state. Using this model, the artificial spectrum, similar to real ones observed by spectrographs, was computed. This model can explain these bursts, especially their line features. Moreover, we think that the different lace lines can be generated in different flux tubes. The accompanying continua can be a superposition of many weak lace lines generated in the neighboring flux tubes or they can be generated by some additional instabilities in the disturbed flare plasma.

Based on the presented model, the lace bursts belong to the same group of fine structures as zebra patterns. The difference is that these bursts are generated in turbulent plasma. A possible source of the turbulence can be the plasma outflows from the magnetic field reconnection. The reconnection is also a probable source of accelerated electrons forming an unstable distribution function. We think that lace bursts provide a unique opportunity to study the flare turbulence.

Acknowledgements. M. Karlický wants to express thanks to FAPESP authorities for supporting his visit at INPE (P.N. 01/00144-5). F. C. R. Fernandes is grateful to the Brazilian Agency FAPESP for support under Proc. 99/10529-0. This work was also supported by the grants S1003006 and A3003003 of the Academy of Sciences of the Czech Republic and the grant 205/00/1727 of the Grant Agency of the Czech Republic under the key project K2043105. The authors also thank the referee for suggestions which led to significant improvement of the paper.

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