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Anisotropic Beam Model for the Spectral Observations of Radio Burst Fine Structures on 1998 April 15

V. G. Ledenev[1,2], Yi-Hua Yan[1] ⋆ and Qi-Jun Fu[1]

[1] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012
[2] Institute of Solar-Terrestrial Physics, Siberian Division of Russian Academy of Sciences, 664033, Irkutsk, P. O. Box 4026, Russia

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Abstract A fine structure consisting of three almost equidistant frequency bands was observed in the high frequency part of a solar burst on 1998 April 15 by the spectrometer of Beijing Astronomical Observatory in the range 2.6–3.8 GHz. A model for this event based on beam-anisotropic instability in the solar corona is presented. Longitudinal plasma waves are excited at cyclotron resonance and then transformed into radio emission at their second harmonic. The model is in accordance with the observations if we suppose a magnetic field strength in the region of emission generation of about 200 G.

Key words: Sun: radio radiation — Sun: activity — Sun: corona

1 INTRODUCTION

Although temporal fine structures (FS) superimposed on solar microwave bursts have been observed for more than 20 years, the understanding of the FS in high frequency ranges is still inadequate (Isliker & Benz 1994; Messmer et al. 1999). Analogous fine structures are observed in other frequency bands. They are, for example, the "zebra"-structure, "stripe"-bursts and other fine structures in meter wave band (Kruger 1979; Slottje 1981). The existence of third harmonic in type II bursts was discussed more recently (Bakunin et al. 1990; Kliem et al. 1998).

Different models with different estimates for the magnetic field have been suggested for bursts with FS in meter range (Rosenberg 1972; Chiudery et al. 1973; Zheleznyakov & Zlotnik 1975; Kuijpers 1975; Tarnstrom & Benz 1978). It is natural to suggest that some of these models can be used for the interpretation of microwave burst FS, but it is necessary to take into account the different conditions of microwave burst generation, particularly, the higher density and stronger magnetic field. Rosenberg (1972) was among the first to suggest an interpretation of the "zebra"-structure in metric type IV bursts. He attributed the origin of the "zebra"-structure to the merging of longitudinal waves at the upper hybrid frequency with Bernstein

⋆ E-mail: yyh@bao.ac.cn

modes whose frequencies are close to cyclotron harmonic frequencies. The magnitude of the magnetic field was inferred from the separation between adjacent emission bands in the "zebra"-structure. Zheleznyakov and Zlotnik (1975), and Kuijpers (1975) speculated that a "zebra"-structure in type IV bursts is generated when a loss-cone instability develops in a magnetic arch. This process is accompanied by the excitation of longitudinal waves at the upper hybrid frequency, with the wave vector directed across the magnetic field in regions where the resonance condition $\omega = s\omega_{\rm Be}$ is fulfilled (here $\omega = (\omega_{\rm pe}^2 + \omega_{\rm Be}^2)^{1/2}$ is the upper hybrid frequency, $\omega_{\rm Be}$ the electron cyclotron frequency, and s the cyclotron harmonic number). Emission is generated either through scattering of longitudinal waves from background plasma ions or as a result of merging of longitudinal waves. This interpretation is similar to the one suggested in this paper, yet there are substantial differences. First and foremost, the phenomenon interpreted in our study cannot be categorized as a type IV burst. It is our opinion that it represents a group of type III bursts in the presence of a weak continuum. Furthermore, the "zebra"-structure, which we observed, consists only of three sufficiently clearly discernible emission bands, whereas the "zebra"-structure of metric type IV bursts usually involves a host (several tens) of emission bands (Kuijpers 1975; Slottje 1981). From this follow also the fundamental differences in the interpretation of these phenomena, and in the estimates of the magnetic field. It was suggested in (Zheleznyakov & Zlotnik 1975; Kuijpers 1975) that the development of a loss-cone instability results in the excitation of longitudinal waves at high cyclotron harmonics (with harmonic numbers $s \sim 50$). The magnitude of the magnetic field in this case is estimated from the distance between adjacent emission bands. In our opinion, the excitation of longitudinal waves at such high cyclotron harmonics at the heights of the corona, where microwave bursts are generated, is unlikely, because of strong collisional damping, and in view of the fact that the loss-cone instability growth rate drops rapidly with increasing harmonic number (Mikhailovsky 1975). It is therefore more natural to expect in the case under consideration that longitudinal waves are excited at low cyclotron harmonics. It must also be assumed that the magnetic field decreases with the height so rapidly that the electron cyclotron frequency $\omega_{\rm Be}$ decreases with the height faster than does the electron plasma frequency $\omega_{\rm pe}$. Hence it follows that, based on our model, the magnitude of the magnetic field in the emission source cannot be estimated directly from the distance between adjacent emission bands in the "zebra"-structure. As in (Zheleznyakov & Zlotnik 1975; Kuijpers 1975), our model assumes that the emission regions of separate bands are spatially separate; however, the sequence of emission regions with changes of the cyclotron harmonic number is the reverse in our model, i.e., the height of emission region increases in the corona with increasing harmonic number. Further, we do not assume excitation of loss-cone instability in the magnetic arch. We think that an anisotropic distribution function of energetic electrons is formed due to kinematic segregation in space of electrons with different velocities along the magnetic field (Ledenev 1994a).

Different interpretations are suggested also for the third harmonic in type II bursts. Ledenev and Urbarz (1993) supposed that the longitudinal waves are excited at cyclotron resonance by an anisotropic electron beam. Then the waves merge into electromagnetic radiation. Zlotnik et al. (1998) considered two nonlinear merging processes to explain the occurrence of the third harmonic on type II dynamic spectra - the coalescence of three plasma waves, and of a plasma wave and electromagnetic wave at twice the plasma frequency.

We think that in our case the most suitable explanation is the excitation of longitudinal waves by an anisotropic electron beam at cyclotron resonance, analogous to that suggested by Zheleznyakov and Zlotnik (1975) and Kuijpers (1975) for an explanation of the "zebra"-

structure (with essential distinctions mentioned above), and suggested by Ledenev and Urbarz (1993) for an explanation of the three harmonic structures in type II bursts, because the observed burst is not so intensive as type II bursts and the development of four-wave processes is unlikely.

2 OBSERVING INSTRUMENT AND OBSERVATION

The data used in the present analysis were observed by the newly developed Solar Radio Broadband Fast Dynamic Spectrometers with high temporal and frequency resolutions (Fu et al. 1995). The parts of 1.0–2.0 GHz, 2.6–3.8 GHz, and 5.2–7.6 GHz for both polarization and intensity observations have been in operation since January 1994, September 1996 and August 1999, respectively, and they are now located at Huairou Solar Observing Station of Beijing Astronomical Observatory (BAO).

As described in Ji et al. (2000), the performance of the 2.6–3.8 GHz spectrometer is very powerful in detecting radio FS. It has a very high temporal resolution of 8 ms with 120 channels to reach a spectral resolution of 10 MHz over the whole frequency range. The sensitivity is 2 percent of the background radiation from the quiet Sun for dual-circular polarization observations and the dynamic range is 10 dB above the quiet Sun emission (Ji et al. 2000).

On 1998 April 15, solar radio bursts occurred in the active region NOAA 8203 at N29W15 of the solar disk. There were many complex radio FS, e.g., subsecond type U burst and millisecond spikes, registered by the 1.0–2.0 GHz and 2.6–3.8 GHz spectrometers at BAO (Huang & Fu 1999; Wang et al. 2001).

The event discussed here was recorded by the 2.6–3.8 GHz spectrometer and is shown in Fig. 1 for a cascade plot of the radio spectrogram in right polarization. On the lower picture one can see three frequency bands of emission. The distance between the adjacent frequency bands is about 70–80 MHz. The left polarization was very weak. So it was a strongly polarized event. The flux at maximum of burst was about 800 s.f.u. (solar flux unit).

It should be noted that analogous structures have been observed earlier in close frequency range (Isliker & Benz 1994), but they have not had an interpretation until now.

3 THE MODEL OF PARAMETERS DISTRIBUTION

We can see from Fig. 1 that the distance between the adjacent frequency bands is very small. Then we can say that the distance is not a cyclotron frequency because it corresponds to $s \approx 50$, where s is the number of the cyclotron harmonic. It is impossible to generate the waves effectively at such high harmonics.

If we suppose the emission was generated at lower harmonics we have to consider the generation in conditions where the magnetic field changes with height faster than does the coronal plasma density. Such situation may exist, for instance, in low coronal magnetic arches where the dimension may be comparable to, or less than the typical scale of density variation (Zirin 1988).

Here, we consider a simpler situation where the emission is generated in the field of a magnetic pivot with its length much longer than the radius. The magnetic field of such a pivot is expressed as follows:

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

where B_0 is the magnetic field at the base of the pivot, b is pivot radius and x is the distance from the pivot base.

We suppose also that the plasma density changes linearly, i.e.,

$$n = n_0 \, (1 - x/L) \,, \tag{2}$$

where n_0 is the density near the base of the magnetic pivot, L, typical scale of the density variation.

It should be noted that our model refers to the part of the corona where the emission is generated. It means that the pivot base does not coincide with the photosphere but is located at a higher level in the corona.

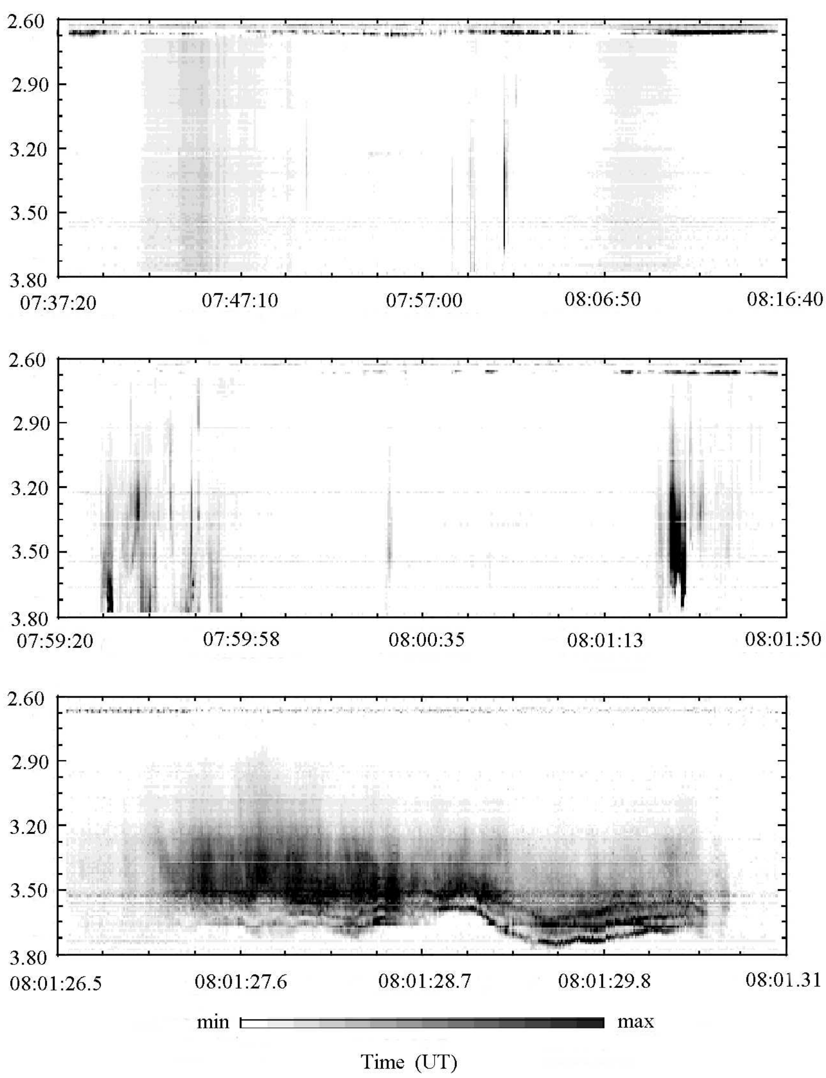

Fig. 1 Cascade plot of radio spectrograms in right polarization, showing the fine structures of the solar bursts on 1998 April 15 in 2.6–3.8 GHz range observed with 10 MHz spectral resolution at BAO. From top to bottom, the temporal resolutions are 0.2 s, 0.2 s, and 8 ms, respectively. The intensity in arbitrary units is shown in gray-scale.

4 EMISSION GENERATION

As a result of local heating in the solar corona there are groups of energetic electrons. In many situations the distribution function of the electrons has an anisotropic character. This is possible in magnetic traps where the electrons with high velocities are captured across the magnetic field. It is possible also when electrons with high velocities along the magnetic field escape from the heating region while electrons with low longitudinal and high transverse velocities stay close to the region. In the case where the temperature of the beam across the magnetic field is larger than the temperature along the field, then beam-anisotropic instability is developed (Mikhaylovsky 1975). The growth rate of that instability for cold background plasma is (Mikhaylovsky 1975)

$$\gamma = -\frac{\sqrt{\pi}\alpha\omega_{\mathrm{pe}}^2}{v_{\mathrm{Te}_\parallel}^3 k^2|k_\parallel|}\left\{\frac{2\omega_{\mathrm{pe}}^2}{\omega^3}\sum_{s=-\infty}^{\infty} I_s \exp\left(-z_\perp\right)\exp\left[-\left(\frac{\omega - k_\parallel v_\parallel - s\omega_{\mathrm{Be}}}{k_\parallel v_{\mathrm{Te}_\parallel}}\right)^2\right]\right.$$
$$\left.\times\left[\omega - k_\parallel v_\parallel - s\omega_{\mathrm{Be}}\left(1 - \frac{T_\parallel}{T_\perp}\right)\right]\right\},$$

where α is the ratio of the beam density n_b to the density of background plasma n, ω_{pe} the electron plasma frequency, $v_{\mathrm{Te}\parallel}$ the thermal electron velocity along the magnetic field, k the wave number, $k_{||}$ the longitudinal component of the wave number, ω is the emission frequency, s the electron cyclotron harmonic number, ω_{Be} the electron cyclotron frequency, $T_{||}$ and $T_\perp$, the energetic electron temperature along and across the magnetic field respectively, I_s, the modified Bessel function, $z_\perp = k_\perp T_\perp / m\omega_{\mathrm{Be}}^2$, m the electron mass, $k_\perp$ the transverse component of the wave number. From this formula we can see that the developed frequencies satisfy the electron cyclotron resonance condition $\omega = k_\parallel v_\parallel + s\omega_{\mathrm{Be}}$, and the waves develop mainly across the magnetic field ($k_\parallel$ is small). In this case $\omega \approx (\omega_{\mathrm{pe}}^2 + \omega_{\mathrm{Be}}^2)^{1/2}$. It follows from this relation that it is impossible for the first harmonic to satisfy the cyclotron resonance condition, for small $k_{||}v_{||}$.

Since the wave numbers of the developed waves are almost transverse to the magnetic field we can say that the situation is favorable for the generation of electromagnetic waves by merging of longitudinal plasma waves (Zheleznyakov 1977; Melrose 1980). An analogous model was suggested in (Ledenev & Urbarz 1994) for an interpretation of type II bursts in the metric frequency range.

So if we have beam-anisotropic instability and suppose the magnetic field is one of magnetic pivot, and suppose the plasma density changes linearly, we have to satisfy the condition $\omega \approx s\omega_{\mathrm{Be}}$. Let us take, at the pivot base, a magnetic field $B_0 = 200\,\mathrm{G}$ and a plasma density $n_0 = 3 \times 10^{10}\,\mathrm{cm}^{-3}$. Taking into account $\omega \approx (\omega_{\mathrm{pe}}^2 + \omega_{\mathrm{Be}}^2)^{1/2}$ and using the formulas (1), (2) for ω_{pe} and ω_{Be}, we get the equation

$$\frac{2.76}{\sqrt{s^2-1}}\sqrt{1 - x/L} = 1 - \frac{1}{\sqrt{1 + b^2/x^2}}. \tag{3}$$

If we take the pivot radius $b = 2\times10^8$ cm and a typical scale of density variation $L = 4\times10^9$ cm we obtain the results from formula (3) shown in Table 1. We can see that under such parameter values, the cyclotron resonance condition is fulfilled beginning from the third harmonic.

The emission frequencies are obtained from the cyclotron frequencies f_{Be} by multiplying by 6, 8 and 10 for third, fourth and fifth harmonics, respectively, taking into account that the emission takes place on double frequencies due to the merging of longitudinal waves. The plot of longitudinal wave frequency $f(x)$ and cyclotron harmonic frequencies $3f_{\rm Be}(x)$, $4f_{\rm Be}(x)$, $5f_{\rm Be}(x)$ versus the distance x from the base of the magnetic pivot is shown in Figure 2. These results are in agreement with the observations (Figure 1) and sufficient for a qualitative illustration of the suggested model, but we think that it is possible to use this calculation for an order-of-magnitude estimation. For a more exact evaluation we need to know the real magnetic field and plasma density distribution with height.

Table 1

Harmonic Number	3rd	4th	5th
Height (cm)	0.05×10^8	0.6×10^8	1×10^8
$f_{\rm Be}$ (Hz)	0.55×10^9	0.4×10^9	0.31×10^9
B (G)	195	142	110

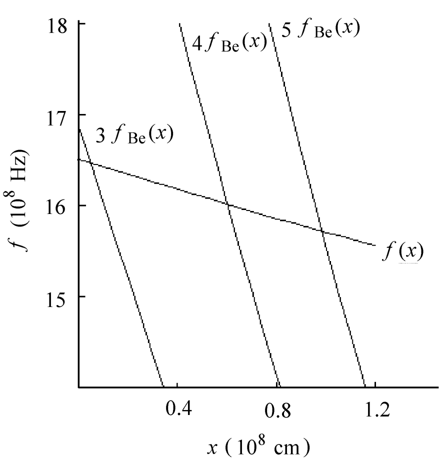

Fig. 2 Plot of longitudinal wave frequency $f(x)$ and cyclotron harmonic frequencies $3f_{\rm Be}(x)$, $4f_{\rm Be}(x)$, $5f_{\rm Be}(x)$ versus distance x from the base of the magnetic pivot. The points of line intersection determine the frequencies of longitudinal waves generation. Frequencies of emission are approximately two times greater.

5 DISCUSSION

We see from Table 1 that in our case the second cyclotron harmonic does not develop because it does not satisfy the cyclotron resonance condition. If we take a magnetic field strength greater than 300 G, we shall have emission on the second harmonic also but the distance between the adjacent frequency bands is substantially greater than that observed. That is why we choose the magnetic field B_0 to be less than 300 G. If we take the magnetic field weaker than 200 G, then the waves begin developing with the fourth harmonic and the distances between adjacent harmonics get smaller.

From Fig. 1 we can estimate the Alfvén velocity v_a and the length of Alfvén waves in the region of emission generation. The typical time of frequency variation and, consequently, the magnetic field variation is about 1 s. For B = 200 G and n = 3×10^{10} cm $^{-3}$ we obtain

$v_a = 3\times10^8$ cm s^{-1}. The corresponding wavelength is about 3×10^8 cm. This wavelength is of the same order of magnitude as the distance between the generation regions of the third and fifth cyclotron harmonic obtained from calculations. but actually we see from Fig. 1 the displacement of emission frequency on the interval correspond to the distance between the first and third frequency bands.

The observations of the fine structures show high polarization. There are no calculations of emission polarization for such strong magnetic field when $\omega_{\rm Be} \sim \omega_{\rm pe}$. But if the calculation for weak magnetic field (Ledenev 1994b) is extrapolated to a stronger field (but under condition $\omega_{\rm Be} < \omega_{\rm pe}$), we can conclude that in our case when longitudinal waves are excited almost across the magnetic field and the emission is generated at the second harmonic of the longitudinal waves, it is possible that strong polarization corresponds to the extraordinary wave mode.

6 CONCLUSIONS

Our calculations show that the FS of the burst on 1998–04–15 (three separate frequency bands with small distances between them) can be interpreted as the generation of longitudinal plasma waves on low cyclotron harmonics. The lowest harmonic number depends on the magnetic field strength in the emission region. A stronger magnetic field gives a lower harmonic number but not lower than the second. These waves develop under beam-anisotropic instability. Then the waves transform into electromagnetic waves from mutual merging. So we receive the emission at twice the frequency of the original longitudinal waves. That is why it does not need to take into account cyclotron damping of the emission in higher levels of the corona.

In our calculations we use a simple model for the variation of the parameters with the height in the corona. The density decreases linearly and the magnetic field is modelled by a magnetic pivot. The calculations show that if we take the values of the parameters at the base of the magnetic pivot, $B_0 = 200$ G and plasma density $n_0 = 3\times10^{10}$ cm^{-3}, and the radius of the magnetic pivot $b = (2-5)\times10^8$ cm, we get the values close to the observed frequencies for a typical scale of density variation $L = (2-4)\times10^9$ cm. The strength of the magnetic field is about 200 G for the third harmonic, about 140 G for the fourth and about 110 G for the fifth harmonics. In any case if it is supposed that the longitudinal waves are generated at the cyclotron harmonics and the emission is generated by the merging of the longitudinal waves, we can estimate the magnetic field strength in the region of cyclotron harmonic generation.

It is possible that the emission is generated by the scattering of longitudinal waves by thermal ions (generation at the fundamental harmonic of longitudinal waves) (Zheleznyakov 1977), but such emission will be depressed due to cyclotron damping at the higher levels of the solar corona (Stepanov et al. 1997).

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