ELECTRON BEAMS IN THE LOW CORONA*

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Abstract. Selected high-resolution spectrograms of solar fast-drift bursts in the 6.2–8.4 GHz range are presented. The bursts have similar characteristics as metric and decimetric type III bursts: rise and decay in a few thermal collision times, total bandwidth ≥3% of the center frequency, low polarization, drift rate of the order of the center frequency per second, and flare association. They appear in several groups per flare, each group consisting of some tens of single bursts. Fragmentation is also apparent in frequency; there are many narrowband bursts randomly scattered in the spectrum. The maximum frequency of the bursts is highly variable.

The radiation is interpreted in terms of plasma emission of electron beams at plasma densities of more than 10¹¹ cm⁻³. At this extremely high frequency, emission from the plasma level even at the harmonic is only possible in a very anisotropic plasma. The scale lengths perpendicular and parallel to the magnetic field can be estimated. A model of the source region and its environment is presented.

1. Introduction

In the early years of solar radio astronomy the general consensus was that the radio signatures of electron beams, the type III bursts, do not extend much beyond 300 MHz. The flux density of the quiet Sun strongly increases in the decimetric wavelength range (0.3–1 GHz). This is the main reason why early work applying analog spectrometry with film recording did not reveal much spectral structure (Fourikis, 1971). The expectation of non-existence of high-frequency type III bursts was also fostered by the belief of complete absorption of plasma emission at frequencies above 300 MHz. Nevertheless, high temporal variations in the microwave region have been known for several decades (e.g., review by Kundu, 1965). They are known today as indicative of coherent emission processes.

Fast-drift bursts have been known to exist in decimeter and microwave regions since the early 1960's (Young et al., 1961: Kundu, 1965). Recently, Allaart et al. (1990) and Bruggmann et al. (1990) have presented spectrograms with fast-drift bursts extending up to 9 GHz. It is clear from investigations of decimeter waves that a fast drift does not define a unique burst type and can have other physical origins than beams (including, e.g., magnetically trapped particles).

The underlying physical process can be inferred by a detailed analysis of high-resolution spectrograms and polarization observations. The characteristics of the unknown bursts are then compared to well-known phenomena properly scaled in frequency. In the case of electron beams, interplanetary and metric type III bursts

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provide such a foothold. This method has been applied to show that narrowband fast-drift bursts at frequencies below 1 GHz (‘blips’) are high-frequency versions of metric type III bursts (Benz, Bernold, and Dennis, 1983). At 3 GHz, Stähli and Benz (1986) have found fast-drift bursts with the properties expected for type III bursts in the microwave region.

The emission frequency is close to the source plasma frequency or its harmonic. Therefore, the source density is immediately known. Electron beams propagating through high density plasmas are expected from hard X-ray flare emission, but the observation of radio signatures of beams in high density plasmas is surprising. What is the maximum ambient density at which beams are observable?

Here we present the results of a study of fast-drift bursts at much higher frequency that are fully compatible with the type III characteristics of lower frequency bursts. This suggests the same physical processes. The problems with an interpretation of the new radio emissions as plasma emission of electron beams will be discussed.

2. Observations

High-resolution spectroscopy in the 6.4–8.6 GHz was recently made possible for the first time in a joint project of the Radio Astronomy Group at ETH Zürich and the Solar Group at Bern University. The solar microwave emission was surveyed for coherent (narrowband) flare radiation with a temporary setup consisting of a 4-m antenna and receiver front end (2000 K noise temperature) provided by the Bern group feeding the PHOENIX spectrometer of ETH Zürich (Benz et al., 1991). The full-Sun observing instrument was programmed to step through 200 frequency channels at 10 MHz bandwidth each in 100 ms. The flux resolution (r.m.s. noise) was 7–9 s.f.u. The data has been calibrated off-line using daily measurements of a noise source in the front end and an antenna calibration of 1988 April 28 on the quiet Sun. The instrument has operated for about 2000 hours from April 1988 to May 1989 and recorded 70 hours of enhanced flux.

First results published by Bruggmann et al. (1990) have shown spectral structures in the forms of patches, millisecond spikes, and drifting structures. The drifting structures had half-power durations of 1–4.5 s, more than an order of magnitude longer than the bursts identified as ‘type III’ at 3 GHz by Stähli and Benz. The long durations make them unlikely type III extensions.

The analysis of the complete data set has revealed a different kind of fast-structures, much shorter than the ones found by Bruggmann et al. A total of six groups of short duration fast-drift bursts were found. The best two examples are presented in Figures 1 and 2 and are analyzed in the next section.

3. Analysis

Figures 1 and 2 exhibit that the emissions consist of many structures. We have analyzed the spectrograms with a software package developed by Aschwanden and Benz (1986) for decimetric pulsations. The program searches for fast-drifting structures in the
Fig. 1. Spectrogram representation of the microwave type III bursts observed by the Zürich/Bern collaboration on 1988 November 1. Frequency increases downward, time to the right. Enhanced flux density in frequency and time is shown bright. The arrows mark the times of the spectra shown in Figure 3. Two enlargements at the bottom show structures down to the resolution size (10 MHz, respectively 100 ms).

frequency–time plane. A high pass filter eliminates long time-scale modulations and the background. Maxima exceeding a certain threshold are tracked through adjacent channels. A minimum of 15 channels (150 MHz) has been set for a reliable detection. The program can also integrate adjacent channels to detect weak structures. In a next step the structures were analyzed. The extent in frequency, mean and peak flux, and spectral indices are automatically determined. The program also finds the time profile
in each channel by quasi-hermetic cubic spline fits. This part of the analysis, however, only works properly if the structures are resolved in time, a condition that was not always fulfilled.

3.1. Fragmentation

The structure recognition and analysis program has found sixteen, respectively twenty elements in the events of Figures 1 and 2. Each structure has been visually verified in time profiles and spectrograms. At its peak, the rate of structures is four per second. In metric type III bursts this number can reach eight (Aschwanden et al., 1990).
We note that a frequency-agile spectrometer can completely miss a structure of shorter duration than the sweep time. We suspect that this is the case here. The measured number and rate then have to be multiplied by the ratio of the sweep time to the single burst duration. On the other hand, bursts that disappear in a certain band and reappear at a different frequency are counted more than once.

The bandwidth of the elements sometimes exceeded the instrumental limit of 2200 MHz (cf. Figure 1). Since it takes the instrument 100 ms to measure a full spectrum, we conclude that the duration of the single burst in these cases is longer. The minimum bandwidth of 150 MHz – set by the structure recognition method – was also observed. The average bandwidth was $510 \pm 380$ MHz. This is a lower limit since some bursts were cut off by the spectral range of the instrument. In addition, as many elements were of durations shorter than the sweep time (100 ms, see below), the bandwidth may have been shortened by the observing method.

3.2. Duration

The structure analysis in time by the fit procedure yields frequency-averaged rise and decay times mostly below 200 ms. Only 10% were above. This indicates that the single elements have not been resolved in time.

If the structure is not resolved in time, the total number of channels in which it appears times the channel dwelling time (0.5 ms) yields a lower limit of the duration. It is between 7.5 and 100 ms, typically 25 ms. The typical total duration has lower and upper limits of 25 and 200 ms, respectively.

Metric and kilometric type III bursts satisfy an empirical relation for the decay time with frequency (in Hz),

$$\tau \approx 10^{7.71} v^{-0.95} \text{ (s)}$$

(Alvarez and Haddock, 1973). The relation has been found to extend into the decimetric and microwave regions (Benz, Bernold, and Dennis, 1983; Stähli and Benz, 1986). If valid at 7 GHz, the average decay time would be about 23 ms. Our observations are compatible with this expectation.

3.3. Drift Rate

A characteristic property of metric type III burst is the drift of time of maximum with frequency. If lower frequencies peak later, the drift rate, $d\nu/dt$, is negative and the drift is said to be 'normal'. It indicates upward motion of the exciter in the corona. If the drift rate is positive, the motion is downward.

Of the 36 elements identified in the two groups (Figures 1 and 2) only five had perceptible drifts. The drift becomes observable if a structure drifts slowly and has a broad bandwidth. The lower limit of the drift rate of the other elements depends on bandwidth and was between 1.5 and 12 GHz s$^{-1}$. The five cases have been analyzed with the software package that determines the drift rate by linear regression of the maxima in the frequency–time plane. The results are $-3.2, 3.7, 7.0, 9, 4, and 20$ GHz s$^{-1}$. The predominant exciter motion is downward.
3.4. Peak flux and spectrum

The flux density generally increases at lower frequency. The strongest bursts were resolved in time and frequency. The peak measured in the 1988 November 1 group was 148 s.f.u. \((1.48 \times 10^{-17} \text{ erg s}^{-1} \text{ Hz}^{-1} \text{ cm}^{-2})\). Subtracting a lower envelope fit, one can take into account overlap with long time-scale structures and finds approximately 100 s.f.u. for the peak of the strongest burst. On 1988 November 13 the maximum was 43 s.f.u. The weakest structure that could be identified by off-line integration had a peak of 5.5 s.f.u.

![Graph showing microwave type III bursts](image)

Fig. 3. Spectra of three microwave type III bursts (cf. Figure 1) and (bottom) of the integrated background on 1988 November 1 before the event.

Figure 3 shows spectra of three bursts at peak time and a background spectrum averaged over 4 s before the event for comparison. Bursts with relatively long duration have been selected and averaged over two sweeps. The effect of finite sweep time on the spectrum should be small. Note the very different shapes of single bursts occurring within 10 s.

3.5. Polarization

Figure 4 presents measurements of circular polarization. A 10\% right polarized background has been subtracted. The bursts were predominantly right-hand polarized. Some left polarization appears at the leading edge of the two major bursts of the first group. The polarization of the second (major) group decreases from 12\% right circular at 6.7 GHz to 8\% at 7.7 GHz. The polarization of the bursts on 1988 November 1 reaches 26\% right circular at 6.7 GHz.
Fig. 4. Time profile in flux density (top) and circular polarization (bottom) of the microwave type III bursts of 1988 November 13 (cf. Figure 2). The channels in the 6.4–8.6 GHz range have been integrated to 0.4 GHz bandwidth. Only the lowest three integrated bands are shown in polarization. Left circular polarization is up (positive).

The two events were associated with flares observed in Hz. The position of these flares can be taken as indicators of the active regions producing the radio emission. On 1988 November 1, San Vito Observatory has reported a 1N flare at N14/E81 peaking at 10:59 UT, and on 1988 November 13, Ramey Observatory has observed an SN flare at N32/E30 with maximum at 13:10 UT lasting until 13:59 UT. In both cases the magnetic polarity of the leading spot is south. If this polarity determines the polarization of the radio emission (leading spot rule), the radiation, observed to be right circularly polarized, has been emitted as $o$-mode. It agrees with the mode of metric type III bursts.

3.6. ASSOCIATION WITH OTHER RADIO EMISSIONS
The two analyzed events were both associated with strong metric type III bursts having normal (upward beam) drifts (Weissenau Observatory). Fixed frequency observations show broadband emission of presumably synchrotron origin. They are also visible in the time profiles of these observations (cf. Figure 4) as slow modulations of the background.
It is interesting to compare the measurements with spectral observations in the 3.2–3.8 GHz range mode by another spectrometer at Bern University (Stähli, 1983) which observed short-duration, drifting narrowband structures of type III. In Figure 5 a small fraction of the 1988 November 1 event is shown. Both spectras contain narrowband peaks. In the first 2 s the 3–4 GHz range has a broad peak that to break up into several reversed-drifting elements in the 6–9 GHz range. A non-drifting broadband component may also be present.

Fig. 5. Flux density time profiles at 6.4–8.6 GHz (0.7 GHz bandwidth) are compared to profiles in the 3.2–3.8 GHz range for the peak of the 1988 November 1 event.
4. Discussion

The structure elements of the fast-drifting radio emission observed in the 6.4–8.6 GHz range have all characteristics of type III bursts: short duration, high drift rate, low polarization, broad bandwidth, and irregular distribution in frequency. They strongly suggest that the radiation is caused by the same process as generally accepted for metric and kilometric type III bursts: plasma emission of Langmuir waves driven unstable by an electron beam. The frequency of emission then is close to the plasma frequency in the source region or its harmonic.

The identification of the radiation with type III bursts most of all yields a diagnostic tool for the source region. Its electron density is given by the relation between observed frequency and source plasma frequency,

$$n_e \approx \begin{cases} 1.26 \times 10^{10} \\ 3.16 \times 10^9 \end{cases} \frac{v_{\text{GHz}}^2}{(\text{cm}^{-3})},$$

where the upper value corresponds to emission at the plasma frequency (fundamental), the lower value to emission at the harmonic. The observed emissions (interpreted as harmonic, see below) indicate source densities between $1.3-2.3 \times 10^{11}$ cm$^{-3}$.

Type III bursts are also probes of the density gradient. With an assumption on the beam velocity, the observed drift rate, $\dot{v}$, is related to the density scale length $H_b$ along the beam path $s$ (presumably the magnetic field line),

$$\dot{v} = \frac{\partial v}{\partial n} \frac{\partial n}{\partial s} v_b = \frac{v v_b}{2H_b}.$$

A lower limit of the beam velocity $v_b$ can be derived from the requirement that the deflection time $t_D$ by Coulomb collisions with thermal particles must exceed the total duration (lower limit 25 ms), where

$$t_D = 3.1 \times 10^{-20} \frac{v_b^3}{n_e} \text{ (s)}.$$

Thus $v_b \gtrsim 5 \times 10^9$ cm s$^{-1}$.

Assuming the typical velocity of electron beam exciting metric type III bursts of $10^{10}$ cm s$^{-1}$ and radial beam motion, we get an order of magnitude estimate of $H_b \approx 35000$ km (using an observed $\dot{v} \approx 10$ GHz s$^{-1}$). In an isothermal atmosphere (which is probably not the case) this would correspond to a temperature of $7 \times 10^5$ K. We take this to suggest that the source is located in the corona.

Radiation close to the plasma frequency is strongly absorbed by inverse bremsstrahlung (free-free absorption). The optical depth $\tau$ of free-free absorption reduces the emitted intensity by a factor of $e^{-\tau}$,

$$\tau = \begin{cases} 46 \\ 1.2 \end{cases} T^{-3/2} v_{\text{GHz}}^2 H_r,$$
where the observing frequency, $\nu$, is in GHz, and $T$ is the coronal temperature in Kelvin. An exponential density decrease along the ray path has been assumed with a scale length $H_r$ (in cm). For an order of magnitude estimate we put $\tau = 1$ and $T = 7 \times 10^5$ K and get

$$H_r = \begin{cases} 
3 \text{ km} & \text{(fundamental)}, \\
100 \text{ km} & \text{(harmonic)}.
\end{cases}$$

This is of the same order found by Bruggmann et al. (1990) for spike events. Taking the value for harmonic emission, Equation (6) requires $H_r \lesssim 10^{-2} \times H_b$ to allow the radiation to escape. Figure 6 sketches a scenario how this may happen. The particle beam propagates in a flux tube of high density ("dense fibre"), where the emission originates. The radiation then escapes quasi-perpendicular to the field lines reaching a lower density where the emitted frequency far exceeds the local plasma frequency $\nu_p^0$. The absorption coefficient in the low density region therefore is much smaller, and the optical depth

Fig. 6. Scenario to explain type III emission from the low corona. A beam descends along the magnetic field lines of a dense fibre. The radiation escapes across the field lines into low density plasma.
amounts to

\[
\tau = 17.4 \frac{(v_p^0)^2 H_0 T_0^{-3/2}}{\cos \phi} \left( \frac{v_p^0}{v} \right)^2 ,
\]  

(7)

where \( \phi \) is the angle between propagation and the vertical. The scale height \( H_0 \) (in cm), plasma frequency \( v_p^0 \) (in GHz) and temperature \( T_0 \) (in K) refer to the ambient plasma outside the dense fibre. We can estimate the outside density requiring that Equation (7) yields \( \tau \leq 1 \). With \( H_0 \approx H_b, T_0 \approx 7 \times 10^5 \) K, \( \cos \phi \approx 1 \) and harmonic plasma emission, we estimate the ratio of the fibre density to the outside density as

\[
\frac{n}{n_0} \gtrsim 18 .
\]  

(8)

We may add here that the beam does have to be limited in size to the dense fibre (as drawn in Figure 6). If a part of it propagated in the ambient medium outside the fibre, the minimum frequency would be 2 GHz, and the total bandwidth would exceed the observed values. Thus the beams generally must be of a typical size of less than the thickness of the fibre (100 km or less). The type III burst observed in the 3–4 GHz range (Figure 5) suggest that beams also have propagated in fibres of lower density. Beams in the low density ambient plasma also may exist, but their radiation cannot escape to nearby regions of lower density. If propagated along B, the scale height is \( H_b \), and the optical depth of absorption, given by Equation (5), is more than 2 orders of magnitude too high for escape even at the harmonic.

5. Conclusion

High spectral resolution observations of a particular class of fast-drift bursts in the 6.4–8.6 GHz range have revealed that they closely resemble type III bursts. We thus interpret these events as the highest frequency signatures of electron beams ever observed.

Electron beams at densities exceeding \( 10^{11} \) cm\(^{-3} \) have been expected from hard X-ray (HXR) emission of flares. It is interesting that these radio observations indicate much higher fragmentation than the associated synchrotron emission (no HXR instrument was observing). The plasma emission process being sensitive to changes in velocity space (injection of new beams) can naturally explain it. Not only the beams are fragmented, but also the medium is highly structured. No plasma emission could escape from a homogeneous atmosphere at this density. Typical scales of 100 km have been derived. They require similar or smaller sizes for the electron beams.

The observations indicate the interesting possibilities of radio spectroscopy in the microwave region. Beams in high-density fibres are highly productive in HXR bremsstrahlung. Higher sensitivity and better time resolution will allow a direct comparison of velocity space distribution (radio) and total particle number (HXR) information.
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