OBSERVATIONS AND INTERPRETATION OF SOLAR DECAMETER TYPE IIIb RADIO BURSTS

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Abstract. Solar decameter bursts of Type IIIb are observed with a multichannel radiometer at wavelengths around 12 m. The time and frequency resolutions were 10 ms and 100 kHz. Observations on the time structure of these bursts are presented. A theoretical model which accounts for various aspects of these bursts is proposed.

1. Introduction

Short duration and narrow band decameter solar radio bursts have been studied by various groups during the last ten years. We have reported some of our observations on the various properties of these bursts (Sastry, 1969, 1971, 1972, 1973). Most of the bursts studied by us previously were isolated occurrences and are probably not associated with any other kind of solar radio brusts excepting that they occur during decameter storm periods. de la Noë and Boischot (1972) observed that chains of short duration and narrow band bursts sometimes occur just before the onset of a normal Type III burst. These are called Type IIIb bursts and their frequency structure was studied in detail by de la Noë and Boischot (1972), McCulloch and Ellis (1977), and others. No measurements on the time profiles and intensities of the elements of Type IIIb bursts have been reported so far. In this paper we present our observations on the time structure of these bursts. We also present a possible theoretical model which will account for the various observed features of Type IIIb solar radio bursts.

2. Equipment

Our observations were made during the period January 1971 to March 1972 using an antenna system of about 25 db gain and a four channel receiver. The center frequency was 25 MHz and the bandwidth and time constant were 13 kHz and 10 ms respectively. The channel separations were usually 100 kHz but can be varied from 20 kHz onwards. In some observations one channel was used to measure polarization characteristics. Details of this equipment were given in Sastry (1972). We would like to point out that it is possible to measure the time profiles accurately with this set up. The obvious disadvantage is the narrow frequency range covered.

3. Observations

Following de la Noë (1974) we have identified groups of short duration bursts that occurred just before the onset of a normal Type III burst as elements of Type IIIb

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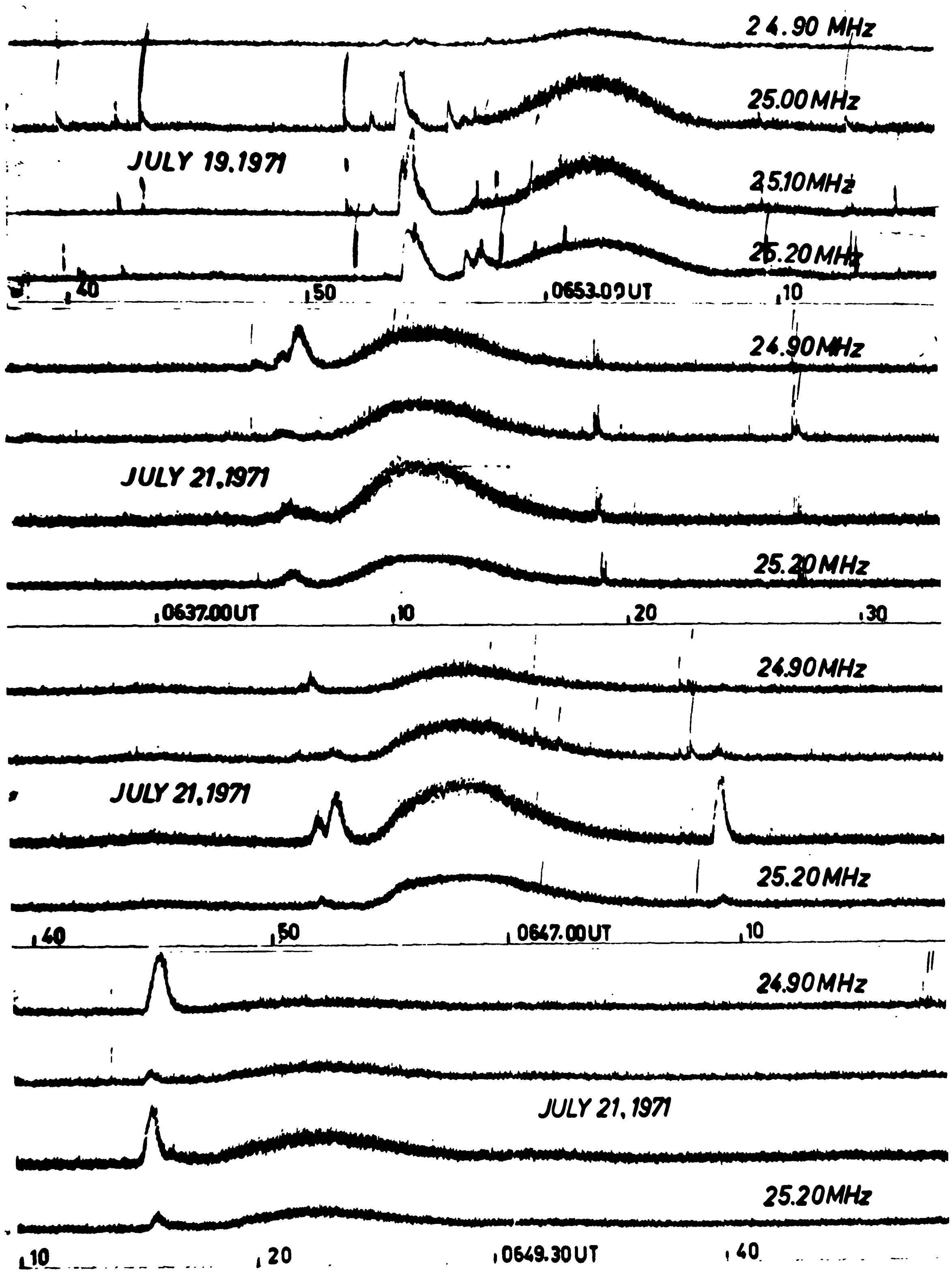

Fig. 1. Typical examples of Type IIIb bursts followed by Type III bursts. The vertical spikes are due to atmospherics. Note the short duration burst at the end of the Type III on July 21, 1971.

bursts. Figure 1 shows typical examples of bursts we have studied. In our data the occurrence of Type IIIb bursts after a Type III is very rare. However, we did observe occasionally sharp duration bursts in one of the four channels following a Type III burst. Since we are not convinced that these bursts can be classified as Type IIIb, we did not include them in our study. Often the bursts overlap and so it is difficult to determine accurately the durations of single elements. We have considered only those elemental bursts whose onset and ending times can be clearly defined and determined their durations. The results are shown as a histogram of the number of bursts versus half power duration in Figure 2. It can be seen that a majority of the

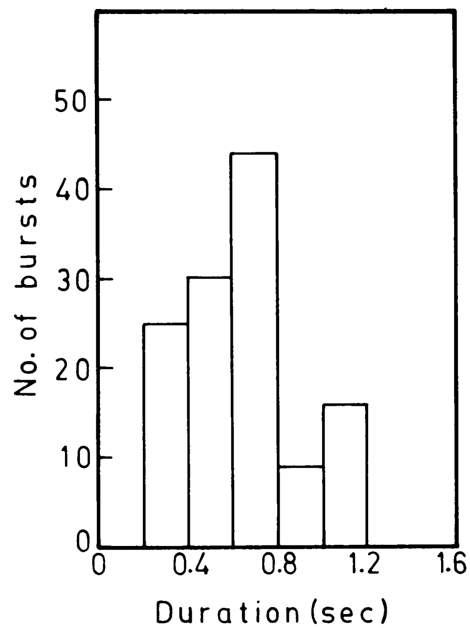

Fig. 2. Distribution of the half-power durations of Type IIIb bursts.

bursts have half power durations in the range 0.4 to 0.8 s. The average half power duration of all the observed bursts is 0.67 s. The average total duration is 1.61 s. Our study includes 53 Type III–IIIb associations and out of these 48 occurred during the period July–August 1971. We could not correlate the duration and position on the Sun due to lack of positional data. Also most of the data are confined to a short interval. Next, we determined the average time profile of an element of a Type IIIb burst. This is shown in Figure 3a. One can see that the profile is very similar to a normal Type III burst i.e. a sharp rise and an exponential type decay. The duration of the exciter, t_E, and the decay time constant, τ determined from the average time profile are equal to 0.88 and 0.31 s respectively. The time profile of the associated Type III burst is shown in Figure 3b. The exciter duration and damping constant in this case are 6.00 and 2.11 s respectively. It is interesting to note that the ratio of exciter durations ('t_E' Type III/'t_E' Type IIIb elements) and the ratio of damping constants ('τ' Type III/'τ' Type IIIb elements) is approximately the same and is equal to 6.82. The ratio of half power durations (''half power' Type III/''half power'

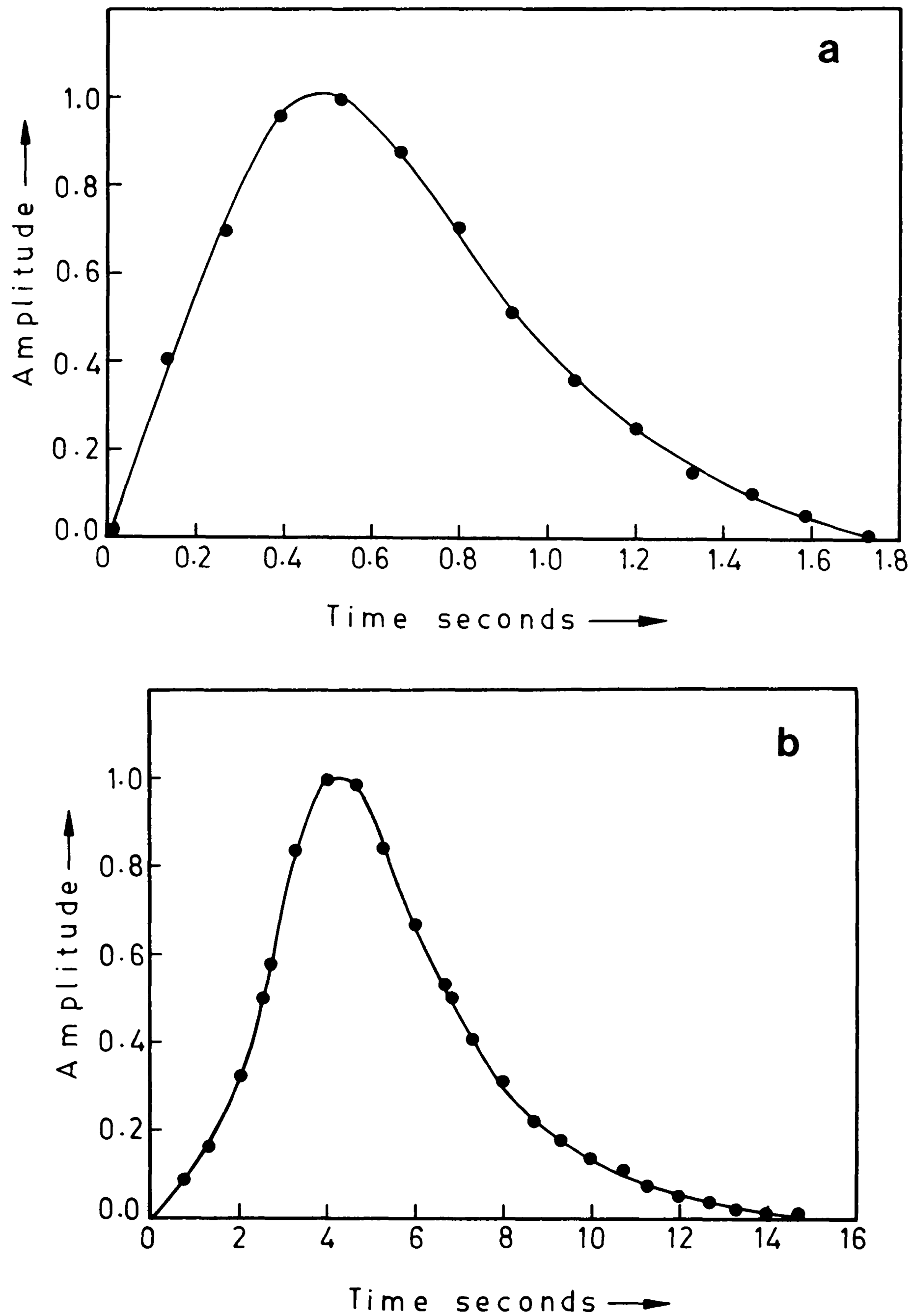

Fig. 3. Time profiles of (a) elements of Type IIIb radio bursts, (b) associated Type III bursts.

Type IIIb elements) is equal to 9.83. In order to see if there is any difference in the time profiles of a Type III associated with Type IIIb and that of an isolated Type III burst during the same period, we measured the average time profile of isolated Type III bursts. The profiles could be different due to the difference in the positions and/or the local conditions of the Type IIIb–Type III and isolated Type III sources. There is no obvious difference and the exciter duration and damping constant for this case are 6.0 and 2.0 s respectively. We have also looked for a relationship between the total durations of the Type IIIb elements and the associated Type III bursts. It would

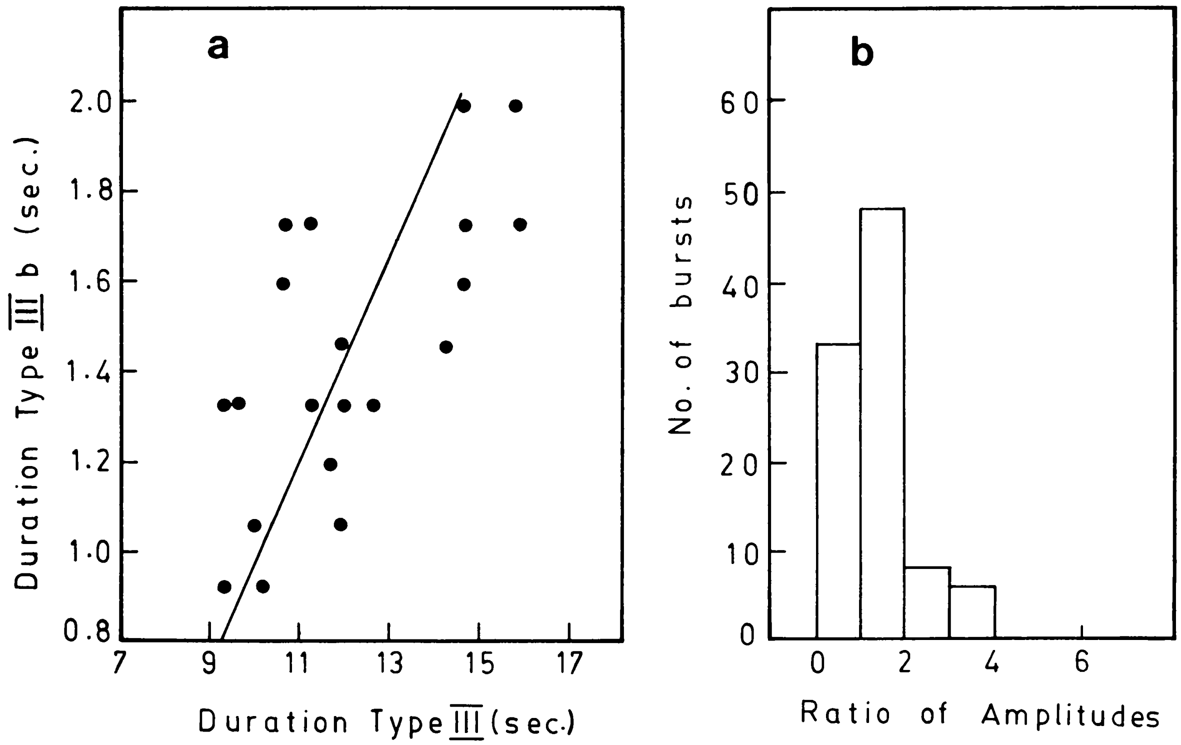

Fig. 4. (a) Correlation of the total durations of Type IIIb and accompanying Type III bursts. (b) Distribution of the ratio of the amplitudes of Type IIIb and associated Type III bursts.

appear that there is a positive correlation between the two. In Figure 4a is shown a typical scatter diagram of the durations. The linear correlation coefficient is +0.65. Figure 4b shows a histogram of the ratio of amplitudes of the Type IIIb elements and Type III bursts. In the case of the bursts we have studied the amplitude of the Type IIIb elements is greater than or equal to the associated Type III bursts.

4. Theory

One of the detailed theories for the generation of Type IIIb radio bursts is due to Smith and de la Noë (1976). They consider a fast electron beam plasma system which is known to develop a two stream instability giving rise to growing electrostatic waves near the electron plasma frequency. It is generally accepted that the Rayleigh scattering of these electrostatic waves at ω_{pl} into electromagnetic waves at ω_{pl} is the generation mechanism for Type III radio bursts at the fundamental. The Type III bursts at the second harmonic are believed to be generated by the coalescence of two plasma waves each at ω_{pl}. Smith and de la Noë (1976) propose that the trapping of the particles in the finite amplitude electrostatic plasma wave is the cause of the frequency structure of Type IIIb bursts and suggest that the electrostatic waves are converted into observable radiation by parametric decay instability. This is an approximate way of dealing with the electric field in the sense that the trapped particle instability occurs at a field strength when the electron bounce frequency becomes comparable to the linear growth rate of the beam-plasma instability.

Further the particles near the bottom of the trough, executing harmonic motion are included. The effects of anharmonic motion executed by the particles near the top of the potential trough are not taken into account. The parametric decay instability is a threshold effect, and Smith and de la Noë (1976) consider the interaction of the normal modes of the plasma system with the electric field considered as an external pump in contrast to the present treatment (as will be shown below) where the plasma is immersed in the electric and magnetic fields and then we study the direct excitation of normal electromagnetic modes. One can consider the magnetoplasma under the influence of an electric field which is oscillating at ω_0. Eventually instead of the beam particles travelling with a uniform speed along the magnetic field, one ends up with a plasma system in which the particles are executing gyromotion in a plane perpendicular to the magnetic field and a quivering motion along the magnetic field. The quiver is produced by the electric field E_0 associated with the instability at ω_0 and the quivering speed $u_e = eE_0/m\omega_0$. The coronal plasma density and the magnetic field are given by the relations (Lang, 1974)

$$N_e(r) = 1.55 \times 10^8 \, (r/R_\odot)^{-6} \,,$$

$$B(r) \simeq B_0(r/R_\odot)^{-2} \,,$$

where $R_\odot$ is the solar radius $\sim 6.96 \times 10^{10}$ cm. The dielectric function for such a system can be calculated by employing the techniques given by Harris (1969) and frequently used before (Krishan *et al.*, 1978; Krishan, 1978). One finds

$$\varepsilon(q, \omega) = 1 - \frac{\omega_{pe}^2}{\omega^2} - \sum_{n,l} \frac{\omega_{pe}^2(\text{eff}) q^2 V_{\text{th}}^2 D_l}{\omega^2\{[(\omega - n\omega_0) - (q_z - n\kappa_0)u_e]^2 - l^2\omega_{ce}^2\}} - \\ - \sum_{n,l} \frac{\omega_{pe}^2(\text{eff}) q^2 V_{\text{th}}^2 D_l}{\omega^2\{[(\omega - n\omega_0) + (q_z - n\kappa_0)u_e]^2 - l^2\omega_{ce}^2\}} \,, \tag{1}$$

where (ω, q) are the frequency and the wave vector of the mode to be excited,

$$\omega_{pe}^2(\text{eff}) = \frac{\omega_{pe}^2}{2} J_{N_e - n}^2(z_e) \,,$$

$$z_e \sim N_e = \frac{e^2 E_0^2}{m \hbar \omega_0^3} \,,$$

$$u_e = eE_0/m\omega_0 \,.$$

κ_0 is the wave vector of E_0. D_l for the first few values of l is given by

$$D_1 = q_\perp^2/4q^2, \qquad D_2 = 4\alpha D_1, \qquad D_3 = \tfrac{3}{16}\alpha^2 D_1 \,,$$

$$D_4 = \tfrac{1}{24}\alpha^3 D_1 \,,$$

and

$$\alpha = \frac{q_\perp^2 V_{\text{th}}^2}{\omega_{ce}^2} < 1 \,.$$

The structure of the dielectric function is quite transparent. The integer n characterizes the periodic motion introduced by the electric field E_0 of the electrostatic beam plasma instability. The integer l signifies the usual cyclotron motion of the particles. The argument of the Bessel function is very large, therefore, the fact has been deployed that the Bessel function is maximum when the argument is equal to the order. To find the electromagnetic modes, one solves the equation

$$\varepsilon(q, \omega) = \frac{q^2 c^2}{\omega^2} \tag{2}$$

for complex roots. The details of the procedure for determining the roots are given in Krishan (1979). One finds a set of growing modes with frequencies ω and growth rates γ given by

$$\omega = \frac{(n_1+n_2)}{2}(\omega_0 \pm \kappa_0 u_e) + \tfrac{1}{2}\sqrt{l_1^2\omega_{ce}^2 - \delta_{n_1 l_1}^2} - \tfrac{1}{2}\sqrt{l_2^2\omega_{ce}^2 - \delta_{n_2 l_2}^2}\,,$$

$$q_z u_e = \frac{(n_1-n_2)}{2}(\omega_0 \pm \kappa_0 u_e) + \tfrac{1}{2}\sqrt{l_1^2\omega_{ce}^2 - \delta_{n_1 l_1}^2} + \tfrac{1}{2}\sqrt{l_2^2\omega_{ce}^2 - \delta_{n_2 l_2}^2}\,,$$

and

$$\gamma = \frac{\omega_{pe}^2 \omega_{pe}^2(\text{eff}) q^2 V_{\text{th}}^2}{2(q^2c^2 - 3\kappa_0^2 V_{\text{th}}^2)^2}\left[\frac{D_{l_1} D_{l_2}}{\sqrt{l_1^2\omega_{ce}^2 - \delta_{n_1 l_1}^2}\sqrt{l_2^2\omega_{ce}^2 - \delta_{n_2 l_2}^2}}\right]^{1/2}.$$

Here n_1, n_2, l_1, and l_2 are positive integers, and

$$\delta_{nl}^2 = \frac{\omega_{pe}^2(\text{eff}) q^2 V_{\text{th}}^2 D_l}{(q^2c^2 - 3\kappa_0^2 V_{\text{th}}^2)}.$$

The detailed study of these modes has been done elsewhere Krishan (1979). Here we point out the relevance of the modes for $n_1 = n_2 = l_1 = l_2 = 1$ for the Type IIIb emissions. The modes for higher values of n and l have smaller growth rates. One finds

$$\omega_\pm = \omega_0 \pm \kappa_0 u_e\,,$$

$$q_z u_e = \sqrt{\omega_{ce}^2 - \delta_{11}^2}\,.$$

Assuming $q_z u_e \ll \omega_{ce}$ and, therefore, choosing $\omega_{ce} \sim \delta_{11}$, we find the growth rate of the modes $\omega_\pm$ to be

$$\gamma \sim \frac{16}{72}\frac{q^2}{\kappa_0^2}\frac{\omega_{ce}^3}{\kappa_0^2 V_{\text{th}}^2}.$$

At $\omega_{pe} \sim \omega_0 \sim 25$ MHz, $V_{\text{th}} \sim 10^8$ cm s^{-1}, $\kappa_0 \sim (2.5/80)$ cm^{-1}, $\omega_{ce} \sim 2$ MHz, beam-plasma density ratios $= n_b/n_0 \sim 10^{-4}$ $u_e \sim 1.5 \times 10^6$ cm s^{-1}, substituting for q^2 from the condition $\omega_{ce} \sim \delta_{11}$ one finds the characteristic rise time of the burst to be

$$t \sim \frac{1}{\gamma} \sim \frac{1}{11} \sim 0.1 \text{ s.}$$

Here one recalls that $q \sim q_{\perp}$ since $q_z u_e$ has been made vanishingly small by choosing $\delta_{11} \sim \omega_{ce}$. The total duration of the burst will be much larger that 1/11 s because the decay process is much slower than the growth. We conclude that a characteristic rise time of 90 ms is in reasonably good agreement with the observations.

The peak intensity of emission can be found by considering the nonlinear saturation mechanism of the instability. If the saturation is due to the perturbation in the particle orbit then the emissions with higher linear growth rate will saturate at higher fields, and so the short duration fast rising elements of Type IIIb radio bursts are expected to be more intense than the Type III radio bursts.

It is also possible to calculate the drift rate of the elements of Type IIIb bursts. In the present model it is the electric field associated with the beam-plasma instability which is acting as a source of Type IIIb radio bursts, and so the frequency drift is caused by the drift of the electric field. The group velocity V_g of the electric field is found to be

$$V_g = \frac{3V_{\text{th}}^2}{u_0},$$

where u_0 is the speed of the electron stream. The drift rate can be determined from the following consideration:

$$\frac{\partial \omega}{\partial t} = \frac{\omega.(r) - \omega(r + \Delta r)}{\Delta r / V_g},$$

$\sim$40 kHz s^{-1} for $u_0 \sim 8 \times 10^8$ cm s^{-1}. This value of the drift rate can either be positive or negative depending on the plasma density variations in the underlying medium.

We could not measure the drift rate accurately because of the limited frequency range of our system. However, the predicted drift rate seems to agree well with that reported by de la Noë and Boischot (1972). In the present model, we get the right estimate of the characteristic rise time under the conditions $q_{\perp} > q_z$. This necessarily dictates the Type IIIb to propagate at a large angle to the magnetic field. Therefore, we predict the Type IIIb to be circularly polarized as has been observed by de la Noë and Boischot (1972).

5. Conclusion

We observed Type IIIb-Type III radio bursts with high time and frequency resolution. We measured the average duration and the average time profile of the elements of Type IIIb radio bursts. The nonlinear evolution of an electron-beam magneto-plasma system is studied in order to interpret the characteristics of Type IIIb solar radio bursts. The present theory, though begins at the same note as that of Smith and de la Noë (1976), the treatment of the electric field corresponding to the beam-plasma electrostatic instability differs in an essential way. In contrast to the theory of Smith and de la Noë (1976), where the electric field interacts with the normal modes of the plasma system, we find the electromagnetic modes of the plasma immersed in the electric and magnetic fields. In the present theory, the electric field enters at the single particle level and, therefore, is accounted in a more exact manner. In addition, the direction of propagation of the Type IIIb radio bursts is very clearly dictated by the theory which is not so in the theory of Smith and de la Noë (1976).

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