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Observations and Interpretation of Solar Decametric Absorption Bursts

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Abstract. The observations of intensity reductions or absorption bursts in the solar decametric radio-continuum are reported. The reductions are interpreted as the absorption of continuum radiation by a shock-generated ion-sound turbulence present in the layer above the continuum level. The duration of the absorption is attributed to the life-time of the ion-sound turbulence while the depth of absorption is determined by the level of Langmuir waves generated as a result of absorption.

Key words: Sun, decametric absorption bursts—ion-sound turbulence

1. Introduction

Fast microstructure in solar radio emission is quite well known in the wavelength range from a few millimetres to decametres (Slottje 1972, 1978; Sastry 1973; McConnell 1982 *etc.*). Slottje (1972) described peculiar absorptions of background continuum at metre wavelengths detected with the Utrecht radio spectrograph. During the course of our observations on the microstructure of the decametric continuum, we have detected many interesting absorption features. The characteristics of these absorption features are found to be different from those at short wavelengths (Sastry, Subramanian & Krishan 1983). Further observations on the time and frequency structure of these features are presented here. A possible theoretical model which will account for some of the observed features is also discussed.

2. Equipment

These observations were made with the NS array of the Gauribidanur radio telescope (Latitude 13° 36′ 12″ N, Longitude 77° 26′ 07″ E) and a multichannel receiver. The NS array has a collecting area of approximately 9000 m^2 and beam widths of 15° and 0.5° in the EW and NS directions respectively. The central frequency of the receiving system is 34.5 MHz. The separation between channels is 50 KHz and the bandwidth of each channel is 15 KHz. The time constant used was 20 ms. The minimum dectectable flux

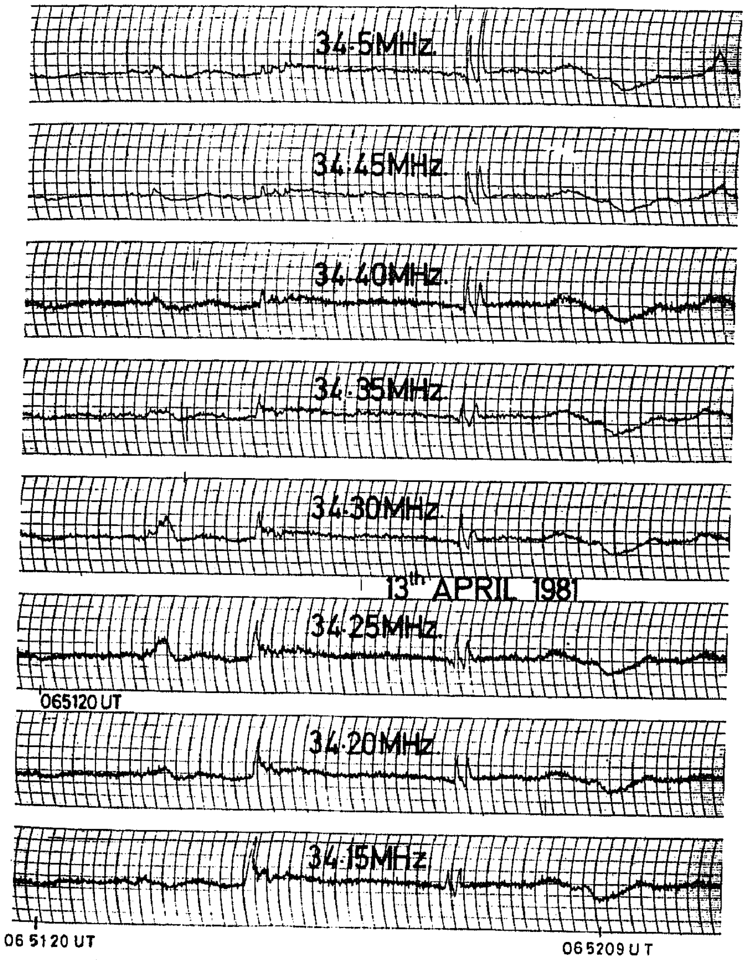

Figure 1. Eight-channel record obtained on 1981 April 13. The ordinate is the intensity of the radio emission.

density is ~ 11 SFU. The data were recorded both in analog and digital forms. The present number of channels is sixteen. The radiometer was operated for about an hour around the local noon during periods of enhanced solar radio emission. Several hundred absorption bursts were recorded during the period 1981 March–July. During the periods April 13–15 and June 23–25, the rate of occurrence of absorption bursts was maximum.

3. Observations

In Fig. 1, one can see a broad-band absorption feature with a duration of 6 s at $06^h\ 52^m\ 09^s$. The absorption bursts at $06^h\ 53^m\ 23^s$ UT is strong and has fine structure. The total duration of the bursts is about 1.4 s. The fall time, *i.e.*, the time taken for the intensity to reach the minimum value is 400 ms and the rise time, *i.e.*, the time taken for the intensity to reach the preabsorption level is about 1 s. The bandwidth of the absorption burst is 500 KHz, whereas the associated emission burst is narrower. Another very-short duration (400 ms) broad-band absorption burst occurred at $06^h\ 53^m\ 28^s$ UT whose fall and rise times were very rapid (150 ms). Two more narrow-band absorption bursts with

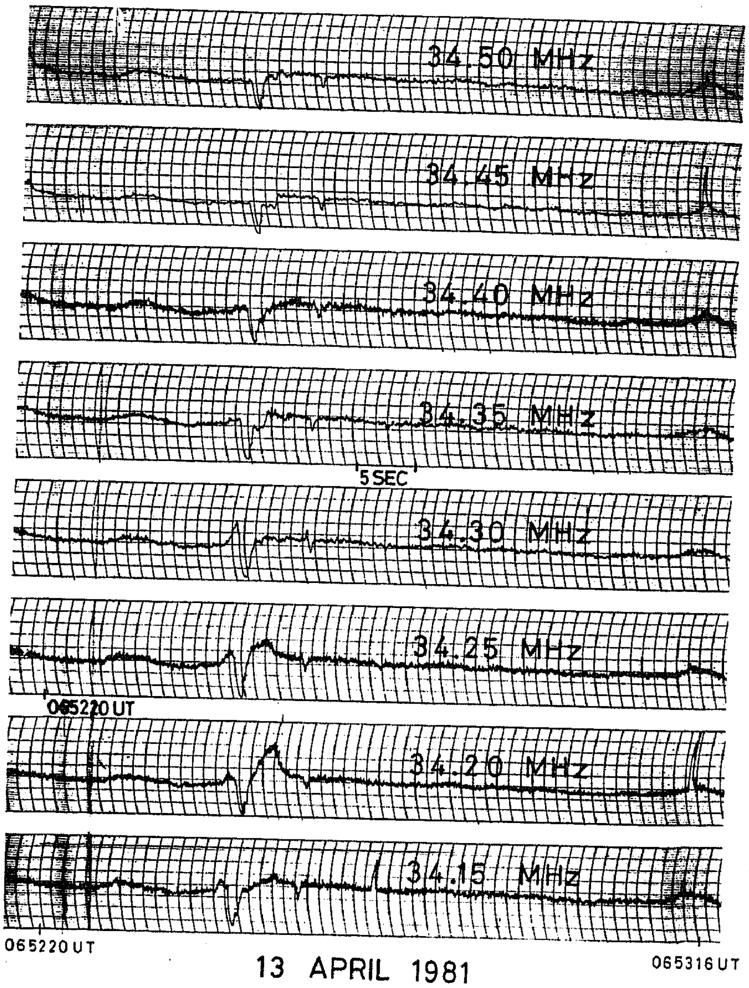

Figure 1. Continued.

bandwidths of 200 KHz and 250 KHz respectively occurred at 06^h 52^m 32^s UT and 06^h 53^m 48^s UT. Note the double structure in the time profiles of absorption in some channels and that the emission bursts which occurred at the same time in some channels are very intense compared to the absorption bursts.

Part of another record obtained on 1981 June 25 is shown in Fig. 2. One can see the reduction in intensity with both sudden and gradual onsets. Note the split time structure of some of the absorption bursts. Another record obtained on 1981 August 20 is shown in Fig. 3. Here we have shown examples of sudden decreases but with very slow recovery. A careful examination of the time profiles of the two bursts occurring at 06^h 32^m 08^s and 06^h 32^m 21^s UT shows that after the initial decrease the intensity recovers only to about half of the initial level and stays there for about two seconds before attaining the preabsorption level. It is interesting to note that the time profiles of these two bursts occurring at different times are exactly similar to each other.

A statistical analysis of several hundred absorption bursts revealed the following characteristics.

(1) The absorption bursts can occur isolated or can be followed or preceded by emission bursts. In some cases absorption and emission can occur simultaneously in different frequency channels.

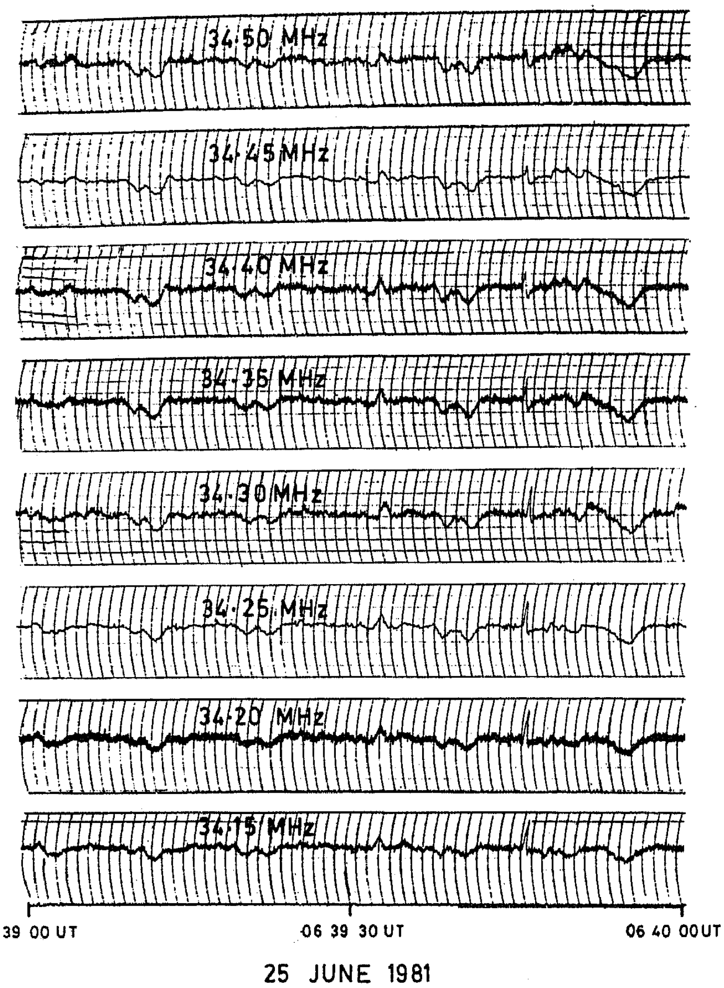

Figure 2. Eight-channel record obtained on 1981 June 25. The ordinate is the intensity of the radio emission.

(2) The bandwidth of absorption bursts is always greater than about 500 KHz whereas those of emission bursts could be as narrow as 50 KHz.
(3) The minimum duration of the absorption bursts is of the order of 1 s, whereas that of the emission bursts can be much smaller (100 ms).
(4) The depth of the absorption is about 30–40 per cent of the continuum level. We also noticed that in some cases where the duration of the absorption burst is small, the depth of absorption can be as high as 70–80 per cent.

4. A suggested explanation

The broad-band reductions in the intensity of continuum radiation have been reported at high frequencies (Benz & Kuijpers 1976; Fokker 1982). Benz & Kuijpers (1976) regard that the continuum radiation in the decimetric wavelengths is due to electrostatic loss-cone instability and the reduction in the continuum is due to the filling of the loss cone by electron streams momentarily, thus stopping the generation of radiation. Fokker (1982) has suggested that the reduction in intensity need not be at the generation stage but can also be at the propagation stage. He proposed that the

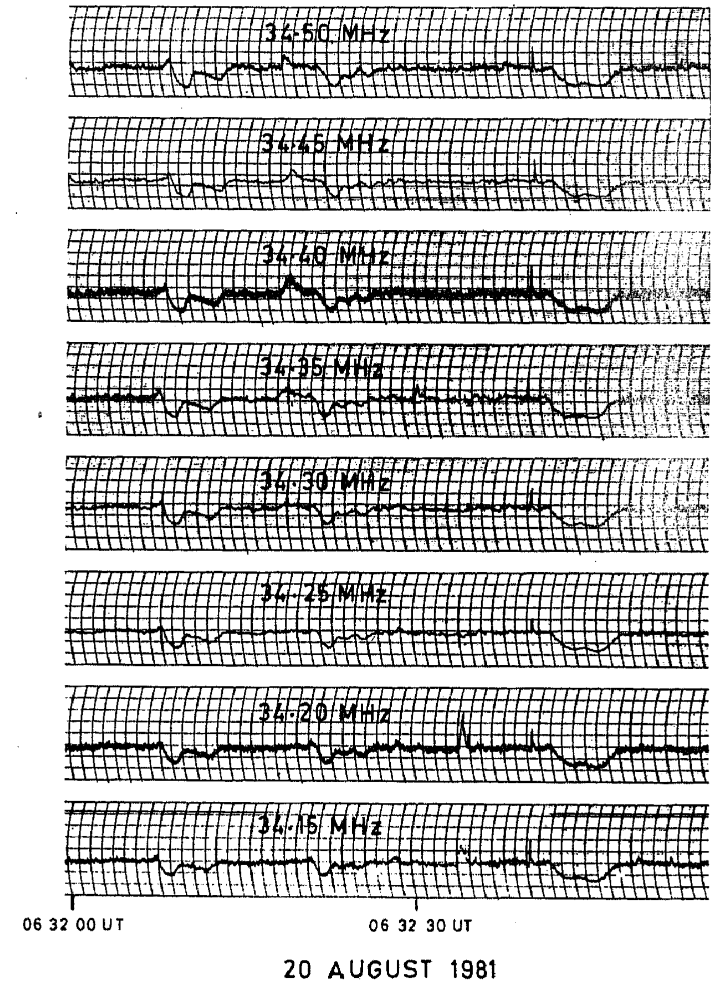

Figure 3. Eight-channel record obtained on 1981 August 20. The ordinate is the intensity of the radio emission.

continuum radiation is ducted through open magnetic flux tubes and the radiation is screened by inhomogeneities created on the path of the radiation by lateral shock waves or solitons impinging on the flux tubes. We are concerned here with the reductions in decametric continuum. The most recent theory on the origin of decametric continuum is due to Levin (1982), who ascribes the continuum to the Rayleigh scattering of plasma turbulence generated by an anisotropic distribution of a diffused electron beam with high transverse temperature. Levin's mechanism does not require a closed magnetic field and hence the loss-cone filling mechanism is not appropriate. So, following Fokker (1982), we assume that the radiation is absorbed on its path, rather than at the generation stage.

It was pointed out by Kaplan & Tsytovich (1973) that ion-sound turbulence can scatter the radio emission of the Sun producing additional maxima or minima in the stationary spectrum. Melrose (1974) explored the possibility of absorption of radiation by ion-sound turbulence to explain Kai's (1973) observations of shadow type III bursts. The generation of ion-sound turbulence can be attributed to many sources (Melrose 1974, 1982). It has also been theoretically shown that shocks under coronal conditions can generate high level of ion-sound turbulence (Lacombe & Mangeney 1969; Kaplan

& Tsytovich 1973; Klinkhamer & Kuijpers 1981). We would like to mention that the shock-generated ion-sound turbulence of nonthermal level can cause absorption in the decametric continuum radiation. This is another important consequence of the presence of shock waves, apart from what Fokker (1982) has considered. A shock propagating perpendicular to a magnetic field can be a source of many types of waves, like the Langmuir, ion-sound, ion-cyclotron, electron-cyclotron *etc.* As pointed out by Galeev (1976) most of the instabilities other than ion-sound are excited at the initial portion of the shock front. Because of these instabilities, the electrons would be essentially heated and the ion-sound instability with the lowest current threshold would stop the magnetic field profile steepening at a level where all the other instabilities are quenched. Moreover, the saturation level of turbulence for other waves is always much less than the ion-sound turbulence level (Spicer, Benz & Huba 1981; Kaplan & Tsytovich 1973). Therefore, one can regard that the ion-sound turbulence is the most favoured one. We assume that a shock propagates perpendicular to the open magnetic field lines in the region overlying the decametric continuum source, generating ion-sound turbulence. The magnetic field gradient of the shock can induce strong electric fields which can accelerate electrons to velocities U greater than the ion-sound velocity V_s so that the condition for ion-sound instability is satisfied. The change in magnetic field H, the induced electric field E and the electron drift velocity U are related by

$$\nabla \times \mathbf{H} = \frac{4\pi}{c}\sigma \mathbf{E} = \frac{4\pi n_e e}{c}\mathbf{U}$$

where c is the velocity of light, σ the plasma conductivity, e the electronic charge and n_e the electron density.

The condition for the ion-sound excitation can be obtained by demanding that U must exceed V_s:

$$\frac{\partial H}{\partial l} > \left(\frac{4\pi n_e e}{c}\right) V_s,$$

where l is the coordinate along the direction of magnetic field variation. For coronal conditions ($n_e = 10^8$ cm^{-3}, $T_e = 10^6$ K), the right-hand side of the above inequality works out to be 1.8×10^{-4} G cm^{-1}. Following Klinkhamer & Kuijpers (1981), the left-hand side can be estimated as $\partial H/\partial l \simeq \Delta H/(7c/\omega_p)$ where ΔH is the jump in magnetic field across the shock and ω_p is the electron plasma frequency. It is well known (Tidman & Krall 1971) that $\Delta H \leqslant 3H_1$, where H_1 is the upstream (ambient) magnetic field. From frequency splitting and polarisation measurements of type I bursts, the coronal magnetic field at decametric level is obtained approximately as 1 G (ter Haar & Tsytovich 1981). Hence for a magnetic field jump $\Delta H/H_1 \gtrsim 0.18$ is sufficient to satisfy the inequality $\mathrm{d}H/\mathrm{d}l > 1.8 \times 10^{-4}$ G cm^{-1}.

The continuum radiation, while propagating towards the observer, encounters the ion-sound turbulence and enters into a three-wave interaction. In other words, the continuum radiation (t-wave) interacts with the ion-sound (s-wave) producing Langmuir wave (l-wave); thus occurs a reduction in the intensity of the t-waves. The conditions under which such an interaction takes place will be worked out below.

If one accepts Levin's theory, then one should consider the possibility of ion-sound turbulence generation by the return current caused by the one-dimensional beam that separates from the diffused beam. It is easy to show that an unusually high beam density is required to generate the required level of ion-sound turbulence. The fact that the return current is unimportant even in other situations is pointed out by Smith (1974).

Let us now estimate the effective temperature of the ion-sound turbulence needed to absorb the radiation. Let the ion-sound turbulence be described by assigning a central or average frequency $\langle \omega_s \rangle$ and a width of $\Delta\omega_s \sim \langle \omega_s \rangle$ to be created over a solid angle $\Delta\Omega$ with an effective temperature $\langle T_s \rangle$. The energy and momentum conservation relations for the three-wave process $t \rightarrow l \pm s$, by which the radiation is absorbed, are given by

$$\mathbf{k}_t = \mathbf{k}_l + \mathbf{k}_s \tag{1}$$

and

$$\omega_t = \omega_l \pm \omega_s, \tag{2}$$

where $(\mathbf{k}, \omega)$ are the wavevector and frequency respectively. These processes cause a net conversion of transverse waves into longitudinal plasma waves, provided they satisfy the condition—under weak turbulence regime—that the effective temperature of the t-waves and (ω_p/ω_s) times the effective temperature of the s-waves exceed that of the generated l waves (Melrose 1970). For such a three-wave process, or its reverse process $l \pm s \rightarrow t$ (Shukla *et al.* 1982), it is shown that the coupling is possible when the wave numbers of the s-wave and l-wave are approximately the same; *i.e.*,

$$k_l \simeq k_s \quad \text{and} \quad k_t \ll k_l, k_s. \tag{3}$$

The frequency–wave-number dispersion relation for the interacting waves is given by,

$$\omega_l = \omega_p\,(1 + \tfrac{3}{2} k_l^2 \lambda_e^2), \qquad k_l^2 \lambda_e^2 \ll 1,$$

$$\omega_s = k_s V_s$$

and

$$\omega_t = \omega_p\,(1 + \tfrac{1}{2} k_t^2 c^2/\omega_p^2), \qquad \frac{k_t^2 c^2}{\omega_p^2} \ll 1 \tag{4}$$

where λ_e is the Debye radius, V_s is the phase velocity of ion sound waves and ω_p is the plasma frequency. The other symbols are standard. Using the resonance conditions (1) and (2) and defining $\Delta\omega_t = \omega_t - \omega_p$ the typical wave number of the generated l-wave is

$$\bar{k} = \left(\frac{2}{3}\frac{\Delta\omega_t}{\omega_p}\right)^{\frac{1}{2}} \frac{\omega_p}{v_e} \tag{5}$$

with

$$\frac{\Delta\omega_t}{\omega_p} \gg \frac{V_s}{6 v_e}$$

and

$$\Delta\omega_t \simeq \frac{3}{2}\frac{\bar{k}^2 v_e^2}{\omega_p}. \tag{6}$$

Then, the fractional bandwidth of absorption defined by

$$B = \frac{\Delta\omega_t}{\omega_p} \tag{7}$$

is obtained as

$$B = \frac{3}{2}\frac{\langle \omega_s \rangle^2}{\omega_{pi}^2} \tag{8}$$

because

$$\bar{k}V_s = \langle \omega_s \rangle. \tag{9}$$

The observed fractional bandwidth of absorption B is 5×10^{-2}. Hence the central frequency of the ion-sound turbulence should be $\langle \omega_s \rangle = \sqrt{\frac{2}{3} B \omega_{pi}^2} \simeq 0.18\, \omega_{pi}$. This is a stable frequency range for the ion-sound waves because the waves of low Landau damping exist with a dispersion relation (4) only for $\omega_s \ll \omega_{pi}$.

The transfer equation for the continuum radiation can be written as

$$\frac{\partial T_t}{\partial s} = -\mu T_t \tag{10}$$

where μ is the absorption coefficient and s is the spatial coordinate along the ray path of the continuum radiation, with an effective temperature T_t. If L is the linear extent of the absorber and μ is independent of spatial coordinates over this region, the optical depth could be written as

$$\tau = \int \mu \, ds = \mu L \tag{11}$$

A reduction in the intensity (absorption) occurs if the optical depth exceeds unity, as can be seen from the solution to the transfer equation (10), *i.e.* the condition for absorption is

$$\mu L > 1. \tag{12}$$

Let us now estimate the linear extent of the source. The thickness L of the absorbing layer is defined by the relative bandwidth of absorption and the scale-length of inhomogeneity L_n of the coronal electron distribution. The maximum thickness could be taken to be

$$L = BL_n, \tag{13}$$

where

$$L_n = \left| \frac{1}{\omega_p} \frac{d\omega_p}{ds} \right|^{-1}. \tag{14}$$

In the undisturbed corona, L_n is calculated from Newkirk's formula for electron distribution as 2×10^{10} cm for the decametric region. Using the observed fractional bandwidth $B \simeq 5 \times 10^{-2}$, the thickness of the absorbing layer can be obtained from Equation (13) as 10^9cm. The absorption coefficient can be estimated as (Melrose 1974)

$$\mu = \frac{r_0 c \omega_p^2}{24\sqrt{3}\pi v_e^3} \frac{\langle T_s \rangle}{T_e} \Delta\Omega, \tag{15}$$

where $r_0 = e^2/mc^2$ is the classical electron radius and T_e is the electron temperature. Under coronal conditions with $v_e \sim 10^8$ cm s^{-1}, one can rewrite the condition (12) as

$$f^2 \langle T_s \rangle \Delta\Omega > 10^7 T_e, \tag{16}$$

where f is the frequency of the radio-waves in MHz. For $f = 35$, $\Delta\Omega = 3$ steradians and $T_e \sim 10^6$K, the condition (16) becomes

$$\langle T_s \rangle > 2.5 \times 10^9\,\mathrm{K}. \tag{17}$$

This effective temperature is an order of magnitude more than that required for the shadow type-III bursts (Melrose 1974). The reason for this is the fact that our relative bandwidth is less than that corresponding to the shadow type-III case by an order of magnitude. The l-waves build up due to the decay process, at the cost of the continuum radiation. Once they have sufficient energy density, the condition for net conversion of the t-waves into l-waves, *viz*.,

$$\text{minimum}\left[\left(\frac{\omega_l}{\omega_t}\right)T_t, \left(\frac{\omega_l}{\omega_s}\right)T_s\right] > T_l \tag{18}$$

will not be satisfied and hence the saturation of absorption is reached. The reverse process becomes significant and hence the final brightness is determined by the level of the l-wave turbulence produced due to the decay process. Once the level of the ion-sound waves falls below the critical level, the absorption mechanism fails to operate and so the intensity recovers back to the continuum level. Thus the duration of absorption could be attributed to the time during which the ion-sound turbulence exists above critical level, satisfying inequality (17).

5. Discussion

We have shown that the sudden reductions in the decametric continuum can be ascribed to the absorption by ion-sound turbulence, generated by a shock wave. The magnetic field gradient necessary to generate such a turbulence and the level of turbulence necessary to cause absorption are derived. The duration of the absorption could be attributed to the period during which the ion-sound turbulence stays undamped above thermal level. The depth of the absorption is determined by the level of Langmuir turbulence generated as a result of the absorption, after which the reverse interaction between the Langmuir waves and ion-sound waves will become important. Since the conditions are most favourable to the generation of ion-sound turbulence and most of the other instabilities are quenched very fast in the front portion of the shock front itself, we did not include any other instability. Nevertheless, one can expect the generation of Langmuir turbulence, though its level is about two orders of magnitude less than the ion-sound level. This small amount of Langmuir waves plays some role in the three-wave interaction process and we have ignored it.

We would like to point out that the ion-sound turbulence could also cause emission by interacting with the Langmuir waves that can originate from two sources: (i) those excited by the shock itself and (ii) those generated during the absorption of continuum radiation. But the conditions under which the emission takes place (the inequalities 12 and 18) are different from those for absorption considered in this paper. The presence of the Langmuir turbulence of low level might slightly affect the final brightness temperature of the continuum radiation.

Though we have assumed shocks travelling perpendicular to the ambient magnetic field lines, the ion-sound turbulence could also be generated by oblique shock waves as discussed by Galeev (1976).

Our interpretation is semi-quantitative and we have not calculated, for example, the life-time of the ion-sound turbulence. Actually, the ion-sound turbulence is generated behind the shock where high gradients in magnetic field are formed. These gradients could even be of a stochastic type i.e., distributed randomly behind the shock front (Kaplan Pikel'ner & Tsytovich 1974). Actual time structure of the absorption could be estimated only when the time dependence of the intensity of ion-sound waves is known. One may estimate the latter by analysing the behaviour of the turbulence in the wake of the shock.

The fractional bandwidth we used in our interpretation is approximate because of the limited bandwidth of our system. The transfer equation for the continuum radiation could be used to estimate the fractional bandwidth of absorption from the absorption coefficient of the ion-sound turbulence calculated by assigning an effective temperature of the ion-sound turbulence $\langle T_s \rangle$ that satisfies the inequality (17). From Equation (15), for $\langle T_s \rangle \sim 2.5 \times 10^9$ K, and $T_e \sim 10^6$ K, μ can be estimated as 2.3 $\times 10^{-8}$ cm. If we take $\mu L \sim 10$, then $L \sim 10/\mu$ so that Equation (13) gives $B \sim 0.02$, which is in the range of observed bandwidths.

The above model assumed that the emission and absorption are independent of each other and hence it can not explain the emission preceeding or following the absorption.

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