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The Mechanism Responsible for 'Shadow' Type III Solar Radio Bursts. I Absorption due to Langmuir Turbulence

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Abstract

The hypothesis is advanced that for 'shadow' type III solar radio events (absorption features with drift rates and bandwidths typical of type III bursts or U-bursts) the absorption mechanism involves Langmuir turbulence, such absorption being the inverse of either fundamental ($f = f_p$) or second harmonic ($f = 2f_p$) plasma emission. The theory for both absorption processes is developed and applied to shadow type III events with the following results: (1) the predicted absorption is confined to a very narrow frequency range ($\Delta f/f \sim 10^{-3}$); (2) effective absorption requires an energy density in Langmuir turbulence (with phase speeds $\sim\frac{1}{3}c$) in excess of 10^{-9} erg cm^{-3} for the fundamental and in excess of 3×10^{-6} erg cm^{-3} for the second harmonic; (3) the brightness of the background source must exceed 10^9 and 10^{16} K for absorption at the fundamental and second harmonic respectively. Comparison of the theory with the properties of an event discussed by Kai (1973) leads to the conclusions: (1) absorption at the second harmonic is unacceptable because of the high brightness temperature required; (2) to explain the observed bandwidth in terms of absorption at the fundamental, the absorbing region and the background source must overlap in height; (3) to explain the observed reduction in brightness temperature requires that the initial brightness temperature exceed $5\cdot5\times10^9$ K (the observed value was 10^9 K).

1. Introduction

Absorption features in solar radio spectra have been noted by a number of authors. 'Bursts in absorption' on background type IV events were reported by Boischot and Fokker (1959) and Aller *et al.* (1966) on the basis of single-frequency records, while Wild *et al.* (1963, p. 313) mentioned 'weak absorption features of short duration' which 'resemble type III bursts in absorption' on background type IV emission. Kai (1973) discussed a type II event of 1968 August 23–4, in which a type III burst and a U-burst in absorption were visible (see Fig. 1 below). Following S. F. Smerd (personal communication), we will describe absorption features with drift rates and bandwidths typical of type III bursts (or U-bursts) as 'shadow' type III events, and in this paper and the following Part II (Melrose 1974, present issue pp. 271–7) we will explore possible mechanisms responsible for these absorption processes. It will be assumed in both investigations that plasma turbulence generated by the exciting agency of a type III burst causes absorption of the background radiation.

In this paper an investigation is made into the possibility that absorption by Langmuir turbulence, i.e. turbulence involving longitudinal electron plasma waves, is responsible for shadow type III events. (The exciting agency, with velocity $\sim\frac{1}{3}c$, should generate Langmuir turbulence initially with phase speeds $v_\phi \sim \frac{1}{3}c$ and so with wave numbers $k = 3\omega_p/c$, where ω_p is the plasma frequency.) The absorption processes are just the inverses of the familiar plasma emission processes and, as such, the hypothesis that shadow type III events result from absorption due to Langmuir turbulence is, *a priori*, the most plausible hypothesis.

The absorption, as with the emission, can occur at either the fundamental $f = f_p$ or the second harmonic $f = 2f_p$ (angular frequencies are used for formal purposes and cyclic frequencies when discussing the applications). Since radiation cannot escape from below the plasma level, absorption at the fundamental requires that the absorber lie immediately above the background source which must be emitting at frequencies close to the plasma frequency. Absorption at the second harmonic requires that the absorber be at the plasma level corresponding to half the observed frequency; the background source could be emitting at the fundamental or second harmonic or anywhere in between, and the required relative position of emitter and absorber depends on this emission frequency.

The purpose of this article is to develop the theory of these absorption processes and to apply the results to the interpretation of shadow type III events. Absorption at the fundamental is treated in Section 2, and at the second harmonic in Section 3, while the application to shadow type III events is considered in Section 4. Difficulties in interpreting the event reported by Kai (1973) in terms of absorption by either mechanism are discussed in Section 5.

2. Absorption at the Fundamental

In the notation used by Tsytovich (1966, 1970), Melrose (1970) and Smith (1970), Langmuir waves and transverse waves are called l-waves and t-waves respectively; the dispersion relations for the two modes are written

$$\omega^l(\boldsymbol{k}') \approx \omega_p + \tfrac{3}{2}k'^2 V_e^2/\omega_p\,, \qquad \omega^t(\boldsymbol{k}) = (\omega_p^2 + k^2c^2)^{\frac{1}{2}}\,; \tag{1a, b}$$

the distributions are described either by the occupation numbers $N^l(\boldsymbol{k}')$ and $N^t(\boldsymbol{k})$, or the effective temperatures

$$T^l(\boldsymbol{k}') = \hbar\omega^l(\boldsymbol{k}')\,N^l(\boldsymbol{k}')\,, \qquad T^t(\boldsymbol{k}) = \hbar\omega^t(\boldsymbol{k})\,N^t(\boldsymbol{k})\,, \tag{2}$$

where $\hbar$ is Planck's constant divided by 2π and Boltzmann's constant is set equal to unity; and the ions (subscript i), which are assumed to be singly charged, and electrons (subscript e) are described by their masses $m_{i,e}$, temperatures $T_{i,e} = m_{i,e}\,V_{i,e}^2$ and number densities $n_i = n_e$.

Plasma emission at the fundamental (subscript 1) is attributed to the scattering of l-waves (Langmuir waves) into t-waves (transverse waves) by thermal ions. When nonthermal distributions of both l-waves and of t-waves (with frequencies close to the plasma frequency) are present, induced scattering causes an exponential growth of one distribution at the expense of the other. The growing distribution is the one with the lower frequency. This process would act as an absorption mechanism for the t-waves if their frequency were slightly greater than that of the l-waves (both must be nearly equal to the plasma frequency).

(*a*) *Induced Scattering*

The evolution of a distribution of t-waves due to the effects of both spontaneous and induced scattering of l-waves by thermal ions may be obtained by combining equations (13) and (15) and using equation (16) of Melrose (1970).* After integrating

* There is an error in equation (14): N^σ should appear in the integrand.

over a Maxwellian distribution of ions with temperature T_i, one has

$$\frac{\partial N_1^t(\boldsymbol{k})}{\partial t} = \int \frac{d^3\boldsymbol{k}'}{(2\pi)^3} w_i^{tl}(\boldsymbol{k},\boldsymbol{k}')\left(\{N^l(\boldsymbol{k}')-N_1^t(\boldsymbol{k})\} - \frac{\hbar\{\omega^t(\boldsymbol{k})-\omega^l(\boldsymbol{k}')\}}{T_i} N^l(\boldsymbol{k}')N_1^t(\boldsymbol{k})\right), \quad (3)$$

with

$$w_i^{tl}(\boldsymbol{k},\boldsymbol{k}') = \frac{(2\pi)^3 n_e e^4}{m_e^2 \omega_p^2} \frac{\sin^2\theta}{(2\pi)^{\frac{1}{2}}|\boldsymbol{k}-\boldsymbol{k}'|V_i} \exp\left(-\frac{\{\omega^t(\boldsymbol{k})-\omega^l(\boldsymbol{k}')\}^2}{2|\boldsymbol{k}-\boldsymbol{k}'|^2 V_i^2}\right). \quad (4)$$

where θ is the angle between $\boldsymbol{k}$ and $\boldsymbol{k}'$. In cases of practical interest one has $k' \gg k$, and equation (4) may be simplified accordingly.

(b) Conditions for Effective Absorption

Four conditions need to be satisfied in order for induced scattering to produce significant absorption of t-waves: (i) the induced scattering must cause a net conversion of t-waves into l-waves and not vice versa; (ii) induced scattering must predominate over spontaneous scattering; (iii) the frequency of the t-waves must be sufficiently close to that of the l-waves for the scattering probability (4) not to be exponentially small; and (iv) the optical depth must be greater than unity.

Let $\Delta\omega_1^t$ and $\Delta\omega^l$ denote the difference between ω^t and ω_p and between ω^l and ω_p respectively. Then, writing $v_\phi = \omega_p/k'$ for the l-waves, equation (1a) implies

$$\Delta\omega_1^t = \omega^t - \omega_p, \qquad \Delta\omega^l = \omega^l - \omega_p \approx \tfrac{3}{2}(V_e^2/v_\phi^2)\omega_p. \quad (5)$$

Conditions (i), (ii) and (iii) reduce to

$$\max(T_i/T^l, T_i/T_1^t) < \Delta\omega_1^t/\omega_p - \tfrac{3}{2}(V_e/v_\phi)^2 < \sqrt{2}\, V_i/v_\phi, \quad (6)$$

where all dependences on wave numbers are left understood.

Assuming the variation in T_1^t due to the scattering to be spatial rather than temporal, equation (3) implies a transfer equation of the form

$$\partial T_1^t/\partial s = \alpha_1 - \mu_1 T_1^t, \quad (7)$$

where arguments are omitted and s denotes distance along the ray path of t-waves. (The term involving only N_1^t on the right-hand side of equation (3) is neglected in (7); such neglect is justified either for $N^l \gg N_1^t$ or when induced scattering predominates over spontaneous scattering.) Condition (iv) can then be written in the form

$$\mu_1 L_1 > 1, \quad (8)$$

where μ_1 is the absorption coefficient (per unit length) and L_1 is the characteristic distance over which absorption occurs. The absorption coefficient is v_g^{-1} times the absorption coefficient per unit time which is given by the factor multiplying $N_1^t(\boldsymbol{k})$ in the final term of equation (3); the group velocity of the t-waves for $\Delta\omega_1^t \ll \omega_p$ is given by

$$v_g = kc^2/\omega^t \approx (\Delta\omega_1^t/\omega_p)^{\frac{1}{2}}\sqrt{2}\, c. \quad (9)$$

If the distribution of l-waves is described by an effective temperature T^l in a range Δv_ϕ about a phase velocity v_ϕ and in a finite range $\Delta\Omega$ of solid angles, the energy density in the l-waves is then given by

$$W^l = \left(\frac{f_p}{v_\phi}\right)^3 \frac{\Delta v_\phi}{v_\phi} \langle T^l \rangle_{\Delta\Omega} \Delta\Omega , \tag{10}$$

where $\langle\,\rangle_{\Delta\Omega}$ denotes an average over solid angle. Explicit evaluation of the terms in equation (3) and so of those in equation (7) gives

$$\alpha_1 = \frac{\pi^{\frac{1}{2}} r_0 c f_p^2}{2V_i v_\phi^2} \frac{\Delta v_\phi}{v_\phi} \left(\frac{\omega_p}{\Delta\omega_1^t}\right)^{\frac{1}{2}} \langle T^l \sin^2\theta \rangle_{\Delta\Omega} \Delta\Omega \tag{11}$$

and

$$\mu_1 = \frac{\alpha_1}{T_i} \frac{\Delta\omega_1^t - \Delta\omega^l}{\omega_p}, \tag{12}$$

where $r_0 = e^2/m_e c^2$ is the classical radius of the electron and f_p $(= \omega_p/2\pi)$ can be identified as the frequency of observation.

3. Absorption at the Second Harmonic

Absorption at the second harmonic (subscript 2) is due to the coalescence process $t \rightarrow l+l$. As explained by Melrose (1970, Section IIf), the properties of the processes $t \leftrightarrow l+l$ are strongly dependent on the angular distribution of the l-waves. It can be argued that more realistic cases can be treated by combining the results for the following two extreme limiting cases: (a) an isotropic distribution of l-waves and (b) a distribution of l-waves confined to a sufficiently small range $\Delta\Omega$ $(<2\pi)$ of solid angles such that no two l-waves can coalesce into a t-wave. For convenience 'anisotropic' shall be used to imply a distribution with property (b). The two cases are treated separately in subsections (a) and (b) below. The saturation of the absorption process is discussed in subsection (c).

(a) *Isotropic Distribution*

The evolution of a distribution of t-waves due to the process $l+l \rightarrow t$ for an isotropic distribution of l-waves with effective temperature $T^l(k')$ evolves according to (e.g. Melrose 1970, equation (17))

$$\partial T_2^t(k)/\partial s = \alpha_2(k) - \mu_2(k)\, T_2^t(k) . \tag{13}$$

For $v_\phi \ll c$, explicit evaluation gives

$$\alpha_2(k) = \mu_2(k)\, T^l(k_0) , \tag{14}$$

so that equation (13) becomes

$$\partial T_2^t(k)/\partial s = \mu_2(k)\, \{T^l(k_0) - T_2^t(k)\} , \tag{15}$$

with

$$\mu_2(\equiv \mu_2(k)) = \frac{4\sqrt{2}\,\pi^2}{45} \frac{r_0 (2f_p)^2}{c^2} \frac{c}{V_e} \left(\frac{\Delta\omega_2^t}{2\omega_p}\right)^{\frac{1}{2}} \frac{T^l(k_0)}{T_e} , \tag{16}$$

where the interaction occurs at $k' = k_0$ with

$$k_0 = \sqrt{\frac{2}{3}} \frac{\omega_p}{V_e} \left(\frac{\Delta\omega_2^t}{2\omega_p}\right)^{\frac{1}{2}} , \tag{17}$$

and with

$$\Delta\omega_2^t = \omega^t(k) - 2\omega_p. \tag{18}$$

Three conditions need to be satisfied in order that the process $t \to l+l$ lead to significant absorption: (i) equation (15) must describe a decrease rather than an increase in $T_2^t(k)$, that is, the process $t \to l+l$ must dominate over the process $l+l \to t$; (ii) the frequency of the t-waves must be sufficiently close to twice the plasma frequency that ω_p/k_0, with k_0 given by equation (17), falls in the range of phase velocities where the l-waves are highly nonthermal; and (iii) the optical depth must be greater than unity. The condition (i) requires $T_2^t > T^l$ initially, and this turns out to be a very restrictive requirement.

(*b*) *Anisotropic Distribution*

The important distinction between the isotropic and anisotropic (in the sense defined above) distributions of l-waves is that for the anisotropic case the process $l+l \to t$ cannot occur. Thus the evolution is described by equation (13) with $\alpha_2(k) = 0$. (The assumption that a distribution is anisotropic may be unrealistic, as discussed in Section 5*a* below.)

Assuming that the l-waves are confined to some finite range $\Delta\Omega$ of solid angles, with $\Delta\Omega < 2\pi$ necessarily, and leaving any dependence on angle implicit, equation (16) is to be replaced by

$$\mu_2 = \frac{\pi}{6\sqrt{2}} \frac{r_0(2f_p)^2}{c^2} \frac{c}{V_e} \left(\frac{\Delta\omega_2^t}{2\omega_p}\right)^{\frac{1}{2}} \frac{\langle \sin^2\theta \cos^2\theta \, T^l(k_0)\rangle_{\Delta\Omega} \Delta\Omega}{T_e}, \tag{19}$$

where k_0 is given by equation (17). (On taking an isotropic distribution, equation (19) reduces to (16) apart from a factor of two.)

Of the three conditions listed in the preceding subsection, condition (i) is automatically satisfied for an anisotropic distribution of l-waves, i.e. there is no practical lower limit to T_2^t (there is a theoretical lower limit $T_2^t > 2T_e$). Although unimportant in practice, there is a formal limitation which arises from the buildup of a secondary distribution of l-waves, and this limitation is derived in the following subsection.

(*c*) *Saturation of Absorption Process*

For an isotropic distribution of l-waves, equation (15) implies that T_2^t decreases only for $T_2^t > T^l$. Although no such condition applies initially for an anisotropic distribution, the process $t \to l+l'$ builds up a secondary distribution of l-waves. Eventually an equilibrium should be approached with, according to arguments given by Melrose (1970, Section II*f*), the effective temperatures T_2^t and $T^{l'}$ of the t-waves and secondary l-waves equal. This provides a lower limit $T_2^t > T^{l'}$ to the values of T_2^t for which absorption can occur; however, $T^{l'}$ depends on the initial value of T_2^t.

Suppose that the above equilibrium is reached. Let us call the equilibrium state the final state and denote it by the subscript F. Saturation of the absorption process is negligible provided that

$$T_F^t = T_F^{l'} \ll T_I^t \tag{20}$$

is satisfied, where here I refers to the initial state and the subscripts 2 are omitted.

The value of $T_{\mathrm{F}}^{l'}$ can be estimated by using conservation laws which follow from the equations describing the processes $l+l' \leftrightarrow t$. These laws can be written in the form

$$\tfrac{1}{2}\Gamma^t T^t + \Gamma^l T^l = \text{const.} = \tfrac{1}{2}\Gamma_{\mathrm{I}}^t T_{\mathrm{I}}^t + \Gamma_{\mathrm{I}}^l T_{\mathrm{I}}^l \tag{21}$$

and

$$T^l - T^{l'} = \text{const.} = T_{\mathrm{I}}^l, \tag{22}$$

where $T_{\mathrm{I}}^{l'} = 0$ is assumed, and the Γ's denote the volumes of wave-number space to which the interacting waves are confined. For the l-waves one has

$$\Gamma^l \approx \Gamma^{l'} = \frac{k'^2\,\Delta k'}{(2\pi)^3}\Delta\Omega = \left(\frac{f_{\mathrm{p}}}{v_\phi}\right)^3 \frac{\Delta v_\phi}{v_\phi}\Delta\Omega, \tag{23}$$

and Γ^l should remain roughly constant. For the t-waves,

$$\Gamma^t = \frac{k^2\,\Delta k}{(2\pi)^3}\Delta\Omega^t = \frac{\sqrt{3}}{2}\left(\frac{2f_{\mathrm{p}}}{c}\right)^3 B_2\,\Delta\Omega^t, \tag{24}$$

with

$$B_2 = [\![\omega^t - 2\omega_{\mathrm{p}}]\!]/2\omega_{\mathrm{p}}, \tag{25}$$

where $[\![\;]\!]$ is used to denote the mean value of the enclosed frequency, and B_2 is the relative bandwidth for which the processes $t \leftrightarrow l+l$ can occur. Initially the range $\Delta\Omega^t$ of solid angles to which the t-waves are confined should be narrow, but as the interaction proceeds the process $l+l' \to t$ produces t-waves over a wider range of angles, implying that Γ^t increases.

Combining equations (20) with (21) and (22), one finds

$$T_{\mathrm{F}}^t \approx \Gamma_{\mathrm{I}}^t T_{\mathrm{I}}^t/(2\Gamma^l + \Gamma_{\mathrm{F}}^t). \tag{26}$$

For highly anisotropic l-waves it is possible to have $\Gamma_{\mathrm{F}}^t \gg 2\Gamma^l$, in which case the processes $t \to l+l' \to t'$ then merely isotropize the t-waves, i.e. the region acts as a region of enhanced scattering. Otherwise, for $\Gamma_{\mathrm{F}}^t \ll 2\Gamma^l$ energy is transferred from the t-waves to l-waves. In both cases $T_{\mathrm{F}}^t \ll T_{\mathrm{I}}^t$ should be well satisfied.

4. Application to Shadow Type III Events

In this section, parameters appropriate to a type III burst are inserted and the requirements on the spectrum of Langmuir turbulence for absorption to be effective at either the fundamental or the second harmonic are then determined.

(*a*) *Thickness of Absorbing Region*

The optical depth $\mu_1 L_1$ or $\mu_2 L_2$, for absorption at the fundamental or second harmonic respectively, is proportional to the thickness L_1 or L_2 of the absorbing region. For both the fundamental and second harmonic, the relative bandwidths

$$B_1 = [\![\omega^t - \omega_{\mathrm{p}}]\!]/\omega_{\mathrm{p}} \qquad \text{and} \qquad B_2 = [\![\omega^t - 2\omega_{\mathrm{p}}]\!]/2\omega_{\mathrm{p}} \tag{27}$$

are very small, that is, the absorption occurs in a very narrow frequency range. Because of this, the thicknesses are limited by $L_1 < B_1 L_N$ and $L_2 < B_2 L_N$ where $L_N = |\,\omega_{\mathrm{p}}/\mathrm{grad}\,\omega_{\mathrm{p}}\,|$ is the characteristic distance over which the plasma frequency varies due to the gradient in electron density in the corona.

For the fundamental, B_1 can be estimated as follows. Setting $v_\phi = \frac{1}{3}c$ for a type III burst, one has

$$\tfrac{3}{2}V_e^2/v_\phi^2 \approx 3\times10^{-3}, \qquad V_i/v_\phi \approx 10^{-3}.$$

It follows from the conditions (6) that the absorption occurs in a relative bandwidth

$$B_1 \approx V_i/v_\phi \approx 10^{-3}, \tag{28}$$

immediately above the frequency

$$\omega^t = \omega_p + \Delta\omega_1^t, \qquad \Delta\omega_1^t \approx 3\times10^{-3}\,\omega_p. \tag{29}$$

Furthermore, conditions (6) then require that the background source have a brightness temperature in excess of 10^9 K for any significant absorption to occur.

For the second harmonic, B_2 can be estimated from equation (17). Let Δv_ϕ be the range of phase velocities over which the l-waves are excited. Then (17) implies that the absorption is confined to a relative bandwidth

$$B_2 \approx \tfrac{3}{2}(V_e^2/v_\phi^2)\Delta v_\phi/v_\phi \approx 10^{-2}\,\Delta v_\phi/c, \tag{30}$$

assuming $v_\phi = \frac{1}{3}c$, and centred on the frequency

$$\omega^t = 2\omega_p + \Delta\omega_2^t, \qquad \Delta\omega_2^t \approx 3\times10^{-3}(2\omega_p). \tag{31}$$

The observed absorption occurs at $f \approx 100$ MHz; one is to identify $f_p = f$ and $2f_p = f$ for absorption at the fundamental and second harmonic respectively. In either case the value of L_N appropriate to the corresponding plasma levels in the undisturbed corona is $L_N \approx 3\times10^{10}$ cm. From equations (28) and (30), one then has

$$L_1 \approx L_2 \approx 3\times10^7\ \mathrm{cm}. \tag{32}$$

These correspond to very thin absorbing regions. It is unlikely that other limitations on the thickness of the absorbing region, e.g. the dimensions of the exciting agency of type III bursts, could result in an even thinner absorbing region. In further estimates below, the thickness of the absorbing region is taken to be 3×10^7 cm.

(b) *Fundamental Absorption*

The absorption coefficient (12) is estimated for

$$v_\phi/c = \tfrac{1}{3} = \Delta v_\phi/v_\phi, \qquad \Delta\omega_1^t/\omega_p - \tfrac{3}{2}V_e^2/v_\phi^2 = 10^{-3}. \tag{33}$$

Assuming that the angular factor $\sin^2\theta$ is $\sim\frac{1}{2}$, one finds

$$\mu_1 \approx 10^{-19} f^2 \langle T^l\rangle_{\Delta\Omega}\,\Delta\Omega/T_i\ \ \mathrm{cm}^{-1}, \tag{34}$$

where f is in megahertz. The optical depth $\mu_1 L_1$ at $f = 100$ MHz exceeds unity only for

$$\langle T^l\rangle_{\Delta\Omega}\,\Delta\Omega \gtrsim 3\times10^{13}\,\mathrm{K}. \tag{35}$$

This, with equation (10), gives the energy density in l-waves as

$$W^l \gtrsim 10^{-9}\ \mathrm{erg\,cm^{-3}}. \tag{36}$$

(c) Second Harmonic Absorption

The absorption coefficient (19) for the second harmonic at $f = 2f_p$ with the choice (33) of parameters reduces to

$$\mu_2 \approx 3\times 10^{-23} f^2 \langle T^l\rangle_{\Delta\Omega}\,\Delta\Omega/T_e \ \mathrm{cm}^{-1}, \tag{37}$$

where f is in megahertz and where the angular average has been approximated by

$$\langle \sin^2\theta \cos^2\theta\, T^l\rangle_{\Delta\Omega} \approx \tfrac{1}{10}\langle T^l\rangle_{\Delta\Omega}.$$

Comparison with estimates made for the fundamental shows that equivalent absorption at the second harmonic would require $\langle T^l\rangle_{\Delta\Omega}\Delta\Omega$ or W^l greater than for the fundamental by a factor of 3×10^3, that is, $W^l \gtrsim 3\times 10^{-6}$ erg cm^{-3} or, for isotropic l-waves,

$$T^l > 10^{16}\ \mathrm{K}. \tag{38}$$

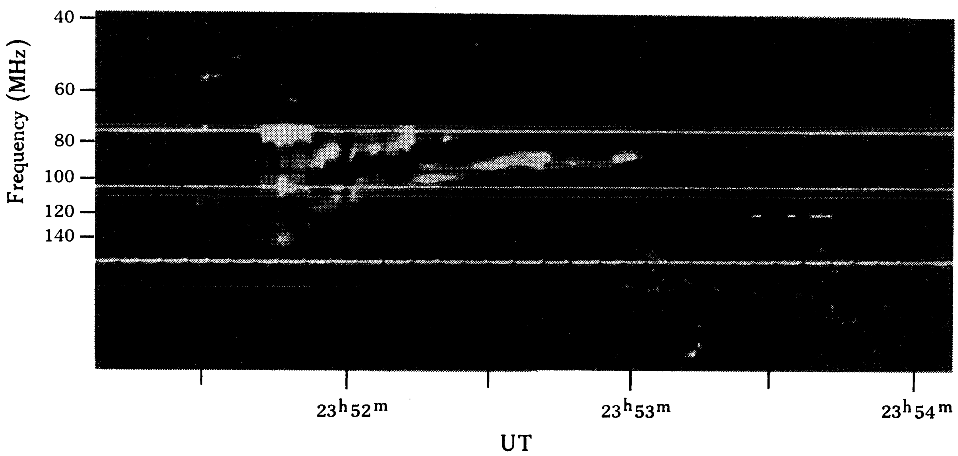

Fig. 1. Dynamic spectrum of the split-band type II burst recorded on 1968 August 23 by Kai (1973). The absorption feature analysed in detail here crossed the 80 MHz line between $23^h 52^m 01^s$ and $23^h 52^m 02^s$.

5. Kai's Event

In this section the application to shadow type III events is developed further with particular reference to the event reported by Kai (1973), the dynamic spectrum of which is reproduced in Fig. 1. Firstly, it is shown that the brightness temperature required for effective second harmonic absorption is unacceptably high. Absorption at the fundamental is then discussed in more detail.

(a) Brightness Temperatures Required for Second Harmonic Absorption

For absorption at the second harmonic to be effective, equation (38) must be satisfied. Using formulae given by Tsytovich (1972, Ch. 6), one can estimate the characteristic time associated with induced scattering of l-waves into l-waves: for $W^l \gtrsim 3\times 10^{-6}$ erg cm^{-3} in l-waves with $v_\phi \sim \frac{1}{3}c$ in the corona this time is less than 10^{-4} s. Thus, if the absorption is at the second harmonic then the l-waves should be isotropic. (There is a weakness in this argument: if the scattering of l-waves is due to ion sound turbulence and not to induced scattering by ions, then this results in a large step-wise change in k, e.g. by $\Delta k > \sqrt{3}\,\omega_p/2c$, such that the coalescence of scattered and unscattered l-waves may not be possible; such a distribution remains anisotropic in the sense defined in Section 2.) If the l-waves are isotropic then one can use equation (15) to find the brightness temperature T^t_{A2} of the absorbing region at the second harmonic. The fact that the absorbing region must be optically thick for the background radiation to be absorbed significantly implies $T^t_{A2} \approx T^l$.

Thus absorption at the second harmonic can reduce the brightness temperature to only $T^t_2 = T^l$. With equation (38), this implies that the background source would have to be brighter than 10^{16} K for the absorption to be significant. This is to be compared with a brightness temperature of 10^9 K before absorption in the event reported by Kai (1973). Thus absorption at the second harmonic appears to be unacceptable. (It might appear that the possibility of the large step-wise changes in k mentioned above could alleviate the difficulty: if a fraction α of the l-waves could coalesce with each other, then in the above arguments 10^{16} K would be replaced by $\alpha\,10^{16}$ K. But the required $\alpha \lesssim 10^{-7}$ seems implausible.)

(*b*) *Bandwidth*

Before discussing the required brightness temperatures for absorption at the fundamental, it is relevant to consider possible explanations of the bandwidth over which absorption occurred in the event reported by Kai (1973). From the frequency profile of a shadow U-burst at its turning point, one can estimate the bandwidth over which the absorption occurs as ~ 10 MHz at 80 MHz, that is, $\Delta f/f \sim \frac{1}{8}$. This is to be compared with $\Delta f/f \sim 10^{-3}$ for the mechanisms under consideration. It seems that one must appeal to absorption over an extended region containing a spread $\Delta f_p \sim \frac{1}{8} f_p$ in plasma frequency. Absorption at the fundamental occurs not only in a narrow bandwidth $\Delta f/f \sim 10^{-3}$ but also, according to equations (29), only for frequencies which exceed f_p by less than $3\times10^{-3} f_p$. This requires that the absorbing region extend over a volume which *contains* the background source.

It may well be unrealistic to assume that a type III source could pass through a type II source (and not just through the wake of a type II source, as discussed by Lacombe and Pedersen 1971) without being affected by the shock wave thought to be associated with a type II source. However, to proceed with the discussion, let us suppose that the two sources have no effect on each other except for the absorption of the type II radiation by the shadow type III.

(*c*) *Brightness Temperatures for Fundamental Absorption*

As with absorption at the second harmonic, the requirement that the absorbing region is optically thick to background radiation also implies that it is optically thick to its own radiation, and this allows one to estimate the intrinsic brightness of the absorbing region. The fact that the background source and the absorbing region must overlap implies that the brightness temperatures for the background radiation and for the intrinsic radiation from the absorbing region are governed by the same transfer equation, namely (7). Integrating equation (7) gives

$$T_F = T_I \exp(-\tau_A) + T_0\{1-\exp(-\tau_A)\}, \tag{39a}$$

or

$$T_F = T_I \exp(\tau_E) + T_0\{\exp(\tau_E)-1\}, \tag{39b}$$

where the suffixes l and t are omitted. In equations (39), I labels the initial state of radiation incident on a layer from below and F the final state as the radiation leaves the layer, τ_A and τ_E are the optical depths for absorption ($\omega^t > \omega^l$) and emission ($\omega^t < \omega^l$) respectively, and $T_0 = (v_\phi/\sqrt{2}\,V_i)T_I$ is $\sim 10^9$ K in the present case.

Consider the background (subscript b) radiation. This encounters a region where it is amplified followed by a region where it is absorbed (separated by the layer with $\omega^t = \omega^l$). Thus one has

$$T_{bF} = T_{bI}\exp(\tau_E - \tau_A) + T_{AF}, \tag{40}$$

with

$$T_{AF} = T_0\{\exp(\tau_E - \tau_A) - 2\exp(-\tau_A) + 1\}. \tag{41}$$

The intrinsic radiation from the absorbing region has brightness temperature T_{AF}, that is, it is given by equation (40) with $T_{bI} \equiv 0$.

In the event reported by Kai (1973) the reduction in brightness temperature corresponded to $T_{bF}/T_{bI} \approx 1/5\cdot 5 \approx \exp(-1\cdot 7)$. From equation (40) it follows that one requires $\tau_A - \tau_E \geqslant 1\cdot 7$ and $T_{bF} \geqslant T_{AF}$ to explain this observation. It then follows that the dominant term in equation (41) is the unit term, that is, $T_{AF} \sim 10^9$ K. Consequently one requires $T_{bI} \gtrsim 5\cdot 5\times 10^9$ K and $T_{bF} \gtrsim 10^9$ K, whereas Kai found $T_{bI} \approx 10^9$ K and $T_{bF} \approx 1\cdot 8\times 10^8$ K. The agreement is reasonable but not entirely satisfactory.

Now $\tau_A \geqslant \tau_E + 1\cdot 7$ requires either that the region where absorption occurs be thicker than that where emission occurs or that the energy density in l-waves be greater in the former region than in the latter. However, one expects the two thicknesses to be comparable (amplification and absorption occur in equal bandwidths on either side of the frequency (29)) and a sharp gradient in W^l would be inconsistent with the nearly uniform absorption reported by Kai (the lower frequencies would be much more strongly absorbed than the higher frequencies). Either explanation would be plausible only for $\tau_A \sim \tau_E \gg 1\cdot 7$, when either the required thicknesses would be nearly equal or the required gradient in W^l would be small.

Also, with this mechanism it would appear equally as likely that the background radiation be amplified as that it be absorbed.

6. Conclusions

The results and implications of the above discussion on absorption due to Langmuir turbulence and its application to shadow type III events, and to the event reported by Kai (1973) in particular, can be summarized as follows.

(1) The absorption occurs in a very narrow frequency range, e.g. $\Delta f/f \approx 10^{-3}$, for either the fundamental or the second harmonic (for parameters appropriate to a shadow type III burst). The thickness of the absorbing region is limited to about 3×10^7 cm because of this narrow bandwidth and the regular variation of the plasma frequency with height in the corona.

(2) The above thicknesses together with the calculated absorption coefficients allow one to estimate the energy density W^l in Langmuir turbulence required for the optical depth to exceed unity: at $f = 100$ MHz one requires $W^l \geqslant 10^{-9}$ erg cm^{-3} for absorption at the fundamental and $W^l \geqslant 3\times 10^{-6}$ erg cm^{-3} for absorption at the second harmonic.

(3) For absorption at the second harmonic the Langmuir turbulence becomes isotropic on a time scale ($\sim 10^{-4}$ s) much shorter than the time over which the absorption persists at a fixed frequency. The combination of an optically thick source with isotropic Langmuir turbulence implies that the absorbing region would have an intrinsic brightness temperature of $\sim 10^{16}$ K. The background source would then need to be brighter than 10^{16} K, which is incompatible with Kai's (1973) observation of 10^9 K.

(4) For absorption at the fundamental, the observed bandwidth $\Delta f/f \sim \frac{1}{8}$ appears to require that the absorbing region and the background source overlap, i.e. that they be contained in the same volume when the absorption occurs. The observed reduction in brightness temperature (from 10^9 to $1\cdot 8\times 10^8$ K) requires that the brightness temperature of the background source exceed $\sim 5\cdot 5\times 10^9$ K (and then be reduced to $\sim 10^9$ K during absorption). There is no reason to expect a preference for absorption rather than amplification of the background radiation at the fundamental.

Thus absorption at the second harmonic can be ruled out. Absorption at the fundamental cannot be excluded but it does encounter several difficulties, e.g. the required coincidence of the absorbing region and the background source, the relatively high brightness temperatures required and the fact that amplification appears equally as likely as absorption are unattractive features. Other possible absorption mechanisms should be considered. In the following Part II the hypothesis is explored that the absorption is due to ion sound turbulence. This turns out to be much more favourable than absorption due to Langmuir turbulence.

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