Aust. J. Phys., 1974, **27**, 271–7

The Mechanism Responsible for 'Shadow' Type III Solar Radio Bursts. II* Absorption due to Ion Sound Turbulence

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Abstract

The hypothesis is explored that ion sound turbulence generated by the exciting agency for type III bursts is responsible for shadow type III events. The possible absorption mechanisms are listed: the most favourable are the coalescence of transverse waves and ion sound waves into Langmuir waves or the decay of transverse waves into Langmuir waves and ion sound waves. These mechanisms can operate only if the background source emits at the fundamental plasma frequency and the absorbing region is directly above it ($\lesssim 3\times10^4$ km). It is found that the event discussed by Kai (1973) can be explained in terms of such absorption with reasonable parameters, e.g. with an energy density in ion sound turbulence $W^s \gtrsim 10^{-12}\,\mathrm{erg\,cm^{-3}}$ at frequencies $\omega^s \sim 0\cdot3\,\omega_{\mathrm{pi}}$ (where ω_{pi} is the ion plasma frequency).

1. Introduction

In the preceding Part I (Melrose 1974, present issue pp. 259–69) it was pointed out that there were difficulties with the hypothesis that the absorption responsible for shadow type III bursts is due to Langmuir turbulence. In this paper, an alternative hypothesis that the absorption is due to ion sound turbulence is explored. It is assumed that the ion sound turbulence is generated by the stream of electrons responsible for the shadow type III bursts. There is no widely accepted mechanism for the generation of ion sound turbulence by a stream of fast electrons. However, if shadow type III events can be explained by invoking ion sound turbulence, and if no other explanation is as plausible, then this would provide evidence that electron streams in the corona do generate ion sound turbulence.

In Section 2 the most favourable absorption mechanism involving ion sound turbulence is identified, and in Section 3 it is shown that this mechanism could account for shadow type III bursts with reasonable choices of the parameters involved.

2. Absorption Coefficient

In this section the processes whereby ion sound turbulence can cause enhanced absorption are discussed and the absorption coefficient for the most favourable case is evaluated.

Extinction Mechanisms

Ion sound turbulence can cause extinction of a background source by three types of processes. (Ion sound turbulence generated within the emitting region leads to

* Part I, *Aust. J. Phys.*, 1974, **27**, 259–69.

further possibilities which are not considered here.) The three processes are:

(i) Absorption by conversion of the transverse waves (t-waves) into Langmuir waves (l-waves). The relevant conversion processes involving ion sound waves (s-waves) are coalescence ($t+s \to l$) or decay ($t \to l+s$). These processes cause a net conversion of t-waves into l-waves provided that both T^t and $(\omega_p/\omega^s)T^s$ are greater than T^l, where T^σ denotes the effective temperature for waves in the mode σ ($= t$, s or l).

(ii) Absorption due to scattering of t-waves into s-waves or to simultaneous absorption of t-waves and s-waves. These processes require s-waves with $k_s \lambda_D \gtrsim 1$, where λ_D is the Debye length; such s-waves are ion plasma oscillations.

(iii) Extinction due to scattering of t-waves by s-waves, i.e. due to the processes $t+s \to t'$ and $t \to t'+s$. These processes require s-waves with small wave numbers (implying low frequencies): specifically in the present context one requires $\omega^s \lesssim 10^{-4}\omega_{pi} \sim 1\text{–}3\ \mathrm{s}^{-1}$, where ω_{pi} is the ion plasma frequency. (This arises from $k_s \sim k_t$; see equation (1a) below.)

Of these three processes only (i), which requires $\omega^t - \omega_p \ll \omega_p$, is highly frequency-selective. Because the interpretation of shadow type III events would appear to require a frequency-selective absorption mechanism, (i) is the most plausible, and only this process is discussed below.

The process (i) is the inverse of the mechanism discussed by Zaitsev (1966) for emission at the fundamental. The emission and absorption mechanisms rely on nonthermal ion sound waves. The absorption mechanism causes l-waves to be generated (most of the initial energy in t-waves is converted into energy in such l-waves). The l-waves so generated have wave numbers that are comparable with those of the s-waves. These should not be confused with the l-waves (with much smaller wave numbers $k_l \sim 3\omega_p/c$) discussed in Part I; the latter l-waves are not relevant to the present discussion.

Resonance Conditions

The three waves involved need to satisfy the conditions

$$\boldsymbol{k}_t = \boldsymbol{k}_l \pm \boldsymbol{k}_s, \qquad \omega^t = \omega^l \pm \omega^s, \tag{1a, b}$$

where the upper and lower signs correspond to the two processes $t \to l+s$ and $t+s \to l$ respectively. The inequalities

$$\omega^s \lesssim \omega_{pi} \ll \omega_p \lesssim \omega^l, \omega^t$$

are always satisfied. The inequality $k_s \lambda_D \ll 1$ also needs to be satisfied, since for $k_s \lambda_D > 1$ the l-waves generated (with $k_l \approx k_s$) would be strongly (Landau) damped. The inequalities

$$k_t \ll k_l, k_s \tag{2}$$

are satisfied except for s-waves with $k_s \lesssim \omega_p/c$, which corresponds to very low frequencies (e.g. $\omega^s \lesssim 10^{-4}\omega_{pi}$).

For $k_s \lambda_D \ll 1$ the frequency of the s-waves is given by

$$\omega^s = k_s v_s,$$

where

$$v_s = \omega_{\text{pi}} \lambda_{\text{D}} = (\omega_{\text{pi}}/\omega_{\text{p}}) V_{\text{e}}$$

is the sound speed. Setting $k = k_l = k_s$ to lowest order in k_t/k, equation (1b) gives

$$\omega_1^t = \tfrac{3}{2} k^2 V_{\text{e}}^2/\omega_{\text{p}} \pm k v_s, \tag{3}$$

with

$$\omega_1^t = \omega^t - \omega_{\text{p}}, \qquad \omega^l - \omega_{\text{p}} \approx \tfrac{3}{2} k^2 V_{\text{e}}^2/\omega_{\text{p}}.$$

Solving for k ($= k_0$ say) gives

$$k_0 = \mp \frac{\omega_{\text{p}} v_s}{3V_{\text{e}}^2} + \left\{ \left(\frac{\omega_{\text{p}} v_s}{3V_{\text{e}}^2} \right)^2 + \frac{2\omega_{\text{p}}^2}{3V_{\text{e}}^2} \frac{\omega_1^t}{\omega_{\text{p}}} \right\}^{\frac{1}{2}}$$

$$\approx \left(\frac{2\omega_1^t}{3\omega_{\text{p}}} \right)^{\frac{1}{2}} \frac{\omega_{\text{p}}}{V_{\text{e}}} \qquad \text{for} \qquad \frac{\omega_1^t}{\omega_{\text{p}}} \gg \frac{v_s}{6V_{\text{e}}}, \tag{4a}$$

$$\approx (\mp 1 + 1) \frac{v_s \omega_{\text{p}}}{3V_{\text{e}}^2} \qquad \text{for} \qquad \frac{\omega_1^t}{\omega_{\text{p}}} \ll \frac{v_s}{6V_{\text{e}}}. \tag{4b}$$

For the relation (4b) to apply one needs to have $\omega_1^t \ll \omega_{\text{p}}/200$. On the other hand, the relation (4a) involves frequencies in the range $\omega_{\text{p}}/200 \ll \omega_1^t \ll \omega_{\text{p}}$. The latter case (4a) is much more favourable, and it is the only one considered below. It corresponds to $\omega^l - \omega_{\text{p}} \gg \omega^s$ in equation (3) and so to

$$\omega_1^t \approx \tfrac{3}{2} k^2 V_{\text{e}}^2/\omega_{\text{p}}.$$

The two processes $t+s \rightarrow l$ and $t \rightarrow l+s$ can be treated together.

Absorption Coefficient

Using equations (17) and (22) of Melrose (1970) the transfer equation due to the processes $t+s \rightarrow l$ and $t \rightarrow l+s$ reduces to the form

$$\partial T^t(\boldsymbol{k})/\partial s = -\mu(\boldsymbol{k})\, T^t(\boldsymbol{k}), \tag{5}$$

provided that both T^t and $(\omega_{\text{p}}/\omega^s)T^s$ are much greater than T^l (where T^l refers to the l-waves with $k_l \approx k_s \approx k_0$). The absorption coefficient (per unit length) is given by

$$\mu = \frac{\pi}{3\sqrt{3}} \frac{r_0 f_{\text{p}}^2 c}{V_{\text{e}}^3} \frac{\langle T^s \sin^2\theta \rangle_{\Delta\Omega} \Delta\Omega}{T_{\text{e}}}, \tag{6}$$

where the notation is the same as in Part I. In equation (6) the dependence of T^s on k_s and θ is to be understood; k_s is to be set equal to k_0 as given by equation (4a).

Under coronal conditions, equation (6) reduces to

$$\mu \approx 10^{-16} f^2 \langle T^s \rangle_{\Delta\Omega} \Delta\Omega / T_{\text{e}} \ \text{cm}^{-1}, \tag{7}$$

where $f = f_{\text{p}}$ is in megahertz and the approximation

$$\langle T^s \sin^2\theta \rangle_{\Delta\Omega} \approx \tfrac{1}{2} \langle T^s \rangle_{\Delta\Omega} \tag{8}$$

has been made.

3. Application to Shadow Type III Bursts

In this section the conditions on the turbulent spectrum under which the processes $t+s \rightarrow l$ and $t \rightarrow l+s$ could account for the absorption observed in shadow type III bursts are determined.

Requirements on Absorption Mechanism

The requirements on the absorption mechanism are similar to those imposed on the process $t \rightarrow l+l$ in Part I:

(i) The frequency of the t-waves must be such that $k_0 v_s$, with k_0 given by equation (4a), falls in the range of frequencies where the ion sound turbulence is excited.

(ii) The optical depth must be greater than unity.

(iii) The absorbing region must not have a brightness temperature in excess of that of the background.

(iv) The relative bandwidth over which absorption occurs should be of the order of (10 MHz)/(80 MHz) $= \frac{1}{8}$, as observed by Kai (1973).

Turbulent Spectrum

To proceed it is necessary to introduce a description of the turbulent spectrum. The description needs to be sufficiently simple that the parameters involved can be estimated from the requirements on the absorption mechanism. Let the spectrum be described by four parameters: a mean frequency $[\![\omega^s]\!]$, a bandwidth $\Delta\omega^s$, a maximum effective temperature $\langle T^s \rangle_{\Delta\Omega}$ at $\omega^s = [\![\omega^s]\!]$, and a range $\Delta\Omega$ of solid angles to which the vectors k_s are confined. Where further simplification is required it is reasonable to assume $\Delta\omega^s \sim [\![\omega^s]\!]$ and $\Delta\Omega \sim$ 1–3 sr (see e.g. Tsytovich 1972, p. 73).

The mean frequency $[\![\omega^s]\!]$ and the frequency spread $\Delta\omega^s$ can be related to the frequency ω_1^t $(= \omega^t - \omega_p)$ and the relative bandwidth $B_1 = [\![\omega_1^t]\!]/\omega_p$ using $\omega^s = k_0 v_s$ with k_0 given by equation (4a):

$$\omega_1^t/\omega_p \approx \tfrac{3}{2}([\![\omega^s]\!]/\omega_{pi})^2\,, \qquad B_1 \approx \tfrac{3}{2}(\Delta\omega^s/\omega_{pi})^2\,. \tag{9}$$

From condition (iv) above, the relative bandwidth $B_1 \sim \frac{1}{8}$ estimated by Kai (1973) and $[\![\omega^s]\!] \sim \Delta\omega^s$ imply

$$[\![\omega^s]\!] \sim \Delta\omega^s \sim 0{\cdot}3\,\omega_{pi}\,. \tag{10}$$

This is a plausible frequency range for ion sound turbulence (see e.g. Tsytovich 1972, Ch. 5).

The alternative suggestion, proposed in Part I, that the observed bandwidth is due to a spread in plasma frequencies through the absorbing region could also be considered here. However, this would be relevant only if the ion sound turbulence had a mean frequency much less than $0{\cdot}3\,\omega_{pi}$. It would then be necessary for the absorbing region and the background source to be in the same volume, as was concluded in Part I. With the present explanation of the bandwidth the absorbing region must lie above the background source and can be separated from it by 3×10^9 cm in height (see below).

The requirement that the optical depth be greater than unity, that is, $\mu L > 1$, involves the thickness L of the absorbing region. Following the arguments given in Part I one could estimate

$$L \sim 3B_1 \times 10^{10}\ \text{cm}\,. \tag{11}$$

For $B_1 \sim 0{\cdot}1$ (in accord with equations (9) and (10)) this would give $L \sim 3\times10^9$ cm. Combining equations (7) and (11), the condition $\mu L > 1$ becomes

$$B_1 f^2 \langle T^s \rangle_{\Delta\Omega} \Delta\Omega > 3\times10^6 T_e, \tag{12}$$

where f is the frequency of observation in megahertz. It is instructive to rewrite the condition (12) in terms of the energy density

$$W^s = [\![\omega^s]\!]^2 \Delta\omega^s \langle T^s \rangle_{\Delta\Omega} \Delta\Omega/(2\pi v_s)^3 \tag{13}$$

in ion sound turbulence. One requires

$$W^s > 10^{-12}(\omega_1^t/\omega_p)^2 f \ \mathrm{erg\,cm^{-3}}, \tag{14}$$

where f is in megahertz and a coronal temperature of 10^6 K has been inserted.

For $f = 100$ MHz, $B_1 \approx 0{\cdot}1$ and $\omega_1^t/\omega_p \approx 0{\cdot}1$, the inequalities (12) and (14) reduce to

$$\langle T^s \rangle > 10^8\ \mathrm{K}, \qquad W^s > 10^{-12}\ \mathrm{erg\,cm^{-3}}. \tag{15}$$

The required energy density (15) for absorption due to s-waves could be compared with the corresponding requirement $W^l > 10^{-9}$ erg cm^{-3} for absorption at the fundamental due to Langmuir turbulence and with $W^l > 3\times10^{-6}$ erg cm^{-3} for absorption at the second harmonic. For absorption due to ion sound turbulence the requirement on the energy density in the waves is relatively mild.

Minimum Brightness Temperature

For absorption at the second harmonic due to isotropic plasma turbulence (see Part I) the brightness temperature T_2^t approaches T^l as the source becomes optically thick. Since the source must be optically thick for absorption to be effective and this requires $T^l \gtrsim 10^{16}$ K, the background source would need to have a brightness temperature in excess of 10^{16} K. An analogous requirement exists for absorption due to the processes $t+s \to l$ and $t \to l+s$. The essence of the above argument for the second harmonic is that T_2^t tends to a value determined by the distribution of l-waves and so this value must be exceeded initially for absorption to occur. In the present case the brightness temperature tends to (Melrose 1970, Section IIf)

$$T^t \approx \min\{(\omega_p/\omega^s)T^s, T^l\}. \tag{16}$$

With $\omega_p \approx 100\,\omega^s$ and $T^s > 10^8$ K, one has $(\omega_p/\omega^s)T^s > 10^{10}$ K, and provided that T^l is less than 10^{10} K the relation (16) reduces to $T^t \approx T^l$. However, in this case T^l refers to l-waves with $k_l \approx k_s$, which corresponds to phase velocities $v_\phi \sim 3V_e$. One has no reason to expect such l-waves to be excited significantly above the thermal level, i.e. above $T^l \sim T_e \approx 10^6$ K. (The absorption process itself does generate such l-waves, but arguments analogous to those given in Section 3c of Part I lead to the conclusion that although this source of l-waves may affect the final brightness temperature it can only become important after significant absorption has occurred.)

The reduction in brightness temperature from $\sim10^9$ K to $\sim1{\cdot}8\times10^8$ K observed by Kai (1973) can be explained directly in terms of absorption due to ion sound turbulence, whereas a final brightness temperature below 10^9 K could not be explained in terms of absorption at the fundamental due to Langmuir turbulence.

4. Discussion

It would appear that absorption due to ion sound turbulence could account for shadow type III events without any implausible assumptions. The absorber needs to be close to the background source ($\lesssim 3\times10^4$ km above it in the specific case discussed) and the background source needs to be emitting close to the plasma frequency. (Ion sound turbulence cannot cause absorption at the second harmonic.) For the event observed by Kai (1973; see Fig. 1 of Part I) the background source was at $\sim 10^9$ K, the area of the absorber was $\sim 10^{21}$ cm^2 and the absorption was over a bandwidth of ~ 10 MHz at ~ 80 MHz. For this event, if the frequency range of the ion sound turbulence is fixed at $\Delta\omega^s \sim [\![\omega^s]\!] \sim 0{\cdot}3\,\omega_{pi}$ to give the observed bandwidth, the required turbulent energy density is $W^s \gtrsim 10^{-12}$ erg cm^{-3}. (The suggested range of frequencies for the ion sound turbulence is about the highest possible; for lower frequencies the limit on W^s is lower.)

It is tempting to conclude that shadow type III events do result from absorption due to microturbulence in the ion sound mode. The implication that the electron streams should generate ion sound turbulence would be an important one in view of current ideas concerning microinstabilities involving electron streams. Of course, all other possible explanations of shadow type III events would need to be explored before this inference concerning ion sound waves could be regarded as an established fact.

Two other possible alternative explanations for shadow type III events are:

(1) The stream of electrons (the exciting agency of an invisible type III burst) passes through the background source and causes absorption of those Langmuir waves responsible for the radiation from the background source, thereby suppressing the background radiation (S. F. Smerd, personal communication).

(2) The stream of electrons causes a change in the properties of the ambient medium such that either conversion of the Langmuir waves into transverse waves or the escape of the transverse waves is inhibited.

These possibilities are less attractive than is absorption at the fundamental due to Langmuir turbulence. However, compared with absorption due to ion sound turbulence, this alternative has three unattractive features. Firstly, the observed low brightness temperatures cannot be explained directly (some additional assumption such as the actual source size being smaller than the apparent size would be required). Secondly, the observed bandwidth can be explained only in terms of a spread in plasma frequencies due to the distribution of the absorbing region with height and this requires that the absorbing region and the background source overlap in height. Thirdly, amplification appears equally as likely as absorption.

It might be commented that observation of a shadow type III event in which the second harmonic band of a type II event were absorbed would exclude both absorption by ion sound turbulence and absorption at the fundamental due to Langmuir turbulence; according to the ideas advanced in these two papers such absorption should never be observed.

A search for further shadow type III events could provide additional information on the properties of the electron streams exciting type III bursts. If it is assumed that shadow type III events and type III bursts are related phenomena, the event reported by Kai (1973) would imply that type III bursts are of large cross sectional area (i.e. the actual size would need to be comparable with typical apparent sizes of type III bursts) and would lend support to the inference that some electron streams produce no observable radiation, i.e. that invisible type III events exist (Lacombe and Pedersen 1971; de la Noë and Boischot 1972).

5. Conclusions

The following two general conclusions might be emphasized.

(1) Although it would seem plausible that the absorption in shadow type III events is the inverse of one of the familiar plasma emission processes, i.e. the absorption is due to Langmuir turbulence generated by the stream of electrons, the detailed investigation in Part I indicates that it is difficult to explain shadow type III events in this way.

(2) If it is assumed that the stream of electrons involved in a shadow type III event generates ion sound turbulence (which would not be regarded as an intrinsically plausible assumption), then the properties of shadow type III events can be explained in terms of a conversion of the energy in the radiation into energy in Langmuir waves through coalescence processes involving the ion sound waves. This absorption process is the inverse of the emission process, for fundamental plasma radiation, suggested by Zaitsev (1966).

Acknowledgments

I would like to thank Dr K. Kai and Dr S. F. Smerd for helpful discussions and Dr G. A. Dulk and Dr J. A. Roberts for useful comments.

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Manuscript received 27 August 1973