LANGMUIR WAVE ENERGY DENSITY IN RADIO STORM SOURCES

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Abstract

An enhanced level of Langmuir wave energy density is postulated in all plasma wave models of radio storm emission. Three different methods are described to measure this quantity: Radar, observations of harmonics, and polarization measurements. These methods have been applied to solar noise storm sources. The results are presented. Only upper limits to the wave energy density have been found. The derivations of these limits depend on the assumed source parameters in different ways. The results are compared and discussed. The best upper limit of the ratio of wave energy density to thermal (kinetic) energy density is $5 \cdot 10^{-6}$ for bursts and about an order of magnitude less for the continuum. The various assumptions which enter these values are discussed.

I. INTRODUCTION

Traditionally there are two lines of models for the emission process of solar radio storms. In one of them direct emission by a cyclotron (maser) instability is proposed. Since this process usually requires a higher magnetic field than normally assumed, the second line of models, based on plasma wave emission, is today better received. However, these models propose the assumption of an enhanced level of high-frequency plasma waves, which has never been confirmed. We will use the term "Langmuir wave" for such a wave independently of its angle to the magnetic field (i.e. we include Upper Hybrid waves implicitly). Recent models have suggested the coalescence of Langmuir waves with low-frequency turbulence (Melrose, 1980; Benz and Wentzel, 1981, Spicer et al., 1981, Wentzel, 1981), or the decay of Langmuir waves (Suzuki, 1981) to be the origin of the radio emission.

Langmuir waves do not propagate out of the coronal plasma and cannot be measured in situ. There are only indirect ways to observe them. Here we discuss three different methods all based on the idea of wave-wave coupling. In section II the solar microwave radar ex-
periment is reviewed. It is based on the coupling of an incident radar wave to an antiparallel Langmuir wave. Section III discusses the coupling of Langmuir waves with an other, nearly anti-parallel Langmuir wave. For storm bursts (emitted at the fundamental) this leads to emission at the harmonic. No such radiation has been found to exceed the instrumental threshold. The same coupling mechanism is applied to the storm continuum in section IV. Since coincidence in time cannot be used to identify harmonic emission in a long duration event, the different polarization properties of fundamental and harmonic emission are applied. In section V the three methods are compared and their reliability is discussed. They depend on the assumed source parameters in different ways. Implications for plasma emission models are drawn, and future work suggested.

II. THE MICROWAVE RADAR EXPERIMENT

The microwave radar experiment conducted at the Arecibo 300 m telescope was designed to scatter radar waves at Langmuir waves in radio storm sources (Benz and Fitze, 1979, Fitze and Benz, 1981). The scattering process is assumed to be a three-wave coupling mechanism with the resonance conditions

\[ \omega_r \pm \omega_L = \omega_e \]  \hspace{1cm} (1)

\[ k_r \pm k_L = k_e \]  \hspace{1cm} (2)

where the indices r, L, and e refer to the frequencies of the radar, Langmuir, and echo wave, respectively. It is further assumed that the wave coupling occurs in the weak turbulence regime, for which Kovrizhnykh (1966) has calculated the growth rate:

\[ \gamma = \frac{\pi \omega_p^2 k_L^2}{8c} \frac{W_L(k_L)}{nm^2} \]  \hspace{1cm} (3)

where \( W_L \) is the wave energy density distribution in k-space. A flat
Langmuir wave spectrum between \( k_{\text{min}} \) and \( k_{\text{max}} \), and zero outside, is assumed. Maximum growth thus occurs at \( k_{\text{max}} \) (\( \approx 0.25k_d \)), and optimum scattering efficiency is at \( \omega_L = 6.7 (v_T/c)\omega_r \), where \( v_T \) is the mean thermal electron velocity. Scattering thus takes place high above the plasma layer (where \( \omega_L \approx \omega_p = \omega_r \)) and free-free absorption can be neglected. The echo energy density can be evaluated from the equation of continuity,

\[
\frac{\partial W_e}{\partial t} - \frac{v}{gr} \frac{\partial W_e}{\partial \lambda} = \gamma W_r ,
\]

(4)

to yield the observed echo flux at earth

\[
F = \frac{\gamma V}{c} \frac{P}{\varphi} \frac{1}{R^2 \Delta \nu}
\]

(5)

where \( V \) is the volume of enhanced Langmuir wave density, \( P \) the radar emission power, \( \varphi \) the illuminated area on the sun, \( R \) the distance to the sun, and \( \Delta \nu \) the bandwidth of the scattered signal. The total energy density \( W_L^t \) of Langmuir waves is

\[
\frac{W_L^t}{nkt} = 4.6 \times 10^{-4} \left( \frac{T}{2.10^6 K} \right)^{-5/2} \left( \frac{V}{10^{29.5} \text{ cm}^3} \right)^{-1} \left( \frac{k_{\text{max}}}{0.25 k_d} \right)^3 F
\]

(6)

with \( F \) in units of Jy. The constants and instrumental parameters are plugged in. The proposed source parameters as suggested from the model of Benz and Wentzel (1981) for the continuum are shown explicitly in the parenthesis on the rhs of equation (6).

The observed upper limits on the echo flux are given in Table I of Fitze and Benz (1981). For the observing run of 1978 Sept. 5, 1635 UT, which is likely to have hit a source region of storm emission (cf. Fig. 1), \( F \leq 1.24 \text{ Jy} \) and \( \beta_L \equiv \frac{W_L^t}{nkt} \leq 5.7 \times 10^{-4} \). There are better cases, but with less probability for hitting a source.
Fig. 1: Position of radar beam compared to radio storm sources. Numbers refer to times of observation in Universal Time. Lines are position measurements from Nançay at 169 MHz, curves are isophotes from Culgoora at 160 MHz.

The microwave radar experiment has probed Langmuir waves in the range from 170 to 270 MHz. It is only sensitive to waves in anti-parallel direction with \( k_L = 2 k_r \). For two reasons the results refer to the average wave energy density in the source of the continuum: (i) integration lasts many minutes. (ii) the small burst source size disfavors scattering compared to the continuum source, e.g. Benz and Wentzel (1981) have \( T = 2 \cdot 10^7 K \) and \( V = 3.6 \cdot 10^{21} \text{cm}^3 \). The resulting upper limit of wave energy density is far below \( (\Delta k / k_D)^2 nKT \), the threshold for strong turbulence. Thus the assumed scattering mechanism seems to be justified.

III. HARMONIC EMISSION OF BURSTS

Instead of introducing a new wave, a Langmuir wave may interact with another Langmuir wave to emit a radio wave (index h). The reson-
ance conditions are

\[ \omega_L + \omega_L' = \omega_h \]  
\[ k_L + k_L' = k_h \]

(7)
(8)

Since \( \omega_L = \omega_L' = \omega_p \) (the source plasma frequency), the radio wave can be searched for at the harmonic of the observed burst frequency. The two Langmuir waves have to be nearly anti-parallel, since \( k_h \approx \omega_h/c \) is much smaller than most \( k \)-values of Langmuir waves. The underlying assumptions are that storm burst emission occurs at the fundamental (arguments are given in Benz and Wentzel, 1981) and that nearly anti-parallel Langmuir waves exist. Again we use weak turbulence theory for the wave coupling coefficients. This will be justified later by the result.

To estimate the Langmuir wave energy density from the observed flux (or upper limit) at the harmonic, some assumptions on the source parameters of noise bursts have to be made. Again we use here the values of the most detailed model by Benz and Wentzel (1981). In this model:

1) The source is optically thick at the fundamental.
2) The phonon density of low-frequency waves is much higher than that of the high-frequency waves.
3) The surface area of the source is the same for fundamental and harmonic.
4) The Langmuir wave distribution is isotropic.

Using the standard wave-wave coupling coefficients, Jaeggi and Benz (1982) derive

\[ \beta_L = 3.2 \cdot 10^{-3} \left( \frac{T}{2.10^7 K} \right)^2 \left( \frac{k_{max}}{0.3 k_D} \right)^2 \left( \frac{k_{min}}{0.1 k_D} \right)^{-3} \left( \frac{\Delta s}{0.1 km} \right)^{-1} \left( \frac{\Delta \Omega}{\pi} \right)^{-1} \frac{F_h}{F_f} \]

(9)

where \( \Delta s \) is the depth of the source, \( \Delta \Omega \) is the solid angle filled by the low-frequency waves, and \( F_h/F_f \) is the ratio of observed fundamental and harmonic radio fluxes.
Jaeggi and Benz (1982) have recently searched for harmonic emission with high sensitivity. The result was negative, even after applying a superposed epoch analysis (Fig. 2). Their 3σ upper limit of the ratio is $F_h/F_f < 1.1 (\pm 0.2) \cdot 10^{-3}$. This leads to an upper limit of $\beta_L < 4 \cdot 10^{-6}$.

Fig. 2: Flux vs time for 34 superposed type I bursts from 235 to 241 MHz from Feb. 10 and 12, 1980 (top). Bottom curve superposed flux at twice the fundamental frequency. The background flux for the superposed harmonic is 115 sfu and the standard deviation is 0.12 sfu.

The advantage of this method over the radar observation is that a much wider range of $k_L$ values are probed. The requirement on the spacial distribution of the $k_L$ vectors, however, is more stringent if it deviates from isotropic: In the case of radar it is sufficient if they are in upward direction (e.g. along the magnetic field). In some part of the source they may then be directed preferentially to the observer. For the analysis of harmonics there have to be nearly antiparallel vectors at any position. The reliability of the estimated $\beta_L$ (or upper limit) in equ. (9) is similar to the value from the radar experiment except for $k_{min}$ which is not well known. The estimated $\beta_L$ here refers to the source of the bursts, which is expected to be considerably different from the average characteristics of the much larger source of the continuum.
IV. POLARIZATION OF THE CONTINUUM

The detection of harmonics of bursts is based on a correlation analysis of time profiles at the fundamental and harmonic. The continuum does not have enough structure in frequency and time to allow for a similar method. Benz and Zolliker (1980) have proposed to analyze the frequency dependence of polarization, since fundamental and harmonic emission are predicted to have very different degrees of polarization. The emission at the harmonic is assumed to arise by wave-wave coupling as suggested in section III (equ. 7 and 8). Its contribution will increase with frequency and may be observable by its influence on polarization: The basic idea is to select a storm continuum with a high degree of polarization at its maximum frequency (i.e. at the fundamental at about 200 MHz).

In order to derive $\beta_L$ (or upper limit) a model of the source and the emission process have to be specified. For definiteness, the continuum model of Benz and Wentzel (1981) is used. They have proposed coalescence of Langmuir (upper hybrid) waves with lower hybrid waves as emission mechanism, which produces fully polarized radiation at the fundamental. The same 4 assumptions made in section III for the burst source are also made for the continuum:

1) The source is optically thick at the fundamental.
2) The phonon density is higher for the low-frequency waves.
3) The surface area of the source is the same for fundamental and harmonic.
4) The Langmuir wave distribution is isotropic.

In addition, it is assumed:
5) that weak turbulence theory is applicable, and we will use the well-known coefficients. In case of strong turbulence prevailing, the method may still be used but with different coefficients.
6) The continuum radiation is assumed to be preferentially emitted at the fundamental (reason: high degree of polarization, details see Benz and Wentzel, 1981).
7) The degree of polarization of the fundamental is constant in frequency.
IVa) POLARIZATION OF THE CONTINUUM

The method to determine the polarization of the continuum is described first. The instrumental problems of polarization measurements with any instrument are enormous, in particular with a broadband spectrometer. Since the continuum is generally weak, the polarization measurement can easily be distorted by slowly varying (background) components. Calibration of flux and polarization are done with the quiet sun (which is rarely completely quiet). For these (and other) reasons, absolute measurements of the degree of polarization are generally inaccurate.

Benz and Zolliker (1980) have developed a technique which is based on relative measurements, but leads to an absolute value. Let us assume that the observed flux in left and right circular polarization (indices L and R, respectively) is composed of radiation from a continuum source, which is slightly variable in time, and a constant. The regression analysis in Fig. 3 between the observed left and right fluxes F then gives the ratio p

\[ p = \frac{F_L^C(t)}{F_R^C(t)} \]  

(10)

of the time variable fluxes of the continuum source (index c).
Fig. 3: Observed right polarized flux vs. left polarized flux for different observing times: x July 10, 1978, 1430-1600 UT, o July 10, 1978, 1614-1650 UT, ■ July 11, 1978, 1436-1609 UT. The regression lines are drawn in.

The weighted average in the data of Fig. 3 at 272 MHz is \( p = 17.2 \pm 2.8 \), which corresponds to a left circular polarization of

\[
\frac{F_L^c - F_R^c}{F_L^c + F_R^c} = \frac{p - 1}{p + 1} = 89 \ (\pm \ 1.5) \% \quad (11)
\]

Instrumental effects on this absolute value are now largely cancelled out. The indicated accuracy is the standard deviation of statistical fluctuations, which is partially due to the source.
IVb) DERIVATION OF HARMONIC CONTRIBUTION

Let us define

\[ P_f = \frac{F_L^f}{F_R^f} \]  

(12)

\[ P_h = \frac{F_L^h}{F_R^h} \]  

(13)

\[ h = \frac{F_L^h + F_R^h}{F_L^f + F_R^f} = \frac{F_R^h (1 + P_h)}{F_L^f (1 + 1/P_f)} \]  

(14)

where the indices \( f \) and \( h \) refer to the contributions of the fundamental and harmonic, respectively. In weak turbulence theory the intrinsic polarization of harmonic emission is low, thus \( P_h \approx 1 \). Assumption 6) requires \( P_f \gg 1 \) (assume left polarization of definiteness), thus

\[ h = \frac{2 F_R^h}{F_L^f} \]  

(15)

A frequency \( \nu \) is now considered near the maximum of the continuum.

Assumption 7) allows to set

\[ p_f (2\nu) = p (\nu) = p, \text{ and thus} \]

\[ F_R^h (2\nu) = F_R^c (2\nu) - F_R^f (2\nu) \]  

(16)

\[ = F_R^c (2\nu) - \frac{1}{p} F_L^c (2\nu) \]  

(17)

By assumption 6) is \( F_L^f (\nu) = F_L^c (\nu) \), i.e. the variable part of the flux is mainly due to fundamental emission.

Using equs. (15) and (17) it is easy to derive
\[ h(2\nu) = \frac{2 \left( F_R^c (2\nu) - \frac{1}{p} F_L^c (2\nu) \right)}{F_L^c (2\nu)} \]  
\[ (18) \]

Having determined \( p \) in section IVa, \( h (2\nu) \) can now be evaluated from a second regression analysis between nominator and denominator of the rhs of equation (18).

The result of this second linear regression has again been averaged by statistical weight. The average value for \( 2\nu \) in the range 465 – 525 MHz is

\[ h = 0.019 \pm 0.012 \]  
\[ (19) \]

Since it is not significantly different from zero, harmonic emission has not been detected. The 3\( \sigma \) upper limit on the ratio of harmonic to fundamental emission is

\[ h < 0.055 \]  
\[ (20) \]

IV c) DETERMINATION OF LANGLMUIR WAVE ENERGY DENSITY

The Langmuir wave energy density can be evaluated in the same way as in section III, since the physics is identical. Taking the source model for the continuum again from Benz and Wentzel (1981), equ. (9) becomes

\[ \beta_L = 5.7 \cdot 10^{-6} \left( \frac{T}{2 \cdot 10^6} \right)^{\nu/2} \left( \frac{k_{max}}{0.25 k_D} \right)^2 \left( \frac{k_{min}}{0.1 k_D} \right)^{-3} \left( \frac{\Delta \Omega}{1 \text{sr}} \right)^{-1} \frac{F_n}{F_f} \]  
\[ (21) \]

where the source depth \( \Delta s \) has been replaced by the height range, \( \Delta h \), where Langmuir waves with the observing frequency \( \nu (= 240 \text{ MHz}) \) can be found, divided by the cosine of the viewing angle. \( \Delta h \) is given by \( \nu \), \( k_{min}, k_{max} \), and a coronal density model (Baumbach-Allen has been used). Combining equ. (20) and (21), the upper limit on \( \beta_L \) becomes:
\[ \beta_L < 3 \cdot 10^{-7} \]  

This limit applies to the continuum source like the radar result. It is 3 orders of magnitude lower than the radar value, but a considerable number of assumptions and estimates of source parameters have to be made. In fact, if the source is optically thick at the harmonic, the ratio \( h \) becomes independent of \( \beta_L \).

V. CONCLUSIONS

The results of the 3 methods described in this review are listed in Table 1.

<table>
<thead>
<tr>
<th>method</th>
<th>object</th>
<th>( \beta_L )</th>
</tr>
</thead>
<tbody>
<tr>
<td>radar</td>
<td>storm continuum</td>
<td>&lt; 6 \cdot 10^{-4}</td>
</tr>
<tr>
<td>harmonics</td>
<td>storm bursts</td>
<td>&lt; 4 \cdot 10^{-6}</td>
</tr>
<tr>
<td>polarization</td>
<td>storm continuum</td>
<td>&lt; 3 \cdot 10^{-7}</td>
</tr>
</tbody>
</table>

Table 1: Summary of observed upper limits of \( \beta_L \), the ratio of Langmuir to thermal energy density.

The continuum source has been measured twice. The radar experiment produced a high, but very reliable upper limit of the ratio \( \beta_L \) of Langmuir wave to thermal energy density. The polarization method gives a surprisingly low value, which is, however, burdened with more assumptions. Any plasma wave model of the continuum will have to conform to the radar measurement and give a reason why the degree of polarization does not considerably decrease with frequency. The implicit assumptions of the polarization method are being analysed further and a more detailed description will be given by Benz and Zolliker (1983). Polarization spectra of the continuum are an important lack in observations.
and an interesting possibility for future work.

The upper limit on $\beta_L$ for burst sources is lower than predicted in most plasma wave models. The only exceptions are the models by Benz and Wentzel (1981) and Spicer et al. (1981), which were carefully made to meet this limit. The other models will have to be changed or dismissed. The upper limit could be further reduced by observations with spacial resolution. This would decrease the background at the harmonic.

The measurement of Langmuir wave energy density is a difficult enterprise which requires both sophisticated instrumentation and well developed theory. It is a crucial test already today for radio storm theories.

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