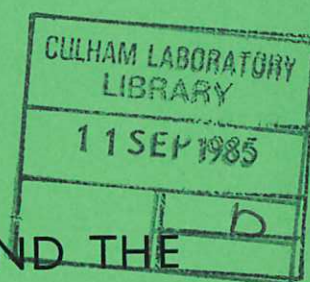




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PHASE SOLAR FLARES

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MICROWAVE RADIATION BURSTS AND THE SUPRATHERMAL
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IMPULSIVE PHASE SOLAR FLARES

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ABSTRACT

We discuss the observations of microwave bursts from impulsive phase solar flares in terms of a simple emission mechanism based on a triple resonance instability. This mechanism relies on the distinctive feature of the parallel electron velocity distribution which has been theoretically predicted to occur in the emitting region: a bump in the high-energy tail. The characteristic velocity required for the bump and the polarisation and frequency predicted for the radiation appear to be consistent with the observations and with existing theoretical work. The demands placed on this emission mechanism complement those given by results from tokamak discharges during current decay. We suggest that this emission mechanism may represent a step towards understanding both sets of results, and supports the theoretical predictions of bump-in-tail suprathermal electron velocity distributions in both cases.

I INTRODUCTION

Information on twenty-two sharp bursts of coincident X-ray and microwave radiation from impulsive phase solar flares has been given by Crannell, Frost, Mätzler, Ohki, and Saba (1978; referred to as CFMOS hereafter). The hard X-ray data, obtained by CFMOS using OSO 5, have an uncomplicated time structure consisting of a simple rise and fall with a duration of a few seconds. CFMOS then conducted a search for records of microwave emission events occurring at the same times as the X-ray spike bursts. Twenty-two bursts of nearly simultaneous X-ray and microwave radiation were examined in detail, and the values estimated for the size, density, and energy of the emitting region were found to be consistent with a source located in the lower solar corona.

We shall discuss some features of these results in terms of the basic impulsive phase solar flare model proposed by Vlahos and Papadopoulos (1979; referred to as VP hereafter), Brown, Melrose, and Spicer (1979), and Smith and Lilliequist (1979). In this model, the plasma electrons at the top of the flare loop are heated impulsively up to a temperature T_e^I . A possible energy source is represented by tearing mode magnetic field reconnection (Furth, Killeen, and Rosenbluth 1963; Spicer 1977) for which a number of trigger mechanisms have been suggested (Sakai and Washimi 1982; Vainshtein and Mazur 1982; Dendy and ter Haar 1984). The heated electrons flow rapidly out of Region I at the top of the loop (see Figure 1) into the cooler Region II. To maintain charge neutrality, a return current from Region II is set up. When the drift velocity associated with the return current exceeds the local ion acoustic velocity, ion acoustic turbulence is excited. VP have shown how the resulting local enhancement of the collision frequency prevents the escape from Region I of all

electrons with $|v_{\parallel}| < v_c$, where v_c is a critical velocity of order $3v_{Te}^I$. The high-velocity electrons in the tail of the distribution in Region I remain free to pass into Region II. Recall that Region II is cooler than Region I. The addition of part of the high-energy tail of the electron distribution of Region I results in the production of a very distinctive distribution in Region II. There is a cool thermal distribution, together with a detached bump at high values of v_{\parallel} which substantially exceed v_{Te}^{II} . This is illustrated in, for example, Figure 2 of VP and Figure 1 of Holman, Kundu, and Papadopoulos (1982). Emslie and Vlahos (1980) have made a related suggestion: the electric field parallel to the magnetic field direction, which is generated by the tearing mode, may exceed the Dreicer limit and produce a bump-in-tail distribution in Region II. An important result on the stabilisation of such distributions was obtained by Papadopoulos, Goldstein, and Smith (1974); see also Bardwell and Goldman (1976), and Smith (1977). Consider the VP mechanism: there will be a sharp positive slope in the distribution function of Region II for $v_{\parallel} > v_c$. The distribution should therefore be unstable against the resonant wave-particle emission of electrostatic waves with frequency ω_p (the plasma frequency) and wave-number $k \approx \omega_p/v_c$. It might be expected that the electrostatic waves would react back on the tail distribution, and that the resonant wave-particle interaction would flatten the bump. However, it has been shown that given a realistic level of electrostatic turbulence within the solar flare, the modulational instability (Zakharov 1972) can shift the waves out of resonance before they have had time to disrupt the tail distribution. Thus the bump in the tail can persist.

There are clearly strong theoretical grounds for supposing that in Region II of impulsive phase solar flares, the electron velocity

distribution has a suprathermal tail with a bump. This region, in the lower corona, is also the region from which the coincident microwave and X-ray bursts reported by CFMOS are believed to originate. Bursts of microwave radiation near the plasma frequency have also been reported (Gandy, Hutchinson, and Yates 1985; Hutchinson and Kissel 1983) from tokamak plasmas during current decay. It is noteworthy that there are also good theoretical grounds for supposing that in the source region of tokamak plasmas, the electron velocity distribution has a suprathermal tail with a bump. In this case, the mechanism for bump generation is the nonlinear evolution of the tail distribution (Liu, Mok, Papadopoulos, Engelmann, and Bornatici 1977; Papadopoulos, Hui, and Winsor 1977) which is relaxing due to the anomalous Doppler effect (Parail and Pogutse 1976). It is also significant that CFMOS reported (page 634) the range of frequencies of the most shortlived microwave burst, event number 17, to include the local plasma frequency.

In this paper, we examine these coincidences further. A simple linear triple wave resonance instability has recently been suggested (Dendy, Lashmore-Davies, and Shoucri 1985; referred to as paper A hereafter) as a possible emission mechanism for the tokamak radiation. This mechanism relies on the existence of a bump in the suprathermal tail of the electron velocity distribution. For this reason, it may represent a step towards explaining the coincidences outlined above. It may also be interpreted as offering support to those theories which have predicted a bump-in-tail distribution, both in the solar flare and the tokamak regimes.

II MICROWAVE RADIATION BURSTS

The contribution to the plasma dielectric tensor of a bump in the tail of the distribution of electron velocities parallel to the magnetic field has been examined in some detail (Stepanov and Kitsenko 1961; Akhiezer, Akhiezer, Polovin, Sitenko and Stepanov 1965). It is often appropriate to neglect the thermal corrections arising from the finite spread of velocities in the bump. This approach, in which the bump is treated as a beam with velocity v_0 , containing a fraction $\xi \ll 1$ of the total number of electrons, was followed also in paper A. It was shown that in the frequency range of interest, waves satisfy the dispersion relation (A.3)

$$\left(1 - \frac{\omega_p^2}{\omega(\omega - \Omega)} - n_z^2\right) \left(1 - \frac{\omega_p^2}{\omega^2} - \frac{\omega_b^2}{(\omega - k_z v_0)^2}\right) = \frac{n_\perp^2 n_z^2}{2} \quad (1)$$

Here n_z and n_\perp are respectively the components of the refractive index parallel and perpendicular to the magnetic field direction; Ω is the electron gyrofrequency; and $\omega_b = \xi^{1/2} \omega_p$ is the plasma frequency associated with the beam electrons. The first bracket in equation (1) describes the right circularly polarised electromagnetic waves supported by the bulk plasma. The second bracket describes the electrostatic waves supported by the bulk plasma and by the beam. Equation (1) applies to the regime $n_\perp^2 \ll n_z^2$.

In the region of interest in the impulsive phase solar flare, it is generally assumed (Holman, Kundu, and Papadopoulos 1982) that $\Omega \approx 3\omega_p$. Since Ω exceeds ω_p , the following triple resonance for equation (1) is possible:

$$\omega_p = k_z v_o = \omega_1 \quad (2)$$

Here, ω_1 is the low-frequency or Whistler branch of the right circularly polarised dispersion relation. It follows from equation (2) that at triple resonance, the parallel refractive index and the beam velocity must satisfy respectively

$$n_z = (1 - x)^{-1/2} \quad (3)$$

$$v_o = (1 - x)^{1/2} c \quad (4)$$

where $x = \omega_p/\Omega$. We note that while v_o may take a value which is a significant fraction of c , relativistic effects are not important in this context (Shoucri, Dendy, and Lashmore-Davies 1984). Solving equation (1) under the triple resonance condition equation (2), we find that there are growing electromagnetic modes with frequency ω close to ω_p :

$$\omega = \omega_p - \Delta + i\gamma \quad (5a)$$

$$\gamma = \gamma_o [f_+(R) - f_-(R)], \quad \Delta = \frac{2}{\sqrt{3}} \gamma_o [f_+(R) + f_-(R)] \quad (5b)$$

$$f_{\pm}(R) = [1 \pm (1-1/R)^{1/2}]^{1/3}, \quad \gamma_o = \frac{\sqrt{3}}{2^{4/3}} \xi^{1/3} \omega_p \quad (5c)$$

$$R = \frac{108}{[n_z^2 P(x)]^3} \frac{\xi^2}{n_{\perp}^6}, \quad P(x) = \frac{(1-x)^2}{2-3x+2x^2} \quad (5d)$$

This mode has both an electromagnetic right circularly polarised component, and an electrostatic component. The ratio of the associated field energies is

$$P_R \equiv \left| \frac{E_R}{E_Z} \right|^2 = 2.16 P(x) \left(\frac{1}{R} \right)^{1/3} \quad (6)$$

for the most strongly growing modes. In terms of R , the angle of inclination of \underline{k} to the magnetic field direction is

$$\theta = \tan^{-1} \left[\left(\frac{\xi^2}{R} \frac{108}{[n_z^4 P(x)]^3} \right)^{1/6} \right] \quad (7)$$

We are concerned with radiation which has both a significant electromagnetic component and a large growth rate. By equation (5b), a large growth rate corresponds to large values of R ; by equation (6), a significant electromagnetic component corresponds to small values of R . The characteristics of the radiation of interest are determined by the balance of these requirements. From Table 1, it is clear that the parameter range to be considered is $20 \leq R \leq 1000$. From equation (7), we see that the associated range of propagation angles is additionally parametrised by the fractional beam density ξ . No detailed calculations of the value of ξ have been carried out for the various models, but a figure of order one per cent appears plausible. In Table 1, the radiation characteristics are given for $\xi = 10^{-2}$ and $\xi = 5 \times 10^{-3}$, see also Figure 2. In contrast to the tokamak case (paper A), the radiation occurs in a fairly broad range of angles, $10^\circ \leq \theta \leq 20^\circ$. The frequency of the radiation can be calculated using equation (5b) for Δ . From Table 2, the

frequency is typically $0.8 \omega_p$. This is lower than in the tokamak case, but is clearly consistent with the observation of CFMOS on page 634. The polarisation of the electromagnetic component which is excited in our theory is purely right circular (extraordinary). This is fully consistent with the polarisation measurements carried out on 6 cm solar microwave bursts by Alissandrakis and Kundu (1978). The sharpness of the resonance condition equation (4) is highly relevant to the bursting nature of the radiation. It is clear from the coincident X-ray observations of CFMOS that the distribution of energetic tail electrons responsible for the radiation is evolving in time. As the tail distribution changes, so does the value of v_o associated with it. When v_o reaches the value given by equation (4), there will be a rapid onset of the instability. Any subsequent small change in v_o will terminate the emission.

So far, we have seen how the frequency, polarisation, and essentially shortlived nature of the radiation given by the theory appear to be essentially consistent with the observations. The bandwidth $\Delta\omega/\omega$ of the excited radiation is given in Table 2. It is typically of the order of five per cent. Although CFMOS give no detailed information on the microwave frequency spectrum, it appears to be broader than this value. It follows that the full range of frequencies observed may not be explicable in terms of a single resonant excitation. Given the extremely simple model employed here, this limitation is by no means crucial. The excitation mechanisms appear to be consistent with the properties of that portion of the frequency spectrum of the solar microwave burst which is centred close to and below the plasma frequency.

We now turn to the consistency of this excitation mechanism with the basic model of the impulsive phase solar flare which was outlined in the previous Section. The key requirement is that the beam velocity must

satisfy equation (4) for instability. It is clear that we require the beam velocity to be comparable to the critical velocity v_c introduced above:

$$v_o \approx v_c \quad (8)$$

Holman, Kundu, and Papadopoulos (1982) have reviewed the literature, and conclude that an estimate

$$v_c \approx 3v_{Te}^I \quad (9)$$

appears reasonable - here, as above, v_{Te}^I is the electron thermal velocity in the upper Region I of the solar flare. They suggest also that $\omega_p/\Omega = x \approx 1/3$. Combining this with equations (4), (8), and (9) we obtain

$$v_{Te}^I/c \approx 0.27 \quad (10)$$

An estimate of the value of v_{Te}^I is given on page 717 of VP:

$v_{Te}^I \approx 8 \times 10^9 \text{ cms}^{-1}$. This is in full agreement with equation (10).

From Figure 5 of Emslie and Vlahos (1980), it is reasonable to take

$$v_o \approx 8 v_{Te}^{II} \quad (11)$$

Here, as above, v_{Te}^{II} is the electron thermal velocity in the emitting Region II of the solar flare. Again taking $\omega_p/\Omega = x \approx 1/3$ equations (4) and (11) give

$$v_{Te}^{II}/c \approx 0.1 \quad (12)$$

From Table 5 of CFMOS, the characteristic temperature of the emitting region is typically 20 kev, which corresponds to $v_{Te}^{II}/c \approx 0.2$. This is clearly compatible with equation (12), given the degree of estimation involved. We conclude that the theoretical constraint placed on the velocity of the beam by equation (4) is entirely compatible with the observational conclusions and with estimates drawn from the literature.

III DISCUSSION

There are two distinct plasma physics contexts in which suprathermal electron velocity distributions with a bump in the tail have been predicted on theoretical grounds. These are the lower coronal sections of impulsive phase solar flares, and low density tokamak discharges during current decay. In both contexts, bursts of electromagnetic radiation have been observed. This paper represents an attempt to relate these facts through a single emission mechanism.

It is important to distinguish certain features of the tokamak and solar flare observations. In the tokamak case, the frequency and bandwidth of the radiation are known in terms of the local plasma parameters to a high degree of accuracy. Due to multiple reflections off the conducting walls of the vacuum chamber, the polarisation is not known. Independent information on the shape and characteristics of the tail distribution is extremely limited. In contrast, the reverse is true in the solar flare case. It is not possible to relate the frequencies characteristic of the observed microwave radiation to the plasma

parameters in the emitting region with certainty. Any such relations are to some extent model-dependent. However, the polarisation has been clearly determined, and a considerable theoretical effort has been devoted to prediction of the tail distribution. The two physical systems therefore place complementary demands on any single theory of the emission mechanism. In paper A, we showed how the triple resonance model could generate narrow-band electromagnetic radiation at the plasma frequency under tokamak conditions. Here, the constraints placed on the tail distribution by the triple resonance condition have been tested in terms of existing impulsive phase solar flare models, and have been found to be consistent. In addition the right circular (extraordinary) polarisation predicted by our emission mechanism is consistent with the solar flare observations. These represent two important additional tests of the emission mechanism. As in the tokamak case, the emission mechanism is compatible with the bursting character of the radiation. While the bandwidth may be too narrow for the full range of the frequency spectrum of the solar microwave bursts to be explicable in terms of a single excitation, the frequency predicted for the radiation appears to be broadly consistent with the observations.

IV CONCLUSIONS

We have discussed the observations of microwave bursts from impulsive phase solar flares in terms of a simple emission mechanism based on a triple resonance instability. This mechanism relies on the distinctive feature of the parallel electron velocity distribution which has been theoretically predicted to occur in the emitting region: a bump in the high-energy tail. The characteristic velocity required for the bump and

the polarisation and frequency predicted for the radiation appear to be consistent with the observations and with existing theoretical work. The demands placed on the triple resonance emission mechanism by the solar flare observations complement those given by results from tokamak discharges during current decay. We suggest that this emission mechanism may represent a step towards understanding both sets of results, and supports the theoretical predictions of bump-in-tail suprathermal electron velocity distributions in both cases.

R	γ/γ_0	P_R	θ°	θ°
			$\xi = 10^{-2}$	$\xi = 5 \times 10^{-3}$
5	0.61	0.46	21.7	17.5
10	0.70	0.36	19.5	15.7
20	0.76	0.29	17.5	14.1
40	0.81	0.23	15.7	12.6
100	0.86	0.17	13.6	10.9
1000	0.94	0.08	9.4	7.5
3000	0.96	0.05	7.8	6.2

Table 1: Growth rate, polarisation, and propagation angle
of excited waves

R	Δ/ω_p	Δ/ω_p
	$\xi = 10^{-2}$	$\xi = 5 \times 10^{-3}$
20	0.21	0.17
1000	0.27	0.21
Bandwidth	6×10^{-2}	4×10^{-2}

Table 2: Frequency shift and bandwidth of excited waves

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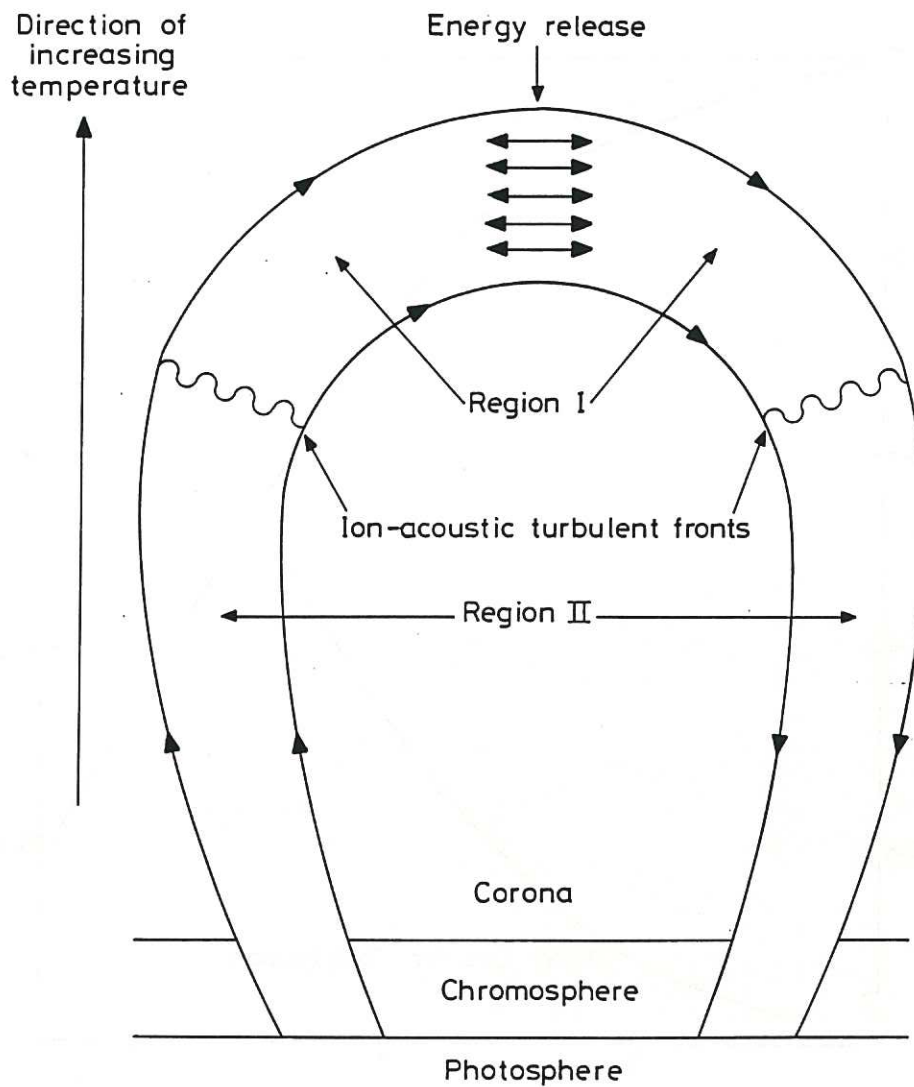


Fig.1 Diagram of the solar flare model (cf Vlahos and Papadopoulos, 1979; Emslie and Vlahos, 1980). The high-energy tail of the high-temperature electron distribution in Region I passes through the ion-acoustic turbulent front into the cooler Region II. This produces a bump-in-tail distribution in Region II.

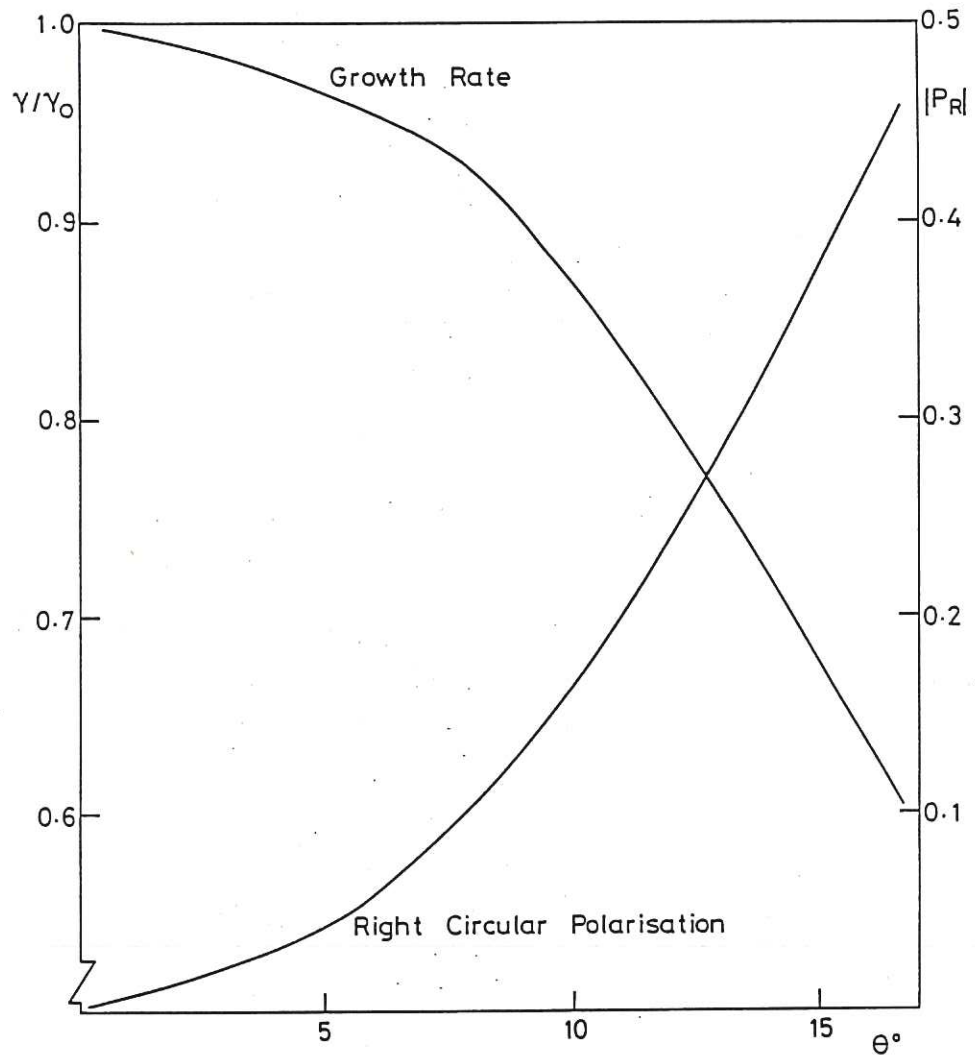


Fig.2 The growth rate γ (in dimensionless units) and the ratio of the right circularly polarised to electrostatic field energy, both plotted as functions of the inclination angle of the wave propagation vector to the magnetic field for the case of fractional beam density $\xi = 0.5 \times 10^{-2}$.

