SESSION III

SOLAR BURSTS - cm WAVELENGHTS

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RADIO BURST EMISSION MECHANISMS: GENERAL REVIEW

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ABSTRACT

This paper is a shortened version of a review of radio emission mechanisms for meter-λ radio bursts.

INTRODUCTION

The only two accepted mechanisms for nonthermal radio emission from the Sun are plasma emission and gyro-synchrotron emission. My purposes in this review are (a) to present the theory of the "standard" version of fundamental plasma emission in such a way as to make it as useful to astronomers as are the theories of synchrotron emission, bremsstrahlung and inverse Compton emission, (b) to summarize possible alternatives to the "standard" version of fundamental plasma emission, (c) to describe second harmonic generation in a way analogous to "standard" fundamental plasma emission to facilitate comparisons, (d) to point out the limitations implied by "saturation" of the conversion processes, and (e) to review analytic treatments of gyro-synchrotron emission particularly for moving type IV bursts. The "standard" version of fundamental plasma emission is scattering by ions, or more specifically scattering of Langmuir waves into transverse waves by nonlinear coupling with the shielding electric fields associated with thermal ions.

THE ANALOGY WITH THOMSON SCATTERING

Scattering by ions is closely analogous to Thomson scattering. The rate of increase per unit length (ℓ) in the energy density in transverse waves (W^t) due to scattering of Langmuir waves with an energy density W^ℓ may be described by

$$\frac{dW^t}{d\ell} = \frac{1}{4}\sigma_T \left(\sum_i Z_i^2 n_i\right) W^\ell , \qquad (1)$$

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where σ_T is the Thomson cross-section and where the sum is over all ionic species with charge $Z_i e$ and number density n_i. The factor 1/4 is actually the fourth power of the ratio λ_D/λ_{De} of the total to the electron Debye lengths, which ratio is 1/4 for singly charged ions and equal electron and ion temperatures. For Langmuir waves with phase speeds in a range Δv_ϕ about v_ϕ, the refractive index n and the bandwidth $\Delta\omega$ of the transverse waves are given by

$$n \approx \sqrt{3}\,\frac{V_e}{v_\phi} , \tag{2}$$

and

$$\Delta\omega \approx \omega_p \left[\frac{V_i}{v_\phi},\; 3\frac{V_e^2}{v_\phi^2}\frac{\Delta v_\phi}{v_\phi}\right] , \tag{3}$$

where V_i and V_e are the electron and ion thermal speeds. Along a ray path outside the source both, W^t and the range $\Delta\Omega$ of solid angle filled by the radiation vary as the refractive index n varies. The quantity I/n^2 is constant where $I = cnW^t/\Delta\omega\Delta\Omega$ is the specific intensity.

INDUCED SCATTERING

Induced scattering (also called stimulated scattering) occurs for all scattering processes. It can be interpreted and described semi-quantitatively in terms of absorption of the beats between the scattered and unscattered waves. For scattering by ions, this absorption tends to limit the level of the beats to a thermal level determined by the ionic temperature. To understand this analogy it is important to distinguish between the cases where the frequency (ω) of the transverse waves is greater and smaller, respectively, than the frequency (ω') of the Langmuir wave. For $\omega > \omega'$ induced scattering limits the effective temperature $T^t(\underset{\sim}{k})$ of the transverse waves to less than about $T_i\,\omega_p/|\omega-\omega'|$, where T_i is the ion temperature. For $\omega < \omega'$ induced scattering tends to reduce the effective temperature $T^\ell(\underset{\sim}{k}')$ of the Langmuir waves to this value. A transfer equation which includes these features is

$$\frac{dT^t(\underset{\sim}{k})}{dt} = \alpha(\underset{\sim}{k})\,\{1 - \frac{\omega}{\omega-\omega'}\,\frac{T^t(\underset{\sim}{k})}{T_i}\} \tag{4}$$

where $\alpha(\underset{\sim}{k})$ is an emission coefficient. When induced scattering (the final term in (4)) is neglected, (4) should reproduce (1) and this allows one to identify $\alpha(\underset{\sim}{k})$:

$$\kappa\alpha(\underset{\sim}{k}) \approx \frac{\pi}{12}\,\frac{\omega_p W^\ell v_\phi}{n_e V_i} , \tag{5}$$

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where κ is Boltzmann's constant and W^{ℓ} is the energy density in the Langmuir waves.

According to (4) with (3) induced scattering is important only for

$$T^t \gtrsim T_0 \approx \frac{v_\phi}{V_i} T_i , \tag{6}$$

which reduces to $T^t \gtrsim 10^9$K for $v_\phi \approx c/3$ and $T_i \approx 1.5 \times 10^6$K.

SOLUTIONS OF THE TRANSFER EQUATION

For $\omega < \omega'$ (4) allows exponentially growing solutions for T^t, and hence allows $T^t >> T_0$ in a uniform plasma. However, in the corona the density gradient causes the frequency ω' of the Langmuir waves to decrease along the ray path of escaping radiation and an absorption layer is encountered. For a linear density gradient (scale length L_N) solution of (4) gives (Melrose 1979a, p. 227)

$$T^t = 2T_0 \, \phi(\tau^{\frac{1}{2}}/2) , \tag{7}$$

with

$$\phi(y) = 2y \exp(-y^2) \int_0^y dt \exp(t^2) \tag{8}$$

and with an optical depth

$$\tau \approx \frac{\pi}{2\sqrt{3}} \frac{\omega_p L_N}{c} \frac{V_i}{V_e} \frac{W^{\ell}}{n_i \kappa T_i} . \tag{9}$$

The maximum value of T^t implied by (8) is $T^t = 2T_0$ for $\tau >> 1$.

To account for bright fundamental emission in terms of the "standard" version seems to require Langmuir waves in intense clumps (a) to avoid absorption limiting T^t to $\leq 2T_0$ and (b) to allow $\tau >> 1$. Alternatively observed fundamental emission could be due to a "non-standard" conversion mechanism. I now discuss two such alternatives.

COALESCENCE WITH LOW-FREQUENCY WAVES

Coalescence of Langmuir waves $(\omega',\underset{\sim}{k}')$ with low-frequency waves $(\omega'',\underset{\sim}{k}'')$ to produce a transverse wave $(\omega,\underset{\sim}{k})$ can occur when the parametric conditions

$$\omega = \omega' \pm \omega'' , \qquad \underset{\sim}{k} = \underset{\sim}{k}' \pm \underset{\sim}{k}'' \tag{10a,b}$$

are satisfied. Suitable examples of low-frequency turbulence include ion-sound waves, lower-hybrid waves, ion-cyclotron waves, resonant

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whistler waves, and any waves with sufficiently large k". According to (10a) line splitting occurs in the emission. The line separation is twice the frequency of the low-frequency waves.

The generation of either line may be described by

$$\frac{dW^t}{d\ell} = \sigma_T n_e W^\ell \frac{T''}{T_e} , \tag{11}$$

where T" is the effective temperature of the low-frequency waves. Amplification, but only in the down-conversion process, occurs for $T^t > T'' \omega_p/\omega''$ provided the inequality $T'' < T^\ell \omega''/\omega_p$ is satisfied. Both lines saturate for $T^t \approx T^\ell$ and such saturation occurs for

$$\frac{W''}{n_e \kappa T_e} > \frac{6\sqrt{3}}{\pi} \frac{c}{\omega_p L_N} \frac{V_e}{v_\phi} , \tag{12}$$

where W" is the energy density in the low-frequency waves which can coalesce with the Langmuir waves.

DIRECT CONVERSION

Direct conversion of Langmuir waves into o-mode waves can occur due to inhomogeneities in the plasma. The Langmuir waves must be propagating in the direction of increasing plasma density. If they fill a solid angle $\Delta\Omega$ about this direction the average efficiency (Q_{av}) of conversion into o-mode waves is (Melrose 1979b)

$$Q_{av} \approx \frac{v_\phi^2}{c\omega_p L_N \Delta\Omega} \left(\frac{\omega_p + \Omega_e}{\Omega_e}\right)^{\frac{1}{2}} , \tag{13}$$

where Ω_e is the electron gyrofrequency. Direct conversion tends to be dismissed without adequate justification. If the corona is inhomogeneous on a fine scale ($L_N \approx 100$km) the efficiency of conversion (13) is larger than for the "standard" version. However, I have found no example where direct conversion is clearly the most favored mechanism.

SECOND HARMONIC EMISSION

Generation of second harmonic plasma emission may be described approximately by

$$\frac{dW^t}{d\ell} = \frac{6}{5} \sigma_T n_e W^\ell \left(\frac{\kappa T^\ell}{m_e c^2}\right) \tag{14}$$

comparison of (14) and (11) shows that the second harmonic is favored over the fundamental for $T^{\ell} \gtrsim m_e c^2/\kappa = 6 \times 10^9$K. The second harmonic saturates at $T^t \approx T^{\ell}$ and saturation occurs for

$$\frac{\kappa T^{\ell}}{m_e c^2} \gtrsim 5\sqrt{3}\ \frac{v_{\phi}^3}{\omega_p^2 L_N r_0 c}\ , \tag{15}$$

where r_0 is the classical radius of the electron. For reasonable parameters in the corona (15) implies $T^{\ell} \gtrsim 10^{15}$K. If the Langmuir waves are clumpy one would expect saturation to occur.

Most treatments, including (14), of second harmonic plasma emission invoke the "head-on" approximation (anti-parallel coalescing Langmuir waves). This approximation leads to significant overestimates (factors of two or so) of the power radiated for $v_{\phi} \approx c/3$ and to large errors (many orders of magnitude) for $v_{\phi} \gtrsim c$ (Melrose and Stenhouse 1979).

POLARIZATION

For all fundamental plasma emission mechanisms the expected polarization is ≈ 100% in favor of the o-mode for reasonable values of the magnetic field strength. The fact that observed fundamental emission (except in Type I) is less than 100% is difficult to explain. The expected polarization of the second harmonic is o-mode for Langmuir waves which are highly collimated along the magnetic field and x-mode otherwise (Melrose, Dulk and Smerd 1978). Type III bursts which show harmonic structure have the second harmonic polarized in the same sense as the fundamental implying highly collimated Langmuir waves. The fact that the x-mode is favored for non-collimated Langmuir waves adds to the difficulty in distinguishing between second harmonic plasma and gyro-synchrotron emissions.

GYRO-SYNCHROTRON EMISSION

Most treatments of gyro-synchrotron emission and absorption have involved detailed numerical calculations. It is desirable to have analytic results, as are available in the non-relativistic (cyclotron) and ultra-relativistic (synchrotron) limits. These limits involve a truncated power series approximation and an Airy-integral approximation, respectively, to the Bessel functions which appear. For mildly relativistic electrons the non-relativistic approximation is reasonable for harmonics s up to about $1/\beta$, where βc is the speed of the electron. Gyro-synchrotron emission at the sth harmonic is then approximated by 2^s-electric multipole emission. Trubnikov has used the Carlini approximation to the Bessel functions to develop an analytic expression for the gyro-synchrotron absorption coefficient for a Maxwellian distribution of electrons. This approximation overlaps the truncated power series approximation at small s and provides an alternative useful approximate expression for large s (Dulk *et al.* 1979). The Carlini approximation does not seem to lead to simple analytic results for power-law distributions. Wild and Hill's (1971) approximation to the Bessel functions is a useful and accurate generalization of the Carlini approximation.

The Razin effect causes suppression of gyro-synchrotron emission for $\omega \lesssim 2\omega_p$. In the non-relativistic limit this can be understood from the fact that 2^s-electric multipole emission implies an emissivity $\propto n^{2s+1}$ with $n = (1 - \omega_p^2/\omega^2)^{\frac{1}{2}}$. For example, for $s = 5$ and $\omega = 1.5\omega_p$ one has $n^{2s+1} \approx 4 \times 10^{-2}$, implying substantial suppression. Wild and Hill gave a more general analytic treatment of the suppression.

It has been widely accepted that moving type IV bursts are due to gyro-synchrotron emission from $\approx$ 100 keV electrons. One then expects absorption to limit the brightness temperature to $\lesssim 3 \times 10^8$K. The observation of bursts with $\gtrsim 10^{10}$K (Stewart *et al.* 1978) casts doubt on this interpretation. Although maser action of gyro-synchrotron emission is possible (Melrose and White 1978) it seems more likely that second harmonic plasma emission dominates in the bright early phase of such moving type IV bursts, with gyro-synchrotron emission dominating in the later, fainter and highly polarized phase.

The full review paper has been submitted to Space Science Reviews.

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DISCUSSION

Papadopoulos: I would like to mention that the arguments used by the speaker are valid only within the realm of weak turbulence theory and its equivalent quantum mechanical formulation. This is because linear eigenmodes obeying the dispersion relation $\omega_\kappa = \omega_e(1 + 3/2\ \kappa^2\ \lambda_D^2)$ become localized clumps when $\frac{\omega}{nT} > (\kappa\lambda_D^2)^2$ since $\omega_\kappa = \omega_e^\kappa(1 + 3/2\ \kappa^2/\lambda_D^2 - 1/2\ \frac{\omega}{nT})$. In this instance only self consistent strong turbulence theories can give the correct answer. Use of weak turbulence or quantum mechanical formulation requires a case by case justification.

Melrose: I don't agree as far as scattering is concerned. Thomson scattering is essentially independent of the wave number and hence of the details of the dispersion relation. Induced scattering is affected; the strong turbulence version of induced scattering $\ell \to t$ is analogous to OTS.

Stewart: Would you expect to observe fundamental radio emission from the Langmuir wave clumps observed recently in space by Gurnett et al?

Melrose: I have not worked out the numbers for induced scattering, although it would be easy to do so. I suspect that the absence of a fundamental is due to an as yet unidentified feature of the source region; e.g., the clumps of Langmuir waves could coincide with low-density regions from which the escape of the fundamental is precluded.

Elgarøy: I have a comment of a more general nature. It would be very useful for those who make observations if theories put more effort into predictions. It is often difficult to test different theories on observations because you have to figure out the consequences of various theories yourself. As a good example of theory with predictions I refer to your recent theory of type I bursts in which you predict second harmonic emission of strong bursts.

Kane: What background densities do you expect inside a moving type IV source?

Melrose: We do not know. The only way we could estimate the density in most moving type IV sources is through a low-frequency turnover due to the Razin effect; however, observed low frequency turnovers can be interpreted as due to self-absorption in most cases.

Vlahos: a. Can we apply this theory in the strongly turbulent regime? This is particularly important for the corona where the conditions for strong turbulence are easy to satisfy. b. Can you elaborate a little more on the polarization properties of the fundamental?

Melrose: As far as the first question is concerned, there are two aspects to that - one is that strong turbulence effects introduce additional ways in which you can convert energy in Langmuir waves into escaping transverse waves. These mechanisms, which I discussed will also work. The fact is that the strong turbulence does not affect these directly because they are a higher order in non-linearity, but what can happen during the process of collapse is that you then have a time changing distribution of energy in the Langmuir waves, and this allows you to get other emission from them, so there is an additional mechanism during the processes.

The second one: I illustrated the problem with the fundamental, normally the Langmuir wave frequency. I plotted out on the right hand side things concerned with ratios of the phase speed and the speed of light and you see I have very low values here for any reasonable value, I forgot what value I used, of gyrofrequency. You can convert the Langmuir waves into ordinary mode waves, but if you try to convert them into extraordinary mode waves you find that you can't do it, because you need to change the frequency by a large amount. So for all fundamental emission mechanisms at any reasonable value of the magnetic field in the corona you would predict that it is 100% polarized, and it is difficult to explain why it's less in type III and type II bursts. For the second harmonic the situation is different. There are a number of minor effects which you have to take into account to calculate what the polarization is, and it turns out that the polarization is the same as for the fundamental only if the Langmuir waves are nearly collimated along the field lines. Only in that case do you get ordinary mode polarization from the second harmonic, and the fact that we always observe ordinary mode polarization tells us something very specific about what the distribution of Langmuir waves is in the source. It is one-dimensional and along the field lines. If you could put numbers on it you'd say that for all energies it is within 20° along the field lines.