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A Theory for the $2f_p$ Radiation Upstream of the Earth's Bow Shock

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A theory for the radiation at the second harmonic of the plasma frequency f_p observed near the earth's bow shock is advanced in which the dominant plasma emission mechanisms are the processes $L + L \pm S \rightarrow t$, proceeding in two three-wave steps, $L \pm S \rightarrow L'$ and $L + L' \rightarrow t$, where L, S, and t denote Langmuir, ion sound. and electromagnetic waves, respectively. This theory receives strong observational support from the correct prediction of the existence and frequencies of a class of low-frequency ion-sound-like waves associated with Langmuir waves in the earth's foreshock. Three predictions of the theory which may be suitable for observational testing are stated. The observed brightness temperature of the $2f_p$ source is calculated to be of the order of 10^{11} K. It is shown that Fung et al.'s (1982) theory cannot explain either the $2f_p$ radiation due to an intrinsic brightness temperature limit of 3×10^9 K for their model or the observed levels of Langmuir waves in the foreshock region.

1. INTRODUCTION

Radio emission in a narrow bandwidth ($\lesssim 5$ kHz) near the earth's bow shock is interpreted as being at the second harmonic of the plasma frequency f_p ($\cong 30$ kHz) [Dunckel, 1974; *Gurnett*, 1975; Hoang et *al*., 19811. This $2f_p$ radiation is thought to be generated from Langmuir (L) waves which are observed in the foreshock region and correlate with enhanced fluxes of 1- to 2-keV electrons [Anderson et al., 1981]. It has usually been assumed that the $2f_p$ emission involves processes analogous to those which operate in type II and type III solar radio bursts, both of which have $2f_p$ components [e.g., Wild et *al*., 1963]. The theory for this emission is quite old [*Ginzburg* and Zheleznyakov, 1958] and has been updated several times [e.g., *Melrose*, 1980*a*]. However, the details of the various processes operating are still not clear. The $2f_p$ emission from the bow shock offers perhaps the best prospect for definitive tests of competing theoretical ideas. Most theories involve (1) a streaming instability which produces L waves concentrated around a particular wave vector $\mathbf{k}_L (= w_P v/v^2$, $\omega_p = 2\pi f_p$, where v is streaming velocity), (2) coalescence of two L waves (L and L', say) into a transverse (t) wave $L + L' \rightarrow t$, and (3) some process which causes the L waves to be scattered into the backward ($-$v) direction. Step (3) is required for the following reason. The conditions for coalescence are

$$\mathbf{k}_L + \mathbf{k}_L' = \mathrm{k}, \quad (1a)$$

$$\omega_L + \omega_L' = \omega_t \quad (1b)$$

$$\omega_L = (\omega_p{}^2 + 3k_L{}^2 V_e{}^2)^{1/2} \quad (2a)$$

$$\omega_t = (\omega_p{}^2 + k_t{}^2 c^2)^{1/2} \quad (2b)$$

where V_e is the thermal speed of electrons; for $v \ll$ c we have $k_L \gg k_t \cong \sqrt{3}\omega_p/c$, thus requiring $\mathbf{k}_L' \cong -\mathbf{k}_L$ in (la). The main difficulty with most theories is in the details of this intermediate step involving the scattering of L waves.

This difficulty is avoided in the theory proposed by Fung et *al.* [1982], hereinafter referred to as FPW. They pointed out that the observational evidence for streaming of the electrons is inconclusive and suggested that the electrons might be regarded as having an isotropic humped electron distribution with a gap below $\cong$1–2 keV, an isotropic gap distribution [Tidman and *Dupree*, 1965]. (There is now stronger evidence for streaming of electrons [e.g., *Fitzenreiter* et al., 19841, but this does not necessarily invalidate Fung et al.'s assumption that the important Langmuir waves are generated in a region where the electrons have become effectively isotropic.) Such a distribution leads to no instability for the L waves, but quite high levels of L waves can be achieved owing to absorption (Landau damping) being weak at phase speeds ω_p/k_L corresponding to the gap. FPW estimated the amplitude E_L which can result when emission and absorption are in balance and concluded that amplitudes as high as the highest observed ($\cong 10$ mV/m) are compatible with the theory. The aforementioned difficulty with $2f_p$ emission does not arise because the L waves are isotropic (for isotropic electrons) and can coalesce with each other directly without any scattering. FPW estimated the volume emissivity at $2f_p$ and concluded that it could account for the observed $2f_p$ emission.

Here we point out that FPW neglected a term in the absorption coefficient which becomes important for L waves with phase speeds in the gap. When this is taken into account, there are strict limits on both E_L and on the level of $2f_p$ emission. The estimates made by FPW violate these limits by large factors, as we show in section 2. We then briefly propose an alternative theory for the $2f_p$ radiation observed upstream of the earth's bow shock (section 3): the plasma radiation is produced by the wave processes $L + L \pm S \rightarrow t$ in the foreshock where nonthermal L and S waves are observed [Anderson et al., 19811. A more detailed description of this theory will be published elsewhere. In this theory, L waves are generated by a streaming instability and then "scattered" by ion sound waves (S) in one or both of the processes $L + S \rightarrow L'$ and $L \rightarrow L' + S$ (written together as $L \pm S \rightarrow E$), with the $2f_p$ radiation resulting from the coalescence $L + L' \rightarrow t$; the overall process is written $L + L \pm S \rightarrow t$. The process $L + L \pm S \rightarrow t$ has been discussed by *Melrose* [1982] in the context of type III bursts in the interplanetary medium (IPM). Melrose considered a delta function primary L spectrum in k, and showed

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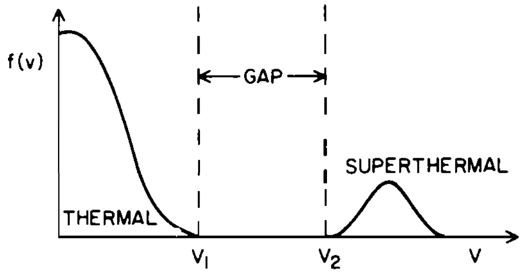

Fig. I. Langmuir waves with phase velocity v_ϕ in the range $v_1 \lesssim v_\phi \lesssim v_2$ are readily excited by the superthermal distribution yet are absorbed with difficulty by the thermal particles. The Langmuir wave temperature in the gap builds up to a limit of 3 × 10^9 K as discussed in section 2.

that kinematic restrictions require the electron temperature $T_e \geq T_{cr} = 4.8 \times 10^5$ K for the process to proceed; this condition is not satisfied in the IPM or the bow shock environment. However, we show here that T_{cr} may be decreased to less than the foreshock region T_e (or increased) by relaxing the delta function L spectrum condition. We briefly show that the available wave data are consistent with the process L + L − S → t operating. Indeed, one prediction specific to this theory for the $2f_p$ radiation is the existence of low-frequency S waves (≤2 kHz) in association with L waves, as observed by Anderson et al. [1981]. Finally, we state three predictions for the $2f_p$ radiation on the basis of our suggested mechanism.

2. LIMITS ON E_L AND T_b $(2f_p)$ FOR AN ISOTROPIC GAP DISTRIBUTION

An idealized isotropic gap distribution [Tidman and Dupree, 19651 is illustrated in Figure 1: the speed distribution $f(v)$ of electrons ($v = |\mathbf{v}|$) has a peak at $v > v_2$ and a gap for $v_1 < v <$ v,. The Langmuir wave absorption coefficient for an arbitrary electron distribution $f(\mathbf{v})$ may be reduced to a sum of three terms [Melrose, 19806, p. 144]: one term involves $f(\mathbf{v})$ evaluated at v $= \mathbf{k}_L\omega_p/k_L{}^2$ and is the only term usually considered (e.g., by Fung et al. [1982]) for an isotropic distribution (this term involves $f(v)$ evaluated at $v = \omega_p/k_L$ for an isotropic distribution), the second term involves a purely relativistic effect, and the third term depends explicitly on any anisotropy and is zero for an isotropic distribution. For an isotropic gap distribution, $f(v)$ is small in the gap, and this leads to a small absorption coefficient when the second term is neglected. Very weak absorption then leads to a very high level of L waves when emission and absorption are in balance. However, the relativistic contribution to the absorption coefficient at k_L depends on $f(v)$ at all $v > \omega_p/k_L$. This term dominates for waves with phase speeds ω_p/k_L in the gap when the number of particles in the gap is sufficiently small [Robinson, 1977; Melrose and Stenhouse, 1977; Melrose, 19806, p. 1421. When this term dominates (for electrons at nonrelativistic energies ≪1 MeV), a balance between emission and absorption leads to an effective temperature for the L waves:

$$T_L \cong \tfrac{1}{2}mc^2 \tag{3}$$

which corresponds to $T_L \cong 3 \times 10^9$ K. Thus for an isotropic gap distribution of electrons, T_L cannot exceed the limit $\frac{1}{2}mc^2$.

Let us estimate E_L by equating the energy density $\varepsilon_0 E_L{}^2$ in L waves to that in waves with $T_L = \frac{1}{2}mc^2$ over a range Ak in k_L:

$$\varepsilon_0 E_L{}^2 = \int \frac{d^3\mathbf{k}}{(2\pi)^3}\, T_L = \frac{2\pi mc^2}{\lambda_L{}^3}\frac{\Delta k}{k_L} \tag{4}$$

where $\lambda_L = 2\pi/k_L$ is the wavelength of the L waves. Using the values $\lambda_L = 300$ m (from FPW) and assuming $\Delta k/k_L$ of order unity, (4) implies $E_L \cong 0.05$ mV/m. Thus one cannot account for the observed amplitudes of ≅1 mV/m (and sometimes 10 mV/m) [Anderson et al., 19811 by this mechanism. The neglect of the relativistic term in the absorption coefficient for L waves led FPW to overestimate the maximum E_L by about 2 orders of magnitude.

Emission at $2f_p$ depends on the fourth power of E_L, and the overestimate of E_L also led FPW to overestimate the $2f_p$ emission by a very large factor. Rather than show this directly, we present an argument which leads to an absolute limit on the brightness temperature T_b for $2f_p$ emission from an isotropic gap distribution.

The argument is in three parts. First, the effective temperature T_t for t (or any other) waves is a constant along a ray in the absence of absorption or scattering, and hence the observed brightness temperature T_b cannot exceed the value T_t at the source, i.e., $T_b \leq T_t$. Second, the coalescence process L + L′ → t proceeds only until T_t reaches a limit at which the reverse process t → L + L′ is in balance with it; for isotropic L waves this balance occurs at $T_t = T_L$ (= $T_L{}'$ here) [Melrose, 1970, 19806, p. 2181. Thus we have $T_t \leq T_L$. Third, for an isotropic gap distribution we have $T_L \lesssim 3 \times 10^9$ K. This leads to an absolute limit of

$$T_b \lesssim 3 \times 10^9 \text{ K} \tag{5}$$

for $2f_p$ emission from an isotropic (nonrelativistic) gap distribution.

The value of T_b at a frequency f may be estimated from the measured flux density $F(f)$ (in W $\mathrm{m^{-2}\,Hz^{-1}}$) using

$$T_b = \frac{c^2}{2f^2k}\frac{F(f)}{\Delta\Omega}\text{ K} \tag{6}$$

where AR is the solid angle subtended by the source and k is Boltzmann's constant. We estimate T_b in Table 1 using data from Hoang et al. [1981]. The flux measurements given in Table 1, rather than those quoted in the work of Hoang et al. [1981] (hereinafter referred to as HFS), are the correct fluxes for the $2f_p$ radiation in the November 19–20, 1978, interval discussed by HFS. These fluxes may be calculated using the antenna temperature T_a (despun = log,, T_a; see Figure 3 of HFS) and dipole antenna solid angle $\Omega_a = 8\pi/3$, the flux conservation relation $T_a\Omega_a = T_b\Delta\Omega$, and (6). This error in the quoted fluxes of HFS was pointed out by one of the referees and has been confirmed by J. L. Steinberg (personal communication, 1984). The source solid angle AR is calculated for the 20° half-width (assumed circular) source size [HFS; Gurnett, 19751 and a 40° half-width source (in parentheses). The temperature in parentheses in the last column, calculated using a

TABLE 1. The $2f_p$ Brightness Temperature

Frequency, kHz	Flux, W $\mathrm{m^{-2}\,Hz^{-1}}$	ΔΩ, sr	T_b/K
80	1.6 × 10^{-19}	0.4	2 × 10^{11}
		(1.5)	(6 × 10^{10})
110	3.1 × 10^{-19}	0.4	2 × 10^{11}
		(1.5)	(6 × 10^{10})

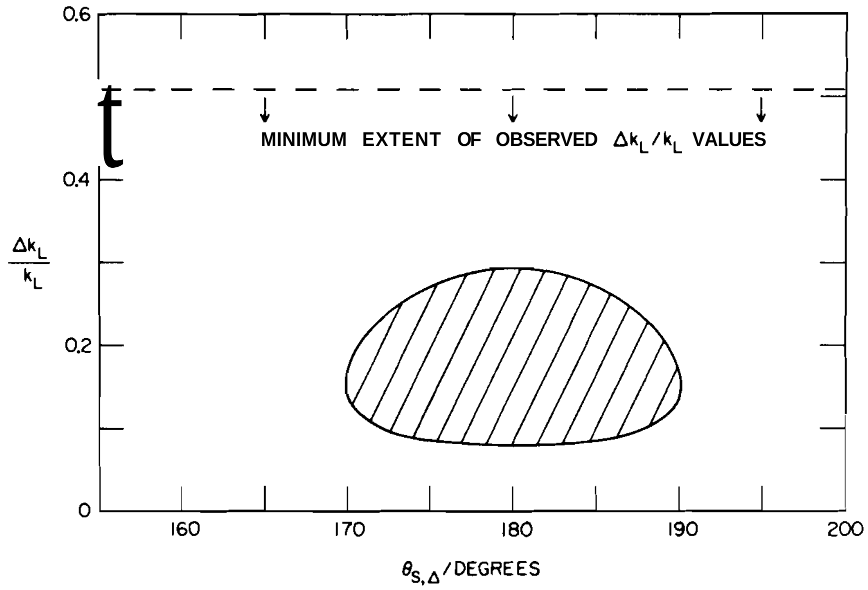

Fig. 2. The relation $B \pm \leq -2k_{SH}^2$ may be solved for the region of $\Delta k_L/k_L - \theta_{S,\Delta}$ space in which the u (or d) process may proceed near the bow shock (here $\theta_{S,\Delta}$ is the angle between $\Delta \mathbf{k}_L$ and $\mathbf{k}_S$). This figure shows the region (shaded) in which u process may proceed for the special case where the primary Langmuir spectrum is unidirectional (i.e., $\Delta \mathbf{k}_L = A\mathbf{k}_L$), and parameter values $k_L = 16\omega_p/c$, $k_0 = 3\omega_p/c$, and $k_{SH} = \sqrt{3}\omega_p/c$ (appropriate to the situation in Figure 14 of Anderson et al. [1981]). The dashed line shows the minimum extent of the inferred observational $\Delta k_L/k_L$ values. The conclusion is that the available Langmuir wave number data are consistent with the idea that the process $L + L \pm S \rightarrow t$ may proceed in the foreshock.

40" half-width source, is a lower limit to the brightness temperature of the $2f_p$ radiation. For conservative estimates of $\Delta\Omega$ we find $T_b \cong 6 \times 10^{10}$ K, and more common values of $\Delta\Omega$ give $T_b \cong 10^{11}$ K. These observed values are incompatible with the limit (5) confirming that a theory based on a gap distribution is unacceptable on quantitative grounds for the $2f_p$ emission from the bow shock.

3. $2f_p$ RADIATION FROM THE PROCESSES $L + L \pm S \rightarrow t$

The theory proposed here involves (1) a streaming instability to provide a primary L spectrum, (2) the processes

$$L \pm S \rightarrow L' \tag{7}$$

to provide a secondary L spectrum, and (3) the coalescence

$$L + L' \rightarrow t \tag{8}$$

providing the $2f_p$ radiation. There is no serious difficulty in accounting for the observed L wave amplitudes in terms of a streaming instability: the maximum possible energy density $\varepsilon_0 E_L^2$ is a sizable fraction ($\rho \sim 1/3$) of the energy density in streaming electrons, and using numbers for the electrons chosen by FPW, one finds $E_L \approx 30\, \rho^{1/2}$ mV/m, requiring only $\rho \sim 0.1$ to account for the largest E_L observed.

The plus or minus sign in (7) corresponds to the two separate pathways for the three-wave process: the u or up process $L + S \rightarrow L$ is a coalescence process, and the d or down process $L \rightarrow L' + S$ ($L - S \rightarrow L'$) is a decay [Melrose, 1982]. The most important qualitative differences between the u and d processes are as follows: First, S waves participating in the u and d processes are oppositely directed, i.e., $\mathbf{k}_{S,u}$ must be nearly antiparallel to $\mathbf{k}_L$, and $\mathbf{k}_{S,d}$ must be nearly parallel to $\mathbf{k}_L$ (since $\mathbf{k}_L' \simeq -\mathbf{k}_L$ and $\mathbf{k}_L \pm \mathbf{k}_S = \mathbf{k}_L'$). Second, the relevant S waves themselves are generated in the d process (i.e., in $L \rightarrow L' + S$), and the relevant S waves are absorbed in the u process. Third, depending on the relative levels of the three wave distributions interacting, it may be necessary to treat the d process using a parametric instability theory (review by Porkolab and Chang [1978]) rather than a weak turbulence theory [e.g., Tsytovich, 1972]: only L waves (the pump) are initially present in a parametric instability treatment, whereas two wave distributions must be present to drive the third wave distribution in a weak turbulence theory treatment. However, the kinematic constraints are identical in both treatments, and we may neglect any nonlinear (pump induced) frequency shifts in this preliminary exposition (Bardwell and Goldman [1976] found these shifts to be small).

The kinematic constraints (the temperature condition and a restriction on $\mathbf{k}_L$) on the processes $L + L \pm S \rightarrow t$ follow from the three-wave matching conditions (i.e., (1), and $\mathbf{k}_L \pm \mathbf{k}_S = \mathbf{k}_L'$ and $\omega_L \pm \omega_S = \omega_L'$ for the processes $L + L' \rightarrow t$ and $L \pm S \rightarrow L'$, respectively) and the requirement that the processes $L \pm S \rightarrow L'$ and $L + L' \rightarrow t$ be sequential. For the processes $L \pm S \rightarrow L'$, with $\omega_S = k_S V_S$ where V_S is the ion sound speed, one finds $k_L'^2 = k_L^2 \pm k_0 k_S$ and $\cos\theta = (k_0 \mp k_S)/2k_L$ where θ is the angle between $\mathbf{k}_L$ and $\mathbf{k}_S$ and where

$$k_0 = 2\omega_p V_S/3V_e^2 \tag{9}$$

is determined entirely by the plasma parameters. The relation $|\cos\theta| \leq 1$ then implies

$$k_S \leq 2k_L \pm k_0 \tag{10}$$

and hence that the maximum difference between k_L' and k_L is k_0. For strictly monochromatic and unidirectional L waves (i.e., a unique $\mathbf{k}_L$) the coalescence of an L and an L' wave requires $4k_L^2 \sin^2\theta + k_0^2 - k_{SH}^2 = 0$ with $k_{SH}^2 = 3\omega_p^2/c^2$ from (2b) for $\omega_{SH} = 2\omega_p$. A necessary condition is then $k_{SH}^2 \geq k_0^2$, which leads to $T_e \geq 4.8 \times 10^5$ K (for ion temperature $T_i \ll T_e$). Physically, this condition follows from the maximum difference in k_L' and k_L being k_0 and the requirement that $\mathbf{k}_L' + \mathbf{k}_L = \mathbf{k}_{SH}$; consequently it is clear that the temperature condition may be relaxed if a spread in $\mathbf{k}_L$ is taken into account. In particular, the temperature condition becomes

$$T_e \geq T_{cr} = 4.8 \times 10^5 \text{ K}/(1 - B\pm/k_{SH}^2) \qquad (11)$$

with $B\pm = (\Delta k_L)^2 + 4\mathbf{k}_L \cdot \Delta k_L + 2\mathbf{K}_S \cdot \Delta k_L(k_0 \pm 2k_L)$ where Δk_L is the difference in wave vector between the L waves in the $L \pm S \to L'$ $(\mathbf{k}_L)$ and $L + L' \to$ t $(\mathbf{k}_L + \Delta k_L)$ steps, and $\mathbf{K}_S = \mathbf{k}_S/k_S$. Thus T_{cr} may be reduced or increased depending upon $B\pm$. In particular, the processes $L + L \pm S \to L'$ may proceed if $B\pm \leq -k_{SH}^2$ $(4.8 \times 10^5 \text{ K}/T_e - 1)$, or $B\pm \leq -2k_{SH}^2$ for the bow shock environment ($T_e \approx 1.6 \times 10^5$ K), subiect to bounds on k_S such as (10).

Interpreting the relation $B\pm \leq -2k_{SH}^2$ as a condition on Δk_L, we may calculate bounds on $\Delta k_L/k_L$ for the process to proceed. Figure 2 shows the allowed range of $\Delta k_L/k_L$ for the u process in the case of a spectrum of unidirectional primary Langmuir waves. Notice that the allowed region is well inside the limits set by observations (Anderson et *al.*'s [1981] Langmuir wave frequency bandwidth $\Delta f/f$ implies a spread in Δk_L determined from (2*a*)).

Anderson et al. [1981] reported a new class of S waves associated with L waves in the foreshock region; here these waves are identified (as suggested by Anderson et al.) as products of the decay $L \to L' + S$. They estimated wavelengths $\lambda_S(= 2\pi/k_S) > 215$ m compared with λ_L in the range 400 m to 780 m: the above theory requires $\lambda_S > \lambda_L/2$ (for $k_L \gg k_0$), and this condition seems to be satisfied. Moreover, calculations of the maximum Doppler-shifted frequency for S wave decay products using (9) agree well with observations.

We now give three predictions based on the foregoing theoretical ideas which may be suitable for observational testing.

1. The $2f_p$ source is in the foreshock (i.e., where nonthermal L and S waves are observed): d process emission may be generated in the entire foreshock, whereas u radiation will come predominantly from the ion foreshock where both beam-excited L and S waves are observed.
2. If the d process is operating, t waves and low-frequency ($f \leq 2$ kHz) sunward propagating (in the solar wind frame) S waves will be generated in association with bursts of L waves.
3. If the u process is operating, t waves will be generated and low-frequency ($f \leq 2$ kHz) S waves propagating earthward will be absorbed in association with bursts of L waves.

4. Conclusion

We have calculated the $2f_p$ source brightness temperature to be of the order of 10^{11} K and have shown that this temperature is inconsistent with the theory of Fung *et* al. [1982], owing to the existence [Robinson, 1977; Melrose, 1980*b*] of a limiting temperature of 3×10^9 K for Langmuir waves excited by an isotropic gap distribution. Moreover, Fung et al.'s theory cannot explain the observed Langmuir wave levels in the foreshock.

We propose that the processes $L + L \pm S \to$ t, through two three-wave steps, are the relevant $2f_p$ emission mechanisms near the bow shock. This model is consistent with the available wave data; indeed, the class of low-frequency ($f \leq 2$ kHz) ion-sound-like waves associated with Langmuir waves in the earth's foreshock [Anderson et *al.*, 1981] is specifically predicted by this theory ($L + L - S \to$ t mechanism). We have suggested three predictions of this theory which may be suitable for observational testing.

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References

Anderson, R. R., G. K. Parks, T. E. Eastman, D. A. Gurnett, and L. A. Frank, Plasma waves associated with energetic particles streaming from theearth's bow shock, J. Geophys. Res., *86,4493, 1981.*

Bardwell, S., and M. V. Goldman, Three dimensional Langmuir wave instabilities, Astrophys. J.,*209,912, 1976.*

Dunckel, N., Low-frequency radio emissions from the earth and sun, Ph.D. thesis, *178* pp., Stanford Univ., Stanford, Calif., *1974.*

Fitzenreiter, R. J., A. J. Klimas, and J. D. Scudder, Detection of bump-on-tail reduced electron velocity distributions at the electron foreshock boundary, Geophys. Res. Lett., *11,496, 1984.*

Fung, S. F., K. Papadopoulos, and C. S. Wu, Generation of electron plasma waves in the upstream solar wind, J. Geophys. Res., *87, 8077, 1982.*

Ginzburg, *V.* L., and V. V. Zheleznyakov, On the possible mechanisms of sporadic solar radio emission (radiation in an isotropic plasma), *Sov.* Astron. Engl. Transl., 2, *653, 1958.*

Gurnett, D. A., The earth as a radio source: The nonthermal continuum, J. Geophys. *Res.*, *80*, 2751, *1975.*

Hoang, S., J. Fainberg, J. L. Steinberg, R. G. Stone, and R. H. Zwickl, The $2f_p$ circumterrestrial radio emission as seen from ISEE 3, J. Geophys. Res., *86,4531, 1981.*

Melrose, D. B., On the theory of type II and type III solar radio bursts, *1,* The impossibility of nonthermal emission due to combination scattering off thermal fluctuations, Aust. J. Phys., *23, 871, 1970.*

Melrose, D. B., The emission mechanisms for solar radio bursts, Space Sci. Rev., *26, 3,* 1980*a*.

Melrose, D. B., Plasma Astrophysics, vol. *2, 434* pp., Gordon and Breach, New York, *1980b.*

Melrose, D. B., Fundamental emission for type III bursts in the interplanetary medium: The role of ion-sound turbulence, Sol. Phys., *79, 173, 1982.*

Melrose. *D.* B., and J. E. Stenhouse, Emission and absorption of Langmuir waves by anisotropic unmagnetized particles, Aust. J. Phys., *30,481, 1977.*

Porkolab, M., and R. P. H. Chang, Nonlinear wave effects in laboratory plasmas: A comparision between theory and experiment, Rev. Mod. Phys., *50, 745. 1978.*

Robinson, R. D., A study of meter wavelength continuum radiation from the sun, Ph.D. thesis, *333* pp., Univ. of Colo. at Boulder, Boulder, *1977.*

Tidman, D. A., and T. H. Dupree, Enhanced bremsstrahlung from plasmas containing nonthermal electrons, Phys. Fluids, *8, 1860, 1965.*

Tsytovich, V. N., An Introduction to the Theory of Plasma Turbulence, *131* pp., Pergamon, New York, *1972.*

Wild, J. P., S. F. Smerd, and A. A. Weiss, Solar bursts, *Annu.* Rev. Astron. Astrophys., *5,291, 1963.*

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