

Predicted Preferential Backward Emission at the Second Harmonic of the Plasma Frequency in Solar Radio Bursts

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Theories which predict a preferential backward emission at the second harmonic in solar radio bursts of spectral types II and III are outdated. The simplest acceptable theory predicts only forward emission, i.e., no emission in the backward hemisphere. Alternative explanations should be sought for those observations presently interpreted in terms of a preferential backward emission.

Smerd *et al.* (1962) pointed out that, contrary to simple theory, it is common for the second harmonic emission in type II bursts to arrive from directions corresponding to much lower heights in the solar corona than the fundamental. A similar result applies for type III bursts where the fundamental and second harmonic at a given frequency arrive from roughly the same height. Smerd *et al.* suggested that their observations could be explained in terms of a preferential backward (i.e., towards the photosphere) emission at the second harmonic. This suggestion would imply that the apparent second harmonic source (seen after refraction through $\sim \pi$ radians) is at lower heights in the corona than the actual source. The discrepancy could also be explained if the apparent fundamental source were at a greater height than the actual source. This alternative has become the accepted interpretation in view of the outward shift of the fundamental source when scattering in the inhomogeneous corona is taken into account (Steinberg *et al.* 1971, Riddle 1972, Leblanc 1973).

Although the original arguments in its favour no longer apply, preferential backward emission continues to be invoked. For example, Labrum and Duncan (1973) suggested it as one possible interpretation for the observation that type V sources are at greater heights than harmonic type III sources at the same frequency. Also, Steinberg (1973) suggested that directivity in second harmonic type III radiation observed in the STEREO experiment could be interpreted in terms of preferential backward emission. At least part of the reason for the continued appeal to preferential backward emission is that the theories which predict it continue to be accepted.

This paper points out that the theories which predict preferential backward emission at the second harmonic are outdated. Furthermore, the simplest theory predicts a preferential forward emission.

EXISTING THEORIES

There are two theories which predict preferential backward emission at the second harmonic.

The earlier theory is that of Smerd *et al.* (1962). They showed that coalescence of two longitudinal electron plasma waves (Langmuir waves), one from a one-dimensional non-thermal distribution and the other from the thermal distribution of such waves, favours backward emission. The effect becomes more important as the phase speed of the Langmuir waves approaches the speed of light; i.e., the effect is a relativistic one. However, the maximum brightness temperature which can result from the assumed mechanism is twice the temperature of the ambient electrons (Melrose 1970a) so that the emission mechanism itself is unacceptable.

The other theory is that of Zheleznyakov and Zaitsev (1970). In their theory the initial Langmuir waves are scattered by thermal ions, thereby producing a secondary non-thermal distribution of the waves. The second harmonic results from coalescence to waves from the initial distribution with waves from the secondary distribution. Zheleznyakov and Zaitsev assumed that the secondary distribution reaches an equilibrium in which the generation is by induced scattering of the initial Langmuir waves and the loss is by collisional damping. They obtained a preferential backward emission for essentially the same reason as did Smerd *et al.* In both cases waves from a one-

dimensional distribution containing a single wave vector, \mathbf{k}_0 say, coalesce with waves from a distribution which is a strong function of neither angle nor wavenumber k for $k \approx k_0$. It can be shown that preferential backward emission would be predicted for a wide class of such secondary distributions. Thus, although the details of the polar diagram for the second harmonic depend on the details of the secondary distribution of Langmuir waves, the predicted preferential backward emission would appear to be a general feature and not dependent on the details of the secondary distribution assumed by Zheleznyakov and Zaitsev.

INDUCED SCATTERING

However, Zheleznyakov and Zaitsev (1970) neglected an effect which is of major importance in determining the radiation pattern at the second harmonic. This effect is that in any induced scattering process the mean frequency of the waves must decrease; see, e.g., Tsytovich (1967), following equation (3.26), or Melrose (1971) for a formal proof of this. Inclusion of this effect drastically alters the predicted radiation pattern at the second harmonic because, contrary to the assumption made by Zheleznyakov and Zaitsev, the secondary distribution is a strong function of k for $k \approx k_0$, being finite for $k < k_0$ and zero for $k \geq k_0$.

A physical explanation of the decrease in frequency during induced scattering is as follows. Induced scattering of waves with frequency ω into waves with frequency ω' is equivalent to absorption by the particles of a fluctuation with frequency $\omega - \omega'$. Energy passes from the waves to the particles if and only if the final frequency ω' is less than the initial frequency ω . For Langmuir waves the frequency is given by

$$\omega(k) \approx \omega_p + (3/2)k^2 V_e^2 / \omega_p, \quad (1)$$

where V_e is the thermal speed of electrons, and so $\omega(k) > \omega(k')$ implies $k > k'$. That is, the wavenumber of Langmuir waves must decrease during induced scattering. If the temperature of the ions in the corona is significantly less than that of the electrons, then the 'scattering' of Langmuir waves into Langmuir waves occurs through a decay process involving ion sound waves; see, e.g., Tsytovich (1972, chapter 6). This process also leads

to a decrease in the wavenumber of the Langmuir waves.

FORWARD EMISSION

The importance of this decrease in wavenumber can be emphasized through the following result: *Coalescence of Langmuir waves with wavenumber \mathbf{k}_0 with Langmuir waves generated by induced scattering of these initial waves produces second harmonic emission confined to the forward hemisphere about \mathbf{k}_0 .*

The proof of this result was given by Melrose (1970b, section V(b)) and is as follows. The scattered waves have wavenumbers $k_{sc} < k_0$. The wavenumber of the second harmonic (transverse) waves is determined by

$$k = \mathbf{k}_0 + \mathbf{k}_{sc}. \quad (2)$$

However then $k_0 > k_{sc}$ implies $k \cdot \mathbf{k}_0 > 0$, which is equivalent to the stated result.

DISCUSSION

Although the above result might suggest that preferential forward emission must always occur, this is not so. Coalescence between the initial waves and the scattered waves would not be possible if the decrease from k_0 to k_{sc} were sufficiently large, specifically for

$$k_0 - k_{sc} > \sqrt{3} \omega_p / c. \quad (3)$$

(For $k_0 \sim 3\omega_p/c$, which is appropriate for type III bursts, in the corona, the discussion by Tsytovich (1972, chapter 6) suggests that relation (3) would apply only if the 'scattering' were due to the decay process involving ion sound waves.) Any second harmonic emission could then arise only from coalescence of the scattered waves amongst themselves. This would favour backward emission (Melrose 1970b).

However, it should be emphasized that the simplest theory predicts forward emission unambiguously. If more detailed observational evidence were to imply backward emission, then this would have important theoretical consequences. Other explanations should be sought for those observations which are presently interpreted in terms of preferential backward emission.

REFERENCES

- Labrum, N. R., and Duncan, R. A., 1973, IAU Symp. No. 57, in press.
- Lebanc, Y., 1973, *Astrophys. Letters*, **14**, 41.
- Melrose, D. B., 1970a, *Austral. J. Phys.*, **23**, 871.
- Melrose, D. B., 1970b, *Austral. J. Phys.*, **23**, 885.
- Melrose, D. B., 1971, *Astrophys. Space Sci.*, **13**, 56.
- Riddle, A. C., 1972, *Proc. Astron. Soc. Austral.*, **2**, 98.
- Smerd, S. F., Wild, J. P., and Sheridan, K. V., 1962, *Austral. J. Phys.*, **15**, 180.
- Steinberg, J. L., 1973, unpublished report to IAU Symp. No. 57.
- Steinberg, J. L., Aubier-Giraud, M., Leblanc, Y., and Boischot, A., 1971, *Astron. Astrophys.*, **10**, 362.
- Tsyтович, V. N., 1967, *Soviet Phys.—Uspekhi*, **9**, 805.
- Tsyтович, V. N., 1972, *An Introduction to the Theory of Plasma Turbulence* (Pergamon Press, Oxford).
- Zheleznyakov, V. V., and Zaitsev, V. V., 1970, *Soviet Astron.—AJ*, **14**, 250.

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