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Beat-type Langmuir wave emissions associated with a type III solar radio burst: Evidence of parametric decay

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Abstract. Recent measurements from the plasma wave instrument on the Galileo spacecraft have shown that Langmuir waves observed in conjunction with a type III solar radio burst contain many beat-type waveforms, with beat frequencies ranging from about 150 to 650 Hz. Strong evidence exists that the beat pattern is produced by two closely spaced narrowband components. The most likely candidates for these two waves are a beam-generated Langmuir wave and an oppositely propagating Langmuir wave produced by parametric decay. In the parametric decay process, nonlinear interactions cause the beam-driven Langmuir wave to decay into a Langmuir wave and a low-frequency ion sound wave. Comparisons of the observed beat frequency are in good agreement with theoretical predictions for a three-wave parametric decay process. Weak low-frequency emissions are also sometimes observed at the predicted frequency of the ion sound wave.

Introduction

Highly structured Langmuir waves associated with a type III solar radio burst have been reported by Gurnett et al. [1993] using plasma wave measurements from the Galileo spacecraft. The Galileo plasma wave instrument includes a wideband receiver that allows the fine structure of the Langmuir waves to be examined at very high resolution, much higher than any previous study. The most striking characteristic of the Langmuir waves is the presence of beat-type waveforms that are produced by interference between two waves of comparable amplitude and slightly different frequency. An example of this type of waveform is shown in Figure 1. Gurnett et al. [1993] found that the electric field intensities of these waves were too low for strong turbulent processes to be important, and suggested that the beat-type waveforms were produced by parametric decay. Parametric decay is a nonlinear process in which the beam-driven Langmuir wave decays into a Langmuir wave and various low-frequency decay products [Papadopoulos et al., 1974; Fried et al., 1976; Bardwell and Goldman, 1976; Smith et al., 1979; Goldstein et al., 1979; Lin et al., 1986; Cairns, 1987; Robinson et al., 1993, 1994]. Recently, Cairns and Robinson [1992] published a theory for a three-wave parametric decay process that gives a specific prediction for the beat frequency in terms of known parameters such as the beam velocity, the solar wind velocity, the ion acoustic speed, and the electron thermal velocity. The purpose of this paper is to compare the Langmuir wave observations with the predictions of this three-wave parametric decay process.

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Description of the Event Detected by Galileo

The beat-type waveforms reported by Gurnett et al. [1993] were obtained by the Galileo plasma wave instrument on December 10, 1990, two days after the first Earth flyby. During this event, the spacecraft was located on the sunward side of the Earth at a geocentric radial distance of 189.5 R_E and a local time of 9.6 hours. The heliocentric radial distance was 0.98 AU. The beat-type Langmuir wave emissions were associated with a type III solar radio burst that was first observed in the Galileo high-frequency spectrum analyzer at approximately 0742 UT. A search of the solar flare reports listed by the *National Geophysical Data Center* [1991] showed that the type III burst is probably associated with a type 2F solar flare that occurred at 15°N latitude, 47°W longitude with an onset time of 0657 UT. The flare reached maximum intensity at 0730 UT. Since the flare was on the west side of the Sun, Galileo was in a favorable position to encounter energetic electrons from this event. The energetic electron instrument first detected electrons arriving from the direction of the Sun at approximately 0820 UT (see Figure 2 of Gurnett et al. [1993]). The Langmuir waves were subsequently detected at approximately 0835 UT and continued sporadically until approximately 1020 UT. During the 105-minute interval in which Langmuir waves were observed, approximately 83,000 electric field waveform blocks were captured, of which approximately 25,000 have clearly identifiable Langmuir wave oscillations. Each waveform block lasts 7.82 ms, and is separated from adjacent blocks by gaps of 58.82 ms (see Gurnett et al. [1992] for details on the instrument operation). Figure 1 is an example of one such waveform block. The oscillation frequency corresponds very closely to the local electron plasma frequency, $f_p = 9\sqrt{n}$ kHz, where n is the electron density in cm^{-3}. The envelope of the oscillations often has a beat-type modulation such as shown in Figure 1. Of the ~25,000 waveform blocks with Langmuir waves, a total of 894 have beat-type modulations of this type. The beat frequencies typically range from about 150 to 650 Hz. Some of the waveforms (see Figure 4d of Gurnett et al. [1993]) appear to have beat frequencies less than 150 Hz. However, the 7.82 ms length of the waveform block and the 58.85 ms gaps make it difficult to determine the extent to which beats occur in this frequency range. Similar beat-type waveforms have been observed upstream of the bow shock at Jupiter [Gurnett et al., 1981], at Venus [Hospodarsky et al., 1994], and at Earth [Hospodarsky et al., 1991].

Interpretation of the Beat-Type Waveforms

Beat-type waveforms of the type illustrated in Figure 1 are almost certainly caused by interference between two waves of similar amplitude but slightly different frequency.

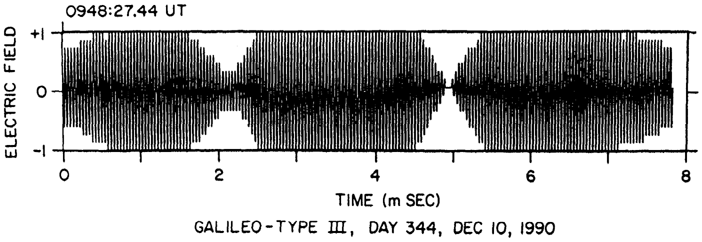

Figure 1. An example of a beat-type waveform. The high-frequency oscillation is at about 24 kHz, which is near the local electron plasma frequency.

Evidence that the waveforms consist of two nearly monochromatic components can be obtained by examining the spectrum of the individual waveforms. Figure 2 shows the spectrum of the waveform in Figure 1. As can be seen, the spectrum consists of two sharply defined emission lines separated by about 400 Hz, which is the approximate beat frequency observed in the waveform. The two emission lines usually have approximately the same amplitude. Only about 10% of the spectrums exhibit amplitude differences > 5 dB. An obvious candidate for explaining the two closely spaced emissions is a three-wave parametric decay process in which the beam-driven Langmuir wave decays into an oppositely propagating Langmuir wave and an ion sound wave. Since the electron beam is propagating away from the Sun, the beam-generated Langmuir wave is expected to be Doppler shifted upward in frequency by the outward radial motion of the solar wind, and the oppositely propagating Langmuir wave is expected to be shifted downward in frequency. Based on this expectation, the higher frequency emission marked L in Figure 2 is identified as the beam-driven Langmuir wave and the lower frequency emission marked L′ is identified as the backward propagating Langmuir wave. As can be seen in Figure 2, a weak low-frequency emission marked S sometimes occurs at the beat frequency (~400 Hz in this case). This emission is believed to be the ion sound wave. Although other processes, such as excitation by electron beams of different speeds, could produce two or more Langmuir waves of slightly different frequencies, only parametric decay can satisfactorily explain why the two waves usually have similar amplitudes.

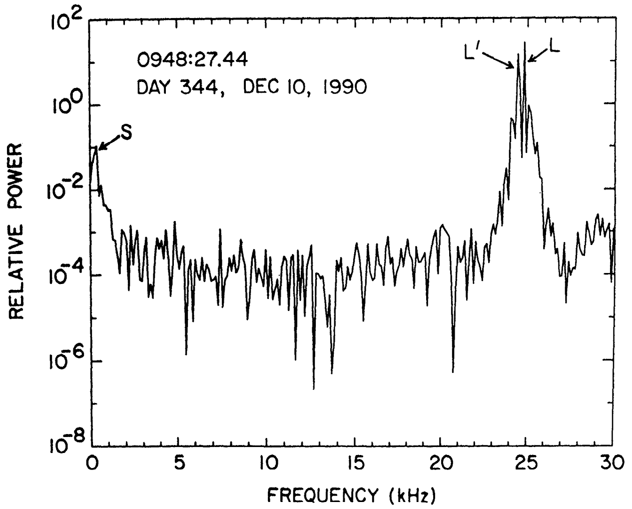

Figure 2. Spectrum of the waveform shown in Figure 1. The main signal near the plasma frequency (~24 kHz) consists of two peaks of comparable amplitude, separated by approximately 400 Hz. The peak marked L is believed to be the beam-generated Langmuir wave, and the peak marked L′ is believed to be the Langmuir wave produced by parametric decay. A weak low-frequency signal marked S can also be seen at 400 Hz. This low-frequency signal is believed to be the ion sound wave generated by the parametric decay process, L → L′ + S.

The three-wave parametric decay process $L \rightarrow L' + S$ must conserve momentum, $\mathbf{k}_L = \mathbf{k}_{L'} + \mathbf{k}_s$, and energy, $\omega_L = \omega_{L'} + \omega_s$. The dispersion relations for the Langmuir waves and the ion sound wave can be written

$$\omega_{L,L'} \cong \omega_p[1 + (3/2)\, k_{L,L'}^2 \lambda_D^2], \text{ and} \tag{1}$$

$$\omega_S \cong k_S V_S \ , \tag{2}$$

where λ_D is the Debye length, $V_s = [k_B(T_e+3T_i)/m_i]^{1/2}$ is the ion sound speed, T_e is the electron temperature, T_i is the ion temperature, k_B is Boltzmann constant, and m_i is the ion mass. Using these dispersion relations and the appropriate conservation laws, Cairns [1987] showed that the decay proceeds fastest when the Langmuir wave L′ and the ion sound wave S are both propagating in a direction opposite to the beam-generated Langmuir wave. It can also be shown that $k_s \approx 2k_L - k_0$ and that $k_{L,L'} \geq k_0/2$, where $k_0 = 2\omega_p V_s/3V_e^2$ is the maximum wavenumber difference between L and L′, and V_e is the electron thermal speed. Since the maximum growth rate of the beam-generated Langmuir wave occurs at $k_L = \omega_p/V_b$, where V_b is the beam velocity, it follows that parametric decay can only occur if $V_b \lesssim 3V_e^2/V_s$. This threshold beam velocity provides a check of the parametric decay theory, since beat-type waveforms should not be observed for beam speeds greater than $3V_e^2/V_s$. It can also be shown that the highest growth rate for the decay process occurs for beam speeds $\lesssim V_e^2/V_s$ [Cairns, 1987].

Using the above ideas, Cairns and Robinson [1992] derived a relationship between the frequency of the ion sound wave and the speed of the electron beam V_b. Assuming that the electron beam is traveling parallel to the magnetic field, and that $\mathbf{k}_L$ is parallel to V_b, they find that

$$V_b = \left[\frac{V_S}{3V_e^2} + \frac{\omega_S'}{2\omega_p|V_s + V_{sw}|\cos\theta||}\right]^{-1} \ , \tag{3}$$

where ω_s' is the frequency of the ion sound wave in the spacecraft frame of reference and θ is the angle between the magnetic field and the solar wind velocity V_{sw}. Since the frequency of the ion sound wave must be the same as the beat frequency, ω_s' also corresponds to the frequency difference between the two Langmuir waves.

In Equation 3 it is usually the case that the first term in the bracket is much smaller than the second term. Since V_s is also usually much less than V_{sw}, the beat frequency ω_s' is then given to a good approximation by

$$\omega_S' \approx \frac{2\omega_p V_{sw}|\cos\theta|}{V_b} \ . \tag{4}$$

This relationship shows that as the beam speed decreases, the beat frequency should increase. From simple time-of-flight arguments the speed of the electron beam is expected to vary inversely with the time from the onset of the event at the Sun. This inverse relationship has been verified by Lin et al. [1981, 1986] and was found to be of the form $V_b = A/(t-t_0)$, where A is the path length, t is the time of the measurement, and t_0 is the onset time of the electron beam.

Equation 4 then shows that the beat frequency should vary linearly with t. To test this prediction, the beat frequencies $f_s = \omega_s'/2\pi$ were measured for each of the 894 waveform blocks containing complete beat envelopes. These data are shown in Figure 3. Although there is considerable scatter, a clear trend can be seen toward a higher beat frequency with increasing time, as predicted by Equation 4. This trend can be more easily seen both from the least-square linear fit to the data points (solid line), and from the 20-minute averages of the beat frequencies (larger open circles). The error bars show the standard deviation.

To see if the predicted beam velocity agrees with the beam velocities allowed for parametric decay, Figure 4 shows the electron beam speeds (smaller solid circles) computed from Equation 3 using the measured beat frequencies and the corresponding value of θ determined from the Galileo magnetic field data (20-second averages). The solar wind velocity is assumed to be in the $-x_{GSE}$ direction for the determination of θ. Unfortunately, no plasma data is available from either Galileo or IMP-8 for the exact time of the type III burst, so the solar wind parameters used in Equation 3 ($V_e \sim 1.4 \times 10^6$ m s^{-1}, $V_s \sim 4.1 \times 10^4$ m s^{-1}, and $V_{sw} \sim 330$ km s^{-1}) were interpolated from the NSSDC IMP-8 plasma data using measurements before and after the event. As can be seen, the beam speeds are below the threshold, $V_b \leq 3V_e^2/V_s = 14.3 \times 10^7$ m s^{-1}, for parametric decay and are in good agreement with the beam speed $V_e^2/V_s = 4.8 \times 10^7$ m s^{-1} that produces the most rapid decay. The large open circles show 20-minute averages of the beat frequencies, and the error bars show the standard deviation. The 20-minute averages clearly show the expected trend toward slower beam speeds with increasing time predicted by Equation 4. The solid line in Figure 4 shows the beam speed calculated from $V_b = A/(t-t_o)$. The path length A = 1.7 AU used in this equation is the value obtained by Reiner et al. [1995] for this same event. The onset time of the flare was taken to be $t_o \sim$ 0730 UT [*National Geophysical Data Center*, 1991]. As can be seen, the beam speeds agree reasonably well with the trend in the speeds determined from Equation 3. Unfortunately, the lowest energy channel of the Galileo energetic electron experiment is 15 keV ($\sim 7.4 \times 10^7$ m s^{-1}), which is too high to allow direct comparisons between the predicted electron beam speeds and the actual speed.

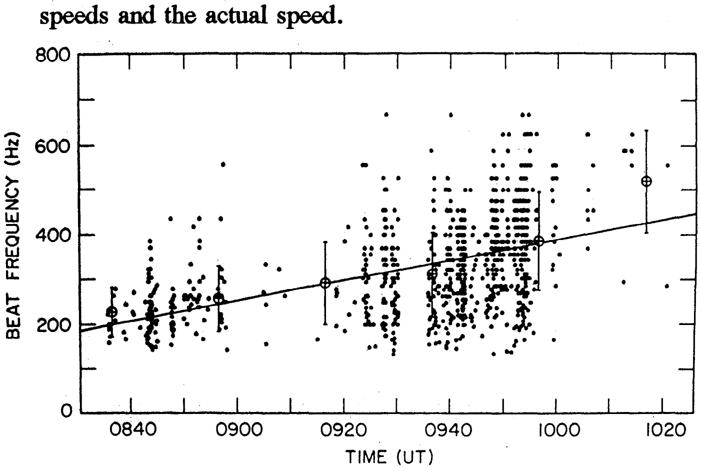

Figure 3. Measured beat frequencies (solid circles) as a function of time. Although there is considerable scatter, a clear trend exists towards higher frequencies with increasing time, as predicted by the theory. The larger open circles are 20-minute averages of the beat frequencies. The error bars show the standard deviation. The solid line is the least-square linear fit to the beat frequencies.

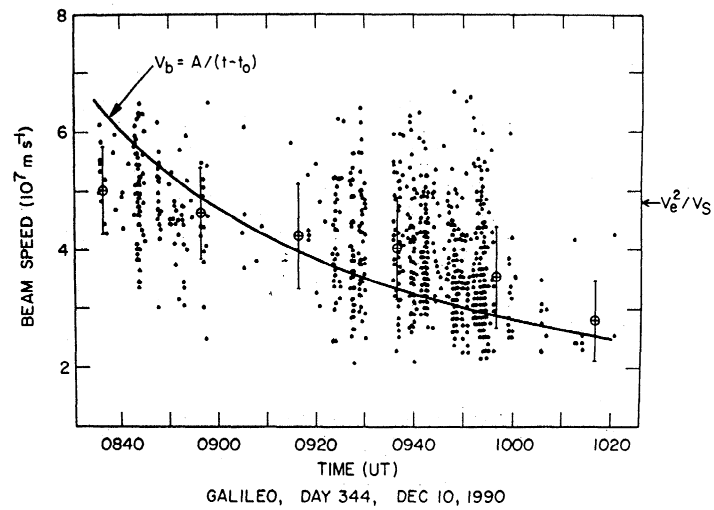

Figure 4. The electron beam speeds (solid circles) determined from Equation 3 using the beat frequencies shown in Figure 3 and the corresponding value of θ determined from the Galileo magnetic field data (20-second averages). Although there is considerable scatter, the predicted trend toward smaller beam speeds with increasing time is observed. The larger open circles are 20-minute averages of the beam speeds. The error bars show the standard deviation. The solid line is the beam speed calculated from $V_b = A/(t-t_o)$.

The scatter evident in Figures 3 and 4 could be produced by a variety of factors. Equation 4 shows that the beat frequency depends primarily on four factors: the beam speed, the solar wind speed, the plasma frequency, and cos θ. Fluctuations in the beam speed and cos θ are believed to be the most likely cause of the scatter, since the solar wind speed and the plasma frequency are nearly constant. Variations in the beam speed could be due to fluctuations in the region of positive slope ($\partial f/\partial v_\parallel > 0$) over which Langmuir waves can be excited. For a given spread in beam velocities, $\Delta V_b/V_b$, Langmuir waves can be produced for k_L values in the range $(1-\Delta V_b/V_b)\omega_p/V_b < k_L < \omega_p/V_b$. Substituting these limits into Equation 4 shows that the spread in the beat frequency is approximately $\Delta f_s/f_s \approx \Delta V_b/V_b$. Assuming beam spreads of the order of $\Delta V_b/V_b \sim 0.1-0.3$ [Lin et al., 1981, 1986], the beat frequency would be expected to vary by approximately 10% to 30%.

Fluctuations in the electron beam speed due to the interactions of the beam with ambient density fluctuations, as proposed in the stochastic growth model of Robinson [1992] and Robinson et al. [1992, 1993, 1994], could also account for some of the scatter. The stochastic growth model predicts that at a given location the beam is made up of multiple beamlets (characteristic time scale ~10 ms), each with its own speed and width in velocity space. Although the average of all the beamlets at a given point produces the beam characteristic reported by Lin et al. [1981, 1986], the individual beamlets could produce very rapid and large variations in the beat frequency. Unfortunately, little is known about the fine-scale velocity space structure of the electron beams.

Variations in cos θ could be produced by the interaction of the Langmuir waves with density fluctuations in the solar wind. It is easily shown that small density fluctuations in the solar wind can cause substantial refraction of Langmuir waves, thereby causing large deviations in the propagation direction related to the beam direction (assumed to be the magnetic field direction). Since little is known about small-scale density fluctuations, the magnitude of the resulting variation in θ is difficult to estimate. Using data from the Helios spacecraft Gurnett and Anderson [1977] found that the propagation direction of Langmuir waves was usually aligned within 20° of the magnetic field direction, which would produce approximately 10% variations in the beat frequency. Larger shifts in the Langmuir wave propagation direction are possible, but these variations would bring the wave out of resonance with the electron beam, resulting in rapid damping.

Conclusions

This paper has examined the Langmuir waves observed in association with a type III solar radio burst. The most striking feature of the fine structure is the occurrence of many beat-type waveforms with beat frequencies ranging from approximately 150 to 650 Hz. The beat-type wave forms are found to be consistent with the predictions of a three-wave parametric decay process. The evidence for parametric decay consists of the following. (1) Parametric decay explains why the waves responsible for the beat-type waveforms have similar amplitudes. (2) The evolution to higher beat frequency agrees with the temporal evolution predicted by the parametric decay theory. (3) The beam speeds determined from the theory agree well with the beam speeds estimated from simple time-of-flight estimates. (4) The beam speeds are below the threshold velocity required for parametric decay and are in the proper range for the most rapid decay. (5) Low-frequency waves predicted by the parametric decay theory are observed in conjunction with some of the beat-type waveforms. These results strongly indicate that three-wave parametric decay is the mechanism responsible for the beat-type Langmuir wave emissions observed in association with type III radio emissions.

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References

Bardwell, S., and M. V. Goldman, Three-dimensional Langmuir wave instabilities in type III solar radio bursts, *Astrophys. J.*, *209*, 912-926, 1976.

Cairns, I. H., Second harmonic plasma emission involving ion sound waves, *J. Plasma Phys.*, *38*, 179-198, 1987.

Cairns, I. H. and P. A. Robinson, Theory for low-frequency modulated Langmuir wave packets, *Geophys. Res. Lett.*, *19*, 2187-2190, 1992.

Fried, B. D., T. Ikemura, K. Nishikawa, and G. Schmidt, Parametric instabilities with finite wavelength pump, *Phys. Fluids*, *19*, 1975-1981, 1976.

Goldstein, M. L., R. A. Smith, and K. Papadopoulos, Nonlinear stability of solar type III radio bursts, II, Application to observations near 1 AU, *Astrophys. J.*, *234*, 683-695, 1979.

Gurnett, D. A., and R. R. Anderson, Plasma wave electric fields in the solar wind: Initial results from Helios 1, *J. Geophys. Res.*, *82*, 632-650, 1977.

Gurnett, D. A., J. E. Maggs, D. L. Gallagher, W. S. Kurth, and F. L. Scarf, Parametric interaction and spatial collapse of beam-driven Langmuir waves in the solar wind, *J. Geophys. Res.*, *86*, 8833-8841, 1981.

Gurnett, D. A., W. S. Kurth, R. R. Shaw, A. Roux, R. Gendrin, C. F. Kennel, F. L. Scarf, and S. D. Shawhan, The Galileo plasma wave investigation, *Space Sci. Rev.*, *60*, 341-355, 1992.

Gurnett, D. A., G. B. Hospodarsky, W. S. Kurth, D. J. Williams, and S. J. Bolton, The fine structure of Langmuir waves produced by a solar electron event, *J. Geophys. Res.*, *98*, 5631-5637, 1993.

Hospodarsky, G. B., D. A. Gurnett, W. S. Kurth, and S. J. Bolton, High resolution measurements of Langmuir waves upstream of the Earth's bow shock, *EOS*, *73*, No. 44, 390, 1991.

Hospodarsky, G. B., D. A. Gurnett, W. S. Kurth, M. G. Kivelson, R. J. Strangeway, and S. J. Bolton, The fine structure of Langmuir waves observed upstream of the bow shock at Venus, *J. Geophys. Res.*, *99*, 13,63-13,71, 1994.

Lin, R. P., D. W. Potter, D. A. Gurnett, and F. L. Scarf, Energetic electrons and plasma waves associated with a solar type III radio burst, *Astrophys. J.*, *251*, 364-373, 1981.

Lin, R. P., W. K. Levedal, W. Lotko, D. A. Gurnett, and F. L. Scarf, Evidence for nonlinear wave wave interactions in solar type III radio bursts, *Astrophys. J.*, *308*, 954-965, 1986.

National Geophysical Data Center, Solar-geophysical data prompt reports, *Rep. 557-Part 1*, Boulder, Colo., Jan. 1991.

Papadopoulos, K., M. L. Goldstein, and R. A. Smith, Stabilization of electron streams in type III solar radio bursts, *Astrophys. J.*, *190*, 175-185, 1974.

Reiner, M. J., K. A. Anderson, E. Roelof, T. Armstrong, G. B. Hospodarsky, J. Fainberg, R. G. Stone, L. Lanzerotti, D. A. Gurnett, J. L. Phillips, and R. Forsyth, Ulysses/Galileo observations of type III radio bursts and associated in-situ electrons and Langmuir waves, *Space Sci. Rev.*, *72*, 261-266, 1995.

Robinson, P. A., Clumpy Langmuir waves in Type III radio sources, *Sol. Phys.*, *139*, 147-163, 1992.

Robinson, P. A., I. H. Cairns, and D. A. Gurnett, Connection between ambient density fluctuations and clumpy Langmuir waves in the Type III radio sources, *Astrophys. J.*, *387*, L101-L104, 1992.

Robinson, P. A., A. J. Willies, and I. H. Cairns, Dynamics of Langmuir and ion-sound waves in type III solar radio sources, *Astrophys. J.*, *408*, 720-734, 1993.

Robinson, P. A., I. H. Cairns, and A. J. Willies, Dynamics and efficiency of type III solar radio emission, *Astrophys. J.*, *422*, 870-882, 1994.

Smith, R. A., M. L. Goldstein, and K. Papadopoulos, Nonlinear stability of solar type III radio bursts, I, Theory, *Astrophys. J.*, *234*, 348-362, 1979.

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