

FORESHOCK THEORIES FOR THE OUTER HELIOSPHERIC RADIO EMISSIONS

Iver H. Cairns, William S. Kurth and Donald A. Gurnett

*Department of Physics and Astronomy, University of Iowa, Iowa City,
IA 52242, U.S.A.*

ABSTRACT

Progress made on recent theories for the 2 - 3 kHz radio emissions in the outer heliosphere is summarized. The theories involve radiation produced near f_p and/or $2f_p$, by nonlinear processes involving Langmuir waves, when solar wind density enhancements enter the foreshock region sunwards of the termination shock. Two classes of events have been detected by Voyager: transient drifting emissions and a relatively continuous 2 kHz component. Foreshock theories for both types of emissions are presented and discussed, with emphasis placed on the role of density inhomogeneities. Our conclusions are as follows. (1) The levels and characteristics of the transient events are consistent with the expectations of the foreshock theory. The source may be located outside 50 AU. (2) The higher foreshock wave levels and enhanced density regions associated with stream-stream interactions in the outer heliosphere provide rationales for McNutt's trigger hypothesis. (3) A foreshock theory cannot easily account for the 2 kHz component's almost constant frequency range. Explanations in terms of steady density enhancements or an alternative source region and/or emission mechanism should be sought.

INTRODUCTION

In 1984 Kurth et al. /1/ presented Voyager 1 and 2 data showing new radio emissions from 2 - 3.5 kHz at heliocentric distances greater than 11 AU. The radiation is at most 10 dB above the Voyager detection threshold /1,2/ but is highly nonthermal /3,4/. After considering emissions from Jupiter, the other outer planets and pulsars Kurth et al. suggested that the radiation is produced at multiples of f_p (by nonlinear processes involving Langmuir waves. e.g. /5/) in the heliosheath region downstream from the termination shock. Fahr et al. /6/ later suggested the heliopause as a source for the radiation. Interest in the radiation is therefore primarily driven by its possible use in remotely locating these heliospheric boundaries.

The radiation is now interpreted in terms of two distinct classes of emission that are only weakly correlated /2,7/ (Figure 1): "transient events" and the "2 kHz component". The 2 kHz component apparently shows little variability in amplitude and frequency. The transient events occur sporadically, drift continuously upward in frequency at ~ 1 kHz/yr, and have starting frequencies that vary significantly in the range 2.0 - 3.5 kHz. There is a clear absence of signals in the 1.4 - 1.8 kHz range below the 2 kHz component and above about 3.5 kHz (where the transient events disappear).

Cairns et al. /2/ propose that the transient emissions are generated near f_p and/or $2f_p$ when solar wind density enhancements enter the foreshock region sunward of the termination shock (Figure 2). This foreshock region /3/, containing high levels of Langmuir waves driven by electrons streaming from the shock, is expected theoretically and empirically by analogy with the standard model for planetary foreshocks /8,9/. Note that the sunward (upstream) side of the termination shock will be the high speed, low density, low magnetic field side, so that electron acceleration and beam production are expected on the upstream side of the shock and not in the heliosheath region downstream from the termination shock /2,3,4/. Similarly, electron acceleration and beam production, and nonthermal Langmuir waves, are not familiar phenomena at planetary magnetopauses. Thus, theoretical models in which the 2-3 kHz radiation is produced at multiples of f_p by nonlinear interactions involving Langmuir waves in a source region downstream from the shock /1,10/ or near the heliopause /6/ are not justifiable based on present knowledge /4/. Such radiation can only plausibly be produced in an upstream foreshock source /2,4/, unless appeals are made to transient shocks in the downstream region /11/. Below

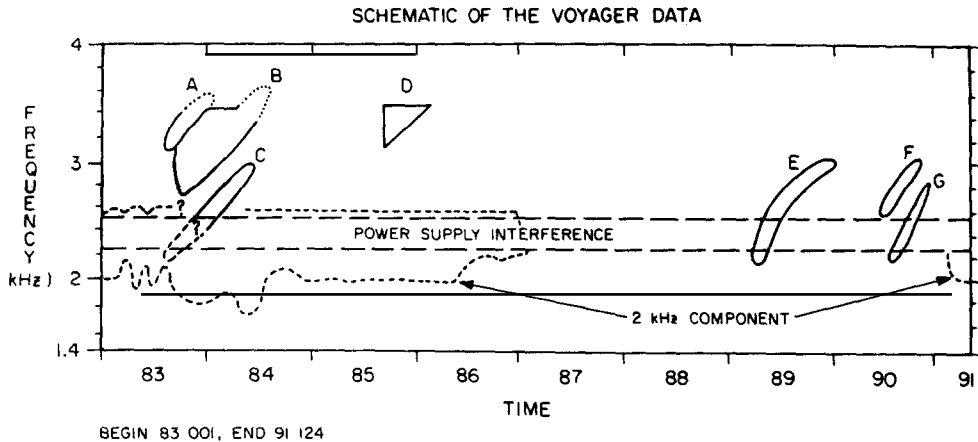


Fig. 1. Schematic illustration of the Voyager radio wave data /2/: transient events A - G, the 2 kHz component, and the interference band near 2.4 kHz due to the spacecraft power supply.

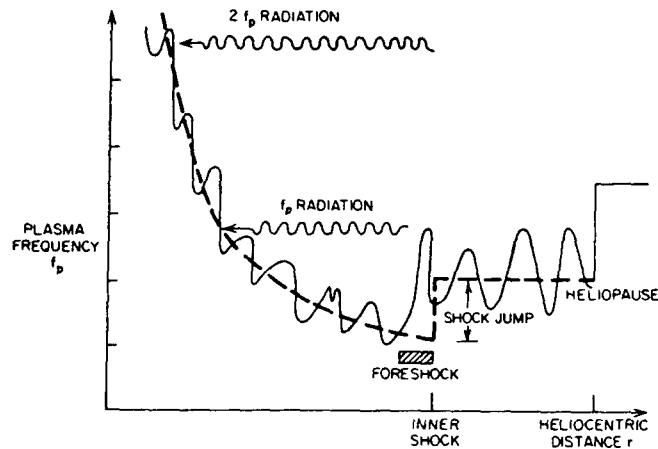


Fig. 2. The foreshock model for the transient emissions /2/: the radiation is generated near f_p and/or $2f_p$ when solar wind density inhomogeneities enter the foreshock sunward of the termination shock. The density enhancements permit generation of radiation at the observed frequencies that can propagate into the inner heliosphere from a source outside 50 AU.

we summarize the strengths of Cairns *et al.*'s /2/ foreshock theory for the transient emissions, showing that it can account qualitatively and semi-quantitatively for all the emission characteristics, before discussing the event triggers /10,12/ in new detail.

Cairns *et al.* /2/ also proposed a foreshock theory for the 2 kHz component and described this theory's strengths and weaknesses. Below we discuss this theory, including requirements on the plasma density in the source region if the theory is to be viable, as well as alternative theories. Kaiser *et al.*'s /13/ recent refurbishing of one of Kurth *et al.*'s /1/ discarded models, that continuum radiation leaking from the Jovian tail forms the 2-3 kHz radiation, is not discussed below. However, as Kaiser *et al.* point out, the observational arguments for and against this possibility need to be reconsidered. Theoretical problems are apparent in obtaining the observed levels and frequency spectra of radiation from leakage. However, we do mention Jovian continuum radiation below as a possible explanation for the 2 kHz component.

FORESHOCK THEORY FOR THE TRANSIENT EMISSIONS

Cairns *et al.* /2/ have shown semi-quantitatively that the radial thickness of the foreshock ($\gtrsim 0.1 - 1$ AU) and the levels of Langmuir waves expected, both theoretically and empirically (by extrapolating the levels in planetary foreshocks to the outer heliosphere /3,4/), should be adequate to explain the observed levels of radiation. The theory relies heavily on regions of enhanced solar wind density moving through the foreshock to account for the detailed properties of the radiation /2/. In particular, density enhancements by factors $\alpha \sim 4 - 10$ (the observed range) can explain generation of radiation with the observed frequencies from

sources outside 50 AU that can propagate in to heliocentric distances $R \sim 10$ AU (where first observed). The widely varying starting frequencies and sporadic nature of the events are consistent with the expected rarity and variability of transient density enhancements. Reflection of the radiation by these density enhancements and the heliospheric cavity wall can also Fermi-upshift the radiation /14/, thereby producing the observed frequency drifts. The sporadic nature of transient events implies that unusual source conditions are required to generate observable radiation: the absence of events starting below about 1.8 kHz implies that these unusual source conditions are associated with *large* density enhancements being present.

The possible triggers for the observed events include a fast solar wind stream /12/ and groups of ram pressure enhancements that collide in the outer heliosphere /10/. Working from a theoretical perspective, Cairns et al. /2/ considered three mechanisms for unusual source conditions: stream-stream interactions, forward and reverse shock pairs resulting from pressure pulses interacting with the termination shock, and instabilities of a cosmic ray-modified shock. McNutt's /12/ and Grzedzielski and Lazarus' /10/ suggestions both fall into the first category. Interactions between fast and slow solar wind streams lead to associated regions of enhanced solar wind density, forward and reverse shock pairs, and mildly energized electrons. Acceleration of these electrons at the termination shock should lead to enhanced electron fluxes in the foreshock, and so enhanced Langmuir wave levels in a larger region of the foreshock. Cairns et al.'s first mechanism can therefore use the triggers identified observationally to produce both density enhancements and plasma conditions likely to produce higher levels of $f_p/2f_p$ radiation in the foreshock.

Grzedzielski and Lazarus /10/ (hereafter GL92) assumed that the radiation is produced near $2f_p$ in the downstream region and used a ballistic propagation, inelastic collision model to estimate the plasma density in the source region. They obtained source densities consistent with the production of $2f_p$ radiation near 2-3 kHz. However, the simple downstream source model is not viable due to the theoretical absence of Langmuir waves /4/. (Langmuir waves associated with transient shocks in the downstream region /11/, although unimportant at Earth, might be attractive once the transient is several AU into the heliosheath and should be considered in detail.) In contrast, we now show that GL92's trigger model can be synthesized with the foreshock theory with little trouble. In particular, GL92 ignore the forward and reverse shocks and other density enhancements familiar from study of corotating interaction regions. It is clear, however, that the density jumps across such strong forward and/or reverse shocks will counteract the factor of 2 decrease in radiation frequency produced by switching the source to the foreshock from the downstream region. The resulting estimates for the shock location are then identical to those for GL92's model. Proper MHD simulations should be performed with GL92's data to better describe the density enhancements predicted in the outer heliosphere, and to compare the foreshock theory with the radio wave data. In summary, GL92's trigger work can be qualitatively incorporated into the foreshock theory with little effort and without changing the estimated shock locations.

FORESHOCK THEORY FOR THE 2 KHZ COMPONENT?

A foreshock theory for the 2 kHz component, essentially identical to that for the transient emissions, can be written down /2/. The theory can account for generation of the observed radiation levels and, if density variations with enhancement factors of 4 – 10 are available, can explain the observed emission frequencies in terms of an outer heliospheric source ($R \geq 50$ AU) /2/. However, the relatively continuous presence and constant frequency range of the 2 kHz component contrast with the transient emissions. A foreshock theory involving transient density enhancements then encounters serious theoretical difficulties (cf. last section). Alternative density enhancements are apparently needed. The above problems could be resolved if a slowly varying (~ 1 year timescale), large spatial scale (≥ 0.1 AU in the radial direction) region with $f_p \sim 1 - 2$ kHz exists in part of the foreshock. With enough faith in the correctness of the foreshock theory, these requirements could be viewed as predictions of the theory. However, no theoretical or empirical arguments for such a region have yet been proposed. Most probably, therefore, these requirements should be viewed as serious arguments against a foreshock theory for the 2 kHz component. Research into different source regions and/or emission mechanisms for this component should therefore be pursued.

The slow time variations of the 2 kHz component suggest that alternative theories should involve a source region that has slowly varying plasma parameters and that is relatively insulated (but perhaps not entirely) from solar wind transients and other variations. Three possibilities include: continuum radiation generated near the heliopause, synchrotron emission from the vicinity of the termination shock, and continuum radiation leaking from Jupiter's magnetotail. Continuum radiation is generated near the upper hybrid frequency, so that the radiation provides a measure of f_p and/or the electron gyrofrequency f_g . Radiation generated near the heliopause should propagate easily into the heliospheric cavity (cf. Figure 2) and depend only on large-scale solar wind variations due to the large distance expected between the heliopause and the termination shock. The origin of upper hybrid waves near the heliopause needs study, as do the theoretical constraints on the

emission mechanism and source plasma. Synchrotron emission, generated at high harmonics of f_p , depends on the spectrum of relativistic electrons so that the 2 kHz component might furnish a remote probe of electron acceleration at the termination shock. Calculations using the spectra of Jovian electrons re-accelerated at the termination shock are required to see if this model is viable. Lastly, the Jovian continuum radiation hypothesis /1, 13/ should be reconsidered since high levels of the radiation are known to exist at low frequencies and the radiation's spectrum varies relatively little. The leakage and subsequent damping of radiation from Jupiter's tail must be investigated in detail.

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