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Outer Heliospheric Radio Emissions
2. Foreshock Source Models

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Low-frequency radio emissions in the range 2−3 kHz have been observed by the Voyager spacecraft during the intervals 1983−1987 and 1989 to the present while at heliocentric distances greater than 11 AU. New analyses of the wave data are presented, and the characteristics of the radiation are reviewed and discussed. Two classes of events are distinguished: transient events with varying starting frequencies that drift upward in frequency and a relatively continuous component that remains near 2-kHz. Evidence for multiple transient sources and for extension of the 2-kHz component above the 2.4-kHz interference signal is presented. The transient emissions are interpreted in terms of radiation generated at multiples of f_p when solar wind density enhancements enter one or more regions of a foreshock sunward of the inner heliospheric shock. Theoretically, and based on extrapolated Langmuir levels in planetary foreshocks, the foreshock should contain sufficient levels of Langmuir waves to produce the radio emissions in path lengths small compared with 1 AU and the estimated radial size of the foreshock. Enhancements of the solar wind density by factors greater than 4 are required for the radiation to be generated at the observed frequencies and to propagate into the inner heliosphere, as observed, from a source outside about 50 AU. Solar wind density enhancements by factors of 4−10 are observed. The radiation can therefore be generated in sources beyond the present locations of the Voyager spacecraft. Propagation effects, the number of radiation sources, and the time variability, frequency drift, and varying starting frequencies of the transient events are discussed in terms of foreshock sources. The available data appear to be qualitatively and semiquantitatively consistent with this foreshock theory for transient events. A similar foreshock theory involving transient density enhancements can explain the levels, characteristic frequency, and inward propagation of the 2-kHz component in terms of a source outside 50 AU. However, the theory encounters significant difficulties in explaining the relatively constant frequency and presence of the radiation, as well as its different properties relative to the transient emissions. Remedies for these problems are briefly explored. However, the 2-kHz component quite likely has a different generation mechanism and/or a different source region than the transient emissions.

1. INTRODUCTION

The plasma wave instruments on the Voyager 1 and 2 spacecraft [*Scarf and Gurnett*, 1977] have detected low-frequency radio emissions at 2−3 kHz that are believed to originate in the outer heliosphere [*Kurth et al.*, 1984, 1986, 1987; *Kurth*, 1990; *Kurth and Gurnett*, 1991] (see, however, *Meyer-Vernet* [1989]). The radio emissions have been observed from 1983 to 1987 and again from 1989 to the present at heliocentric radial distances greater than 11 AU. The standard model for the interaction of the outflowing solar wind with the local interstellar plasma involves an inner heliospheric shock (or termination shock), a heliopause, and possibly an outer heliospheric shock [e.g., *Baranov et al.*, 1979; *Fahr et al.*, 1986; *Baranov*, 1990]. Previously suggested models for the emissions include radiation generated at multiples of f_p near either the inner heliospheric shock [*Kurth et al.*, 1984, 1987] or the heliopause [*Fahr et al.*, 1986]. These interpretations and deep space observations of the Lyman alpha glow [*Gangopadhyay et al.*, 1989; *Judge et al.*, 1990] have excited considerable interest since they suggest that the inner heliospheric shock is located near 50 AU, considerably closer to the Sun than previously expected.

Despite their possible importance, little work was done on theories for the radio emissions until recently [*Macek et al.*, 1991a,b; *Cairns and Gurnett*, this issue]. *Cairns and Gurnett* [this issue] place detailed constraints on the emission processes and source characteristics required for generation of the observed levels of radio emissions. The emission processes considered produce radiation at multiples of the plasma frequency f_p by nonlinear, weak turbulence wave-wave processes involving Langmuir waves. Using the derived constraints, Cairns and Gurnett show that the two previously suggested source locations for the radiation, downstream of the inner heliospheric shock [*Kurth et al.*, 1984] and the heliopause [*Fahr et al.*, 1986], face severe theoretical problems. These problems center on the expected absence, based on both theoretical arguments and observational data at the outer planets, of sufficiently intense Langmuir waves in these regions to generate the observed radiation levels. In contrast, Cairns and Gurnett's calculations indicate that a new source region [*Macek et al.*, 1991a,b; *Cairns and Gurnett*, this issue], in the foreshock region expected sunward of the inner heliospheric shock, should naturally contain sufficient levels of Langmuir waves to produce f_p and $2f_p$ radiation with the observed brightness temperatures in distances small compared with 1 AU. In contrast, much higher Langmuir wave levels $T_L \sim 10^{22}$ K are required to produce similar levels of $3f_p$ radiation in these distances.

In this paper we consider in detail the generation of the radiation at f_p and/or $2f_p$ in one or more regions of the foreshock. Matters discussed include propagation of the radiation into the inner heliosphere, the number and location of foreshock sources, and the time variability and frequency characteristics of the radiation. Arguments against $3f_p$ radiation processes are also given. In

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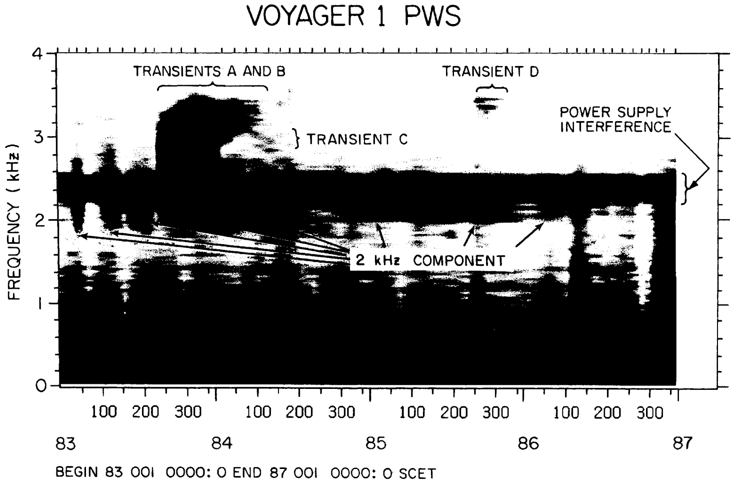

Fig. 1. Wideband spectrogram of Voyager 1 data from 1983 to 1987, constructed using the procedure given in the text. Only relative amplitudes are plotted. The effects of the notch filter near 2.4 kHz have been removed. The existence of multiple drifting transient emissions and a relatively constant 2-kHz component is clear. Comparison with previous work shows the necessity of removing the notch filter. A new weak transient C is identified while transients A and B cannot be separated in this figure. There is no evidence for a low-frequency null between the 2-kHz component and interference signal near 2.4 kHz. There is evidence for the 2-kHz component extending above the notch filter at low levels. Transients A, B, and D show evidence for a high-frequency cutoff near 3.5 kHz. Frequency blocking effects are responsible for the modulations in the 2-kHz component in 1983 [McNutt, 1991].

section 2 we present new displays of the observational data and summarize the characteristics of the radiation. The emissions are separated into two classes, sporadic "transient" events which drift upward in frequency from widely varying starting frequencies and a relatively continuous "2-kHz component" that remains in a relatively constant frequency range. New evidence is presented that while individual drifting features in the 2-kHz component cannot be presently identified, the radiation's characteristics are consistent with the continual generation of radiation that drifts to higher frequencies as it is damped. In section 3 we justify the presence of intense Langmuir waves in the suggested foreshock region and show that the foreshock is sufficiently large for production of the observed levels of radiation with plausible Langmuir wave levels. Our conclusion is that a foreshock source can plausibly produce f_p and $2f_p$ radiation with the observed brightness temperatures. Propagation of the radiation into the inner heliosphere is considered in section 4: regions of enhanced solar wind density moving through the foreshock are vital in producing the radiation at sufficiently high frequencies for propagation into the inner heliosphere. These density enhancements may also play a role in the frequency upshifting of the transient bursts [cf. *Czechowski and Grzedzielski*, 1990]. Arguments are given that frequency blocking by high-density regions is responsible for some quantitative differences in the radiation detected by the two spacecraft, but not for the major time variations observed. Major time variations of the radiation are considered in terms of unusual source conditions in section 5. Interpretations are provided in terms of radiation mechanisms and of the foreshock plasma being modified by transient solar wind phenomena (e.g., stream-stream interactions [cf. *McNutt*, 1988]) or termination shock phenomena. The frequency drift characteristics of the radiation components are discussed in section 6 [cf. *Czechowski and Grzedzielski*, 1990]. New arguments for the radiation being produced in either multiple source regions or regions of a single extended source with differing plasma frequencies are described in section 7. The relationship between the transient events and the 2-kHz component is discussed explicitly in section 8. Matters raised include the frequency ratios of the emissions and the possibility of distinct sources regions and/or emission mechanisms. Separate theories for the transient emissions and the 2-kHz component are summarized in section 9, together with each theory's strengths and weaknesses. The paper's conclusions are given in section 10.

Before proceeding we wish to emphasize that the theories advocated in this paper, that the emissions are generated at multiples of f_p when solar wind density enhancements enter the foreshock region sunward of the inner heliospheric shock, are not necessarily the only viable theories. For instance, the available data do not necessarily constrain viable theories to involve this radiation mechanism or this source region [e.g., *Cairns and Gurnett*, this issue, section 6]. Arguments against several alternative theoretical interpretations, such as radiation from the outer planets and astrophysical sources, as well as quasi-thermal plasma noise, are discussed elsewhere [*Kurth et al.*, 1984, 1986, 1987; *Meyer-Vernet*, 1989; *Kurth*, 1990]. We remain open to alternative theoretical explanations for the radiation. However, the theories developed here are the only detailed, potentially viable ones that are presently able to qualitatively account for all or many of the properties of the transient bursts and the 2-kHz component, respectively.

2. CHARACTERISTICS OF THE RADIATION

The Voyager spacecraft have detected the outer heliospheric radiation during limited portions of the period 1983 – 1987 [*Kurth et al.*, 1987] and from late 1989 to the present (late 1991) [*Kurth and Gurnett*, 1991]. A detailed review of the temporal and

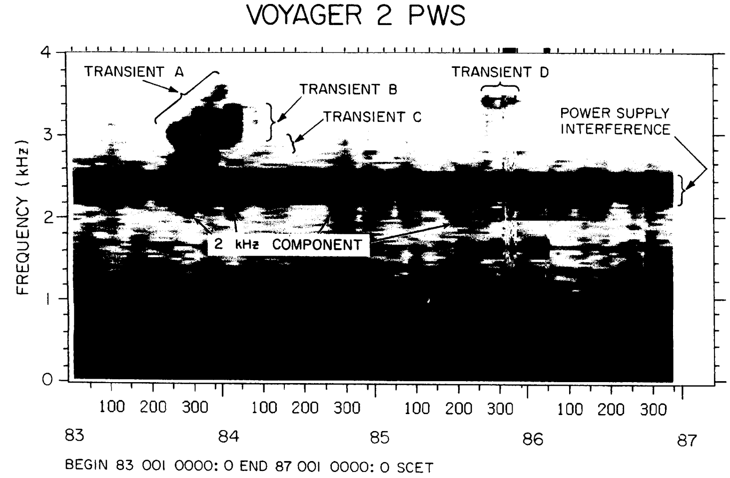

Fig. 2. Wideband spectrogram of Voyager 2 data prepared in a similar way to Figure 1. Transients A, B, and C, as well as the 2-kHz component, are clearly distinguishable. There is evidence that the 2-kHz component extends weakly across the interference band. The more extensive amplitude and frequency modulation of the 2-kHz component at Voyager 2 compared to Voyager 1 is qualitatively consistent with frequency blocking.

frequency variations of this radiation is appropriate for four reasons: first, to identify and summarize the experimental quantities that a successful theory must explain; second, to exploit differences between the radiation observed during the periods 1983–1986 and 1989 to the present in order to obtain new information on the classification of the emissions; third, to correct the wave data for the effects of a notch filter near 2.4 kHz and thereafter to reassess whether the radiation near 2 kHz shows evidence for upward frequency drift; and, fourth, to point out the existence of multiple components in the 1983/1984 radiation event that imply the existence of multiple source regions capable of producing observable radiation.

Color-coded wideband spectrograms for the period 1983–1987 are shown in *Kurth et al.'s* [1987] Plates 1 and 2. Similar gray scale spectrograms with significantly different scalings are shown here in Figures 1 and 2. Figures 1 and 2 also differ in an important way from Kurth et al.'s Plates 1 and 2. The wideband receiver [*Scarf and Gurnett*, 1977] has a notch filter, centered at 2.4 kHz, to reduce interference from the spacecraft power supply. The spectrograms in Figures 1 and 2 are our first attempts to correct for the effects of the notch filter. The quantitative effects of the notch filter are explicitly demonstrated in Figure 3. In fact, the notch filter is quantitatively important in determining (1) whether or not the emissions near 2 kHz show evidence for upward frequency drifts and (2) the frequency and amplitude variations of the emissions in the range 2.2–2.6 kHz. Our correction procedure involves simply multiplying the measured spectrum by a correction function $S(f)$, where $\log S(f) = -R(f)/20$ and $R(f)$ is the theoretical filter function measured in voltage decibels down from a reference signal. This procedure will overestimate the true spectrum where the measured spectrum is very close to or at the receiver noise level. However, spot checks indicate that this limitation does not affect the results presented in this paper. Figure 4 shows *Kurth and Gurnett's* [1991] recent Voyager 1 observations for the period 1989 to mid-1991 corrected for the effects of the notch filter. The data used in these spectrograms are power spectra calculated from 15-s snapshots of wideband data [*Scarf and Gurnett*, 1977] taken at intervals of order 1 month (Figures 1 and 2) or 1 week (Figure 4). The spectrograms are constructed by placing the wideband spectra in their time-designated positions and filling any intervening pixels using straight-line interpolation in time (but not in frequency). Ticks at the tops of Figures 1, 2, and 4 show when wideband spectra are available. Clearly care must be taken to avoid over interpreting time variations in the data. The gray

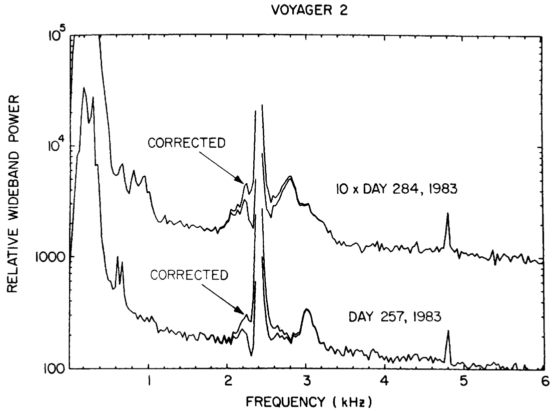

Fig. 3. Voyager 2 wideband spectra on days 257 and 283, 1983, showing the effects of the notch filter. The lower line of each pair of spectra shows the spectrum without correcting for the filter. Since the filter reduces the interference signal by a factor of 10 at the filter's central frequency, filter effects are quantitatively important in the range 1.9 – 2.9 kHz. Comparison between the uncorrected and corrected spectra shows that the relative nulls above and below the interference signal in previous works are due to the notch filter and that the 2-kHz component does extend above the interference signal. Comparisons between days 257 and 283 show that transient A definitely started before, but remains visible throughout much of, transient B.

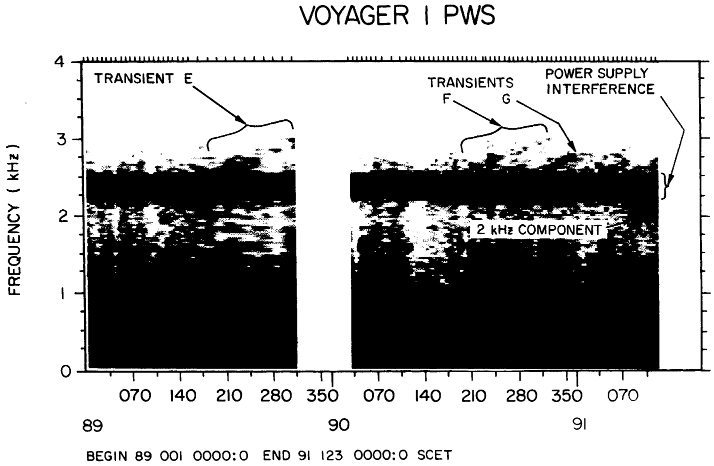

Fig. 4. Voyager 1 data, corrected for notch filter effects, for the period 1989 – 1991 discussed by Kurth and Gurnett [1991]. Transients E, F, and G are clearly visible, as is the return of the 2-kHz component in early 1991. Transients E and G appear to start below 2.2 kHz and extend above the interference signal.

scales show relative wave intensity using severely stretched ranges: Figures 1 and 2's gray scales correspond to only 2.5 dB and 1.5 dB in intensity, respectively, leading to saturation of the gray scale by the stronger emissions. *Kurth et al.* [1984, 1987] have discussed other sources of noise and interference signals in the wideband spectrograms. We caution that the narrow-band, horizontal lines in Figures 1, 2, and 4 from 1.6 to 4 kHz are due either to interpolating statistically uncorrelated, but neighboring noise enhancements over long sampling intervals or to high harmonics ($n \sim 4-6$) of lower-frequency interference signals. This first effect is nicely illustrated by the differences between the Voyager 1 and 2 data during the Uranus Observatory Phase of transient D: the rapidly sampled Voyager 2 data show no horizontal lines. A schematic illustration of all the radiation events observed to date, together with the new identifications and classifications introduced below, is shown in Figure 5.

Spectrograms for the period 1983 – 1987 shown in Figures 1 and 2 have been interpreted previously in the following terms: first, a relatively intense emission band that starts near 2.5–3.2 kHz in late 1983 and becomes less intense as it drifts upward in frequency at a rate of approximately 1 kHz/yr; second, a weaker emission near 1.8–2.3 kHz that shows little change in frequency or amplitude [*Kurth et al.*, 1987]; and, third, a weak emission that starts near 3.2–3.5 kHz in late 1985 and whose lower-frequency cutoff drifts upward. Similarly, the 1989–1991 data have been interpreted in terms of a component near 2 kHz and three transient emissions starting near 2–2.5 kHz that show upward frequency drifts of order 1.5 kHz/yr [*Kurth and Gurnett*, 1991]. The relatively steady emissions in the range 1.8–2.3 kHz are termed the "2-kHz component" below.

A detailed reexamination of the data in Figures 1 to 4 (and *Kurth et al.'s* [1987] Plates 1 and 2) leads to the following new results. (1) The Voyager 2 data in Figure 2 (and Plate 2) show that the intense emission band near 3 kHz during the 1983/1984 event is composed of at least two separate drifting emissions A and B with different starting times and frequencies. (2) Both Figures 1 and 2 show that a very weak, drifting, transient feature C exists in the range 2.5–2.9 kHz contemporaneous with the two drifting emissions A and B near 3 kHz. This feature can be extrapolated back to a starting frequency near 2–2.3 kHz during the first intensification of the 2-kHz band. A strong similarity to Figure 4's weak transient features is evident. (3) The transient 1983 and 1985 events acquire an approximately triangular shape with a fairly constant high-frequency cutoff once the radiation drifts up to about 3.5 kHz. This triangular shape is most evident in the Voyager 1 data, with the Voyager 2 data showing some weak drifting emission above the cutoff. The absence of brightening at the high-frequency cutoff indicates that radiation moving above the cutoff is lost from the system. Note, however, that the Voyager 2 data show weak radiation above this high-frequency cutoff. (4) The starting frequencies of transient events A–G vary by a factor of order 2 from near 2 kHz to near 3.5 kHz. (5) Both the transient feature C in Figures 1 and 2 and the transient features in Figure 4 have minimum bandwidths of order 100 Hz. (6) The 2-kHz component is present almost continuously during the period 1983–1986. It does show evidence for amplitude and frequency variations. However, Figures 1 and 2 show that the peak intensities of this component remain in the narrow range 2.0–2.5 kHz below and including the notch filter. (7) The 2-kHz component shows no evidence of transient enhancements drifting upward in frequency like the transient events. (8) There is no evidence for a gap between the 2-kHz component's upper frequency and the interference signal near 2.4 kHz. (Figure 3 demonstrates that the apparent gaps in Kurth et al.'s Plates 1 and 2 and Kurth and Gurnett's Figures 1 and 2 are due primarily to the notch filter.) Instead, whenever the 2-kHz component is present, signals cover the entire frequency range between the interference signal and the frequency at which the 2-kHz component has its maximum intensity. (9) Figures 1, 2, and 4 show evidence for the 2-kHz band extending above the interference band, with significantly reduced amplitude, for much of the period 1983–1985 (while the 2-kHz component was relatively intense). The line spectra in Figure 3 illustrate these points further. For future reference we note that items 1, 2, 4, 6,

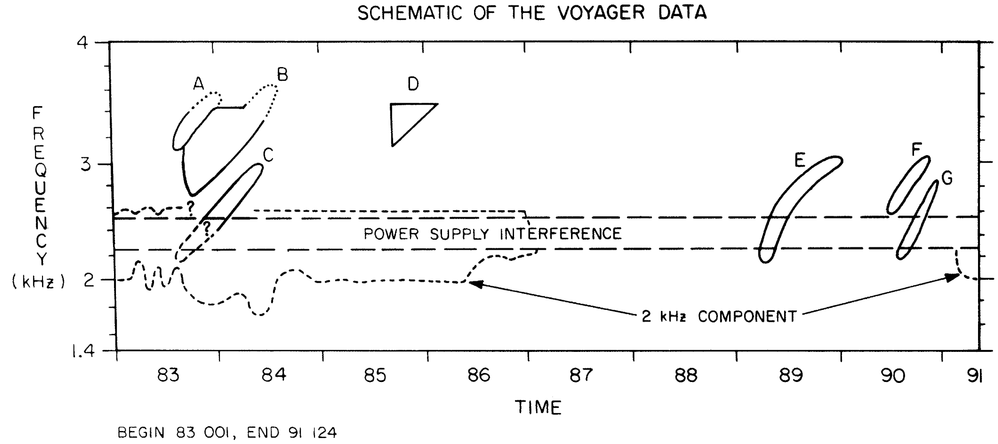

Fig. 5. Schematic illustration of the seven transient events observed to date and the onsets and disappearances of the 2-kHz component.

and 7 are consistent with classification of the emissions into two classes, items 1, 2, 5, and 6 are consistent with multiple source regions for the transient radiation, and item 3 is consistent with trapping of the radiation inside the heliospheric cavity.

The experimental data therefore support a classification of the emissions into two classes, as done implicitly by *Kurth and Gurnett* [1991]: "transient events" and a relatively steady "2-kHz component." Transient events have the following properties: they occur sporadically for limited time periods with significant upward frequency drifts of ~1−2 kHz/yr, a wide range of starting frequencies from ~2.0 to 3.5 kHz, an upper cutoff for upshifted radiation of order 3.5 kHz, and minimum bandwidths of order 100 Hz. They may occur singly or in groups. In contrast, the 2-kHz component is present relatively continuously, shows changes in amplitude and both upper and lower frequency, and remains in the frequency range 1.8−2.7 kHz with no discernible features drifting upward in frequency. The significantly different properties of transient events and the 2-kHz component indicate that their generation mechanisms and/or source regions are different. Accordingly, transient events and the 2-kHz component will be discussed separately in much of the rest of the paper. We note that this recognition potentially removes several questions, such as the relative frequencies and time variations of the 3-kHz transients and the 2-kHz component, from being central problems for theories involving emission at multiples of f_p.

Transient events A, B, and C from the 1983 event show clear evidence, especially in *Kurth et al.'s* [1987] Plates 1 and 2, for the radiation becoming less intense as it drifts upward in frequency. Accordingly, finding that transient event C can be extrapolated back to start in the 2-kHz component during this band's major intensification in late 1983, it is tempting to argue that this event is radiation upshifting from this unusually intense, transient brightening of the 2-kHz component and not a distinct transient event. This possibility could only be definitively eliminated or proved if accurate spectra in the frequency range of the interference signal were available. However, first the strong analogy between event C and the three recent transient events E, F, and G and then the absence of the 2-kHz component during events E, F, and G argue that event C is unlikely to be an intense burst of upshifting radiation from the 2-kHz component. It is still possible that the start of transient C coincides with a brightening of the 2-kHz component.

The question of whether or not the 2-kHz component is composed of radiation drifting upward in frequency can be reviewed as follows. First, points 8 and 9 above demonstrate the absence of definitive proof that the 2-kHz component is not composed of continuously generated drifting radiation. This is due to the absence of a frequency gap between the 2-kHz component and the interference band (point 8) and to the 2-kHz component extending weakly just above the interference band for long periods (point 9). Second, the absence of clearly identifiable drifting features in the 2-kHz component (point 7 and the previous paragraph) prevents a definitive answer "yes." Third, points 8 and 9 above are not inconsistent with the 2-kHz component being composed of continuously produced radiation that weakens in intensity as it drifts upward in frequency.

The flux density and brightness temperature of the emissions can be summarized as follows. *Kurth et al.* [1987] found that the intense transient emissions near 3 kHz during the 1983/1984 event had a maximum combined flux density of $\sim 3 \times 10^{-17}$ W m^{-2} Hz^{-1}. This flux density corresponds to a minimum brightness temperature of 3×10^{14} K [*Macek et al.*, 1991a,b; *Cairns and Gurnett*, this issue]. Figures 1 to 3 show here that after correcting for the notch filter, the 2-kHz component sometimes approaches (while generally remaining smaller than) the brightness temperature of the intense transient events. More detailed investigations indicate that the emissions always remain less than 10 dB above the effective noise level of the wideband instrument (for 15-s samples of wideband data). Thus less than a factor of 10 decrease in intensity is sufficient to render the 2-kHz component and the transient events unobservable by the Voyager plasma wave instrument.

3. THE FORESHOCK SOURCE MODEL FOR THE RADIATION

Macek et al. [1991a] have suggested that electron acceleration and growth of Langmuir waves takes place in a foreshock region sunward of the inner heliospheric shock. We have suggested

[*Macek et al.*, 1991a,b; *Cairns and Gurnett*, this issue] that the outer heliospheric radio emissions are generated in a region of the foreshock that contains intense Langmuir waves. The foreshock results from electrons energized and reflected at the quasi-perpendicular region of the shock streaming sunward along the primarily tangential magnetic field. Competition between electron motion along the magnetic field (sunward) and the $\boldsymbol{E} \times \boldsymbol{B}$ drift velocity (shockward) imposed by the solar wind convection electric field requires that electrons have a minimum speed (the so-called cutoff speed) along the magnetic field in order to escape from the shock [*Filbert and Kellogg*, 1979; *Cairns*, 1987b]. The sunward streaming electrons then naturally have a beamlike distribution function and drive Langmuir waves by the beam or two-stream instability [*Filbert and Kellogg*, 1979; *Cairns*, 1987b; *Fitzenreiter et al.*, 1990]. Macek et al. constructed a model for the spatial variation in the cutoff speed v_b in this foreshock. This foreshock model is directly analogous to the accepted theory at Earth [*Filbert and Kellogg*, 1979; *Cairns*, 1987b; *Fitzenreiter et al.*, 1990]. Accordingly, the prediction of a foreshock sunward of the inner heliospheric shock [*Macek et al.*, 1991a] has substantial theoretical support and is consistent with the Voyager observations of foreshocks containing significant levels of Langmuir waves upstream from the bow shocks of all the outer planets.

Postulating the radiation's source to be in this foreshock region naturally provides beam-driven Langmuir waves. The calculations in sections 4 and 5 of *Cairns and Gurnett* [this issue] indicate that there is then no theoretical problem, in principle, in generating Langmuir waves at high enough levels to produce the observed radiation in distances less than or of order 1 AU. The characteristic size of the foreshock region can be estimated using *Macek et al.'s* [1991a] Figure 2. This figure shows the variation in v_b for electrons leaving the modeled inner heliospheric shock (with nose location at 100 AU) at heliographic longitude ϕ and latitude δ: v_b is large ($\geq 5 \times 10^6$ m s^{-1}) compared with the electron thermal speed and solar wind speed (~ 400 km s^{-1}) within 10° of the nose in heliographic longitude and $\pm 70°$ in latitude. Other nose distances D for the shock lead to similar figures with a maximum beam speed proportional to D. The figure implies that the foreshock should extend approximately 10 AU in the azimuthal direction and considerably in excess of 10 AU in the polar heliographic direction. In contrast, the almost tangential nature of the spiral magnetic field should severely limit the radial extent of the source region. Using the simple shock shape of *Macek* [1989], the 10° extent of the high v_b region in heliographic longitude implies a radial extent of 0.25 and 0.5 AU for $D = 50$ and 100 AU, respectively.

Experience in the inner solar system provides strong evidence that electron streams leaving the inner heliospheric shock should propagate a significant fraction of an astronomical unit while generating Langmuir waves and radiation at multiples of f_p. For instance, electron streams associated with type III bursts propagate approximately 1 AU while generating high levels of Langmuir waves and electromagnetic radiation [*Gurnett and Anderson*, 1977], and electron streams from Earth's bow shock sometimes travel 0.01 AU (i.e., to ISEE 3 in its halo orbit) while generating high levels of Langmuir waves (R. R. Anderson, personal communication, 1990). Moreover, variations in the plasma parameters between 1 AU and the outer heliosphere indicate that the growth rate for the beam instability decreases by an additional factor of $5-10$ relative to the rates of nonlinear processes capable of saturating the instability (i.e., $L \rightarrow L' + S$) for the same Langmuir wave spectrum and beam parameters. This theoretical argument implies preservation of the electron streams for greater distances in the outer heliosphere. Therefore, arguing strictly by analogy and without a detailed understanding of the beam persistence problem, it seems likely that electron streams may travel distances of at least $0.1-1$ AU from the termination shock while generating high levels of Langmuir waves. The foreshock region containing large Langmuir wave levels therefore plausibly extends distances of order $0.1-1$ AU in the radial direction and $0.1-10$ AU in the azimuthal and polar heliospheric directions. Accordingly *Cairns and Gurnett's* [this issue] calculations and Figure 2 show that the proposed foreshock source is large enough to produce f_p and $2f_p$ radiation with the observed brightness temperature using plausible levels of Langmuir waves for a foreshock environment ($T_L \sim 10^{17}$ K). On the other hand, Cairns and Gurnett's calculations indicate that implausible, although possible, Langmuir wave levels ($T_L \sim 10^{22}$ K) are required to generate observable $3f_p$ radiation in such sources.

The analogy with planetary foreshocks implies that this foreshock should be a continuously present feature, thereby predicting the continual generation of f_p and/or $2f_p$ radiation. The observation of the 2- to 3-kHz emissions only during limited time periods [*Kurth et al.*, 1984, 1987] might then raise doubts that the radiation is generated in the foreshock source. However, various observational and theoretical arguments suggest that foreshock-generated radiation would most likely show significant time and amplitude variability. First, f_p and $2f_p$ radiation generated in Earth's foreshock varies in brightness temperature by several orders of magnitude and is observed less than 50% of the time [*Hoang et al.*, 1981; *Cairns*, 1986; *Burgess et al.*, 1987; *Lacombe et al.*, 1988]. Corresponding radiation at $3f_p$ is observed extremely infrequently [*Cairns*, 1986]. Second, the observed radiation intensity is only a factor of at most 10 above the noise level of Voyager's wideband instrument (section 2). The observed radiation therefore probably constitutes the peak levels of foreshock-generated radiation present more continuously at levels below the instrumental background. Third, as discussed in sections 4 and 5, special source and propagation conditions are required for generating the radiation at sufficiently high frequencies and levels to be observed by the Voyager spacecraft.

4. PROPAGATION OF THE RADIATION

4.1 *The Role of Density Enhancements*

For several reasons, propagation of radiation from the foreshock source into the inner heliosphere might appear to be a significant problem with our source model. First, f_p radiation cannot propagate significant distances sunward for a simple r^{-2} solar wind density model. Second, based on this model the Voyager spacecraft should already have passed through the source region if the source is located sunward of the inner heliospheric shock (assuming no solar cycle variations). The calculations of *Suess and Dessler* [1985] and *Kurth et al.* [1984] give (heliocentric) shock positions at 15 AU and 23 AU, respectively, on switching the source location from the downstream to the upstream side of the shock. (These positions are a factor of 2 smaller than the

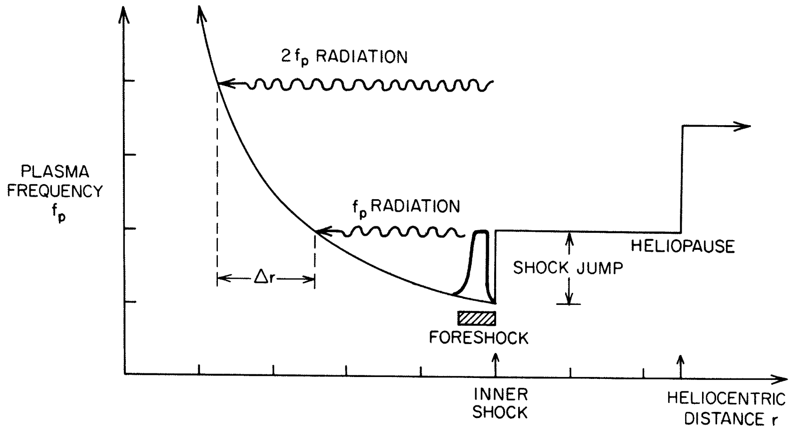

Fig. 6. The role of regions of enhanced solar wind density in generating f_p and $2f_p$ radiation capable of propagating from a source in the foreshock region into the inner heliosphere. The region of enhanced solar wind density (by a factor of 4) in the (shaded) foreshock region produces radiation capable of propagating a distance $\Delta r = R/2$ further sunward than a similar region with the nominal solar wind density. Radiation produced in this density enhancement in the foreshock propagates an identical distance to radiation produced behind the shock in the absence of the density enhancement.

published values of these authors due to removal of the factor of 4 density jump expected at the shock.) However, *Czechowski and Grzedzielski* [1990] have interpreted the frequency drift of the transient emissions in terms of Fermi scattering of trapped radiation from large outward moving density variations that are observed in the solar wind. This suggests a natural resolution of this propagation problem (Figure 6): The observed emissions are f_p and/or $2f_p$ radiation generated when regions of enhanced solar wind density (relative to the steady state r^{-2} level) pass through the foreshock region. The radiation then propagates inward when the solar wind density is small enough, but suffers multiple reflections (and frequency upshifting) by density enhancements whenever the local plasma frequency exceeds the radiation frequency.

The heliocentric radial distance R to the source (in astronomical units) is estimated using the frequency f and harmonic number n of the radiation (i.e., nf_p radiation), the plasma frequency f_{p1} at 1 AU, a R^{-1} falloff of the solar wind plasma frequency, and the density enhancement factor α in the foreshock:

$$R = \frac{\sqrt{\alpha}\, nf_{pl}}{f} . \tag{1}$$

Kurth et al. [1984] assume f_{p1} = 35 kHz, corresponding to the ~2-kHz low-frequency cutoff of the radiation [*Kurth*, 1990], while *Suess and Dessler* [1985] use the long-term average f_{p1} = 23 kHz. A more appropriate average value of f_{p1} for the period 1983 – 1988 is given by *Lazarus and McNutt's* [1990, Figure 3] Voyager 2 data: f_{p1} = 28 kHz. Density enhancements by a factor of 4 in the foreshock region are sufficient for production of $2f_p$ radiation at 3 kHz from a source located at R = 46 AU, 30 AU, and 37 AU using Kurth et al.'s, Suess and Dessler's, and the 1983 – 1988 average values for f_{p1}, respectively. Larger density enhancements permit the source region of the radiation to be located at greater heliocentric distances than these estimates, consistent with the present positions of the Voyager spacecraft, without appealing to solar cycle variations or other effects. Table 1 shows the source distances corresponding to radiation with various frequencies f and harmonic numbers n. Most attention should be given to the fourth and sixth columns, corresponding to Kurth et al.'s and Lazarus and McNutt's values for f_{p1}. In comparison, Voyager 1's present heliocentric distance is of order 45 AU. Table 1 shows that f_p and/or $2f_p$ radiation can be produced at the observed frequencies for sources at heliocentric distances greater than Voyager 1's provided that solar wind density enhancements with $\alpha \sim 10$ exist. In addition, Table 1 implies that radiation produced near 3 kHz is most plausibly $2f_p$ radiation while 2-kHz radiation can plausibly be either f_p or $2f_p$

TABLE 1. Source Distances R

			R / AU		
α	f / kHz	n	f_{p1} = 35 kHz	f_{p1} = 23 kHz	f_{p1} = 28 kHz
4	2	1	35	23	28
4	2	2	70	46	56
4	3	1	23	15	19
4	3	2	47	31	37
10	2	1	55	36	44
10	4	2	111	73	89
10	3	1	37	24	30
10	3	2	74	48	59
10	3	3	111	73	89

radiation. Note also that identifying the 3-kHz radiation in terms of $3f_p$ radiation still requires density enhancements to play a vital role in generating the radiation at high enough frequencies for the source to be outside Voyager 1's present position.

Data from Pioneer 10 and 11 and Voyager 2 show that density enhancements by a factor of 4 are common over a variety of time scales, while factor of 10 enhancements occur relatively infrequently, out to heliocentric distances of at least 35 AU [*Gazis*, 1987; *Gazis et al.*, 1988; *Lazarus and Belcher*, 1988; *McNutt*, 1988; *Lazarus and McNutt*, 1990]. It is important that these factor of 10 density variations are visible even when time averaging over periods of at least 10 days is performed [e.g, *Gazis et al.*, 1988; *Lazarus and McNutt*, 1990]. This indicates that large-scale regions of greatly increased solar wind density exist (a 10-day period corresponds to a radial distance of order 2 AU for $v_{sw} \sim 400$ km s^{-1}), presumably together with superposed smaller-scale density variations. The available solar wind data therefore show the existence of short time scale (hours to tens of days) density variations with enhancement factors of 4 – 10. Equation (1) indicates that the least stringent conditions on the solar wind density involve both f_{p1} and α being large. Since the termination shock must remain effectively stationary (on a 1-AU scale) in response to the observed large-scale ram pressure variations [*Lazarus and McNutt*, 1990], enhanced large-scale values for f_{p1} can be used when estimating the location of the source region, as done implicitly by *Kurth et al.* [1984]. Constraints on the duration of the density variations follow from *Cairns and Gurnett's* [this issue] path length calculations and the estimated radial size of the foreshock source: $L \sim 0.1-1$ AU. This restricts the density enhancements required in the theory to last a minimum of a fraction of a day to several days. Generation of f_p and $2f_p$ radiation at the observed frequencies is therefore plausible in a foreshock source outside 50 AU. We note that the relative infrequency of large (i.e., factor of 10) density inhomogeneities is qualitatively consistent with the rarity of observing transient events.

The absence of density data from Voyager 1 is potentially important for at least two reasons: (1) This spacecraft is moving out of the ecliptic plane and approximately in the expected direction of the nose of the inner heliospheric shock (a likely source region for the radiation). (2) There is some observational evidence that the solar wind has greater and more sudden density enhancements away from the ecliptic plane in the outer heliosphere [*Gazis et al.*, 1988, Figure 4; *Lazarus and Belcher*, 1988, Figure 9]. Perhaps *McNutt's* [1988] suggestion that a large fast solar wind stream is associated with the 1983/1984 transient bursts of radiation may be understood in this context: the density variations resulting from this stream's interaction with the surrounding plasma survive into the outer heliosphere ($r \geq 50$ AU) away from the ecliptic plane and are particularly favorable for foreshock-generated f_p and $2f_p$ radiation to propagate into the inner heliosphere.

Other mechanisms may conceivably cause additional steady state enhancements to the solar wind density upstream from the inner shock, thereby reducing the size of the required density enhancement factors in the outflowing solar wind; for example, charge exchange between solar wind protons and interstellar hydrogen [e.g., *Baranov*, 1990]. Transient means to enhance the solar wind density are discussed in section 5. Further research on density enhancements and the radial profile of the solar wind in the outer heliosphere is clearly required. However, the above ideas and the available observational data lead to the following summary: the larger density enhancements observed in the solar wind could plausibly lead to the generation of f_p and $2f_p$ radiation at the observed frequencies in a foreshock source located near or well outside 50 AU.

4.2 *Propagation Into the Inner Heliosphere*

The propagation path of radiation generated in the foreshock region depends on the three-dimensional structure and time history of the solar wind density, as well as the location of the radiation source. For instance, spherically symmetric, equally sized solar wind density enhancements (by a factor of 4) spaced less than 10 – 20 AU apart would prevent propagation of both f_p and $2f_p$ radiation in to 25 AU if the source was located more than 45 AU from the Sun. Latitudinal and longitudinal structures in the density enhancements are then vital in creating pathways for the radiation to propagate into the inner heliosphere. Qualitatively, as illustrated in Figure 7a, the most favorable conditions for the radiation to reach the inner heliosphere involve primarily quiet solar wind conditions with only a few large transient density enhancements (to provide radiation at sufficiently high frequencies to propagate significantly sunward). Quantitatively, assuming a standard r^{-2} falloff for the solar wind number density, a density enhancement (located at r_i with enhancement factor α_i and base plasma frequency f_{p1i} at 1 AU) is able to block further inward propagation of nf_p radiation generated in the foreshock source (distance r_s, density enhancement factor α_s, and f_{p1s}) if

$$r_i \leq \sqrt{\frac{\alpha_i}{\alpha_s} \frac{f_{p1i}}{nf_{p1s}}} r_s \ . \qquad (2)$$

Thus observation of nf_p radiation at, say, 10 AU from a source outside 50 AU requires that $f_{p1s} \sqrt{\alpha_s} \geq 5/n \ f_{p1i} \sqrt{\alpha_i}$. These restrictions are not unrealistically severe given the observed density variations described above, particularly for $2f_p$ radiation.

During the period 1983 – 1987 the 2-kHz component was present almost continuously while only infrequent transient events occurred, generally at frequencies near 3 kHz. The different time behavior of these emissions is not consistent with simple models for frequency blocking by regions of enhanced density between a single source and the spacecraft since the 2-kHz component should be blocked preferentially relative to the (higher frequency) transient events. Measurements of the local plasma density by J. W. Belcher during the 1983 – 1984 event, reported by *Kurth* [1990], confirm that the plasma frequency local to Voyager 1 was less than 2 kHz for the entire time period. Similarly, the different time behaviors of the events during the period 1989 to present cannot be explained simply in terms of frequency blocking. Even assuming distinct sources for the two classes of radiation events (see sections 6 and 8) does not alter this conclusion: radically different density profiles along the propagation paths to the spacecraft are required to explain the time histories of the emissions in terms of frequency blocking. Furthermore, widely separated spacecraft would most likely observe significantly different time histories and characteristics for radiation subject to major frequency blocking, especially if more than one radiation source exists. Instead, despite being separated by some 10 AU

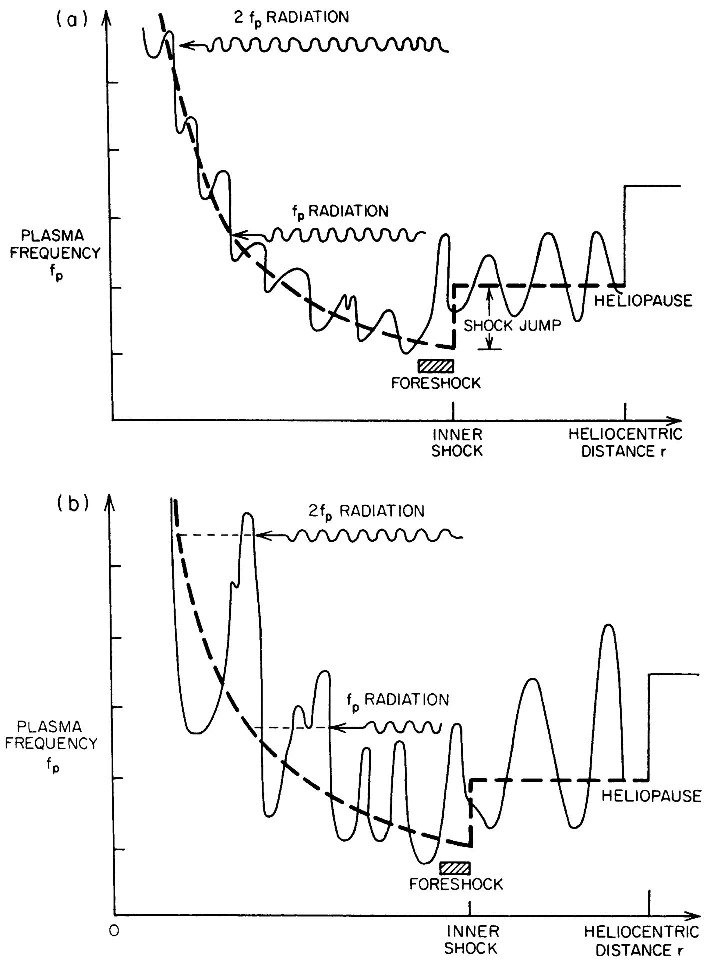

Fig. 7. Propagation of radiation into the inner heliosphere from a foreshock region. The thick dashed line shows the steady state r^{-1} falloff in the plasma frequency, while the solid line illustrates the actual profile for the plasma frequency. (a) Quiet solar wind conditions with a few large density enhancements are most favorable for propagation into the inner heliosphere. (b) Turbulent solar wind plasma conditions inhibit propagation of f_p and $2f_p$ radiation well into the inner heliosphere. Equation (2) gives an analytic constraint on the propagation distance of the radiation.

perpendicular to and 8 AU parallel to the ecliptic plane, Voyager 1 and 2 observed very similar emissions from 1983 to 1987 [*Kurth et al.*, 1986, 1987; *Kurth*, 1990]. We conclude that frequency blocking cannot explain the qualitative time history of the radiation observed from 1983 to 1987 and from 1989 to the present day. Similarly, frequency blocking does not appear to be a viable interpretation for the absence of radio emissions in the period 1987 – 1989.

Quantitative differences between the amplitudes and time histories of the emissions at Voyager 1 and 2 do indicate a role for frequency blocking. *Kurth et al.'s* [1984, 1987] Voyager 1 observations of amplitude modulations at approximately the solar rotation period, as expected for steady stream structures, point to frequency blocking. Recently, *McNutt* [1991] has confirmed that these amplitude modulations are indeed quantitatively consistent with plasma density variations inferred from the Voyager 1 plasma instrument. Additional evidence for frequency blocking comes from Figures 1 and 2. Detailed comparisons show that the Voyager 1 and 2 observations of the 2-kHz component differ substantially in the period 1983 – 1984 but become increasingly similar with time. In particular, from 1983 to 1984, Voyager 1 observed the 2-kHz component both more frequently and extending to lower frequencies than Voyager 2, as expected if the plasma frequency was higher at Voyager 2. During this time period, Voyager 1 moved from $R = 15$ AU to $R = 22$ AU while Voyager 2 moved from $R = 10$ AU to $R = 16$ AU. Since $f_p(R) = 28/R$ kHz on average [e.g., *Lazarus and McNutt*, 1990], it is readily apparent that these differences in the 2-kHz component are qualitatively consistent with frequency blocking. Transients A and B also appear somewhat differently in the Voyager 1 and 2 data. This is due in part to the different timing of wideband observations for the two spacecraft; in particular, there is no Voyager 1 counterpart to the Voyager 2 observations (day 257, 1983) that showed transient A before transient B had started. (In addition the instrumental noise levels differ by a few decibels for the two spacecraft.) In our opinion, scattering effects and the different positions and density environments of the two spacecraft are responsible for much of the quantitative differences between the Voyager 1 and 2 observations of transients A and B.

The first period of radio emissions, 1983 – 1987, brackets the period of solar minimum. Traditionally, the solar wind flow is expected to be most uniform at solar minimum with few transient shocks and corotating interaction regions. These would be ideal conditions for radiation to propagate into the inner heliosphere [e.g., *Lanzerotti et al.*, 1985]. Similarly, near solar maximum the solar wind is traditionally expected to be more turbulent due to more transients and stream-stream interactions occurring, as illustrated in Figure 7b, thereby preventing the radiation from propagating into the inner heliosphere. *Lazarus and McNutt's* [1990, Figure 2] data, however, show little difference in the variability of the 10-day-averaged solar wind density from 1978 to 1989. Indeed, if anything, their data indicate that large solar wind density variations were unusually frequent during the 2-year period from 1983 to 1985. This period coincides with an almost continuous 2-kHz component and the most intense transient events seen to date. Accordingly, the radio and density data are not inconsistent with the important role played by density enhancements in the foreshock theory.

5. TIME VARIABILITY

With frequency blocking ruled out as a likely explanation for the qualitatively different time variabilities of the 2-kHz component and the transient events, other explanations are required. The transient emissions show frequency drifts at a rate of order 1 kHz/yr [*Kurth et al.*, 1984, 1987]. *Czechowski and Grzedzielski's* [1990] interpretation for each drifting feature involves radiation generated in a short period that suffers Fermi upshifting due to multiple scattering by density enhancements. Thus both the low rate of occurrence of transient events and Czechowski and Grzedzielski's frequency drift interpretation imply that unusual source conditions are required to produce transient events observable by the Voyager spacecraft. Similarly, the disappearance of the 2-kHz component between 1987 and 1991, and its reappearance well after several intervening transient events, implies that source conditions are not always appropriate for production of an observable 2-kHz component.

Most nonthermal radio sources show variations in amplitude by many orders of magnitude. Since the radio emissions reach a maximum intensity that is at most only 10 times the noise levels of the Voyager instruments, the observed radiation may well constitute the peak levels of emissions that are usually below the Voyager detection threshold [*Kurth et al.*, 1987]. Changes in the source plasma [e.g., *McNutt*, 1988] and production efficiency are therefore very likely to be key factors in understanding the limited time periods when the radio emissions have been observed. Furthermore, the Voyager data cannot rule out the intriguing possibility that a weaker version of the observed emissions is generated (in the foreshock) and exists almost continuously in the heliospheric cavity. Such foreshock-generated radiation would then be somewhat analogous to the trapped and escaping continuum radiation observed in the magnetospheres of Earth [e.g., *Gurnett*, 1975], Jupiter, and Saturn. Observation of this weaker, continuous radiation would require the spacecraft to be in the near vicinity of a pointlike source (due to the r^{-2} falloff of the radiation intensity). For instance, if the observed emissions were generated 50 AU from the Voyager spacecraft in 1983/1984 (i.e., a source near 70 AU) and were 100 times more intense than the continuously produced radiation, then Voyager would observe the continuous emissions only when within 5 AU of the source. On the other hand, the intensity may falloff more slowly than r^{-2} for an extended source region, thereby perhaps precluding the Voyager spacecraft from observing such continuous radiation.

Calculations of the source conditions necessary to produce the measured levels of f_p and $2f_p$ radiation [*Cairns and Gurnett*, this issue] can potentially address both the different time variabilities of the 2-kHz component and the transient events, as well as some differences in the starting frequencies of the transient events. For the same Langmuir wave level $T_L \sim 10^{17}$ K, Cairns and Gurnett show that the path lengths of 0.02 AU and 0.23 AU are necessary to produce f_p and $2f_p$ radiation, respectively, with the observed brightness temperatures. In detail, the path lengths s_1 and s_2 for f_p and $2f_p$ radiation are [*Cairns and Gurnett*, this issue, equations (9) and (12)]

$$s_1 \propto T_L^{-1} \tag{3}$$

and

$$s_2 \propto T_L^{-2} . \tag{4}$$

Accordingly, obtaining higher levels of f_p radiation than $2f_p$ radiation, or vice versa, can be qualitatively understood in terms of the path lengths and Langmuir wave levels available in a spatially limited, time-variable, and spatially inhomogeneous outer heliospheric source. In particular, if $T_L \sim 10^{17}$ K in a source with size less than 0.2 AU, one expects the production of observable f_p radiation but not $2f_p$ radiation. On the other hand, if $T_L \sim 10^{18}$ K, then $s_2 < s_1$, and one might expect the production of higher levels of $2f_p$ radiation than f_p radiation. Differences in the starting frequencies of transient events can therefore be understood in terms of f_p versus $2f_p$ emission due to different source characteristics, as well as differences in the density enhancements entering different foreshock sources. For instance, transient events A, B, and D could be grouped as $2f_p$ emission, with events C, E, F, and G being considered f_p radiation. Similarly, the different time behavior of the 2-kHz component and the transient events near 3 kHz might, with more difficulty (section 7), be interpreted in terms of f_p versus $2f_p$ emission.

Figures 1 to 5 show that the observed transient events have widely varying starting frequencies. For instance, events C, E, and G start near 2 kHz while event F starts near 2.5 kHz, events A and B start near 3 kHz, and event D starts near 3.3 kHz. This range of starting frequencies can be plausibly interpreted in terms of a range of density enhancement factors α in the source regions. (Additional interpretations include the possible differences in emission mechanism, i.e., f_p versus $2f_p$ radiation, source distance R, and the plasma frequency f_{p1} at 1 AU for the various events.) Since a distribution of density enhancements is expected theoretically (and observed in the inner heliosphere), the widely varying range of starting frequencies for the transient events is qualitatively consistent with the proposed foreshock model. In contrast, we note that the relatively constant frequency range of the 2-kHz component is difficult to reconcile with the range of frequencies expected from $f_p/2f_p$ emission occurring when density enhancements enter a foreshock sunward of the termination shock. The discreteness and restricted frequency range (1.9–3.5 kHz) of the transient emissions have additional implications, however. In particular, if the unusual source conditions required to produce observable radiation were uncorrelated with the size of the density enhancements, then the frequency distribution of radiation events should be heavily biased toward frequencies of order 1 – 2 kHz and below (extrapolating $f_{p1} \sim$ 20–35 kHz to 50 – 100 AU implies $0.4\ \mathrm{kHz} \leq 2f_p \leq 1.4\ \mathrm{kHz}$). In contrast to this expectation there are clearly no observable transient events in the range 1.4 – 2.0 kHz in Figures 1, 2, and 4. We therefore interpret the discreteness and restricted frequency range of the transient events in the following way: the unusual source conditions required for production of observable radiation must be related to the presence of unusually large density enhancements in the foreshock region.

Detailed models for the cause of the unusual source conditions evidently responsible for production of both classes of radiation events are not presently available. However, we note that the recent events reported by *Kurth and Gurnett* [1991] demonstrate that radiation events are not produced solely near solar minimum, as might have been surmised otherwise from the 1983–1987 timing of the first events. Three possible causes of unusual source conditions, the first two of which involve the presence of large density enhancements in the foreshock, are as follows. (1) A fast stream may act as a trigger for a radiation event [*McNutt*, 1988]. We note that the interaction of fast and slow streams leads to associated regions of enhanced solar wind density and that such density enhancements are required here to produce radiation with the observed frequencies in the outer heliosphere. In addition the mildly energetic electrons and heated plasma produced by the stream interaction might provide an enhanced level of seed particles suitable for acceleration at the termination shock and the production of an enhanced level of foreshock Langmuir waves. There are therefore several rationales for fast streams being associated with radiation events. We note that recent work (Grzedzielski and Lazarus, personal communications, 1991) further supports a correlation between the 1983/1984, 1985, and 1989 transient events and merging solar wind streams likely to cause unusually large density enhancements in the outer heliosphere. (2) Forward or reverse shocks driven by pressure/density pulses interacting with the termination shock [*Lazarus and McNutt*, 1990] might also lead to unusual foreshock conditions such as enhanced density regions, electron beams and Langmuir wave levels in the foreshock, and the existence of multiple foreshock regions. These pressure pulses may be associated with stream interactions. (3) *Zank et al.* [1990, and references therein] have found that energetic particle-modified shocks can be unstable. Events in which the inner heliospheric shock breaks up and then re-forms may be relevant.

6. FREQUENCY UPSHIFTING

The question of whether both the 2-kHz and the transient events show evidence for upward frequency drift (section 2) has major potential implications for the interpretation and theoretical modeling of the radiation. In particular, this observation is relevant to whether the two classes of events have distinct sources and/or generation mechanisms and whether *Czechowski and Grzedzielski's* [1990] theory for upward frequency drift is correct.

It might seem tempting to interpret the frequency drifts in terms of continuous emission from a source with increasing local plasma frequency f_p. This would immediately require that transient emissions and the 2-kHz component have different source regions and/or generation mechanisms. However, neither the required large base levels for f_p nor the required monotonic increases in f_p for periods of order 6 months can be easily reconciled with a foreshock source [e.g., *Cairns and Gurnett*, this issue] driven continuously and directly by the solar wind in the outer heliosphere. A reasonable model for the required source variations is necessary before this interpretation should be pursued.

Czechowski and Grzedzielski [1990] have suggested that each drifting event be interpreted in terms of a burst of radiation, trapped in the heliospheric cavity, that undergoes Fermi upshifting due to repeated scattering between outward moving solar wind density enhancements and the outer density wall of the heliospheric cavity. The observed frequency drifts ~1-2 kHz/yr are reproduced using a cavity with characteristic size ~50 - 100 AU. The characteristic bounce time for each radiation photon is of order 1 day. One crucial point, however, is that this mechanism should apply to all radiation trapped within the heliospheric cavity. Accordingly, if the properties of the 2-kHz component were inconsistent with frequency upshifting, this would either invalidate Czechowski and Grzedzielski's theory or imply that the 2-kHz component is not a freely propagating radio emission.

In section 2 we conclude that although individual drifting features cannot be presently identified, the characteristics of the 2-kHz component are consistent with continuously generated radiation that suffers slow damping as it drifts upward in frequency. Both classes of emissions therefore have properties consistent with upward frequency drift. *Czechowski and Grzedzielski's* [1990] theory therefore remains viable, and the issue of frequency drift does not necessitate different emission mechanisms and/or source locations for the 2-kHz component and the transient events.

The following three characteristics (section 2) of the transient events are consistent with, and therefore provide support for, Czechowski and Grzedzielski's theory. (1) There is an effective high-frequency cutoff to the radiation. This cutoff presumably corresponds to the characteristic plasma frequency of the high-density region forming the outside of the heliospheric cavity ($f_p \sim$ 3.5 kHz). This places an upper limit on the characteristic plasma density beyond the inner heliospheric shock: $n_e \sim 0.15\ \mathrm{cm}^{-3}$. The observation of some weak radiation being upshifted above the cutoff can be interpreted in terms of localized high-density regions superposed on the average cavity structure. (2) The radiation decreases in intensity as it drifts upward in frequency. This is consistent with the radiation being generated in a limited time period and then being gradually lost from the system and absorbed as it drifts upward in frequency. (3) All seven transient events observed thus far have similar upward drift rates, consistent with the expectations that the cavity's size remains reasonably constant and that the global solar wind environment varies little. Periods of negative drift rate have not been observed. However, Czechowski and Grzedzielski's theory can explain deviations from monotonic frequency drift due to, for example, time variations in the density structures scattering the radiation and the cavity size and shape. Further evidence of the local and global state of the solar wind density being important comes from differences in the radiation detected by the two widely separated Voyager spacecraft, as discussed in section 4.2.

7. MULTIPLE OR EXTENDED SOURCES FOR THE RADIATION

Fahr et al. [1986] and *Kurth et al.* [1986] first suggested that the radiation might come from more than one source. Their arguments rested on the different time histories of the 2-kHz component and the intense 1983/1984 emissions near 3 kHz, as well as the frequency ratio of these emissions being near 1.5 and not the value 2 expected for simple $f_p/2f_p$ emission. Here we present several new arguments that both the transient events and the 2-kHz component are generated in either multiple regions of an extended source or multiple distinct sources. Arguments that transient events and the 2-kHz component are generated in distinct source regions or have different emission mechanisms are deferred to the next section.

Strong evidence for transient events being generated in more than one source region comes from the new recognition (section 2) that the intense 1983/1984 event was composed of at least three separate transient events with similar frequency drifts but different starting frequencies and times (as well as the 2-kHz component). This argues for either three distinct source regions or three distinct regions of a single extended source being able to produce observable radiation almost simultaneously. (An additional implication is that transient events and the 2-kHz component are unlikely to share a common source.) Both possibilities can be understood, within the context of the foreshock model, in terms of spatially inhomogeneous density enhancements and/or triggering events. A second line of evidence for both the transient emissions and the 2-kHz component having multiple source regions comes from wideband spectra showing multiple, narrow-band (≤ 100 Hz), time-varying peaks for both classes of events [*Kurth et al.*, 1986, Figure 2; *Kurth*, 1990, Figure 7]. While different propagation paths through a spatially inhomogeneous scattering medium might introduce some similar structure, these multiple peaks are also naturally interpreted in terms of simultaneous emissions from regions of a foreshock source with varying plasma density. Radiation generated near f_p and $2f_p$ in Earth's foreshock sometimes shows multiple narrow-band peaks due to several regions with different plasma frequency being simultaneously in the foreshock [*Cairns*, 1986; *Burgess et al.*, 1987].

A third argument, applying to both the transient events and the 2-kHz band, involves the bandwidth of the observed radiation. The 2-kHz component and the transient events have relative bandwidths $\Delta f/f$ in the ranges 0.07–0.2 and 0.03–0.25. In a source with constant plasma frequency the relative bandwidths of f_p and $2f_p$ radiation generated by the processes $L \rightarrow t(f_p) + S$ and $L + L \rightarrow t(2f_p) + S$ are [*Cairns*, 1987a, 1988]

$$\frac{\Delta f}{f_p} = 3\left(\frac{V_e}{v_b}\right)^2 \frac{V_b}{v_b} \qquad (5)$$

and

$$\frac{\Delta f}{2f_p} = 12\left(\frac{V_e}{v_b}\right)^2 \frac{V_b}{v_b} \ , \qquad (6)$$

respectively. Here v_b is the beam speed of the electrons driving the Langmuir waves, and V_e and V_b are the thermal speeds of the solar wind and beam electrons, respectively. Taking $T_e = 10^4$ K for the solar wind electron temperature, $V_e \sim 400$ km s^{-1} is of the order of the solar wind speed v_{sw}. Assuming $V_b \leq V_e$ and restricting consideration to the high beam speed region of the foreshock (where the highest Langmuir wave levels are expected) with $v_b \geq 10\ v_{sw}$, one finds

$$\frac{\Delta f}{f_p} \leq 0.003 \qquad (7)$$

and

$$\frac{\Delta f}{2f_p} \leq 0.01 \ . \qquad (8)$$

The observed bandwidths are therefore inconsistent with f_p and $2f_p$ emission from a source with constant plasma frequency. However, the density inhomogeneities already required in the theory (section 2) and the large spatial extent of the predicted foreshock naturally imply the generation of f_p and $2f_p$ radiation (with the intrinsic bandwidths above) in regions with significantly different plasma frequency. Thus the bandwidths of both the 2-kHz component and the transient events are consistent with generation of $f_p/2f_p$ radiation in either multiple sources or multiple regions of an extended source with significantly different plasma frequency. These interpretations fit naturally with the important role of density inhomogeneities in other aspects of the theory.

8. DISTINCT SOURCES OR EMISSION MECHANISMS FOR THE 2-KHZ COMPONENT AND THE TRANSIENT EVENTS?

There are four basic arguments that the two classes of events have different source regions and/or emission mechanisms. First, the existence of multiple, essentially simultaneous transient events (section 2) indicates that multiple distinct sources for transient events exist. It is then unlikely that the source regions of the 2-kHz component and the transient events overlap unless these events have different emission mechanisms or the 2-kHz source envelops the transient source regions. Second, the lack of multiple events in the 2-kHz component requires that transient events and the 2-kHz component have different generation mechanisms if they have a common source, and vice versa.

The next two arguments involve the frequency ratios and variations of the two classes of events. Third, the frequency ratio between transient events and the 2-kHz component varies from approximately 1.0 to 1.8, with an average near 1.6, depending upon the time period under consideration. These ratios are not consistent with unmodified $f_p/2f_p$ emission from a single source [*Fahr et al.*, 1986; *Kurth* et al., 1986], while $2f_p/3f_p$ emission is implausible [*Cairns and Gurnett*, this issue] due to the very high Langmuir wave levels required. This most likely implies that the two classes of emissions have different sources and/or generation mechanisms. An unlikely alternative is that the 2-kHz component might be f_p radiation that is heavily modified while propagating from the source to the spacecraft. It is true that heavy absorption, frequency blocking, and upshifting should lead to frequency ratios significantly less than 2.0 (cf. *Stewart's* [1974] frequency ratios of 1.8 for some solar type III bursts). Nevertheless, Voyager's failure to observe unmodified f_p radiation casts substantial doubt on this possibility. Fourth, and last, the different variations in starting frequency, almost constant versus widely scattered for the 2-kHz component and the transient events, respectively, argue strongly for different source locations and/or different emission mechanisms. As described in section 5, the spectrum of large density inhomogeneities expected in the outer heliosphere should lead theoretically to a broad distribution of starting frequencies for radiation generated at multiples of f_p in foreshock sources. This is consistent with the transient events but not the 2-kHz component. Table 1 and section 4 show that density inhomogeneities are vitally important in producing $f_p/2f_p$ radiation at the observed frequencies in the outer heliosphere unless significantly enhanced steady state solar wind densities are hypothesized somewhere in the foreshock. Thus, to explain this component's relatively large and constant frequency, it is necessary to assume either a foreshock source with enhanced steady state plasma densities, some other source of $f_p/2f_p$ radiation in the outer heliosphere (see, however, *Cairns and Gurnett* [this issue]) or a different emission mechanism.

One direct argument for the sources and/or generation mechanisms for the 2-kHz component and the transient events being related is the following: the 1983/1984 transient events occurred almost simultaneously with a major intensification of the 2-kHz component. We note, however, that *Kurth and Gurnett's* [1991] recent observations indicate that this association may be fortuitous and that the apparent 1983/1984 association may correspond simply to transient C's onset (section 2). One interpretation of this relationship is that the two source regions share a common trigger, so that the two sources have heliocentric distances R_1 and R_2 and solar wind speeds v_{sw1} and v_{sw2} that are related by

$$\frac{R_1}{v_{sw1}} = \frac{R_2}{v_{sw2}} \, . \tag{9}$$

When $v_{sw1} \sim v_{sw2}$, the two source regions are at very similar heliocentric distances (a 10-day time difference corresponds to a radial separation of 2 AU for $v_{sw} = 400$ km s^{-1}). Restricting consideration to radiation generated at multiples of f_p in foreshock sources [e.g., *Cairns and Gurnett*, this issue], this interpretation potentially has substantial implications for variations in the solar wind characteristics and shock position with heliographic latitude and longitude.

9. DISCUSSION

The preceding analyses demonstrate the plausibility of the following theory for the transient emissions observed in the outer heliosphere: the radiation is generated near f_p and/or $2f_p$ when solar wind density inhomogeneities enter one or more regions of the foreshock predicted sunward of the inner heliospheric shock. This theory relies heavily on density inhomogeneities observed in the solar wind to explain many features of the radiation in natural ways. The strengths of the theory, as developed here, are summarized below. At the present time this theory appears to have no qualitative or semiquantitative deficiencies.

1. The theory accounts semiquantitatively for the generation of f_p and $2f_p$ radiation with the observed high brightness temperatures under plausible foreshock conditions. Langmuir waves with $T_L \sim 10^{17} - 10^{18}$ K, which are plausible based on extrapolations from planetary foreshocks and theoretical estimates, can generate the observed levels of radiation in distances small compared with 1 AU and the estimated radial thickness of the foreshock source.

2. Generation of f_p and $2f_p$ radiation at the observed frequencies (2 – 3 kHz) from foreshock sources outside 50 AU can be quantitatively explained in terms of solar wind density enhancements entering the foreshock. Density enhancements with factors of 4 – 10, as observed in the solar wind, are required. These requirements are lessened if steady state or transient density enhancements above the expected r^{-2} falloff in the solar wind density occur in the outer heliosphere. The density enhancements are required to last at least a fraction of a day to several days.

3. The f_p and $2f_p$ radiation generated in these enhanced density regions of the foreshock can propagate in to heliocentric distances of order 10 AU under plausible conditions.

4. The sporadic nature of the transient events is not plausibly due to frequency blocking, even in models involving distinct sources for the 2-kHz component and the transient events. Plausible explanations involve unusual source conditions required for generation of observable f_p and/or $2f_p$ radiation, and natural amplitude variations in natural signals close to the instrumental background.

5. Qualitative theoretical interpretations for the relatively unusual source conditions evidently required for generation of observable radiation exist: triggering by fast solar wind streams [*McNutt*, 1988], forward/reverse shock pairs resulting from pressure/density pulses interacting with the inner heliospheric shock [*Lazarus and McNutt*, 1990], and instabilities of a cosmic ray-modified inner heliospheric shock [*Zank et al.*, 1990]. The first two interpretations imply the likely presence of large density enhancements and increased Langmuir wave levels in the foreshock.

6. The theory predicts a wide variability in the starting frequency of the emissions, as observed, due to the considerable differences in density enhancement factor expected theoretically (and observed) in the solar wind. The absence of observable transient events well below 2 kHz implies that the unusual source conditions required for observable emission are connected with large density enhancement factors. The sporadic occurrence of transient emissions is consistent with large enhancement factors being relatively rare, as expected.

7. The fine structure in and overall bandwidth of the radiation require that the radiation is generated in either distinct multiple source regions or a single extended source with regions emitting at different frequencies. These requirements are consistent with the role played by density enhancements elsewhere in the theory.

8. The frequency drift of the transient emissions is interpreted in terms of finite-duration bursts of radiation undergoing Fermi upshifting due to multiple scatterings between outward moving solar wind density enhancements and the outer density wall of the heliospheric cavity [*Czechowski and Grzedzielski*, 1990]. The effective high frequency cutoff for the radiation near 3.5 kHz, the decreasing radiation intensity with time, and the similar drift rates for all seven transients thus far observed are consistent with the Czechowski and Grzedzielski model.

9. Implausible Langmuir wave levels are required to generate $3f_p$ radiation with the observed brightness temperatures in path lengths small compared with 1 AU and predicted foreshock dimensions. The $2f_p/3f_p$ emission models, while explaining the sporadic nature and frequencies of the radiation naturally, are therefore not favored over $f_p/2f_p$ models.

The 2-kHz component can also be explained in terms of f_p or (most probably) $2f_p$ emission from an extended region of the foreshock sunward of the termination shock. Strengths 1, 2, 3, 7, and 9 for the transient theory are also applicable for this theory. The available observational data are consistent with radiation that is generated and upshifted relatively continuously (section 2), consistent with *Czechowski and Grzedzielski's* [1990] theory. Additional strengths and features of the theory are as follows.

1. The short time scale amplitude and frequency variations of the 2-kHz component show evidence for frequency blocking effects, particularly in the Voyager 2 data. However, the radiation's disappearance in 1987 and onset in 1991 are not plausibly due to frequency blocking. Plausible explanations involve changes in the source conditions and natural amplitude variations of signals close to the instrumental background.
2. These unusual foreshock conditions may result from long-term variations, possibly due to instabilities of a cosmic ray-modified shock, of the termination shock. The relatively constant frequency and slowly varying amplitude of the radiation indicate that transient phenomena such as stream-stream interactions and pressure pulses are unlikely to be related to the required unusual source conditions.

The $f_p/2f_p$ theory for the 2-kHz component has several major weaknesses. First, the relatively constant frequency range and relatively continuous nature of the radiation are inconsistent with the range in density enhancement factors and expected rarity of large density enhancements required to produce radiation with the observed frequencies in the outer heliosphere. Second, generation of $f_p/2f_p$ radiation at the observed frequencies in the outer heliosphere ($R \geq 50$ AU), as apparently required by the available Voyager observations [*Kurth et al.*, 1984, 1987], requires large density enhancements over the densities predicted on the basis of 1-AU ecliptic data. If transient density enhancements are ruled out as above, then long-term, large-scale density enhancements are required. No model for such density enhancements in the outer heliosphere presently exists. Third, differences between the transient events and the 2-kHz component argue (section 8) that these emissions have different generation mechanisms and/or source regions. We note that if a model existed for long-term, large-scale but localized enhancements in the foreshock plasma density then transient density inhomogeneities could be removed from the 2-kHz theory. The above weaknesses might then become strengths for the modified theory. Further research on long-term density enhancements in the outer heliosphere and other generation mechanisms for the 2-kHz component are clearly required.

The foregoing theories appear capable of explaining all attributes of the transient emissions and many attributes of the 2-kHz component. The theoretical interpretation of the data is hampered by the fact that the radiation levels are close to the detection thresholds of the Voyager plasma wave instruments. Future plasma wave observations will hopefully further constrain the theories. However, flexibility is clearly essential when constructing future tests of these theories. One strength of the theory for transient emissions, the strong role of solar wind density enhancements in providing qualitative and semiquantitative explanations for many aspects of the radiation, is also a potential weakness. In particular, observational and theoretical research is required on (1) the density enhancement factors expected in the outer heliosphere, (2) the correlation of transient events with solar wind phenomena [cf. *McNutt*, 1988], (3) the global three-dimensional structure of the solar wind, (4) the likelihood of distinct source regions with substantially different plasma conditions, and (5) the degree of frequency blocking, absorption, and Fermi upshifting of f_p and $2f_p$ radiation in realistic, inhomogeneous solar wind plasmas. Attention should also be devoted to estimating the damping rate for the upshifting radiation: the time scale of the 1983–1984 transient events implies a damping rate $\gamma \geq 5 \times 10^{-8}\ \mathrm{s}^{-1} \sim 5 \times 10^{-11}\ \omega_p$, which appears rather small. Analyses of foreshock modifications associated with fast solar wind streams [*McNutt*, 1988], forward/reverse shock pairs driven by pressure/density pulses near the termination shock, and an unstable cosmic ray-modified termination shock [*Zank et al.*, 1990] should be pursued. Finally, the foreshock source models suggested here make no appeal to solar cycle variations in positioning the inner heliospheric shock, so as to locate the inner heliospheric shock further out than the present positions of the Voyager spacecraft. Further work is required to see if such effects are important [cf. *Lazarus and McNutt*, 1990].

10. CONCLUSIONS

Prior to developing our theories for the outer heliospheric radio emissions we presented important reanalyses of the Voyager plasma wave data. One aspect of these analyses involved removing the effects of the notch filter near 2.4 kHz from the wideband data. The notch filter is found to be qualitatively and quantitatively important in affecting the characteristics and interpretation of the 2-kHz component. The observed emissions can be placed in two classes with significantly different properties: transient emissions and the 2-kHz component. Important results recognized here include the widely varying starting frequencies and multiplicity of the transient emissions, as well as the demonstration that the characteristics of the 2-kHz component are consistent with radiation that is generated, upshifted, and absorbed quasi-continuously. Three aspects of the transient emissions are found to be qualitatively consistent with *Czechowski and Grzedzielski's* [1990] theory for frequency drift.

The properties of the transient emissions can be plausibly explained in terms of f_p and/or $2f_p$ radiation generated when regions of enhanced solar wind density convect through one or more parts of a foreshock sunward of the inner heliospheric shock. In particular, this theory can apparently explain all aspects of the emissions qualitatively or semiquantitatively in terms of foreshock sources located outside 50 AU. An analogous theory involving transient density enhancements in an extended foreshock source can account for the levels and characteristic frequency of the 2-kHz component. However, this theory is qualitatively unable to account for the relatively constant frequency and presence of the 2-kHz component. These difficulties could be alleviated by locating the source in a large-scale, localized, slowly time-varying foreshock region with significantly enhanced plasma density. Most likely, however, these theoretical difficulties imply that the 2-kHz component and the transient emissions have different generation mechanisms and/or source regions.

Future plasma wave and solar wind density observations will further constrain theories for the radiation, as will quantitative theoretical analyses of the multiple roles played by density inhomogeneities. Solar cycle variations in positioning the termination shock or in enhancing the steady state plasma density near the shock should also be investigated. Since Voyager 1 is traveling approximately toward the expected apex of the inner heliospheric shock (a likely source region) at a rate of order 3.5 AU/yr, in situ testing of the foreshock theories developed here may be possible in the foreseeable future.

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