COSMIC WINDS AND THE HELIOSPHERE

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About the cover:

The front cover is a composite of an optical image of the starburst galaxy NGC 253 and the X-ray emission in the energy range 0.1–0.4 keV, as detected by the ROSAT PSPC instrument (white contour). This extended X-ray halo, signifying hot gas outflow to beyond 10 kpc, is probably not related to the current nuclear starburst—it is most likely the relict signature of an earlier event, which occurred about 10^8 years ago. The total mass ejection is estimated at five million solar masses. Image courtesy of the Max-Planck-Institut für extraterrestrische Physik.

About the back cover:

The back cover is a composite image of the solar corona as captured in white light during a solar eclipse on 30 June 1973, with an Hα picture obtained simultaneously. The coronal picture has been processed in order to enhance small-scale intensity gradients. See the Chapter by Esser and Habbal. Figure courtesy of S. Koutchmy.

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CONTENTS

OUTER HELIOSPHERIC RADIO EMISSIONS

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In this chapter we review the observations and various interpretations of the 2 to 3 kHz heliospheric radio emissions that have been detected by the plasma wave receivers on the two Voyager spacecraft over the last decade or so. A new event which began in mid-1992 has offered unprecedented information on the details of the emission. We concentrate on interpretations that involve emission at the plasma frequency or its harmonic near the heliopause. The emissions appear to be triggered by a system of interplanetary shocks associated with a global merged interaction region that had its origins in a series of spectacular solar events in the spring and early summer of 1991. Using a model for the propagation of these disturbances throughout the heliosphere and the observed delay from the activity on the Sun to the onset of the radio emission, estimates of the distance to the source region are derived ranging from 110 to 160 AU. We demonstrate the rich nature of the radio emission spectrum and the type of information it may provide about the heliopause and the triggering interplanetary shocks.

I. INTRODUCTION

From our perspective on Earth, it is natural to think of the Sun's atmosphere as extending to the upper reaches of the corona, primarily because with proper visual inspection the corona appears analogous to the Earth's upper atmosphere and ionosphere. However, another way to view the solar atmosphere is to trace it to its farthest reaches, to the limit of its primary influence on the surrounding medium. In this definition, the Sun's atmosphere extends to the heliopause which is the boundary of the region of space dominated by magnetic fields and plasmas originating in the Sun. Certainly in the context of "cosmic winds" it is more appropriate to take this more expansive point of view than the former.

Low-frequency 1.8 to 3.6 kHz radio emissions observed in the outer heliosphere are the subject of this chapter. We will make a strong case that these radio emissions are the result of the interaction of the Sun with the interstellar medium, similar in some respects to the more familiar solar type II and III radio bursts which are the result of the interaction of certain types of solar activity, coronal mass ejections, high-speed plasma streams, and other types of solar activity with the solar wind within 2 AU. By analyzing these high-frequency radio emissions (from about 30 kHz to above 400 MHz) a great deal has been inferred about the physics of the inner heliosphere; for example, the radial variation of the solar wind plasma density and the trajectory of disturbances propagating outward from the Sun.

The low-frequency radio emissions discussed in this chapter are a relatively new phenomenon, first reported in 1984 (Kurth et al. 1984*a*). Because they are restricted to the frequency range between about 1.8 and 3.6 kHz, they cannot normally propagate in the solar wind inside of about Saturn's orbit (~10 AU). This limit arises due to the cutoff of electromagnetic radio waves propagating in the so called free-space modes at the electron plasma frequency $f_p = 9000(n_e)^{1/2}$ where n_e is in cm^{-3} and f_p is in Hz. Because the Voyager spacecraft are the first to carry very low frequency receivers significantly beyond the orbit of Earth, they have provided our first (and only) opportunity to explore the very low-frequency end of the solar spectrum. Current evidence strongly suggests that these radio emissions are the result of the Sun's interaction with the surrounding interstellar medium and herald that most-distant extreme of the Sun's upper atmosphere, the heliopause.

The first observations of the low-frequency heliospheric radio emissions were of a major emission event which began in the latter part of 1983 and which extended into 1984 (Kurth et al. 1984*a*). This event was detected while Voyager 1 was at a heliocentric radial distance of about 17 AU and Voyager 2 was at about 13 AU. After the recognition of this event, it was also noted that a number of weaker events had been observed as early as 1982 by Voyager 1 as close as 15 AU to the Sun (Kurth et al. 1984*b*). As we will discuss at length, the events of the early 1980s were still strongly influenced by the relatively high density of the solar wind surrounding the spacecraft and some of the important aspects of the emissions remained largely masked for nearly a decade.

The early reports of the radio emissions discussed a number of different possible sources but most of the sources had substantial problems in explaining the observations. While speculative, the favored source had to do with the complex interaction of the solar wind with the interstellar medium and focused on the region near the termination shock where the supersonic solar wind slows to subsonic speed in response to the slowly moving surrounding interstellar medium. However, literally years passed with no major re-occurrences of the radio emission while the Voyagers moved outward through the heliosphere; it became more and more difficult to consider a source in the very distant heliosphere.

During the period of 1989–1991 a small number of very weak events were detected (Kurth and Gurnett 1991) that fueled continued interest in the phenomena and, further, suggested a consistent morphology for the events consisting of a relatively stable low-frequency component centered near 2 kHz and a more transient higher frequency component which appeared as one or more upwardly drifting tones extending to the 3 to 3.6 kHz range. Finally, beginning in 1992, nearly a decade (and perhaps more importantly, a solar cycle) later, another major event appeared, stronger than even the 1983–1984 event (Gurnett et al. 1993). This event, observed from the vantage points of 39 and 51 AU by Voyagers 2 and 1, respectively, was apparently unaffected by any local effects, hence, provided an unadulterated view of the entire spectrum and eliminated most possibilities for a source in the inner heliosphere. Simultaneous observations by Ulysses of the low-frequency Jovian radio spectrum were also available during this recent event (M. L. Kaiser, personal communication) and the Ulysses observations are used below to argue against a Jovian source (Gurnett and Kurth 1994*a*).

Given the strong new event, the lack of local effects, arguments that the source was not located in the inner heliosphere (<10–15 AU), and a concerted effort by the Voyager Project to obtain more high-resolution observations than were available during the 1983–84 event, Gurnett et al. (1993) offered a new model for the source of the radio waves and a new proposal for the triggers of the events. This model involved a system of interplanetary shocks associated with unusual levels of solar activity in the declining phase of the solar cycle that propagate outward through the solar wind and excite radio emissions in the cold plasma just beyond the heliopause. Two of the strongest Forbush decreases ever monitored are thought to be indicators of strong, global regions of turbulent magnetic fields and plasmas which interact with the interstellar medium to act as triggers for the two major radio emission events observed to date. Subsequently Czechowski et al. (1995), Zank et al. (1994), and Whang and Burlaga (1994) have proposed somewhat different models involving the interaction of solar wind disturbances (shocks) with plasmas between the termination shock and the heliopause to generate the radio emissions.

In this chapter we will review the salient features of the observations which bear on the interpretation of the source of the radio emissions and the clues they provide on various possible sources. Then, we review models which have been proposed to explain the frequency-time structure of the emissions. We will provide a summary of the basic generation mechanism which has been discussed at length for the radio waves. We then discuss the different types of triggering events that have been proposed and demonstrate why the events associated with two major Forbush decreases would seem to be the most likely. The identification of plausible triggering events naturally leads to an estimate of the distance to the source region through time-of-flight considerations. We will summarize the results of these analyses to date. Because these radio emissions are the first direct observations of an interaction associated with the outer most regions of the heliosphere, and because a number of questions are raised about certain aspects of the models, it follows that additional work is suggested and we discuss avenues of continued research which should help to clarify the situation.

II. OBSERVATIONS

The observations of heliospheric radio emissions are limited to the two Voyager spacecraft over the time interval beginning in about 1982 and continuing to the present. During this time, the spacecraft have traversed some 40 AU and have moved in significantly different directions. Figure 1 shows the trajectories of the two spacecraft relative to the outer planets in two orthogonal views. The left panel shows the trajectories projected into the ecliptic plane. The right panel shows the trajectories rotated into a common meridional plane. Note the marked departure of Voyager 1 to northern ecliptic latitudes after its encounter with Saturn in 1980 and the deflection of Voyager 2 into the southern hemisphere subsequent to its Neptune encounter in 1989. Voyager 1 is moving about 3.5 AU yr^{-1} while Voyager 2 is traveling at about 3.0 AU yr^{-1}. The vector $\mathbf{V}_S$ represents the velocity of the Sun with respect to the local interstellar medium (Ajello et al. 1987).

The observations of the heliospheric radio emissions are best summarized by the frequency-time spectrograms in Color Plates 13 and 14. The Voyager 1 observations are provided in the top panels of Plates 13 and 14 and those from Voyager 2 are in the bottom panel of each. In both plates, the wave observations are presented as intensity as a function of time (abscissa) and frequency (ordinate) over the range of 1 to 4 kHz. Intensity is encoded according to the accompanying color bar wherein red represents the most intense waves and blue the least intense. Relative amplitudes are provided by the decibel scale accompanying the color bar, but some caution should be exercised in the use of this scale. The wideband receiver which provides these observations utilizes an automatic gain control (AGC) circuit, hence, absolute amplitudes are not directly available from these data (see Scarf and Gurnett 1977). In particular, because the input signal strength could vary enough, particularly from interference below about 1 kHz (not shown), to affect the gain of the AGC amplifier, the amplitudes from two different times cannot be accurately compared. However, we believe that the presentations in Plates 13 and 14 do not suffer from significant shifts in gain and the qualitative comparisons we discuss herein should be faithfully represented in the plates. The relative amplitudes across frequency can be accurately compared for a single time period, but because only a narrow range of dynamic range (10 dB in Plate 13 and 13 dB in Plate 14) has been mapped to the color bar, signals stronger than the maximum of this range will all appear as red.

While the data in Plates 13 and 14 appear to be continuous, the actual measurements are only available at times indicated with tics along the top of the spectrogram. Specifically, prior to about mid-1987 measurements are only available about once per month on each spacecraft and the spectra are linearly interpolated from one measurement to the next. Later, measurements are made once per week or even more often. Each measurement consists of a spectrum averaged over about 15 s. For the 2 to 3 kHz emissions, the improved temporal resolution (up to 1 spectrum per 2 hr in one case) give us confidence that the interpolation across month-long intervals prior to mid-1987 does not introduce misleading features in the spectrograms. The narrowband line at 2.4 kHz is an interference band from the spacecraft power supply; a notch filter is centered on this frequency to minimize the intensity of this interference and may impose a gap in an otherwise continuous spectrum

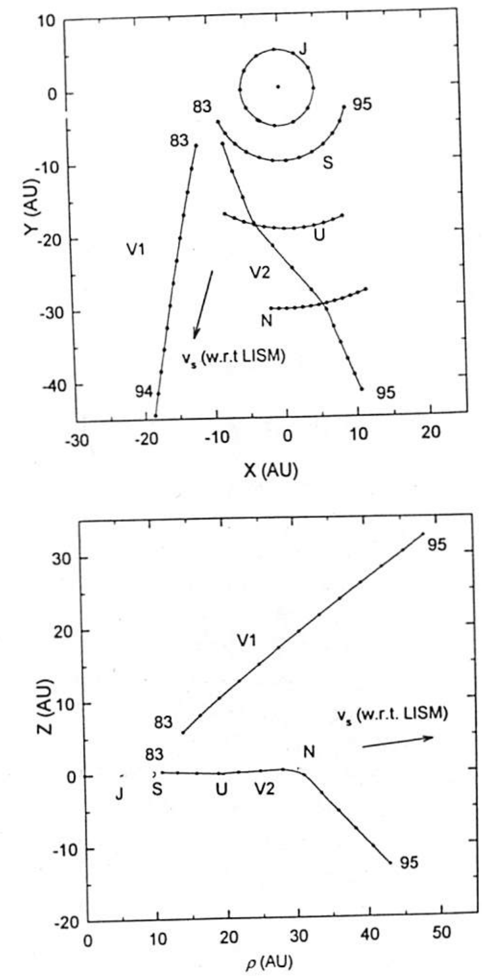

Figure 1. A summary of the geometry of the observations presented in Color Plate 13 including the positions of the outer planets and the two Voyager spacecraft from 1983–1995.

for real signals at this frequency.

Plate 13 covers the period from 1983 through 1994 and, subject to the caveats above, shows the relative strength of the various radio emission events over the 12-yr-long interval. The original event begins on about day 242 of 1983 and lasts for 6 to 9 months, although there is some evidence of the 2-kHz component extending into 1987. The most intense period of activity commences on about day 188 of 1992 and extends in the 3-kHz range until late 1994; the low-frequency component is still visible in the most recent observations which extend through the end of 1994. This event appears to comprise secondary events, such as the renewed activity beginning on about day 195 of 1993, seen most prominently near 3 kHz; at low frequencies this renewed activity overlaps the decaying phase of the 1992 event. The re-intensification in 1993 qualifies as the third most intense period of activity observed to date. Still another secondary event appears in early 1994 and extends to the middle of the year.

Four more events can be seen at much weaker intensities in the interval from 1989 through 1991 and one isolated event in late 1985. These weaker events, especially those observed in 1989–1991 are only marginally detectable in the Voyager 1 spectrogram in Plate 13; there is only a hint of the 1991 event in the Voyager 2 observations.

The lowest frequency extent of any of the observed events is about 1.8 kHz. The low-frequency component is much more prominent and is strikingly steady in the 1992 event and we will argue below that the lack of similar low-frequency emission in the 1983 event is due to significant local plasma effects associated with the relatively high local plasma frequencies at the locations of the spacecraft (between about 13 and 17 AU). The maximum frequency extent of any of the emissions is about 3.6 kHz. As described by Kurth and Gurnett (1991) the two components of these several radio emissions can be described as a relatively continuous low-frequency component and transient high-frequency components consisting primarily of narrowband emissions which rise in frequency with time. Kurth et al. (1987) reported that the 3-kHz emission beginning in 1983 increased in frequency at a rate of about 1 kHz yr^{-1}. Kurth and Gurnett (1991) reported frequency drift rates ranging from 1.4 to 1.8 kHz hr^{-1} for the events in 1989 and 1990 and the maximum drift rate in the 1992–1993 event is about 3.0 kHz yr^{-1} (Gurnett et al. 1993).

The radio emission events depicted in Plates 13 and 14 are remarkable for a number of reasons. These represent the longest-lived radio emission events ever detected from a solar system source excluding quasi-permanent phenomena such as Jovian decimetric emissions and continuum radiation trapped in planetary magnetospheres. The fact that the heliospheric events show discrete, coherent frequency-time structure over time scales of several months to over a year indicate a dynamical process operating over very long distance scales for any reasonable range of velocities expected in the interplanetary medium whether related to bulk plasma motion or characteristic speeds such as the Alfvén or sound speeds. An alternative way of viewing the very long dynamical structures is relative to a process which evolves in a monotonic manner over the time scale of many solar rotations. This would seem to be incompatible with the normal stream structure observed in the interplanetary medium out to the most distant spacecraft some 60 AU from the Sun.

Another point to notice from Plates 13 and 14 is the strong similarity between the observations made at the two spacecraft. Over the interval of observation the spacecraft were separated by distances ranging from about 10 to 54 AU. This is conclusive evidence that the phenomena must be a radio emission propagating from a distant source and not an effect associated with the plasma environment near the spacecraft. This, coupled with the fact that the emissions, especially near the end of the intervals presented, are at frequencies well above the highest characteristic frequency of the plasma $\sim f_p$ near a few hundred Hz confirm the identification of these emissions as freely propagating radio emissions.

There are some subtle differences between the spectra observed by the two spacecraft. Some of these may be due to the slight differences in sensitivity between the two receivers and some may be actual differences in intensity possibly due to differing relative distances from the source. Kurth et al. (1994) have performed preliminary analyses of these differences from the assuming they are due to differing distances between the source and the two spacecraft. While such analyses suggest that these differences might be used to locate the source (in conjunction with the direction-finding studies discussed below), the cross-calibration between the two instruments is not known well enough to be confident in the results at this time.

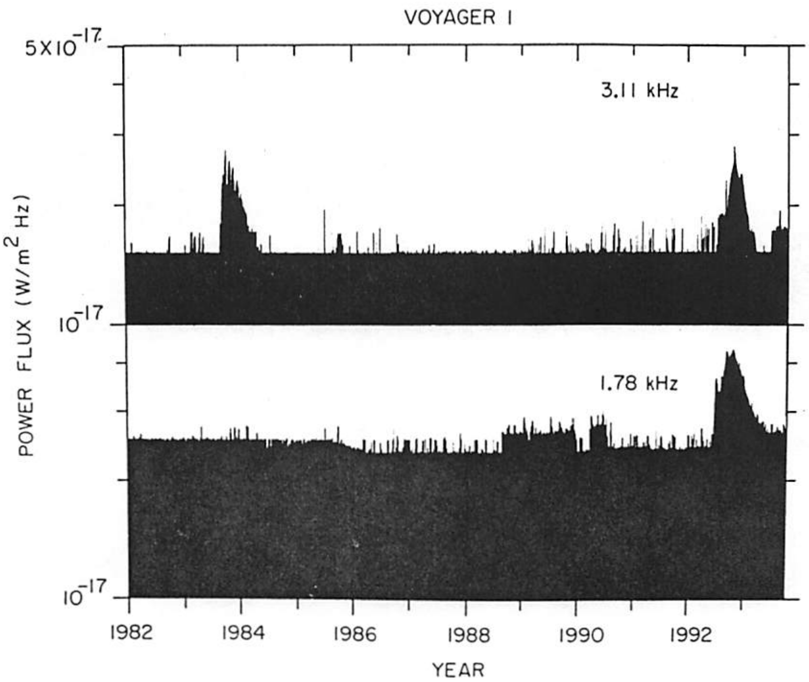

Figure 2. The time history of intensities in the Voyager 1 1.78- and 3.11-kHz spectrum analyzer channels from 1983 through late 1993.

Figure 2 provides calibrated intensity as a function of time for the time period from 1982 through late 1993 for discrete spectrum analyzer channels at 1.78 and 3.11 kHz as observed by Voyager 1. Unfortunately, because of a failure in the Voyager 2 spacecraft data system a few months after launch, similar observations are not available from Voyager 2. Nevertheless, the intensity information in Fig. 2 is useful to obtain absolute amplitude information and provides a more continuous set of observations in that the intensities in these channels are sampled every 4 to 96 seconds, depending on the telemetry mode of the spacecraft, at least when the spacecraft is being tracked which ranges from nearly continuously to as little as about 12 hours per day over this time interval. Because of the smooth variations in the intensity of these radio emissions, we linearly interpolate over the tracking gaps in this figure. The 1983-1984 event and the 1992–1994 event are most prominent in this presentation, but the late 1985 event and the most recent (1993–1994) activity are also easily discerned. The weaker events between 1989 and 1991 are not visible in these data; the effective integration of the signal from the wideband receiver utilized for Plates 13 and 14 make the wideband observations a few dB more sensitive than the spectrum analyzer channels.

Figure 2 shows the primary difference in the two major events as a near absence of any response in the 1.78-kHz channel for the earlier event. Figure 3 provides a comparison of the 3.11-kHz observations of the 1983 and 1992 events on common time and amplitude scales. In these temporally expanded views, another important difference in the two events is apparent. As reported by Kurth et al. (1984*a*), there are quasi-periodic decreases in the amplitude of the earlier event with a period of about 25 days. Kurth et al. speculated that these decreases were due to the periodic increase in the local solar wind plasma density often associated with the stream structure in the outer heliosphere. This speculation was later confirmed by R. L. McNutt (personal communication) and also by L. F. Burlaga (personal communication) by noting that these diminutions occurred during times of high solar wind plasma densities at Voyager 1. Now, with the benefit of the 1992 observations, it is also apparent that the low-frequency spectrum of the 1983 event was significantly affected by the relatively high solar wind plasma densities inside of 20 AU. This explanation would predict little or no such effect (periodic decreases in intensity and an attenuated low-frequency component) at the larger radial distances where the more recent observations were made. Assuming an r^{-2} variation in the local plasma density, the latter observations would be made with average plasma densities a factor of about 6 lower than the earlier ones; the associated plasma frequencies would be 2.5 times lower. Hence, one aspect of the earlier observations which was local in nature has been shown to be unimportant for observations in the more distant heliosphere.

Because the peak intensity is only a few times the background (instrumental) noise level, accurate estimates of the wave intensities must be obtained by subtracting this background level from the observed intensities. Hence, the apparent peak of the 1992 event at 1.78 kHz of 4×10^{-17} W m^{-2}Hz^{-1} actually corresponds to about 1.8×10^{-17} W m^{-2}Hz^{-1}. By assuming an isotropic source at a distance of at least the relative distance between the two spacecraft (because they both observe approximately the same intensity according to

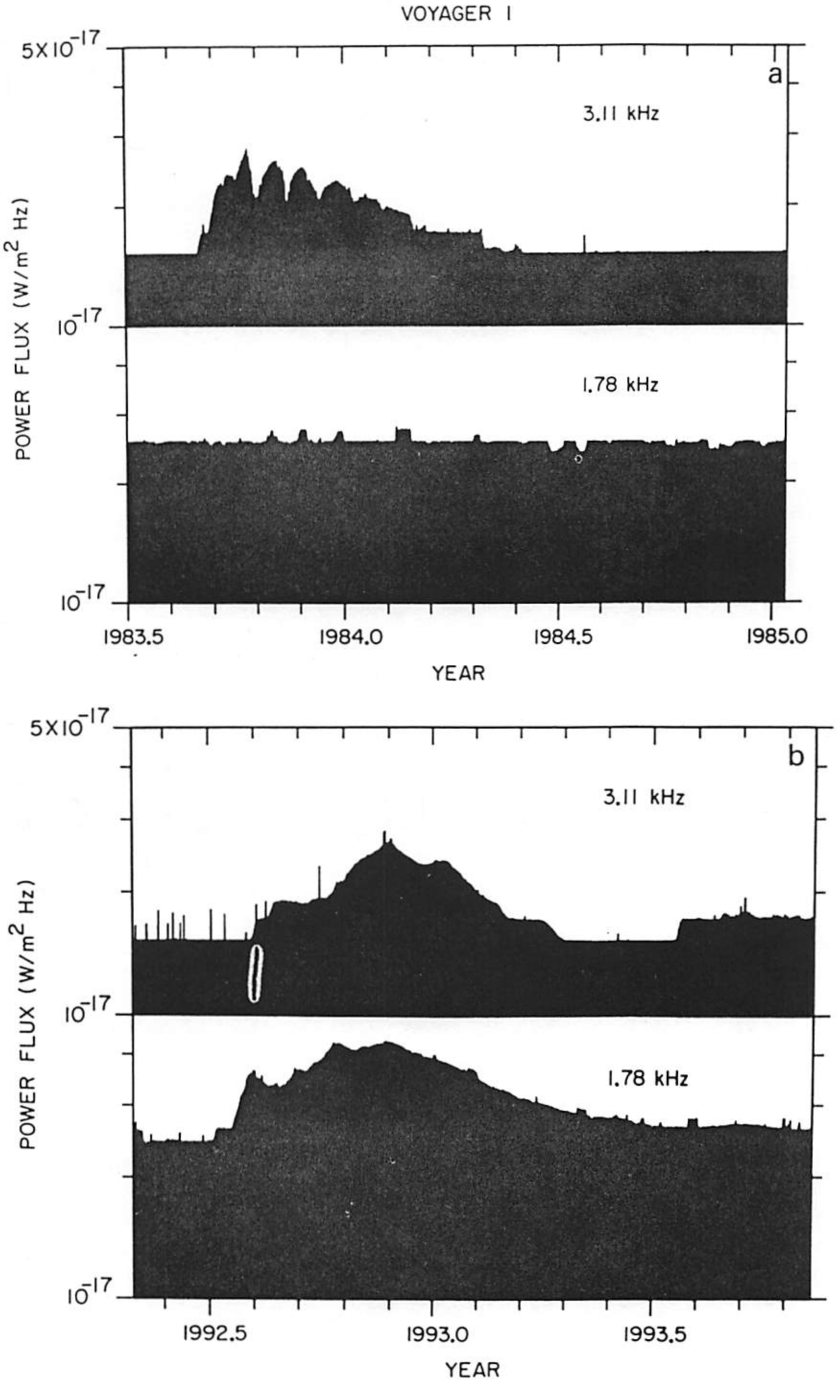

Figure 3. Expanded time scale plots showing the differences in the appearance of the (a) 1983 and (b) 1992 events.

Plate 14), Gurnett et al. (1993) estimate a total power of about 10^{13} W for this event at its peak, making it perhaps the most intense radio emission in the solar system. From observations obtained by Helios, the most intense solar type III radio emissions are just under 10^{13} W and the integrated average Jovian radio emission spectrum is 4×10^{11} W (Alexander et al. 1981).

Plate 14 provides an expanded view of the observations since early 1992, including the major event of 1992 and the renewed activity of 1993 and 1994 as viewed by Voyager 1 (top panel) and Voyager 2 (bottom panel) in the same format as in Plate 13. Here, the highly complex structure of the 1992–1994 event becomes quite clear. Below about 2.5 kHz the spectrum is dominated by the so called 2-kHz component that is generally more intense than the higher-frequency component. The 2-kHz component exhibits less spectral and temporal variation than the higher-frequency component, as was described as a general characteristic of the emissions by Kurth and Gurnett (1991). Even so, it is possible to see the onset of at least two narrowband structures near the leading edge of the low-frequency component and there is some evidence that these structures increase at least slightly in frequency over time. Toward the end of the event, near day 100 of 1993, there appear to be two distinct, constant-frequency emissions centered near 2 kHz and separated by 300 Hz or so. Hence, the "2-kHz continuum" component is not entirely continuous and exhibits some of the same, if less pronounced, drifting structure as the higher-frequency transient component.

The transient components at higher frequency earned this adjective because of their narrowband, increasing frequency natures. It is possible to identify clearly at least three of these features in the frequency range above 2.5 kHz during 1992, but there is evidence of one or more bands whose identity is more questionable due to their proximity to other bands. The first transient rising band forms the leading edge of the higher-frequency component of the 1992 event, beginning shortly after the 2-kHz component. The first two bands appear to drift to about 3.6 kHz as an asymptotic limit. Other bands do not rise to as high a frequency before they drop below detectability. The renewed activity in 1993 and 1994 consists of a pair of transient rising tones near 3 kHz in both cases, but with the maximum frequency attained in 1993 at about 3.4 kHz and only slightly above 3 kHz in 1994. The bands drifted at about 1 kHz y^{-1} in 1993 and those in 1994 drifted at about 1.5 kHz y^{-1}. In both pairs of bands, the band separation is approximately 200 Hz. Upon close inspection, the upper band of the 1994 re-intensification shows some evidence of fine structure (band splitting) with a separation of about 30 Hz. Both the 1993 and 1994 re-intensifications are accompanied by renewed or intensified emission in the 2 kHz band, as well. The renewed 2-kHz activity is superimposed on the decaying phase of the 1992 event and is, therefore, somewhat less noticeable. The new 1993 and 1994 activity is not as intense as the 1992 event.

As we will discuss in detail later, the narrowband emissions provide important information about the source of the waves. Because the emission frequency is almost certainly associated with the electron plasma frequency in the source region, the narrowband nature of the individual bands suggests that there is very little variation in density across the emitting region and that there is likely more than one emitting region. Because of natural variations in plasma densities at a variety of scale sizes in all known solar system plasmas, the narrow bands strongly suggest the source regions for these narrowband emissions are fairly localized and might be thought of as radio "hot spots" where conditions are optimal for wave generation.

III. SOURCE

Kurth et al. (1984*a*) considered several different possible sources for the 1983–1984 radio emission. Jupiter was thought to be the most reasonable of the possible planetary sources because it was known to be the source of rather intense radio emissions in the same spectral range as the heliospheric emissions (Scarf et al. 1979). However, because the two Voyagers observed virtually the same intensity despite their separation of several AU and, therefore, differing distances to the outer planets, radiation from a compact source such as a planetary magnetosphere was considered unlikely. Further arguments against the Jovian source included the fact that no 10-hour variations in the intensity of the heliospheric emissions were observed while such variations are characteristic of the Jovian continuum radiation and the spectral shape of the heliospheric emission was significantly different from the Jovian spectrum. These arguments were questioned, however, after it was suggested that the rising tones in the radio emission spectrum might be explained by a Fermi scattering effect caused by repeated reflections off of density irregularities moving outward from the Sun at an average of 400 km s^{-1} (Czechowski and Grzedzielski 1990,1992). Because this model for the frequency drifts required no *ad hoc* assumptions about the source of the radio emissions, it gained reasonable respect in the literature and was used to argue that the heliospheric cavity was relatively small, with a scale size of about 100 AU. Given the possibility that the radio emissions are trapped in a cavity, Kurth (1993) reconsidered the original arguments used to rule Jupiter out as a source and found that cavity effects might explain each of the observed characteristics which had been used to rule out this source. Kaiser et al. (1992) also thought that Jupiter should be reconsidered as the source of these emissions. A more complete discussion of the reconsideration of a Jovian source is provided in Kurth (1993).

Kurth (1993) also outlined a method by which a Jovian source might be verified or disproved via the use of Ulysses and Voyager observations during the time when Ulysses could still detect radio emission from Jupiter, specifically the continuum radiation below about 10 kHz. The proposed method basically relied upon the detection of an anomalously strong outburst of Jovian radio activity in the few-kHz range concurrent with the detection of a heliospheric radio event. Such a set of observations would provide a strong

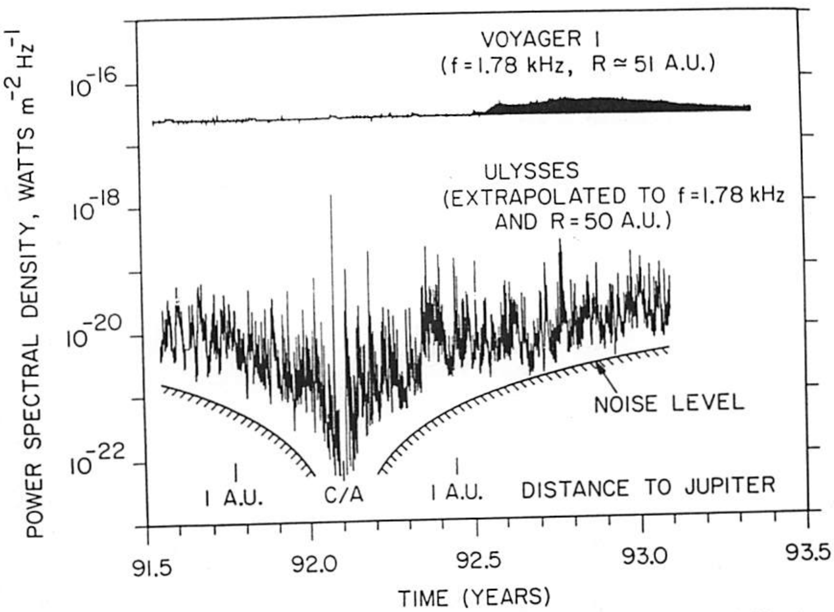

Figure 4. A comparison of radio emission observations from Ulysses and Voyager showing that there is a very large difference between the Voyager and Ulysses radio emission intensities. Also, note that there is no outstanding feature in the Jovian observations which correlates with the onset of the heliospheric emissions (figure from Gurnett and Kurth 1994*a*).

Jovian connection. Fortunately, the strong 1992 event provided an ideal case to form the basis for such a study. The results of the joint Ulysses-Voyager observations are given by Gurnett and Kurth (1994*a*). Figure 4 summarizes the results of this study. In this illustration, the Ulysses observations of Jovian continuum radiation at 10 kHz (M. L. Kaiser, personal communication; see also Stone et al. 1992) are used as an indication of activity at lower frequencies, because the solar wind plasma frequency at Ulysses for the several months around the Jupiter encounter ranged from less than about 2 to more than 5 kHz; it would be difficult to remove local solar wind density effects from the observations at 2 to 3 kHz. However, both Gurnett et al. (1980) and Kaiser (personal communication) report that Jovian continuum radiation falls off as $\sim f^{-4}$, hence, the 10-kHz intensities observed easily by Ulysses could be extrapolated to 1.78 kHz with reasonable assurance that no major Jovian radio events would be missed. Further, the Ulysses intensities were extrapolated to a distance of 50 AU assuming that they propagate freely from Jupiter as from a compact source. The lower plot in Fig. 4 shows the extrapolated Ulysses data. The effective noise level of these observations is shown as a hatched line below the observations. It might be argued that the r^{-2} extrapolation is incorrect based on an inspection of the trend in the Ulysses data to see weaker emissions closer to Jupiter. It could be that Jupiter is actually an extended source and the emission drops off somewhat more weakly than r^{-2}. However, this possibility does not generally affect the conclusions of the study.

There is no obvious intensification of the Jovian emissions which correlates with the onset of the heliospheric emission which is plotted on the same time and intensity scale. Furthermore, the intensities at Voyager with the background properly subtracted are some 300 times greater than the Jovian emissions extrapolated to 1.78 kHz. The only way to reconcile the differences in intensity would be to assume that the heliosphere forms a high-Q cavity, with Q of order 300 (Gurnett and Kurth 1994), in order to allow the energy density of the Jovian emissions to build up to the level observed by Voyager.

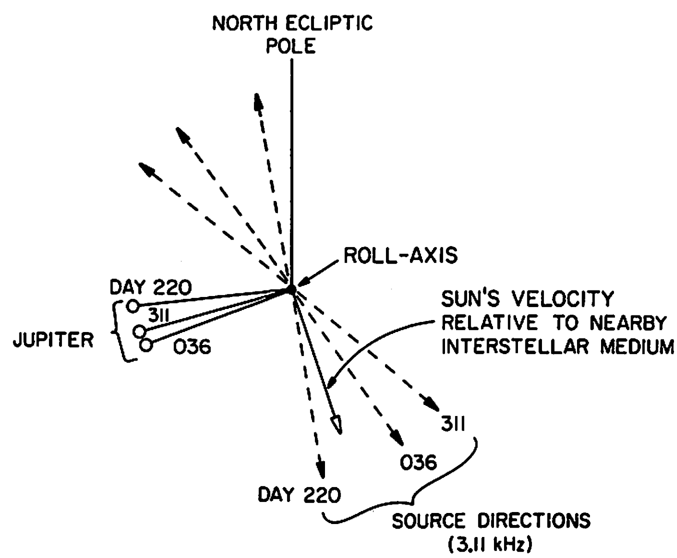

Figure 5. The results of direction-finding analysis performed for data obtained while Voyager 1 was executing roll maneuvers in order to calibrate the magnetometer. In general, the results are consistent with a source in the general direction of the arriving interstellar wind (figure from Gurnett et al. 1993).

Direction-finding observations obtained during the 1992–1994 event also argue against a Jovian source. Figure 5 shows the results of three such measurements reported by Gurnett et al. (1993), but we have added the position of Jupiter. In the plane of the sky as observed from Voyager 1, Jupiter does not seem to be consistent with the observed directions. From Fig. 1 it is clear that Jupiter is very close to the direction to the Earth, hence, the rotating dipole technique would not provide a reasonable direction to a possible source so close to the rotation axis. It is just this point, however, which may be the best evidence to exclude Jupiter. Along with measuring a roll phase angle which identifies the plane including the source of the radio emissions, the spin modulated signal also provides one other piece of information. The peak-to-peak amplitude of the modulation pattern is also measured. In some cases, this modulation is as much as 50% and in all cases measured so far, is a minimum of 10%. The strongest modulation would be for a point source located in a plane exactly perpendicular to the rotation axis of the spacecraft with no scattering. Scattering, an extended source, and a location closer to the axis of rotation are all effects which tend to decrease the modulation of the signal as the dipole antenna rotates. If we attribute all of the decrease in modulation to only the angle of the source from the rotation axis, then this would define a minimum angle with respect to the rotation axis of the spacecraft at which the source would have to be. If one includes the effect of an extended source (for which we have no estimate) or scattering (which Cairns [1995] estimates can account for all of the observed decrease in modulation), then the source must lie even farther from the axis of rotation than the limiting angle and closer to the plane perpendicular to that axis to account for the observed modulation depth. Because in 1992 the Voyager 1 was greater than 47 AU from the Sun and because the maximum perpendicular separation of the Earth (toward which the spacecraft rotation axis points) and Jupiter is about 6 AU, then the maximum angular separation of Earth and Jupiter is about 7°. The measured depth of modulation, if attributed only to the angle from the rotation axis, implies angular separations between the Earth and the source ranging from about 15° to 45° for events analyzed. Therefore, the modulation depth precludes Jupiter as a source.

Because an explanation for the drifting structures in the heliospheric radio emissions had been given by Czechowski and Grzedzielski (1990,1992) as the result of repeated reflections within a heliospheric cavity, it was necessary to determine the probability that the radio emissions were, indeed, trapped. Gurnett et al. (1993) showed that the 3.11-kHz component of the wave spectrum shows significant spin modulation due to the anisotropic distribution of wave vectors arriving at the Voyager 1 spacecraft. Such anisotropies would not be expected to exist in a high-Q cavity unless very stringent symmetries were present which would organize multiple reflections in some way. One known example of a natural radio cavity is the Earth's magnetosphere in which nonthermal continuum is trapped. While there is definite spin modulation observed for these terrestrial waves due to the fact they are propagating down the magnetotail and eventually leaving the system, the Q is very small, estimated to be only about 3 (Gurnett 1975). Hence, only a small number of reflections keep the continuum radiation trapped in any fixed volume. The spin modulation observation, then, suggests that at least the 3-kHz component of the heliospheric radio emission is not trapped. The 1.78-kHz channel does not show any evidence of spin modulation. While this result is consistent with trapping, there is also the possibility that scattering (Cairns 1995) or interference in this channel due to the operation of the spacecraft gyros, which are always operating when the spacecraft is rotated, explains the lack of spin modulation.

Inspection of Plate 14 shows a number of subtle (few dB) variations in intensity between the two spacecraft. For example, the leading edge of the

3-kHz component at the start of the activity is more prominent at Voyager 2 than Voyager 1. The upper-most band of the 3-kHz pair in the 1993 re-intensification is more prominent at Voyager 1. While the cross-calibration of the two instruments is known only to a few dB at present, that the relative intensities vary in such a manner can only be explained by true differences in the spectra. Such differences are not expected for trapped emissions, which would be virtually the same amplitude throughout the low-density volume of the heliosphere. We also point out that Czechowski and Grzedzielski (1990) determined that a 1 kHz yr^{-1} drift in the frequency of the radio emissions would imply a relatively small heliosphere, with a scale size of 100 AU or so. For some of the more recent events the drift rates are higher, up to about 3 kHz yr^{-1} for the 1992 event. Because it is the reflections off of the outward moving density irregularities and the number of these reflections over an interval of time which determine the frequency drift rate, it seems clear that the Czechowski and Grzedzielski (1990) model runs into difficulty with the more recent higher drift rates of up to 3 kHz yr^{-1}. This would almost certainly imply even shorter distance scales in the heliospheric cavity and the higher drift rates become increasingly difficult to support. However, Zank et al. (1994) and Czechowski et al. (1995) have suggested that transitory density structures downstream of the termination shock could serve to confine the waves in a volume of scale 70 AU, hence, drift rates up to the observed values could be supported, even though the heliopause is much more distant. In this case, though, it would seem important for the transitory structures to have reasonably long lifetimes of a few months.

Farrell (1993) has suggested another mechanism for the drifting features which also involves multiple reflections between the inner heliosphere and the heliopause. In this theory, however, the reflections are required to be resonant with monochromatic oscillations of the heliopause such that the wave travel time is an integer ratio of the boundary oscillation period for fixed frequency bands. The bands could drift in response to a gradually changing cavity size or to changing heliopause oscillation period. While this work offers a tantalizing new mechanism for the drifting features, it would seem that the resonance conditions are just too severe to expect them to hold over the 100+ AU of heliocentric distance scales and over the several-month periods which represent the lifetime for many of the observed bands. The irregularities observed in the interplanetary medium out to the most distant spacecraft would seem to be sufficient to disrupt any such resonances long before a discrete band could form.

We conclude that the waves are not trapped at the highest frequencies (>2.5 kHz). This still leaves the possibility that the lower-frequency waves might be trapped. However, if the source strength of the radio emission is roughly constant in frequency, then the observations in Plate 14 argue that the Q of the cavity is very small, because the intensity of the 2-kHz component is not more than 5 or 6 dB greater than the 3-kHz component.

The anisotropic distribution of wave electric fields allows a one-dimensional determination of the source direction following the technique of Kurth et al. (1975) and Baumback et al. (1976). Gurnett et al. (1993) reported this analysis for the Voyager spin-modulated observations at 3.11 kHz early in the 1992–1993 event and determined that the emissions were arriving from a direction which is consistent with the direction of arrival of the interstellar wind as determined by Ajello et al. (1987). Figure 5 shows the directions of arrival for three different determinations made possible by Voyager 1 roll maneuvers in late 1992 and early 1993 from Gurnett et al. (1993). Because the determinations of direction from the rotating dipole antenna technique only provide information on the plane of the source, we can show the results by showing the intersection of this plane with the plane of the sky. The reasonable agreement between the source directions shown in Fig. 5 with the direction of arrival of the interstellar wind is significant and contributes strongly to the Gurnett et al. (1993) source in the pile up region at the nose of the heliosphere. The variation in directions between the various determinations are much larger than the $\sim$1 degree uncertainties in the directions. By comparing the times when these directions were determined with the portion of the spectrum which was within the 3.11-kHz channel's passband at the time, it is clear that each direction determination is of a different transient narrowband emission. It follows that these bands are limited in size and are in somewhat different directions; this aspect contributes to the concept of radio "hot spots" introduced above. Further, additional direction-finding results show a systematic trend for the source to rotate from a direction consistent with the direction from which the interstellar wind comes to a direction some 90° away. This trend has been interpreted by Gurnett and Kurth (1994*b*) as a movement of the triggering shock's interaction region progressively moving from the nose toward the flanks of the heliosphere. Cairns (1995) point out that scattering might account for apparent changes in direction of arrival, but one would expect random variations from scattering, not systematic ones. The only direction-finding results from the 1983 event were reported by Kurth (1988); this result was consistent with radio emissions propagating radially either inward toward the Sun or outward from the Sun (a 180° ambiguity is an attribute of the rotating dipole direction-finding technique); however, an asymmetric modulation pattern prohibited any detailed analysis of this result.

Kurth et al. (1984*a*) also considered a distributed source in the inner heliosphere (in the heliocentric distance range of 10–15 AU) where the solar wind plasma frequency drops through the 2 to 3 kHz range. This source was eliminated because of a lack of *in-situ* observations in this region of significant Langmuir wave activity which might constitute a source for the radio waves (see the section on generation mechanism, Sec. IV below) and because it seemed unreasonable to expect the highly variable stream structure to generate a stable (on time scales of several solar rotations), narrowband radio emission.

Millisecond pulsars were also considered by Kurth et al. (1984*a*) as potential sources, but were ruled out on energetic arguments even though

Lipunov (1983) had estimated that a power flux similar to that observed might be expected. The increasing frequency of the emission and its complex spectrum, though, did not seem plausible for a fast pulsar source.

In considering other possible sources external to the solar system, Kurth et al. (1984*a*) hypothesized that average stellar systems might be the source of very low-frequency radio emissions at large radial distances from the parent star where the characteristic frequencies of the stellar plasmas would be in the few kHz range. However, if one considers such a source as being commonplace, it is only natural to look at the closest star, and in this case, the Sun is the obvious candidate. The Sun is also the obvious choice simply from the point of view of received intensity; for another star to dominate the solar radio spectrum, the emission intensity of the other star would have to be exceptionally high. The low frequency of the radio emissions and the known density profile of the solar wind immediately suggested that such radio emissions might be the result of solar wind interactions with the surrounding interstellar medium. Therefore, they proposed that a possible source might be associated with this interaction region and concentrated on the termination shock, the innermost portion of the interaction region.

The termination shock source was favored for several years. Several difficulties existed with this interpretation, dealing primarily with the details of the emission spectrum. Generating the emission at the observed frequency for reasonable termination shock locations was perhaps the most severe problem, because for source locations beyond the Pioneer and Voyager locations, it was difficult to understand how the source plasma frequency could be high enough to explain the emission frequencies. One tack was taken by Kurth et al. (1984*a*) in assuming the source had to be on the downstream side of the termination shock and the characteristic frequency would then increase by a factor of 2 if the shock were strong. Cairns and Gurnett (1992) pointed out that the normal generation regions for bow shock-associated radio emissions and some interplanetary shocks were not on the downstream, high-density side, but the upstream, low-density side of the shock. They suggested density variations of order 4 to 10 above ambient could boost the source frequency on the upstream side of the termination shock high enough to explain the observed frequencies. In updating this discussion, the Voyager 1 and Pioneer 10 are now at or beyond 60 AU from the Sun and the usual r^{-2} model for the solar wind plasma frequency places the local plasma frequency at about 300 Hz. To consider generation at the plasma frequency in the supersonic solar wind requires extraordinary conditions and special models. Partially in response to this problem, Zank et al. (1994) have studied the propagation of density enhancements through the termination shock and the possibility of generating radio emissions in the observed frequency range.

Another problem, not necessarily limited to the termination shock source, is the observed spectrum of emissions including two general bands near 2 and 3 kHz. The generation mechanism to be discussed below can result in emission at both the plasma frequency and its harmonic. The two observed bands often suggest an $f_p - 2f_p$ pair, but the ratio of the observed frequencies is generally considerably less than 2:1.

Previous to the 1992 event, there was also no satisfactory (or at least unique) explanation for the differences in the low-frequency, quasi-steady component and the higher-frequency transient (drifting) component. Different source regions for the two components were suggested, but this did not seem compatible with nearly simultaneous onsets for the two components.

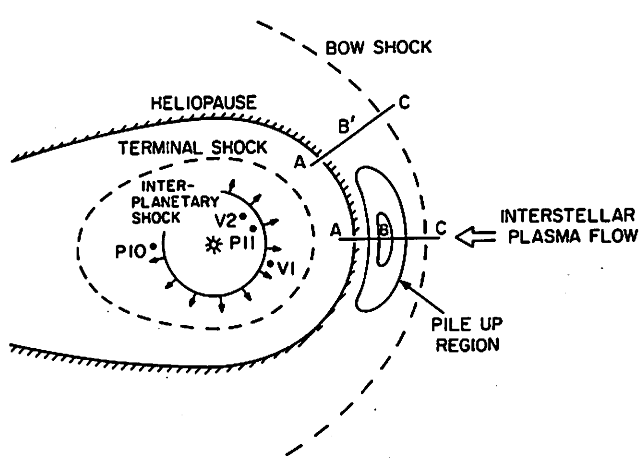

Figure 6. A model heliosphere showing the propagation of an interplanetary shock towards the heliospheric boundary (figure reprinted with kind permission from Elsevier Science Ltd.; from Gurnett et al. 1993).

Fahr et al. (1986) suggested that the heliopause itself might be the source of radio emissions. While they suggested a number of plasma wave modes involving ions as possible wave turbulence which could result in the emission of radio waves, these modes are almost certainly too low in frequency to be of importance here. However, Fahr et al. also suggest that there could be an "electrostatically turbulent heliopause layer" in which the characteristic frequency could be about 1.3 kHz (assuming an electron density of about 0.02 cm^{-3}). They suggested that radio emissions at such a frequency could propagate inwards to within about 16 AU of the Sun. They further suggested that the local magnetic field conditions at the heliopause might only be favorable for the generation of the electrostatic plasma waves at certain times, possibly associated with the phase of the solar cycle.

Subsequent to the detection and analysis of the 1992 event shown in Plate 14, Gurnett et al. (1993) interpreted the radio emissions as the result of an interplanetary shock moving through the plasma just beyond the heliopause generating electrostatic waves at the local plasma frequency. The electrostatic waves, as described below, then couple into electromagnetic waves at either the local plasma frequency or its harmonic, or both. This interpretation explains the rising frequency bands in the transient, higher-frequency component of the radio emission as the motion of the excitation source moving through a region of plasma with increasing density, possibly the interstellar plasma which is piled up at the nose of the heliosphere. The steadier, low-frequency component is interpreted by Gurnett et al. as a similar process as above but occurring near the flanks of the heliopause where there is little or no plasma pile up. This model is illustrated in Figs. 6 and 7.

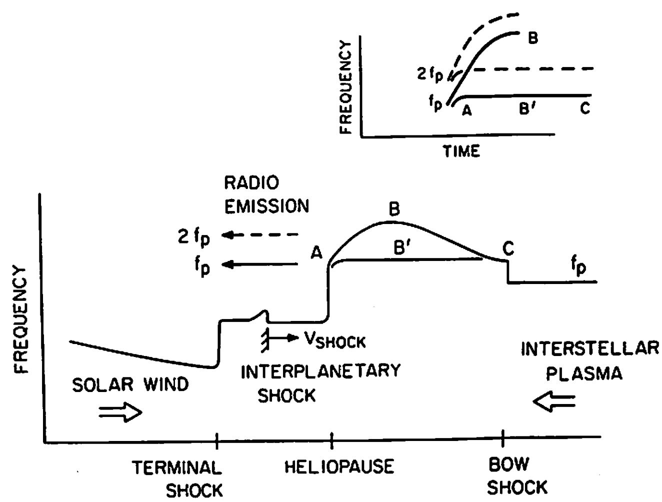

Figure 7. A schematic of the type of observations the model of Gurnett et al. (1993) predicts assuming a general structure for the outer heliosphere including a plasma pile up region near the nose (figure reprinted with kind permission from Elsevier Science Ltd.; Gurnett et al. 1993).

Figure 6 shows a model of the heliosphere including a termination shock and heliopause. The model is motivated by the work of Steinolfson et al. (1994) and includes a region upstream of the heliopause where interstellar plasma piles up as it is slowed and deflected around the heliopause. Shown in the interior of the supersonic solar wind is a more-or-less spherical shock wave moving outward from the Sun past the various outer heliospheric spacecraft and towards the interstellar medium. Two different cross sections are shown through the post-heliopause interstellar medium. First, section A-B-C crosses through the pile up region near the nose of the heliosphere. Second, section A-B′-C crosses through the post-heliopause interstellar medium closer to the flank of the heliosphere.

Figure 7 shows the profile of the plasma frequency (proportional to the square root of the plasma density) in the outer heliosphere through the very local interstellar medium downstream of the heliospheric bow shock. Between the heliopause and the bow shock, two plasma frequency profiles are shown, corresponding to cross sections A-B-C and A-B′-C in Fig. 6. Also indicated in

Fig. 7 is an interplanetary shock moving outward through the solar wind. The inset of Fig. 7 shows a schematic frequency-time spectrogram in the form of Plate 14 showing the form of narrowband emissions which might be expected for radio waves being generated along the two cross sections at either f_p or $2f_p$. Together, Figs. 6 and 7 form the basis for the Gurnett et al. (1993) model for the generation of the heliospheric radio emissions.

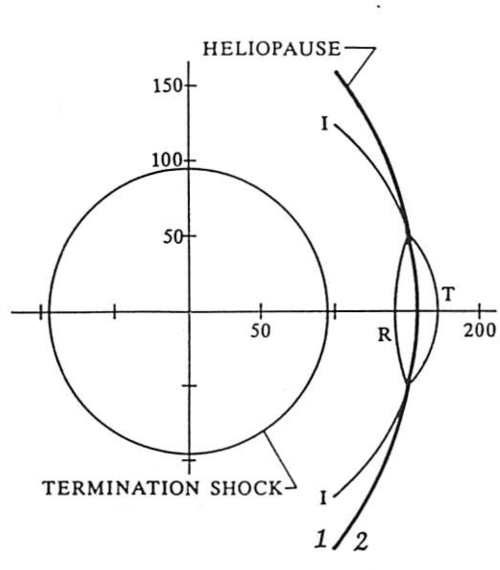

Figure 8. A schematic from Whang and Burlaga (1994) highlighting the salient features of their model. As an incident interplanetary shock (I) encounters the heliopause, both a reflected (R) and a transmitted (T) shock are formed. The transmitted shock is the triggering agent for the 3-kHz component of the radio emission spectrum and the reflected shock is responsible for the 2-kHz component in the Whang and Burlaga theory.

Whang and Burlaga (1994) have addressed the existence of different bands of emissions near 2 and 3 kHz in a different way than Gurnett et al. (1993). Whang and Burlaga point out that a shock which impinges on the heliopause, which they model as a tangential discontinuity with a strong density jump, would result in both a transmitted shock which continues into the interstellar medium and a reflected shock which propagates sunward in the post-termination shock solar wind as shown in Fig. 8. They calculate the plasma frequency in the vicinities of the transmitted and reflected shocks as a function of the incident shock speed and the position of the termination shock (which depends on the magnitude of the interstellar magnetic field). In this way, Whang and Burlaga show that the emissions near 2 kHz can be generated at the reflected shock while emissions near 3 kHz can be generated near the transmitted shock for a fixed location of the termination shock. They provide solutions for radiation generated at either f_p or at $2f_p$. This model suffers from at least two difficulties. First, is the reflected shock strong enough to generate radio emissions? The second, related problem is concerned with how the reflected shock could produce radio waves in the shocked solar wind downstream of the termination shock, but the original shock would not when it was in the same region prior to encountering the heliopause. We assume that the transmitted shock moves into a much cooler plasma in the interstellar medium, hence, we would expect Landau damping to be significantly reduced and radio emission to be more likely (Gurnett et al. 1993).

Zank et al. (1994) have studied the possibility of generating the heliospheric radio emissions in the region between the termination shock and the heliopause, where the solar wind is subsonic. This region, under stable conditions, would not normally be favored as a source regions because the nominal plasma density is only four times that of the supersonic solar wind just inside the termination shock assuming a strong gas-dynamic shock. However, this group has explored the modification of the downstream solar wind resulting from the propagation of shocks and density enhancements as one would expect from global merged interaction regions (GMIRs) and other outer heliospheric structures through the termination shock. They argue that the downstream solar wind would have significant density variations, including enhancements which could bring the perturbed density more in line with those required to support f_p or $2f_p$ radiation in the 2 to 3 kHz range. Simply stated, the propagation of a density enhancement through the termination shock will result in a propagating region of significantly elevated densities. Subsequently, should a solar wind shock follow such a disturbance, it could generate radio emissions as it propagates through the density enhancement, causing emissions with the appropriate frequency and frequency drift to explain the observed signals. Figure 9 illustrates the salient features of the Zank et al. model. It should be noted that Zank et al. calculate an expected distance to the termination shock in the range of 60 to 70 AU. Furthermore, they rely on emission at $2f_p$ in order to support frequencies as high as those observed. Given the current distances of the Voyager 1 and Pioneer 10 spacecraft (between 60 and 65 AU) with no clear indication of the termination shock in the near vicinity of the spacecraft, one would have to question this model simply on the basis of the quoted distance to the shock. The situation is even more questionable if the emission is at f_p; some arguments favoring emission at f_p are given in the discussion below.

Czechowski et al. (1995) have considered the interaction of the neutral interstellar hydrogen with the heliosphere and suggest that there could be a thin, cold, dense layer of plasma just inside of the heliopause resulting from the charge exchange interaction of the neutrals with the solar wind protons. They demonstrate that a shock propagating through such a layer with reasonable propagation speeds could generate radio emissions with the observed drift rates. Figure 10 shows the frequency drifts which could be obtained for reasonable conditions near the heliopause. In a sense, this model

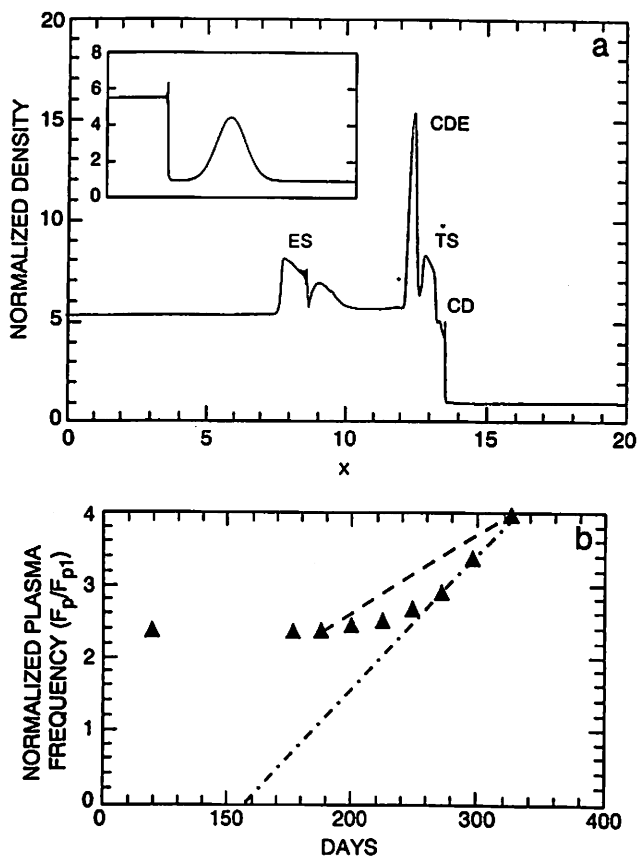

Figure 9. (a) A representation from Zank et al. (1994) depicting how an interplanetary shock propagating in the post-termination shock region can produce emissions drifting upward in frequency by exciting emissions near f_p as it moves through an increasing density structure set up by a previous density enhancement in the solar wind. A shock (*ES*) is emitted by the initial interaction of the density enhancement and the termination shock. The compressed density enhancement is denoted by *CDE*. *TS* is the transmitted interplanetary shock. *CD* is a new contact discontinuity. The inset shows the original density pulse prior to its interaction with the termination shock. (b) The frequency-time evolution of radio emissions generated by the transmitted shock as it crosses the *CDE* using two methods for calculating frequency drift.

does not deviate greatly from the of Gurnett et al. (1993). What is new here is the suggestion that a cold plasma with a suitable density gradient may exist just inside the heliopause and that the source region could lie sunward of the heliopause.

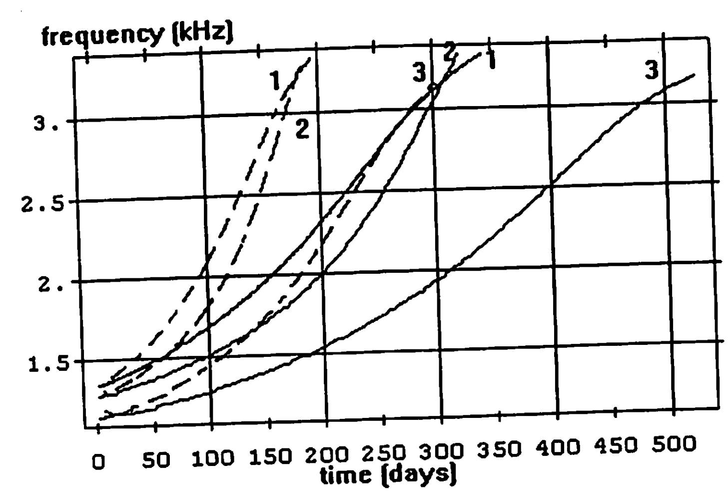

Figure 10. An illustration from Czechowski et al. (1995) showing rising frequency tones which might be emitted from the propagation of a shock through a proposed cool, dense layer just inside the heliopause. The cold plasma is the result of charge exchange processes with interstellar neutrals. The dashed (solid) lines represent shocks with an initial speed of 500 km s^{-1} (300 km s^{-1}) moving through cold plasma layers computed for three different heliospheric models.

IV. GENERATION MECHANISM

Given a source in the outer heliosphere, the only generation mechanism which has been addressed with any detail is a mechanism which is similar to that which is thought to be responsible for radio emissions from planetary bow shocks, interplanetary shocks, and solar type II radio bursts. The basic model relies on electrons being scattered or accelerated by the shock forming a bump-on-tail distribution which is unstable to Langmuir waves (also known as electron plasma oscillations). The Langmuir waves are local oscillations in the plasma and do not propagate appreciable distances. However, a number of theories have been developed that involve nonlinear interactions between the Langmuir waves and low-frequency waves such as ion-acoustic waves which result in the emission of an electromagnetic wave near the electron plasma frequency, hence, a radio wave which can freely propagate away from the source region. Another possible scenario is that two Langmuir waves nonlinearly interact to form an electromagnetic wave at about twice the electron plasma frequency. This basic picture was invoked by Kurth et al. (1984*a*) and Kurth (1988). The theory was seriously developed through a series of papers (Macek et al. 1991*a*,*b*; Cairns and Gurnett 1992; Cairns et al. 1992; Macek 1994) which attempted to determine the feasibility of generating the observed brightness of the radio waves within a reasonably sized generation region and with Langmuir waves of reasonable intensity. With the assumption of a source extending over a significant region of the termination shock with a thickness of no more than about an AU, the required amplitude of Langmuir waves is reasonably consistent with the expected amplitude obtained by extrapolating observed Langmuir waves upstream of planetary bow shocks to ~100 AU. Further, Kurth and Gurnett (1993) argued that such a layer of Langmuir waves is a reasonable expectation for the region just upstream from the termination shock.

The strong suggestion of radio "hot spots" based on multiple, narrowband emissions may invalidate somewhat the assumption of a source which extends over a significant region of the termination shock, but no quantitative analysis of the impact of a smaller source exists. Also, we assume in this review that the theoretical work mentioned above which was applied to the region near the termination shock is more or less transferable to the region near the heliopause. Of course, detailed treatment of such a transfer is required in order to justify this.

The Gurnett et al. (1993), Zank et al. (1994), Whang and Burlaga (1994), and Czechowski et al. (1995) models all rely on some mechanism which is likely similar to that described here, except that it is an interplanetary shock which serves as the source of the energetic electrons which produce the Langmuir waves just ahead of the shock. Gurnett et al. (1993) suggest that when the shock enters the much colder plasma beyond the heliopause (Czechowski et al. [1995] would argue the cold plasma layer should exist inside the heliopause) Landau damping is reduced, hence, generation of Langmuir waves is more likely. This line of reasoning would not be consistent with generation in the relatively hot subsonic solar wind as required by Zank et al. (1994) or at the reflected shock in the Whang and Burlaga (1994) model.

V. TRIGGERS

The 1983-1984 and 1992-1994 radio events were clearly uncommon events. Most radio emissions in the solar system exhibit several orders of magnitude variations in intensity over time, so it is reasonable to assume the heliospheric radio emissions do, also. It follows, though, that the limited Voyager sensitivity actually acts as filter for only those most intense events, whether or not weaker emissions are present. The question which arises, then, is what is the mechanism causing the emission to turn on rather suddenly, or at least reach the intensities which are observed only once in a decade. With this line of reasoning, a number of efforts were undertaken to find a signature in the solar wind which might explain the onset of the heliospheric radio emissions. Lanzerotti et al. (1985) reported a decrease in solar wind-accelerated protons which implied a quiet solar wind condition and reasoned that a decrease in solar wind structure between the Voyagers and the source might make it easier for low-frequency waves to propagate inwards toward smaller heliocentric distances. A similar comment was made by J. A. Van Allen (personal communication). But this line of reasoning did not explain the duration of the 1983 event nor could it explain the brief reappearances of the emission in

1989–1991. Other attempts to find concurrent features in the mid-heliospheric plasma which would correlate with the radio emission were unsuccessful.

In 1988, McNutt (1988) searched the entire Voyager plasma data set from the beginning of the mission in order to identify a signature of some solar wind event which might correlate with the radio emissions, with no constraint on temporal concurrence. The result was the identification of two very fast high-speed streams in 1979 and in early 1983. McNutt suggested that these high-speed streams might be reasonable triggers for the radio emissions when they reached the source region, which was presumed to be the termination shock. The delay from the earliest Voyager 2 detection of the 1983 stream at 11 AU to the onset of the radio emission was about 250 days. The maximum stream speed reported by McNutt was 780 km s^{-1}. Hence, the maximum distance from the Sun to the source region using simple time-of-flight considerations is about 123 AU. McNutt determined time-of-flight using the peak of the radio emission and reported a maximum distance of about 140 AU. McNutt also considered that the shock might slow to a minimum of about 400 km s^{-1} by the time it reached the source, hence estimated a minimum distance of about 70 AU. The 1979 stream would have reached a similar heliocentric distance while the Voyagers were well inside 10 AU; hence they would not have been in a sufficiently low-density plasma to observe whether there was any corresponding radio event. The maximum distance reported by McNutt is in the range of the possible distances reported by Gurnett and Kurth (1995), however, by assuming the source was the termination shock, McNutt was forced to hypothesize transient density enhancements in the shocked solar wind and second harmonic emission to explain even the low-frequency component of the emissions.

McNutt's attempt at finding a trigger was only partially successful. First, with only a single event to study, it was impossible to verify the hypothesis of a high-speed stream trigger. Second, when the 1985 event appeared, there was no obvious high-speed stream as the 1983 feature with which to associate the new event. He continued to search for streams and predicted the onset of the radio emission on the basis of new streams. Notably, upon detecting fast streams associated with the 1991 solar activity, McNutt and colleagues predicted the onset of radio emissions in late 1991 or early 1992 (McNutt et al. 1991).

Grzedzielski and Lażarus (1993) refined McNutt's trigger model by noting that the 1983 (and subsequent radio emission events) followed an extended interval of increasing solar wind pressure. They further reasoned that the trigger might be the result of a number of smaller streams which coalesce at or near the source region, thus making a stronger effect near the source than they would individually in the middle heliosphere where Voyager detects them. They plotted the trajectories of a number of streams and found a number of combinations which merged near 90 AU at about the time of onset for three of the events.

After the detection of the 1992 event, Gurnett et al. (1993) appealed to the notion that the very intense events of 1983 and 1992 must have highly unusual triggering events associated with them. They noted that the most intense Forbush decrease ever recorded with the Deep River neutron monitor occurred on day 164 of 1991, 1.1 yr prior to the onset of the 1992 event. Analyses of this event by Van Allen and Fillius (1992) and Webber and Lockwood (1993), showed the association of this Forbush decrease with very strong cosmic ray intensity decreases and/or interplanetary shocks at the Pioneer 10 and 11 and Voyager spacecraft as well as with the very intense solar activity in the March–June 1991 time frame. Using the velocity range estimated by Van Allen and Fillius and Webber and Lockwood of between 600 and 800 km s^{-1} and using an estimate of the speed of the shock in the outer heliosphere associated with this activity based on modeling performed by R. S. Steinolfson (personal communication), Gurnett et al. established the distance to the source using time-of-flight considerations which ranged between 116 and 177 AU. Based on the Gurnett et al. model of the source region lying just beyond the heliopause, this locates the heliopause within the same distance range.

While the association of the most intense Forbush decrease on record with the most intense heliospheric radio emission meets the criterion of having a highly unusual event for a trigger, a single correlation such as this remains open to conjecture just as was the case with McNutt's (1988) high-speed stream trigger hypothesis. However, Gurnett et al. (1993) also reported a very similar association between a very intense Forbush decrease with the 1982-1983 event. In this case, a Forbush decrease beginning on day 195 of 1982, the second most intense on record at the Deep River monitor, came 1.1 yr prior to the onset of the radio emission. It should be noted that this Forbush decrease occurs nearly 6 months prior to the high-speed stream reported by McNutt (1985). Hence, even taking into account the time-of-flight to the 11 AU position of Voyager 2, the solar activity responsible for the 1982 Forbush decrease cannot be associated with McNutt's high-speed stream. Estimates for the velocity of the solar wind disturbance associated with the Forbush decrease (Van Allen and Randall 1985; Webber et al. 1986) were 810 to 850 km s^{-1}. Figure 11 shows the Deep River neutron monitor data including these two Forbush decreases at Earth in relation to the onset of the two major radio emission events as seen in the Voyager 1 3.11-kHz channel (Gurnett and Kurth 1996). That a similar case can be made for both of these events with similarly significant solar wind disturbances significantly strengthens the hypothesis that the Forbush decreases mark solar wind disturbances which can be identified as triggers for the radio emissions.

Gurnett and Van Allen (1993) have looked at the other, weaker radio emissions and the neutron monitor data in an attempt to find similar triggers for the remaining events. By doing a superposed epoch analysis, they have identified possible features of lesser magnitude than the previously discussed Forbush decreases which lead some of the other radio emission events by an interval of time somewhat larger than the 1.1 yr found for the two major event.

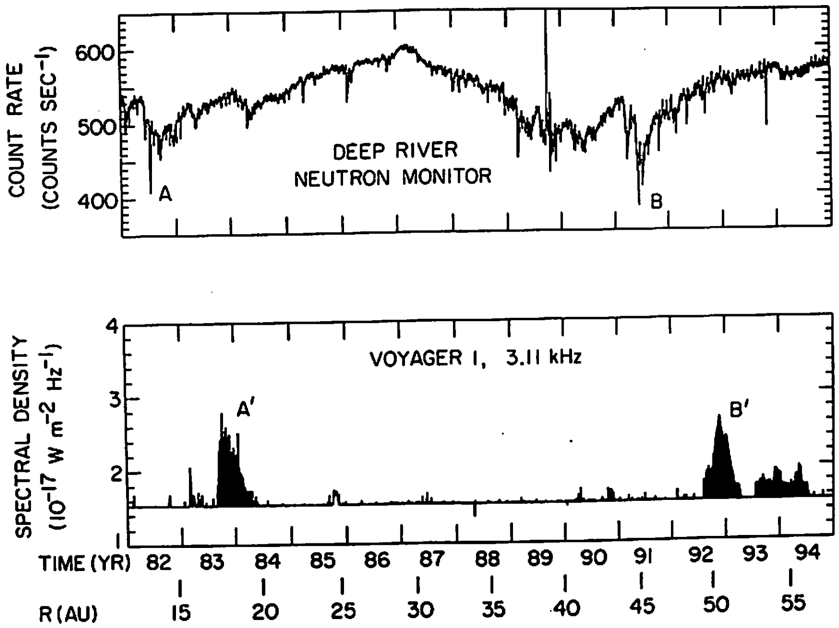

Figure 11. Deep River neutron monitor data (upper panel) and Voyager 1 3.11-kHz intensities as functions of time showing the delay between the two deepest Forbush decreases on record and the onset of the two most intense heliospheric radio events (figure from Gurnett and Kurth 1996).

Because no velocity information is currently available for these disturbances, it is not possible to determine whether the distance to the source is similar to the two major events or not.

Using the two major events, Gurnett et al. (1993) proposed that an interplanetary shock associated with the Forbush decrease propagated out through the heliosphere and triggered the emission when the shock arrived in the cold, post-heliopause plasma. The rising frequency bands in the dynamic spectra shown most clearly in Plate 14 are, therefore, due to the propagation of the triggering shock through a density gradient, probably associated with plasma piled up near the nose of the heliopause due to the interaction with the oncoming interstellar wind based on the model of Steinolfson et al. (1994).

Because the shock speed downstream of the termination shock is probably somewhat smaller than it is in the upstream region and because the distance between the termination shock and the heliopause is not known, Gurnett et al. (1993) estimated the distance to the heliopause by using Eq. (1).

$$R_H = \frac{V_1 T \alpha}{1 - (1 - \alpha)\delta} \qquad (1)$$

Here, V_1 is the shock speed in the supersonic solar wind, $\alpha = V_1 / V_2$ where V_2 is the speed in the downstream region, T is the total time required for the shock to propagate to the source, and δ is the ratio of the distances to the termination shock R_T and the heliopause R_H. Using values of α of 0.7±0.1 and δ of 0.75±0.05 based on a gas-dynamic model of the heliosphere by R. S. Steinolfson (personal communication) and a range of 600 to 800 km s^{-1} for V_1, a range of heliopause distances of 116 to 177 AU is obtained for the 1992–1993 event. Using this range for R_H and the same range for δ as above, the distance to the termination shock can be between 81 and 142 AU.

Gurnett and Kurth (1995) recalculated source distances ranging from 116 to 196 AU using the time-of-flight technique described above, but considered all published values of shock speeds for the shocks associated with the two Forbush decreases. However, they point out that the shocks do not likely propagate at constant velocities in the solar wind as implied by Eq. (1), but slow down with time, hence, the calculated time-of-flight distances could be high by on the order of 20%. They suggest that a more reasonable range of distances to the source, then, is 110 to 160 AU. Using a value of $R_T/R_H = 0.73$ (for the ratio of the termination shock distance to the distance of the heliopause) as a typical value from various numerical simulations, corresponding termination shock distances range from 80 to 115 AU. Other models (see, for example, the chapter by Suess and Nerney) have different values for R_T/R_H, in particular, smaller than 0.73 which would have the effect of decreasing the range of termination shock distances.

The termination shock distance range of 80 to 115 AU is considerably larger than that deduced by Cummings et al. (1994) using the observations of the intensity of anomalous helium and carbon cosmic rays during the last solar minimum (1986–1989). Of course, it is reasonable to expect the heliopause and termination shock to "breathe" in and out in response to changes in internal (or external) pressure. For example, Whang and Burlaga (1993) suggest the termination shock could fluctuate between about 88 and 102 AU throughout a solar cycle, for a 16% variation. Because the Gurnett and Kurth (1995) distance is determined just past solar maximum in mid-1992, there is no reason to expect agreement with Cummings et al. whose results were determined from data obtained near solar minimum. Whang and Burlaga (1993) suggest that the heliosphere should be of maximum size around solar minimum because the solar wind has relatively large momentum during the declining phase of the solar cycle. The shock moves inward during the rising phase and is near minimum just past solar maximum. As 1992 is in the declining phase of the solar cycle, this line of reasoning would imply that the heliosphere should be near minimum size when Gurnett and Kurth determined the distance to the heliopause, but the 1986–1989 period is one in which the heliosphere is moving inward from its maximum distance. Hence, the differences in termination shock distance determined by these two experimental techniques would seem to be even more disparate than at first glance. It should be noted that by modeling the spectrum of anomalous cosmic rays observed in 1994, A. C. Cummings and R. G. Stone (personal communication) have derived a new distance to the termination shock of about 98 AU. This value is certainly

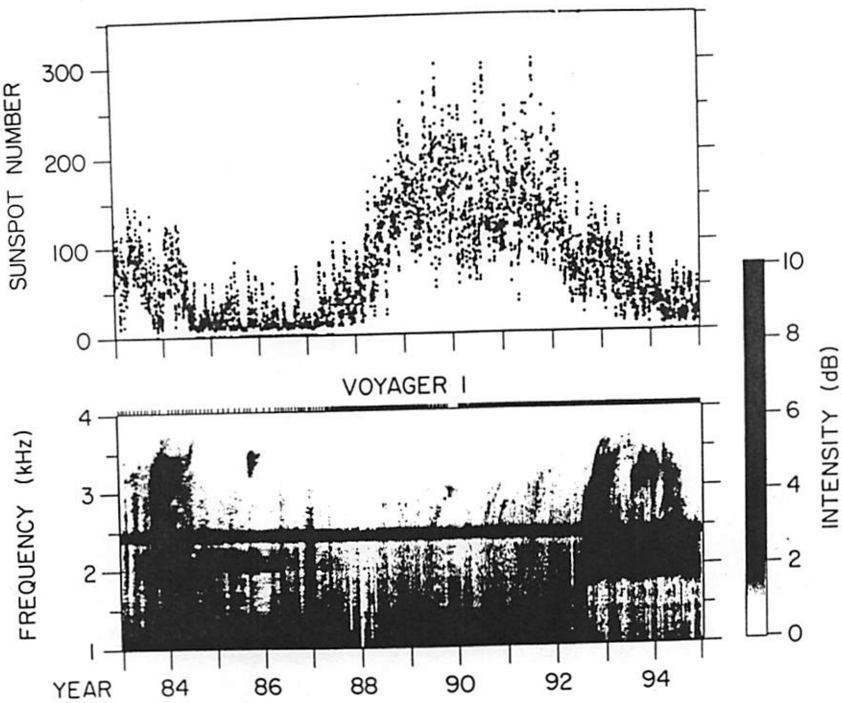

Figure 12. A comparison of solar activity as indicated by daily sunspot numbers and the heliospheric radio emission activity for the period 1983–1995. Both major radio events occur in the declining phase of the 11-yr solar cycle; the weak events in 1989–1991 occur near sunspot maximum.

comparable to that determined by Gurnett and Kurth.

The apparent causal relationship between the solar activity responsible for the two large Forbush decreases and the onsets of the two major radio events suggests a correlation between solar activity and the generation of the radio emissions. Further, the decade-long interval between radio emission onsets is similar enough to the ~11-yr solar activity cycle period to suggest a correlation with the solar cycle. In Fig. 12, the upper panel shows daily sunspot numbers obtained from the National Geophysical Data Center and the lower panel is a gray-scale version of the Voyager 1 spectrogram given in Plate 13. While there is barely more than one 11-yr solar cycle shown, some evidence of a pattern is apparent, although the correlation is not straightforward. There is definitely a correspondence between the two major radio events and the declining phase of the solar cycle. This amounts to a correlation with the peak of sunspot activity with a lag of some 2 yr. Given the 1.1-yr time-of-flight delay demonstrated in Fig. 11, one might attribute some of the observed lag to this. However, there is no simple explanation of the remaining 1-yr lag. The weak events between 1989 and 1991 occur during the broad peak in sunspot activity.

VI. DISCUSSION

The new interpretations of Gurnett et al. (1993), Zank et al. (1994), Czechowski et al. (1995) and Whang and Burlaga (1994) provide a number of solutions for previous uncertainties in the explanation of the heliospheric radio emissions. However, these theories rely on models of the heliosphere and its interaction with the interstellar medium for some critical aspects of the interpretations. For example, Gurnett et al. suggest that the increasing frequency bands are related to emission at the plasma frequency or its harmonic in the source region, which implies a density gradient through which the triggering shock propagates. Using the Steinolfson et al. (1994) model for the solar wind interaction with the interstellar medium (as well as others such as Baranov and Malama's [1993]), the current interpretation identifies this density gradient with the region of interstellar plasma pile up near the nose of the heliosphere. The 2-kHz component, which does not show frequency drifts as large as those at higher frequencies, then, would apparently come from the flanks of the post-heliopause interstellar wind as shown in Figs. 6 and 7. The radio emissions, then, seem to verify the existence of a pile up region; however, there is no incontrovertible evidence which ties the radio emission directly to the post-heliopause region. The Czechowski et al. (1995) model including a cold dense layer due to interstellar hydrogen charge exchanging with solar wind protons is an example of another possibility for generating the density gradient.

In the Whang and Burlaga (1994) model, the drifts of 3-kHz transient emissions are also explained by propagation of the transmitted triggering shock through the post-heliopause pile up region. In this model, however, the reflected shock propagates back into the subsonic solar wind and the lower plasma frequency there is responsible for the lower frequency component of the radio emission.

Zank et al. (1994) use the propagation of triggering shocks through elevated density regions in the subsonic solar wind caused by the earlier passage of enhanced plasma structures to generate transient radio emissions in the required frequency range. In this case, however, use of the two major Forbush decreases as triggers probably does not work; the earlier density enhancements associated with the GMIRs led by the shock causing the Forbush decrease would be required to build up the subsonic solar wind density and shocks embedded in the GMIRs would then be necessary to act as triggers. This would seem to lose the compelling temporal correlation between the Forbush decreases and the onset of the two major emissions of which the Gurnett et al. (1993) model takes advantage. Further, placing the source region just beyond the termination shock effectively moves this boundary out to the range of 110 to 160 AU based on the time-of-flight considerations of Gurnett and Kurth (1995); the heliopause would then be another 30% more distant.

An open issue is the question of how the trigger acts to "turn on" the radio emissions. Even if one presumes the general model of emission at the plasma frequency or its harmonic as described above, something must change radically at the source region to increase the efficiency of radio emission generation, otherwise one would expect radio emissions to be generated by the shock all along its trajectory, including that portion through the supersonic and subsonic solar wind. Gurnett et al. (1993) suggest that the abrupt increase in radio emission efficiency may arise just beyond the heliopause when the triggering shock enters a region of greatly reduced plasma temperature. Such a plasma would be less prone to Landau damping of the Langmuir waves than the hotter subsonic solar wind. Should this concept be valid, then it provides another tie point to the post-heliopause region (or the cold layer just inside the heliopause) as the source region.

The distances to the source region calculated from the trigger/time-of-flight technique are dependent on models for the propagation speed of the trigger along its trajectory, and models of the thickness and plasma characteristics of the subsonic solar wind. Steinolfson and Gurnett (1995) provide just such a study by simulating the propagation of a shock through the heliosphere and varying the external pressure in order to achieve the observed 1.1-yr time-of-flight. Even given the observed speed of the shock in the inner heliosphere as provided by multiple spacecraft observations, the speed beyond the most distant spacecraft is model dependent, particularly relative to the path length through the shocked solar wind, i.e., the distance from the termination shock to the heliopause, and the speed with which it propagates through this totally unobserved region. While the bulk speed of the solar wind would decrease at the termination shock, the Alfvén speed would increase. These two effects tend to oppose each other in terms of the shock speed, but it is almost certainly not the case that there is no change in speed. Gurnett et al. (1993), using results from R. S. Steinolfson (personal communication), estimate that the termination shock is 73% of the distance to the heliopause and that the downstream shock speed is about 60% of the observed speed (but see Steinolfson and Gurnett [1995] for updated values). While Steinolfson and Gurnett (1995) report relatively small uncertainties for these values, other models for the heliosphere have significantly different values, at least for the relative distance to the termination shock (see the chapter by Suess and Nerney). In summary, then, the model dependencies of the Gurnett et al. interpretation leave substantial uncertainty as to the distance to the heliopause and the termination shock.

Gurnett et al. (1993) have identified two major Forbush decreases observed at Earth as indicators of unusually disturbed solar wind conditions which would provide the unique trigger seemingly implied by the once-per-decade occurrence of strong heliospheric radio emissions. They show in detail that the 1991 Forbush decrease is associated with effects including a shock and other major disruptions such as sharp decreases in the galactic cosmic ray flux which were observed to propagate out to the distances of the Voyager and Pioneer spacecraft. They argued that such evidence was consistent with a near global shock and associated solar wind turbulence which helps to qualify the disturbance as the trigger. The discovery of a similar event associated with the 1983-1984 event certainly reinforces this line of reasoning. However, the narrowband emissions seen in Plate 14 and the direction-finding results in Fig. 5 suggest that there are local radio "hot spots" in the source region. The narrow bands imply that there is little variation in the source electron plasma frequency or electron density over the emitting region. Provided even a general model for the post-heliopause density structure suggested in Fig. 6 and described in Steinolfson et al. (1994), it is clear that the "hot spots" cannot subtend a very large region, either in radial distance or in azimuth and meet the requirements of a narrowband emission. Hence, while it may be that a global disturbance is at the heart of the triggering mechanism, it is also the case that much of the radio emission is actually being emitted in relatively small regions. In fact, Fahr et al. (1986) have already suggested that the magnetic field configuration at the heliopause may strongly influence the region's ability to generate radio waves. We would also point out that variations in the conditions along the triggering shock, including magnetic field orientation, may also be important in the generation of radio "hot spots."

The Gurnett et al. (1993) model suggests that single shocks acted as triggers for the two major radio emission events shown in Fig. 11. However, close inspection of Plate 14 reveals the existence of a very complex set of narrowband emissions which must be explained in terms of such a triggering shock. It is not possible to deconvolve these narrowband emissions fully into a clear picture of how such a shock would result in the observed emission, but it is illustrative to consider some limiting cases of hypothetical radio spectra and ask how they might be generated under the general ideas of the Gurnett et al. model. Figure 13 consists of a set of schematic frequency-time spectrograms in the format of Plate 14 and a simple model of the heliospheric interaction with the interstellar medium based on Fig. 6. In the top two panels, the spectrograms are hypothetical sets of narrowband emissions. On the right side of each panel, "trajectories" of at least a portion of a shock front through radio hot spots are shown. In the top panel, we provide the hypothetical case of nearly simultaneous onset of three bands at different frequencies, each of which rises in frequency to varying degrees, and asymptotically arrive at three different frequencies. These bands are labeled A, B, and C and correspond to the three "trajectories" in the heliospheric model in the top panel. This hypothetical situation closely resembles the Gurnett et al. model for three "hot spots" cutting through three different regions of the post-heliopause interstellar medium. Band A, at the highest frequencies must propagate most closely through the peak of the pile up region. Band C, at the lowest frequencies and showing the smallest frequency drift, must propagate through the flank region. Band B is an intermediate case. Spherical symmetry in both the triggering shock and the distance to the heliopause results in the simultaneous onset times.

In the middle panel, we show a different set of hypothetical radio emission bands. In this case, the three bands have the same beginning and ending

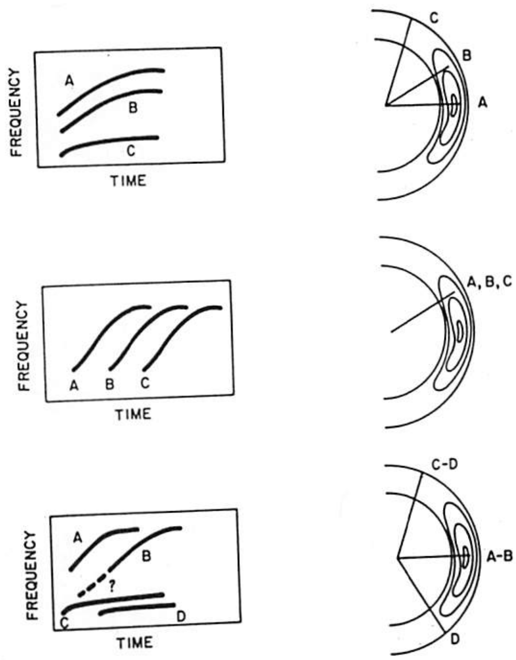

Figure 13. Sets of hypothetical dynamic spectra and what they might mean in terms of the source and triggering of the radio emissions. In the bottom panel, a schematic of some of the bands based on the data in Plate 14. Using these constructs, we can conclude that it is likely that the 1992–1993 radio emission event was triggered by a complex global merged interaction region with several imbedded shocks.

frequency but have different onset times. The fact that they all have the same ending frequency can only mean that they move through the same region of the pile up region, hence, the "trajectory" of the hot spot must be the same for all three bands. Because the onset times for the three bands is different, the conclusion is that there are three different triggering shocks which move through the same region.

In the bottom panel of Fig. 13, we have tried to represent schematically a number of the features seen in the actual spectrograms in Plate 14. While these are idealized to a minor extent, the reader should agree that we have selected features which are obvious upon close inspection of the Plate. Bands A and B represent the first two high-frequency drifting bands. Bands C and D represent two bands with different start times in the 2-kHz portion of the emission spectrum. The dashed line connecting band B to lower frequencies is included to indicate that it is difficult to know whether or not this band may have started at lower frequencies or not. For the purposes of this discussion, we will assume that the band starts at the higher frequency. Bands A and B exhibit the same type of characteristics as those in the hypothetical case in the middle panel of Fig. 13, having different start times but the same asymptotic ending frequency. We interpret these two bands as evidence of multiple shocks acting as triggers in approximately the same region of the post-heliopause interstellar medium. Bands A and C seem to fit the pattern in the top panel of the figure, that is, having similar onset times but different drift rates and different asymptotic frequencies. Therefore, we interpret these two pairs of bands as evidence that a single shock could excite hot spots in different regions, very similar to the original Gurnett et al. model. The fact that band C actually begins a bit earlier than band A suggests an asymmetry in either the shock front or the heliopause. Bands C and D show different starting times and possibly slightly different asymptotic frequencies. Therefore, these two bands could be due to multiple shocks exciting slightly different regions or a single shock exciting different hot spots, but with definite asymmetries in either the shock front or the heliopause distance. Finally, bands A and C might also be construed as fundamental and harmonic radiation from the same shock moving through a single emitting region and the difference in frequency is related to the $f_p - 2f_p$ emitting frequencies. The primary problem with this interpretation is that the ratio of the frequencies of these two bands is not 2:1 but closer to 1.3:1 and varies as a function of time.

The foregoing discussion of the hypothetical and observed dynamic spectra in Fig. 13 serves to help the reader understand how the spectrum of the radio emissions might be used to determine information from the source region or the triggering shock fronts themselves. Furthermore, the discussion leads to the distinct possibility that the radio emissions observed in the 1992–1994 event are the result of multiple shocks. In spite of the fact that a single, very intense Forbush decrease has been identified with this event, the fact that the solar activity during the March–June 1991 time frame was extremely complex including multiple coronal mass ejections and interplanetary shocks, it is reasonable to consider the existence of two or more triggering shocks associated with this general interval of disturbance. In fact, McDonald and Burlaga (see their chapter) and McDonald et al. (1994) provide evidence of a global merged interaction region (GMIR) on the basis of Pioneer and Voyager measurements at several tens of AU. This GMIR includes a number of imbedded shocks and is a very complex system. McDonald and Burlaga have argued that some of the observed structure in this GMIR may, indeed, explain some of the details of the extended 1992–1993 radio emission event. While we agree with this conclusion in general, it is important in interpreting temporal variations in the 3.11-kHz channel intensities (such as provided in Fig. 3b) to recall that the narrowband emissions drift through the passband of the channel (which has a bandwidth of about 300 Hz). Hence, at least some of the temporal variations exhibited in Fig. 3b are due to the appearance of different narrowband emissions at 3.11 kHz at different times. A simple comparison of the data in Fig. 3b to the GMIR structure is presented by McDonald et al. (1994). While we agree that there is reason to expect some features of the GMIR to correlate with some features in the radio emission intensity vs time profile, the frequency drift effect mentioned here must be considered when interpreting intensity variations in the 3.11-kHz channel.

If it is true that radio emissions such as the 1992-1994 event are due to multiple triggers embedded in a GMIR, and if it is true that the hot spots are rather localized regions, then it becomes even more difficult to compute accurately the time-of-flight of the triggering shocks in order to arrive at distance estimates for the source regions. Instead of using the average propagation of the entire GMIR as would be derived from times-of-flight to the several different spacecraft in different directions, it would be more important to know the propagation of an individual shock moving toward the hot spot. Belcher et al. (1993) have calculated the propagation speed of a shock associated with the spring 1991 solar activity as about 550 km s^{-1}, somewhat less than the previously published estimates for the cosmic ray intensity decrease associated with this time period. Perhaps it is important to recall a simulation of a series of solar wind disturbances and how they merge into a GMIR as performed by Akasofu and Hakamada (1983). The resulting structure, an example of which is given in Fig. 14, includes several different interplanetary shocks and a GMIR which exhibits strong asymmetries.

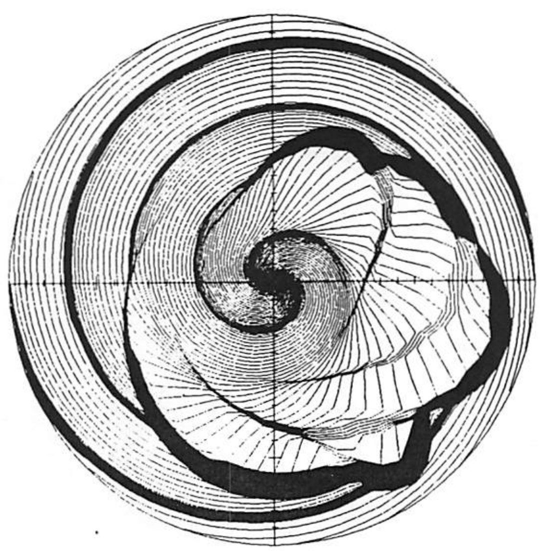

Figure 14. A contour plot taken from simulation studies by Akasofu and Hakamada (1983) showing the nature of asymmetries which can appear in the solar wind due to a series of solar events taking place a various times during the solar rotation. While this simulation only extends to 15 AU, the result emphasizes the difficulty in trying to determine the time a triggering event might reach any given distance in the outer heliosphere. Given that the heliospheric radio emissions tend to suggest that there are relatively small emitting regions or "hot spots," it is clear that great care must be taken in using observation times of a specific shock at spacecraft located at various azimuthal positions in the solar wind (not to mention various latitudes) to determine average shock speeds.

Yet another question to be answered has to do with whether the heliospheric emissions are generated at the local plasma frequency in the source or its harmonic, or both. This question has as its premise that the basic generation mechanism described above is correct. However, the efficiency of generation at f_p relative to $2f_p$ is dependent upon details of the mechanism and the detailed conditions in the source. Some of the considerations bearing on which emission is more efficient are discussed in Cairns and Gurnett (1992) and Cairns et al. (1992). The importance of answering this question bears directly on how one interprets the spectrograms in Plate 14 relative to the plasma densities in the source region. Given that the general model of Gurnett et al. is correct, this uncertainty leads to an uncertainty in the source (interstellar) plasma frequency of a factor of 2 or in the plasma density of a factor of 4. There is some evidence in the data consistent with radiation at f_p. First, there is no obvious down-turning in frequency of the emission bands. If the radiation were generated at $2f_p$ then it would be possible for the second harmonic waves to continue to propagate inward towards the Sun, even after the triggering shock crossed the peak in the pile up and moved into a negative gradient region. At f_p, any waves generated as the shock propagated to lower densities than the peak would not be able to propagate back towards the Sun. We do not consider this to be conclusive evidence of radiation at f_p, however. Second, Lallement et al. (1993) report local interstellar plasma densities in the range of 0.06 to 0.1 cm^{-3} which corresponds to plasma frequencies from 2.2 to 2.8 kHz. Generation at $2f_p$ would result in emission frequencies well above the observed range. Third, Whang and Burlaga (1994) conclude that f_p emission is consistent with their model of emission from shocks transmitted and reflected at the heliopause. Using a termination shock distance of 60 AU (implying an interstellar $|B|$ of 0.8 nT in their model), they can explain emission bands near 3 kHz from the transmitted shock and near 2 kHz from the reflected shock.

The final question we raise here has to do with the nearly constant lower-frequency limit in the 1992–1994 activity at about 1.8 kHz seen in Plate 14. Such a constant limit often implies a propagation cutoff. That is, a high-density region between the observer and the source with a plasma frequency of 1.8 kHz would create a cutoff in the spectrum at 1.8 kHz provided the source generated waves to frequencies down to 1.8 kHz or lower. Gurnett et al. (1993) suggest this cutoff is due to the interstellar plasma frequency being 1.8 kHz; this implies an interstellar plasma density of 0.04 cm^{-3} and is close to recent estimates of the very local interstellar plasma density of 0.06 to 0.1 cm^{-3} (Lallement et al. 1993). Of course, this would be the density in the flanks of the post-heliopause interstellar wind where there is no significant pile up. Belcher et al. (1993) suggest that the cutoff could be due to the subsonic solar wind density. While the average density in the subsonic region should be considerably less than this, normal density irregularities in the solar wind would be preserved as they propagate through the termination shock; hence, Belcher et al. argue that a significantly higher cutoff frequency could be supported than that derived from the normal densities at this distance from the Sun. In order for these density irregularities to be so effective at creating a radio cutoff, however, the density irregularities would almost certainly be required to be extended completely around the Sun, otherwise lower frequencies could leak into the inner heliosphere through gaps or holes in such a density structure.

One other interpretation of the lower-frequency limit of the emission is that it is symptomatic of the conditions in the source region. That is, the 1.8 kHz cutoff could be a minimum in the emission spectrum at the source. For waves being generated in the flanks of the post-heliosphere interstellar medium where there is no pile up, the local plasma frequency profile could be basically flat and the lower-frequency limit of the emission could simply represent this fact.

VII. CONCLUSIONS

Based on the critical information provided by the 1992–1994 heliospheric radio emission activity, considerable progress has been made in understanding the source of the emissions. It seems unlikely that the highest frequency portion of the radio emission spectrum (>2.5 kHz) is trapped. This implies that the interstellar plasma density is less than about 0.08 cm^{-3}, entirely consistent with the values obtained by Lallement et al. (1993). If the lower portion of the spectrum is trapped, it is unlikely that the Q of the cavity is more than 2 or 3. It also seems quite certain that Jupiter cannot be the source of the radio emission, especially if the radiation is not durably trapped. The elimination of the Jovian source removes the most viable of the originally suggested solar system sources except for the interaction of the solar wind with the interstellar medium. Further, the great distances implied by the time-of-flight considerations and the high densities in the source region strongly suggest the source of radio emissions is in the vicinity of the heliopause. The very good correlation between large Forbush decreases and the onsets of the two strongest radio emission episodes observed over a 12-yr period makes a compelling case that the most intense radio events are triggered by solar activity. We suspect that in the case of the 1992 event it is a complex set of shocks associated with a global merged interaction region which is responsible. The source appears to be in the range of 110 to 160 AU, suggesting that the heliopause is at similar distances if one assumes the model of Gurnett et al. (1993) is generally correct.

Further studies of the radio emissions, of the interplanetary shocks that trigger them, and the improvement of heliospheric models should decrease the uncertainties in the current estimates of the distance to the heliopause and termination shock. These studies should also allow us to determine the density profile in the source region, implying remote sensing of the plasma pile up region near the nose of the heliosphere. The fact that we observe multiple radio "hot spots" suggests that the radio emissions may eventually allow a more global view of the heliopause.

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