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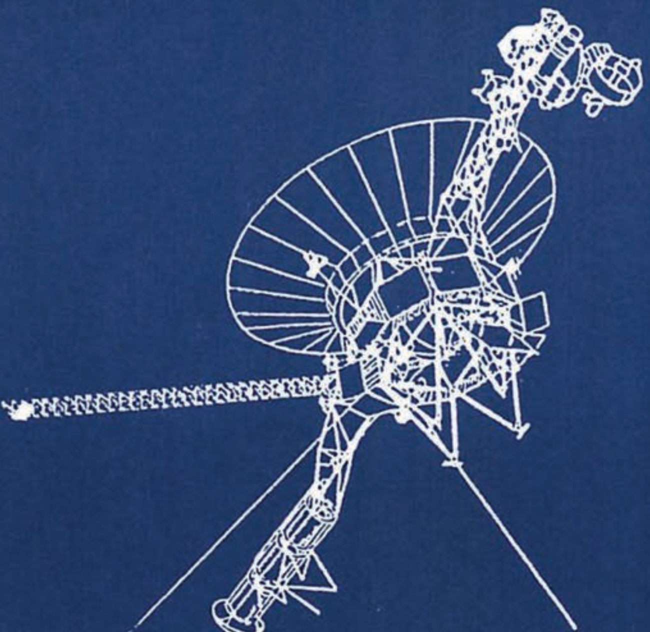
June 25-27, 1996



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A LOW-FREQUENCY WAVE INVESTIGATION FOR AN INTERSTELLAR PROBE MISSION

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Abstract

A mission to the interstellar medium should include an instrument which could monitor the 2-3 kHz heliospheric radio emissions as well as survey plasma waves in the solar wind to the heliopause and beyond. Since the low-frequency radio emissions apparently provide a fundamental means of remote sensing the heliopause, including a monitor of such emissions on any mission to the distant heliosphere or interstellar medium could provide important information on the three-dimensional shape of the heliosphere. A survey of plasma waves in the outer heliosphere and interstellar medium is also important to thoroughly understand the various plasma processes that occur in each regime and, in particular, the boundaries.

Introduction

An Interstellar Probe mission to deep into the local interstellar medium ~1000 Astronomical Units (AU) or even a probe to the outer heliosphere should be equipped with a low-frequency radio and plasma wave receiver to monitor heliospheric radio emissions, determine their source, and to carry our a comprehensive survey of plasma waves in the outer heliosphere and local interstellar medium.

Voyager observations of radio emissions in the frequency range of 1.8 - 3.6 kHz perhaps represent our first direct information from the vicinity of the heliopause. These emissions have occurred in two major events beginning in 1983 and in 1992 [1,2] and several weaker events during the intervening time period [3]. The two largest Forbush decreases on record at the Deep River Neutron Monitor preceded the two major radio emission events by approximately 1.1 years and have been proposed as triggers for the major radio emission events [2, 4]. Through time-of-flight considerations, this has led to the conclusion that the source region of the radio emissions must be in the radial distance range of 110 to 160 AU [4]. Given the observed frequency and the likelihood that the emissions must be generated near the plasma frequency in the source, the source must have a plasma density in the range of 0.01 to 0.16 cm^{-3}. Since the r^{-2} dependence of the solar wind plasma density requires the nominal extrapolated density at 130 AU to be of order 3×10^{-4} cm^{-3}, corresponding to a plasma frequency of about 150 Hz, it is difficult to understand how the solar wind could support the observed radio emissions at such distances. However, pressure balance across the heliopause implies interstellar densities of the appropriate magnitude and UV observations have suggested densities in the range of 0.06 to 0.1 cm^{-3} [5]. Hence, a good case can be made that the radio source is at or near the heliopause.

While the Voyager plasma wave receivers [6] are providing exploratory measurements of waves in the outer heliosphere, these instruments suffer from two shortcomings which suggest improvements for a new spacecraft which would travel to the outer reaches of the solar wind and beyond. First, Voyager does not carry a sensor designed to detect wave magnetic fields above about 10 Hz; the magnetometer provides measurements below that approximate frequency. Second, while Voyager has provided good coverage of wave instabilities in the solar wind such as ion acoustic waves [7] and Langmuir waves upstream of planetary bow shocks [8,9,10,11], the wave spectrum definitely decreases in amplitude with increasing distance to the sun, at least inside of the termination shock. Furthermore, it is not clear how far the Voyagers will travel before a catastrophic failure occurs, they run out of power, or funding to track and operate them simply runs out. It seems likely that they will at least traverse the termination shock, but it is not at all certain that even Voyager 1 will reach the heliopause.

In this paper we investigate current knowledge of heliospheric radio emissions and their importance to the study of the structure of the heliosphere, the current status of plasma wave studies in the distant heliosphere, and projections for what lies ahead of Voyager. Second, we list prioritized objectives for a wave investigation on an Interstellar Probe or other outer heliospheric mission. Finally, we discuss implications of the wave observation requirements for the instrumentation and spacecraft.

Low-Frequency Heliospheric Radio Emissions

Observations

The low-frequency heliospheric radio emissions were first reported in 1984 [1] based on Voyager 1 and 2 observations in 1983 at distances of 17 and 13 AU, respectively. They consist of what Kurth and Gurnett [3] referred to as a low-frequency continuous component centered near 2 kHz and a higher frequency transient component which appears as a narrowband tone rising at the rate of 1 to 3 kHz per year in the frequency range from about 2.5 to 3.6 kHz. The low-frequency component has been observed to last for a few years at a time while the transient components typically require a few to several months to appear, drift to higher frequencies, and fade below the Voyager receivers' threshold. Figure 1 shows frequency-time spectrograms of Voyager 1 and 2 observations of these emissions over the time span of 1983 - 1995. In these spectrograms, the amplitude of waves is

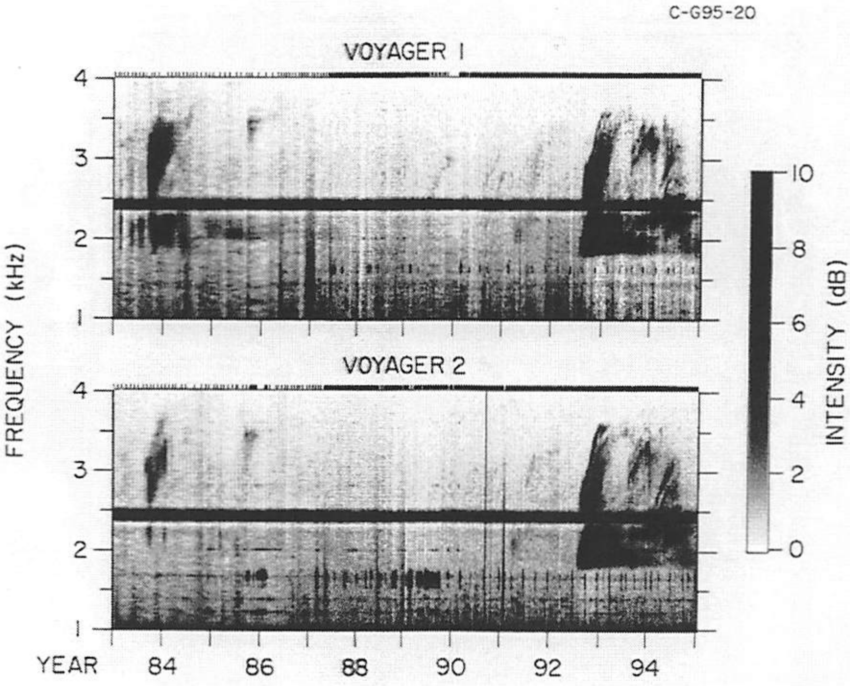

Figure 1. Frequency-time spectrograms from the two Voyager plasma wave receivers over the time span of 1983 to 1995 showing the occurrence of low-frequency heliospheric radio emissions. The two main events are those which start in mid-1983 and in mid-1992.

plotted as a function of frequency (ordinate) and time (abscissa) with black representing the most intense waves and white representing the receiver background. The dynamic range plotted here is only about 10 dB, hence, emissions of greater intensity are all plotted as black. The narrowband tone at 2.4 kHz in both spectrograms is interference from the spacecraft power system. A notch filter at this frequency designed to minimize the power supply interference also reduces the apparent intensity of "real" waves just above and below 2.4 kHz, so it is difficult to know how some of the emissions track from below to above this frequency.

The dominant event in Figure 1 is the one beginning in mid-1992. This event was reported by Gurnett et al. [2] and serves as a basis for most current theoretical and modeling efforts on the emissions. As can be seen in Figure 1 and an expanded version in Figure 2, the 1992 event is highly complex and extends at some level to the end of the plotted interval and even to the most recently-obtained data in early 1996. A number of transient features can be seen near the onset of this event in 1992 and strong reintensifications occur in mid-1993 and again in early 1994. There is some evidence in Figure 2 for the low-frequency component to consist of at least two bands at times and for these bands to drift to higher frequencies with time, albeit at much slower drift rates than the higher frequency transient features. About a half-dozen significantly weaker transient emissions can be seen with proper scaling of the amplitudes. These weaker emissions occur between 1985 and 1991 [3].

The general similarities between the Voyager 1 and Voyager 2 observations seen in Figures 1 and 2 are solid evidence that the emissions must have a common source which is not local to either spacecraft. Near the end of the plotted time intervals, the typical solar wind plasma frequency at the

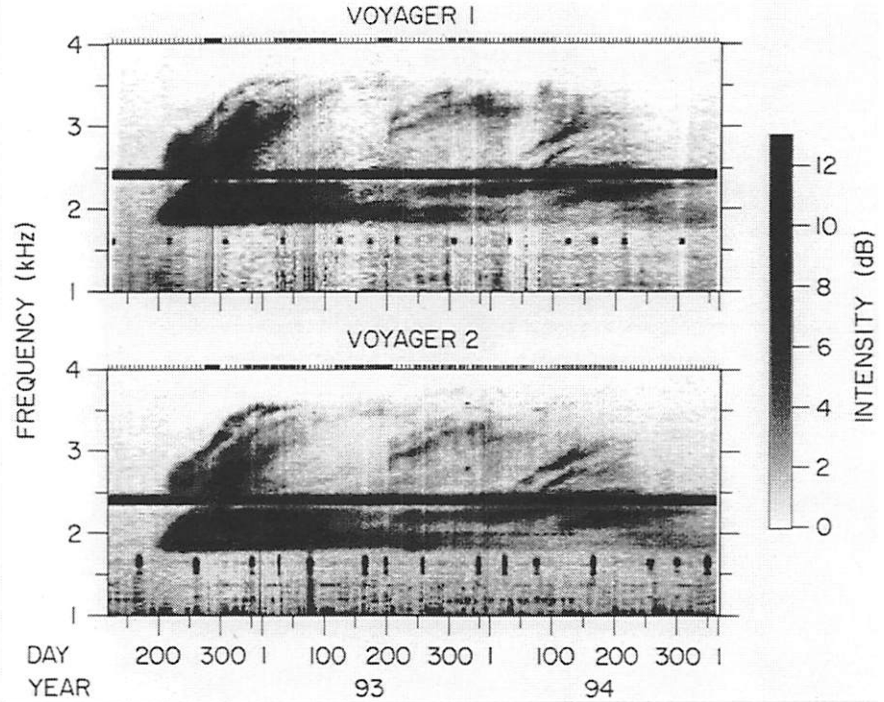

Figure 2. Frequency-time spectrograms similar to those in Figure 1 except showing the 1992 heliospheric radio emission with greater temporal resolution. While the emissions are similar as observed at the two spacecraft, there are subtle differences which suggest a source which is of a similar distance to the two spacecraft as the spacecraft-to-spacecraft separation, which is ~50 AU.

spacecraft is only a few hundred Hz, hence, these must certainly be radio waves propagating to the two receivers. On closer inspection, one can see differing relative amplitudes for some of the features as viewed from the two spacecraft. We interpret these differences as evidence of propagation from a distant source which is closer to one spacecraft or the other. (One must also take into account the details of the dipole antenna pattern in order to fully explain the relative amplitude differences.) The general conclusion is that these relative differences are evidence of sources at distances of the same order as the spacecraft-to-spacecraft distance. In 1996, the spacecraft are separated by some 50 AU.

The fact that major emission activity has occurred only twice since 1983, a span of some 13 years, begs for some triggering mechanism to be identified. In fact, Gurnett et al. [2] showed that each of the two major events, in 1983 and 1992 were preceded in time by the two largest Forbush decreases on record at the Deep River Neutron Monitor. The lead time for the Forbush decreases was approximately 1.1 y in each case. Figure 3 shows the temporal relationship between the neutron monitor data and the intensity of the radio emissions. Gurnett et al. argued that the Forbush decreases are symptomatic of a region of considerable solar wind disturbance led by a shock which would continue to propagate out through the interplanetary medium. When the shocks cross the heliopause and interact with the cold interstellar plasma, conditions might be prime for the generation of radio waves at the local plasma frequency or its harmonic. Hence, knowing when the disturbance was launched from the sun; having an estimate for its velocity through the solar wind based on detection by the Voyager, Pioneer, and other interplanetary monitoring spacecraft; and having a

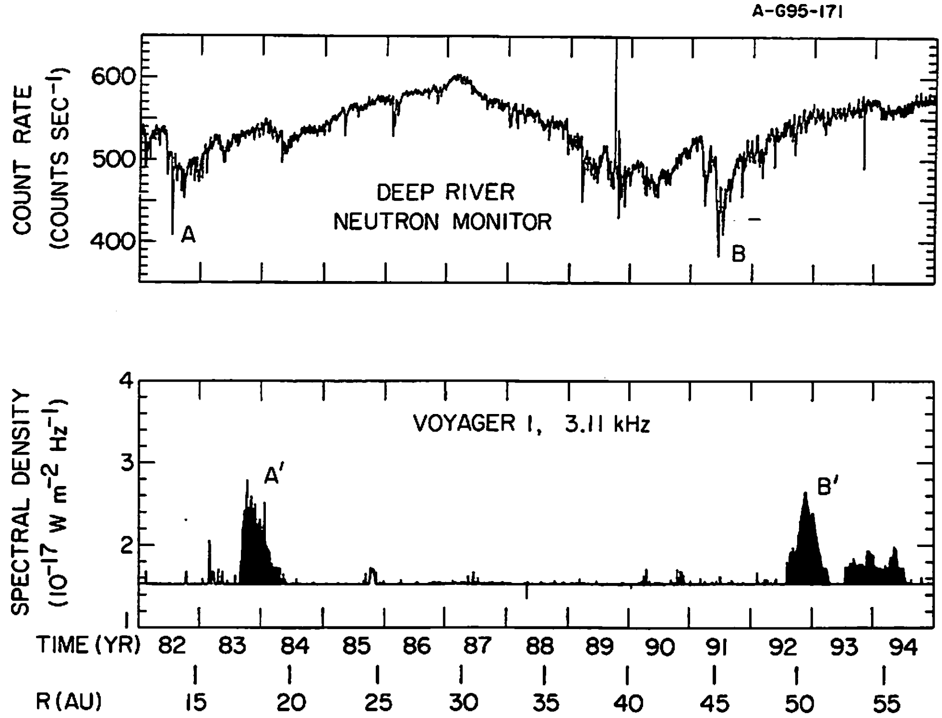

Figure 3. Deep River Neutron Monitor observations and the intensity of the 3-kHz radio emissions as a function of time. Events labeled A-A' and B-B' show the temporal correlation of the two very large Forbush decreases and the onset of the two major radio emission events [4].

model for the propagation of the shock through the termination shock and subsonic solar wind, one can calculate the heliocentric distance based on the 1.1-y travel time. The primary issue with this distance determination centers around the uncertainty of the velocity of the shock front; estimates from the different interplanetary monitoring spacecraft vary from ~600 to 800 km s^{-1} for both events, and considerable modeling is required to estimate its speed through the as yet unobserved subsonic solar wind. Hence, the distance estimates to the heliopause range from 110 to 160 AU [4]. Nevertheless, scaling a likely termination shock distance range from this estimate of the heliopause distance yields 80 to 115 AU, similar to other current estimates based on independent lines of reasoning. For example Stone et al. [12] recently reported a distance for the termination shock of 85 ± 5 AU based on Voyager observations of anomalous cosmic ray spectra.

A small number of direction-finding measurements have been made with the Voyager 1 instrument [2], taking advantage of spacecraft roll maneuvers performed as a calibration of the magnetometer. These direction-finding results are consistent with a source in the general direction from which the interstellar medium flows, but they are only 1-dimensional determinations and occur at infrequent intervals. Significant scatter or motion of the source(s) is observed.

Models

Since the report of the 1992 heliospheric radio emission event, several models for the generation of the emissions have been proposed [2, 13, 14, 15]. All of the models utilize shocks propagating through density gradients as the triggering mechanism, implicitly relying on known mechanisms for generating waves at f_p or $2f_p$ via conversion from Langmuir waves excited by electron beams from the shock [cf. 17, 18]. The primary differences in these models lie in where the signals are generated.

Gurnett et al. [2] argued that the transient features could be generated as the shock moves through a density gradient near the nose of the heliopause in the direction from which the interstellar wind flows. Because the solar wind density decreases as r^{-2} in the supersonic region (assuming no systematic slowdown of the bulk flow), the local plasma densities at distances consistent with 1.1-y shock times-of-flight are so low that frequencies in the range of 2 - 3 kHz cannot be generated in the solar wind with emission at f_p or $2f_p$. Even utilizing a strong shock for the termination shock and the resulting density step of a factor of four does not bring the plasma frequency sufficiently high to account for the observed frequencies. The heliopause, however, is a rotational discontinuity and the density jump across this boundary can be whatever is required to balance the pressure across the boundary. Hence, it is possible to have plasma densities entirely consistent with the observed frequencies. Several models of the region just outside the heliospheric nose suggest that there may be a plasma pile-up region here and whether the emission is at f_p or $2f_p$, the excited frequency will increase as the shock moves into regions of progressively higher plasma density. This model suggests that the lower frequency component displaying little frequency drift might be generated on the flanks of the heliosphere where the pileup is diminished or nonexistent.

Whang and Burlaga [13] suggest that a shock impinging on the heliopause will result in a transmitted shock which continues on into the interstellar medium and a reflected shock which propagates sunward back into the subsonic solar wind. They suggest that the transmitted shock can generate radio waves corresponding to the higher frequency transient features and the reflected shock can generate the low-frequency component.

Zank et al. [14] model the transmission of density enhancements through the termination shock and argue that these will result in high plasma frequencies in the subsonic region. When a subsequent shock overtakes and passes through this transitory high density region, radio emissions of the observed frequencies can be generated and observed frequency drifts can be explained by the shock's motion in the density gradient of the transitory structure.

Czechowski et al. [15] discuss the charge exchange interaction between interstellar neutral hydrogen and protons of solar origin. They suggest that this interaction can result in a cold, thin layer of plasma just inside the heliopause. A shock passing through this region could generate radio waves with the observed frequency and frequency drift.

A review of the heliospheric radio emissions provides additional observational detail as well as an expanded discussion of the various theories [16].

The Importance of Continued Observations

There are certainly additional arguments for and against each of these models. However, the point of this summary of the models is not to argue that one is better, but to highlight the importance of obtaining additional information about the emissions, especially to determine the source location with respect to the heliopause. Given the uncertainty of Voyager's survivability to the currently estimated heliopause, it is essential that an Interstellar Probe or other outer heliospheric mission carry an adequate wave investigation. Two-dimensional direction-finding capability on a regular basis would greatly enhance the utility of such an investigation. If the relationship between the source of the heliospheric emissions and the heliopause can be determined, then remote sensing of the radio waves can provide information on the size of the heliosphere as function of time without requiring actual traversals of the heliopause for each determination. Furthermore, the narrowband spectral features and one-dimensional direction-finding results strongly suggest that there are radio "hot spots", perhaps more than one at any given time. If so, direction-finding of each of multiple "hot spots" can provide multi point determinations of the source position, hence, some information on the shape of the boundary. Direction-finding of one "hot-spot" over time can provide information on the motion of a given emission region.

Outer Heliospheric Plasma Waves

Gurnett [19], using results from the Helios plasma wave receivers which provided observations to within 0.3 AU of the sun found that most common solar wind plasma wave phenomena showed a clear trend to higher intensities at smaller heliocentric radial distances. This was found to be the case for Langmuir waves, ion-acoustic waves, and whistler mode emissions. Certainly, Voyager observations in the outer heliosphere are consistent with these reports. While Langmuir waves and electrostatic modes are seen to great distances in the solar wind, their occurrence probability and intensity are significantly smaller than at 1 AU. With the limited Voyager sensitivity, existing observations are likely to be only the most intense examples beyond several AU.

This is not to say that plasma waves are not present or important in the outer heliosphere. Kurth and Gurnett [20] presented observations of an interplanetary shock observed by Voyager 1 at 46 AU which was preceded by Langmuir wave activity for several hours and which could be easily identified in the wave observations by broadband turbulence, probably of an electrostatic character. Whistler modes are likely associated with these shocks as they are in the inner heliosphere, but the electron cyclotron frequency which provides an upper frequency cutoff for the whistler mode is of the order of a few Hz, thus dropping these waves below the 10 Hz lower frequency limit of the instrument and placing them in the passband of the magnetometer.

Kurth and Gurnett [20] argued that Langmuir waves would herald the Voyager approach to the termination shock and provide as much as several weeks warning of a pending encounter with that shock. They estimated the amplitude of such waves on the basis of extrapolating the intensity of Langmuir waves observed upstream of the outer planets' bow shocks to distances of the order of 100 AU and predicted termination shock associated Langmuir waves would have amplitudes in the range of 2 to 10 μV/m. Furthermore, they inferred from electrostatic waves in the bow shocks themselves that similar phenomena would be observed at the termination shock.

Of course, there are no direct observations of the plasma wave spectrum in the subsonic solar wind beyond the termination shock. The radio emission models of Zank et al. [14] and Whang and Burlaga [13] place the generation of heliospheric radio emissions in the subsonic solar wind; this would require the capability of driving plasma waves such as Langmuir waves and perhaps ion acoustic waves near interplanetary shocks. More broadly, the heating which occurs at the termination shock, the pickup of interstellar neutrals, and the subsequent transition from a radial flow to a flow parallel to the heliopause could result in plasma distribution functions which could be unstable to various wave modes. We know from virtually all other solar system plasmas that wave-particle interactions provide means of transferring energy in one form to another, thereby acting as critical intermediaries in the energy budget of the system.

In some sense, one can draw a crude analogy between the situation at the heliopause and the magnetopause of a planetary magnetosphere. These boundaries separate two distinct plasma regimes with their own plasmas and magnetic fields. It is reasonable to expect currents flowing on the boundary, some diffusion processes, perhaps reconnection [21], or other processes to occur at this boundary which may result in the generation of waves. The magnetopause of a planetary magnetosphere is a likely site for the occurrence of broadband electrostatic noise, probably related to the currents flowing in the boundary. Also, there are several reports of electron cyclotron harmonic emissions (Bernstein waves) and upper hybrid emissions at the magnetopause [22, 23]. Such waves, if present, provide an additional possible source for the heliospheric radio emissions, just as planetary continuum radiation has been shown to be generated via mode conversion from electrostatic upper hybrid bands in most of the known planetary magnetospheres, even at the magnetopause [24].

Beyond the heliopause, it is very difficult to know what to expect for plasma wave turbulence. Given the slow bulk speed, the great distances from the source of the interstellar gas and plasma, and the inferred temperatures of some 7000 K, it is easy to speculate that the interstellar wind has evolved to a near-equilibrium state and that there is little reason to expect that plasma instabilities exist. However, given the opportunity to make in situ measurements, it would be extremely important to actually make the measurements which would verify such a state. On the other hand, the interaction of the interstellar wind with the heliosphere may well have its own local influence on the interstellar wind. Certainly the flow is diverted by the heliosphere and there may be a heliospheric bow shock. Furthermore, the photoionization of neutrals is increasing as heliocentric distance decreases. These processes may serve to generate unstable distributions in the interstellar plasma.

Wave Observation Priorities for an Interstellar Mission

A wave investigation for an Interstellar Mission, or one to the outer heliosphere should have the following priorities:

1. **Monitor the low-frequency heliospheric radio emissions**: Given that these are electromagnetic waves, it is almost certainly most efficient to measure the electric component of these waves; there would be no need to also measure the magnetic component. This objective would require a frequency range up to about 5 kHz and sensitivity at least an order of magnitude greater than that of Voyager, which is approximately 1.5×10^{-17} W m^{-2} Hz^{-1} at 3 kHz. Due to the very slowly varying nature of these emissions, temporal resolution is not an issue; hourly averages would be sufficient. Good spectral resolution would be important, however. The Voyager wideband observations have about 28-Hz resolution which should be considered the minimum. A very high priority additional capability should be to be able to determine the polarization and direction-of-arrival of the heliospheric radio emissions.

2. **Survey plasma waves in the outer heliosphere and local interstellar medium**: The emphasis here should be on studying Langmuir waves and waves associated with interplanetary shocks, since these are known to be present and important even at large distances. Extending the sensitivity well beyond that of Voyager, however, will be most important in optimizing the instrument for waves in the unexplored regions of the heliosphere and interstellar medium. In view of the lack of magnetic field measurements on Voyager, consideration should be given to including magnetic field sensors in addition to the electric antennas required for the radio

emissions. However, close coordination with the magnetometer investigation should occur; usually "DC" magnetometers become more efficient at measuring wave magnetic fields than search coils in the range of 1 to 10 Hz. The 5-kHz upper frequency limit for electric fields required by the heliospheric radio emission requirements would suffice for radial distances beyond about 5 AU. If resources permit and if the scientific return is deemed important enough, consideration should be given to extending this range to 50 kHz or so in order to study plasma waves in the range of 1 to 5 AU. For distant solar wind plasma waves, emphasis must be placed on good spectral resolution particularly at the lowest frequencies, suggesting a low frequency band below, say 100 Hz. Because plasma waves in the solar wind are typically highly sporadic, good temporal resolution is suggested. Some method for providing high temporal resolution without requiring a high data rate would be important.

3. Measure the plasma density accurately and with high temporal resolution: The Wind Thermal Noise Receiver has shown the utility of measuring the response of a long electric antenna near the plasma frequency to accurately determine not only the plasma density, but also the temperatures and densities of multi component plasmas. This technique involves identifying the frequency of and analyzing the shape of a spectral feature just above the plasma frequency with an antenna which is long compared to the Debye length of the local plasma [25]. Good spectral resolution is required as is a very clean spacecraft in an electromagnetic sense. The frequency range required is the same as that for the plasma wave survey: 5 kHz and below for distances beyond 5 AU or a higher frequency band for regions between 1 and 5 AU, if resources permit.

Instrumentation Considerations

For any payload destined for the distant heliosphere or interstellar medium, mass and data rate must be kept to an absolute minimum. One of the greatest challenges of providing a highly sensitive, low-mass plasma wave investigation is to find a way of maximizing the length of the electric antennas. Those shared by the plasma wave and radio astronomy investigations on Voyager were a pair of 10-m elements extended perpendicular to each other; these should be considered as only minimally acceptable where great sensitivity is required. Long antennas provide greater sensitivity to electric fields simply because $V=E\ell$ where V is the detected voltage, E is the electric field, and ℓ is the effective length of the antenna, for $\ell \ll \lambda$ the wavelength. However, they are also beneficial because they are more effectively removed from the vicinity of the spacecraft where they capacitively couple to the chassis and unwanted interference. A spinning spacecraft can help by allowing wires to be held perpendicular to the rotation axis via centrifugal force, reducing mass required for a rigid equivalent. However, many missions are not well suited to spinning spacecraft and other solutions must be found. We suggest that lightweight antennas be the subject of one or more technology development studies in order to find one or more methods of maximizing antenna length per unit mass. Such a development should take into account the dynamical and thermal properties of the elements to minimize unwanted disturbances to the spacecraft attitude due to vibration or thermal bending.

Of course, a sensitive wave receiver necessitates the need for an electromagnetically clean spacecraft. This is not a new concept so we will not dwell on the issue here. Suffice it to say that sound engineering practices can produce a spacecraft with minimal electromagnetic interference and there are several examples of these, such as Ulysses and Wind.

The low-frequency heliospheric radio emissions lend themselves to suitable study with very low data rates because of their very slow temporal variations. The dynamic spectrograms shown in Figures 1 and 2 comprise measurements that range from 1 month to about 2 days temporal resolution, with 1 week being typical. The tic marks at the top of the spectrograms indicate when data were available. We do not suggest such extremely low temporal resolution for this investigation. However, spectral resolution should be favored in the trade between temporal and spectral resolution. One method which could be effectively pursued would be to perform onboard Fourier transforms of wideband waveforms with a bandwidth of 5 kHz and average the resulting spectra in time to 1) reduce the downlink requirements, and 2) to decrease the noise in the spectra. We have found with Voyager that close to 90 dB of dynamic range is achievable even with only 4-bit resolution waveforms if the Fourier transforms are averaged for just several seconds when the spectral features are stable for similar time periods. A 500 point spectrum could be downlinked once per hour for 1 bps and adequately monitor the heliospheric radio noise.

Bursty plasma wave phenomena are much more difficult to capture with low data rates. For these, some spectral resolution can be sacrificed for temporal resolution and data compression needs to be seriously considered. Very little data could be transmitted to the ground when there is little change in the wave spectrum and the rate could increase when activity is detected. A number of techniques could be considered for such compression. Additionally, some algorithms may have to be developed which could dynamically adjust the severity of compression should the average rate of data being collected exceed the allowed budget. One concern for onboard handling of potentially bursty data is that spacecraft interference can sometimes masquerade as bursty phenomena. One must protect against situations where "interesting" events turn out to be spacecraft interference.

The high priority for polarization and direction-of-arrival measurements of the heliospheric radio emissions implies the need for tri-axial electric field sensors and dual receivers to enable the measurement of the required set of amplitude and phase measurements. Such a configuration is being prepared for flight on the Cassini mission to Saturn and similar techniques have been utilized on Ulysses, where the third antenna axis is obtained via the rotation of one of the antennas due to the spin of the spacecraft. Ladreiter et al. [26] have developed an elegant solution to this problem which yields all four Stokes parameters plus a two-dimensional direction-of-arrival measurement. Unfortunately, the additional antenna and receiver add to the mass budget of the investigation.

Summary

The inclusion of a low-frequency radio and plasma wave investigation on an Interstellar Probe or other mission to the outer heliosphere would provide further understanding of the heliospheric radio emissions and serve to complete a survey of plasma waves in the outer heliosphere and local interstellar medium. Once the relationship between the heliospheric radio emission source and the heliopause is understood, then remote measurements of the radio emissions will enable monitoring of the shape and motion of the heliospheric boundary. The role of plasma waves in the physics of the termination shock and heliopause as well as the regions on either side of these boundaries is important to understanding how energy is transformed from one form to another in these regions. Assuming that the heliosphere is typical, we can generalize these processes to other heliospheres and use the in situ observations to extend our knowledge of other stars in the galaxy.

Acknowledgments

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