VOL. 84, NO. A7 JOURNAL OF GEOPHYSICAL RESEARCH JULY 1, 1979

High-Resolution Spectrograms of Ion Acoustic Waves in the Solar Wind

W. S. KURTH, D. A. GURNETT, AND F. L. SCARF[1]

Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242

Ion acoustic waves, similar to those detected by the Helios spacecraft from 0.3 to 1.0 AU, have now been detected by the Voyager spacecraft in the solar wind out to heliocentric radial distances of 1.7 AU. High bit rate waveform measurements provide the first high resolution, frequency-time spectrograms of these waves. The Voyager spectrograms show that the ion acoustic waves consist of narrowband bursts which last for a few seconds or less. The center frequency of the bursts can fluctuate rapidly in frequency, usually in the range between the electron and ion plasma frequency f_p^- and f_p^+ (These waves have been previously referred to as $f_p^+ < f < f_p^-$ noise.) Comparisons of the high-resolution spectrograms from the Voyager spacecraft with similar measurements from earth-orbiting spacecraft show that spectra of the ion acoustic waves in the solar wind at 1.7 AU are identical to spectra of short wavelength ion-acoustic waves detected upstream of the earth's magnetosphere. The latter waves have been associated with protons streaming into the solar wind from the bow shock. This close similarity suggests that the ion acoustic waves detected in the solar wind by Helios and Voyager may be driven by an ion beam instability, as has recently been suggested in a theoretical analysis by Gary.

1. INTRODUCTION

Plasma wave measurements on the Helios 1 and 2 spacecraft [*Gurnett and Anderson,* 1977] have shown that sporadic bursts of electrostatic turbulence occur in the solar wind at frequencies between the electron and ion plasma frequencies f_p^- and f_p^+. This turbulence was initially called $f_p^+ < f < f_p^-$ noise. Later analyses by *Gurnett and Frank* [1978] provided substantial evidence that this noise consists of short wavelength ion acoustic waves below the ion plasma frequency which are Doppler-shifted upward in frequency by the motion of the solar wind. Gurnett and Frank also demonstrated that the waves detected in interplanetary space by Helios have characteristics very similar to waves detected upstream of the earth's magnetosphere [*Scarf et al.,* 1970] in association with suprathermal protons streaming into the solar wind from the bow shock.

Ion acoustic waves similar to those detected by Helios have now been detected in the solar wind at heliocentric radial distances up to 1.7 AU by plasma wave experiments on the Voyager spacecraft. By using the very high bit rate (115 kb/s) waveform data from the Voyager plasma wave experiment we have obtained the first high resolution, frequency-time spectrograms of these waves. These spectrograms show that the waves detected by Voyager consist of nearly monochromatic emissions lasting for only a few seconds, often with a rapidly varying center frequency. Comparisons of the Voyager spectrograms with similar spectrograms of waves detected in association with suprathermal protons upstream of the earth's bow shock strongly support the conclusion of *Gurnett and Frank* [1978] that these two classes of waves are essentially identical. This similarity provides added evidence that the ion acoustic waves detected in the solar wind by Helios and Voyager are driven by an ion beam instability as has been recently suggested by *Gary* [1978]. Although the exact mechanism for generating these waves has not yet been established we will continue to refer to these waves as ion acoustic waves, even though, as pointed out by *Gary* [1978], the actual plasma wave mode associated with the instability may involve a distinctly different 'ion-acoustic-like' mode produced by the charge particle beam which causes the instability.

2. INSTRUMENTATION

The Voyager plasma wave experiment has been previously described by *Scarf and Gurnett* [1977], however we shall briefly review some of the aspects of the experiment which are important to this paper, especially the waveform receiver. The Voyager plasma wave instrument uses an electric dipole antenna, consisting of two 10-m conducting elements extended perpendicular to each other, to detect the electric field of plasma waves. The instrument electronics consists of a step frequency receiver and a waveform receiver. The step frequency receiver has 16 narrowband filters logarithmically spaced from 10 Hz to 56.2 kHz. The field strength in each frequency channel is determined once during each frequency scan, which takes a minimum of 4 s for the highest possible telemetry rates. The duty cycle for detecting short impulsive bursts in a given channel is approximately 1/80 at the highest telemetry rates and drops to about 1/1920 for the lowest cruise rate. The step frequency receiver is operated continuously throughout the mission.

The waveform receiver utilizes a special high bit rate (115 kb/s) mode of the spacecraft telemetry system to provide high resolution waveform measurements over the frequency range from 50 Hz to 12 kHz. The waveform receiver consists of a bandpass filter to limit the bandwidth of the received signal and an automatic gain control circuit with a time constant of 0.5 s to maintain the signal output at an approximately constant amplitude. The waveform output of the automatic gain control circuit is digitized into four bit words at a rate of 28,800 samples per second. The high rate waveform data are transmitted during selected times when pictures are not being transmitted by the imaging experiment. The waveform data is normally obtained in 48-s bursts.

On the ground the waveform receiver data are processed entirely using digital techniques to produce frequency-time spectrograms. This approach is a change from the normal method of producing VLF spectrograms, which usually relies on analog spectrum analysis. The frequency-time spectrograms shown in this paper were all produced at the Image Processing Laboratory of the Jet Propulsion Laboratory in Pasadena, California, with the use of standard fast Fourier transform techniques.

---

[1] TRW Defense and Space Systems Group, Redondo Beach, California 90278.

Paper number 8A1171.
0148-0227/79/008A-1171$01.00

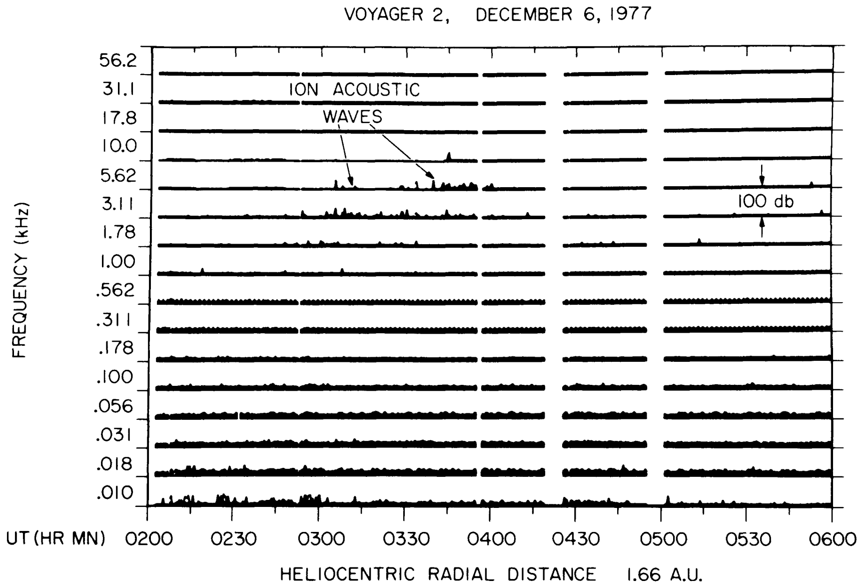

Fig. 1. An example of ion acoustic waves detected by the Voyager 2 plasma wave step frequency receiver. The solid lines and vertical bars (solid black areas) indicate the peak and average electric field strengths. The data below 1 kHz have been filtered to remove interference associated with attitude control jets firing.

3. VOYAGER OBSERVATIONS

A typical example of the ion acoustic waves detected by the Voyager 2 spacecraft is shown in Figure 1. This illustration shows the electric field intensities in the 16 frequency channels of the step frequency receiver for a 4-hour interval at a heliocentric radial distance of about 1.66 AU. The ordinate for each channel is proportional to the logarithm of the electric field strength over a range of 100 db from about 1 μV m^{-1} to 100 mV m^{-1}. The vertical bars (solid black areas) give the average electric field intensity averaged over 24-s intervals, and the solid lines above the bars give the maximum electric field intensities over the same intervals. Some data points in the low-frequency channels have been eliminated because of interference caused by firings of the attitude control thrusters.

The ion acoustic waves in Figure 1 appear as a series of sporadic bursts predominantly in the 1.78- to 5.62-kHz channels from about 0250 to 0430 UT although a few isolated

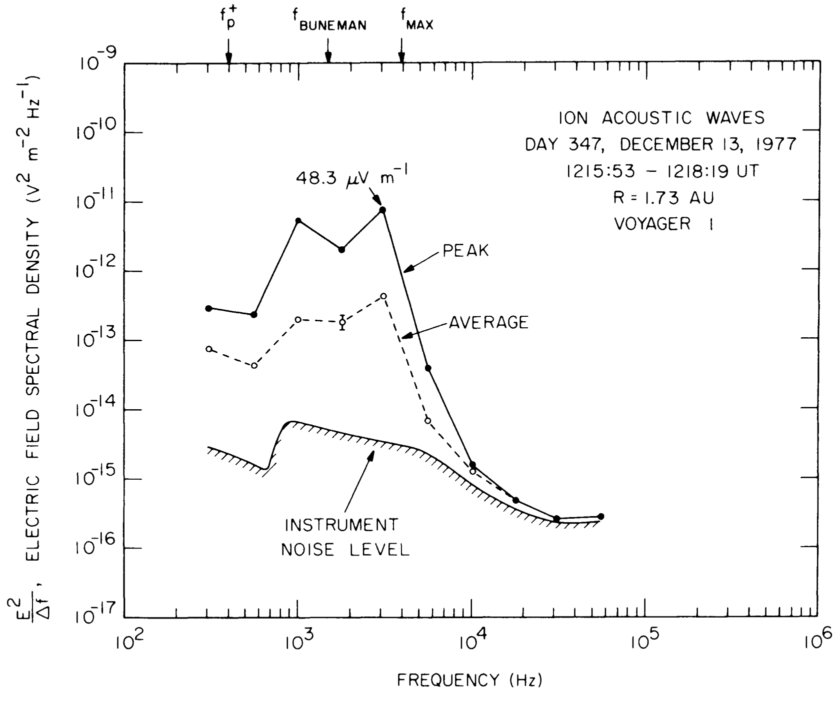

Fig. 2. A peak and average electric field spectrum of a burst of ion acoustic waves detected by Voyager 1 at 1.73 AU. The frequency range of these waves lies between the local ion plasma frequency f_p^+ and f_{max}, which is the maximum frequency to which ion acoustic waves can be Doppler shifted by the motion of the solar wind. The error bar indicates the instrumental uncertainty in the measurement of the voltage at the receiver input. The peak in the spectrum is expressed in units of electric field strength, since we believe the waves are nearly monochromatic at an instant in time. The average spectrum shows a broad bandwidth because several bursts which fluctuate rapidly in frequency are averaged together (compare Figures 3, 4, and 5).

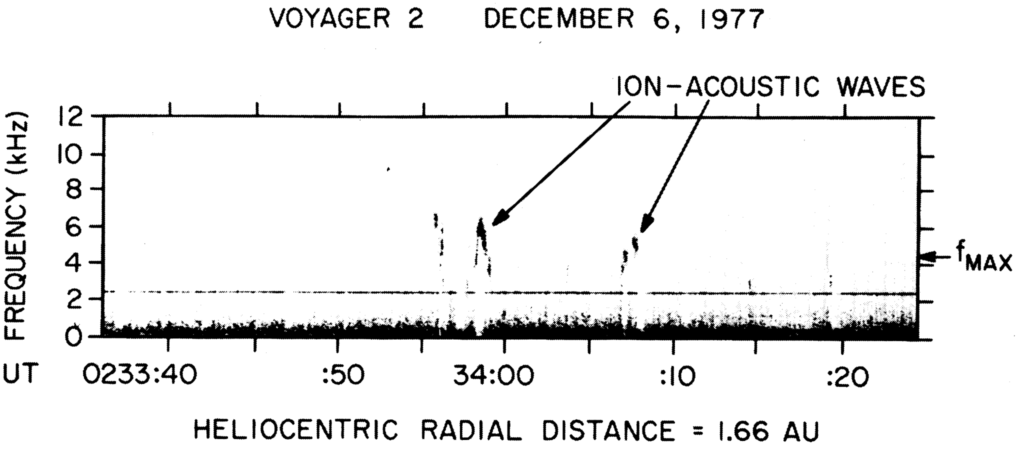

Fig. 3. A high-resolution spectrogram showing the detailed time and frequency signature of a burst of ion acoustic waves. The spectrogram is the result of fast Fourier transforming high rate waveform measurements from the Voyager 2 plasma wave experiment's waveform receiver. The line at 2.4 kHz is interference from the spacecraft power supply.

bursts occur at other times in the frequency range from 1.0 to 10 kHz. (All times given in this paper are spacecraft event times, i.e., corrected for the one-way light time from the spacecraft to the earth.) Usually the ion acoustic waves detected by the Voyager spacecraft tend to occur in 'storms' which last from a few hours to 1 or 2 days, similar to the event in Figure 1. Ion acoustic wave activity similar to that shown in Figure 1 is observable to some extent during 50 to 70% of the days when the step frequency receiver is operating at its highest data rate (i.e., one frequency scan every 4 s). The periodic fluctuations in the 311- and 562-Hz channels are due to spacecraft-related interference at 400 Hz. The fluctuations $\lesssim$ 178 Hz are believed to be whistler mode turbulence.

A typical electric field spectrum selected during another burst of ion acoustic wave activity detected by the Voyager 1 spacecraft at 1.73 AU is shown in Figure 2. The average spectrum shown in Figure 2 is obtained by averaging over approximately 2.5 min of measurements. This involves averaging together several bursts of ion acoustic wave activity, hence the average spectrum shows the range of frequencies of several individual bursts. The points making up the peak spectrum in Figure 2 are obtained individually by choosing the maximum in each frequency channel during the same 2.5-min interval. Since we believe the individual bursts to be quite narrowbanded (compare Figures 3, 4, and 5), we have noted that the most intense burst at 3.11 kHz has an equivalent sine-wave amplitude of 48.3 μV m^{-1}. This spectrum compares very favorably with the ion acoustic wave spectra (previously called $f_p^+ < f < f_p^-$ noise) given by *Gurnett and Anderson* [1977] and by *Gurnett and Frank* [1978] from the Helios spacecraft. The frequency range of the ion acoustic wave spectrum in Figure 1 at 1.73 AU is, however, shifted to somewhat lower frequencies than the frequency spectra observed by Helios at 0.29–1.0 AU. This shift appears to be generally consistent with the results of *Gurnett and Frank* [1978], which show that the upper frequency limit varies approximately as $f_{\max} \propto 1/R$, where R is the heliocentric radial distance. The general morphology of the ion acoustic waves detected by Voyager, consisting of sporadic bursts of noise lasting for periods from several hours to a few days also appears to be consistent with the Helios observations closer to the sun.

In order to verify that the Voyager wave observations can also be interpreted in terms of Doppler-shifted ion acoustic waves as in the case of the Helios observations, we estimate the maximum Doppler shift for the shortest wavelength oscillations having $\lambda_{\min} \simeq 2\pi\lambda_D$ (λ_D is the Debye length). *Gurnett and Frank* [1978] have shown that for typical solar wind parameters the frequency of ion acoustic waves detected in the spacecraft frame of reference is, to a good approximation,

$$f = (V_{sw}/\lambda)\cos\theta_{kV} \tag{1}$$

(valid for $f >> f_p^+$) where θ_{kV} is the angle between the propagation vector $\mathbf{k}$ and the solar wind velocity $\mathbf{V}_{sw}$ and f_p^+ is the rest frame proton plasma frequency. Then by using a simplified ion acoustic wave dispersion relation for $\lambda \simeq 2\pi\lambda_D$ the maximum wave frequency in the spacecraft frame would approximately be

$$f_{\max} \simeq V_{sw}\cos\theta_{kV}/(2\pi\lambda_D) + f_p^+/(2)^{1/2} \tag{2}$$

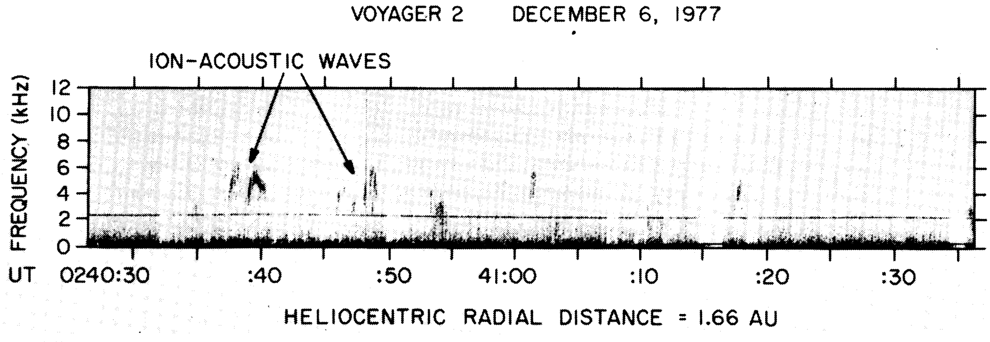

Fig. 4. Additional examples of bursts of ion acoustic waves similar to those in Figure 3. Notice the narrowband structure and very rapid frequency fluctuations of the waves.

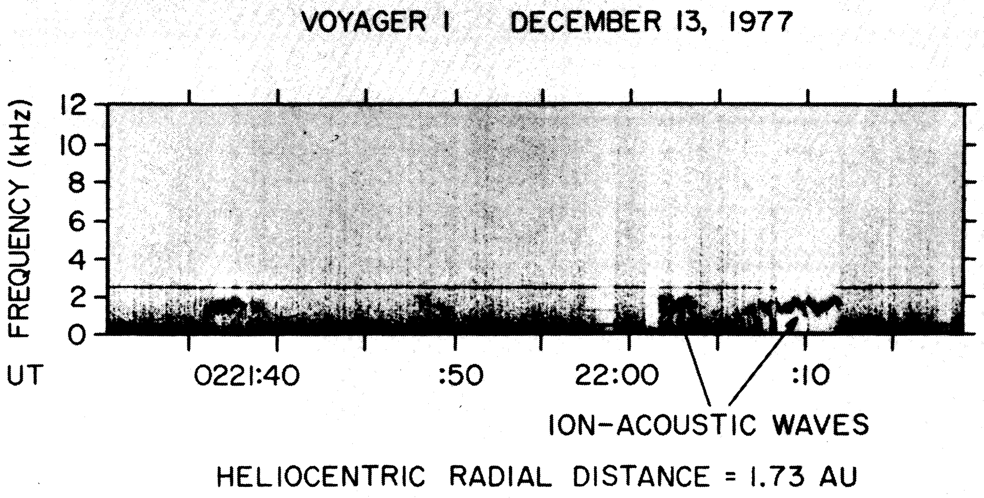

Fig. 5. An example of ion acoustic waves detected by Voyager 1 at 1.73 AU. The waves shown in the spectrogram are similar to the ones shown in Figures 3 and 4 but at a lower frequency.

A relation similar to (2) was given initially by *Gurnett and Anderson* [1977]. Another variation of (2) is found in the work of *Scarf* [1977].

Gurnett and Frank [1978] demonstrated that the ion acoustic waves propagate very nearly parallel to the interplanetary magnetic field. If we assume the waves discussed in the present study also propagate parallel to the magnetic field and also assume that $\mathbf{V}_{sw}$ is in the radial direction, cos θ_{kV} is given by the ratio of $B_R/|B|$, where B_R is the radial component of the interplanetary field and $|B|$ is the magnitude of the field. As an example, $f_{\max}$ can be computed for the data of Figure 2 by using plasma parameters derived from preliminary analysis of data from the MIT Faraday cup on Voyager and the magnetic field measured by the Goddard Space Flight Center magnetometer. Specifically, during the 1200–1300 UT interval on December 13, 1977, the wind speed was typically 334 km/s, the electron temperature was 8.7×10^4 °K, and the density was 3.9 cm^{-3} (J. Sullivan and H. Bridge, private communication, 1978), giving $f_p^+ = 413$ Hz and $\lambda_D = 10.4$ m. The maximum ratio of $B_R/|B|$ during the time interval represented in Figure 2 is 0.70 (N. Ness, private communication, 1978). Hence we shall use cos $\theta_{kV} = 0.70$. Equation (2) then predicts $f_{\max} \simeq 3.9$ kHz in the spacecraft frame. This calculated Doppler-shifted frequency maximum agrees well with the observed upper-frequency cutoff shown in Figure 2, and we conclude that the ion acoustic wave identification can be used for the Voyager observations. For reference, f_{Buneman} [*Buneman,* 1958] is also shown on Figure 2.

Figures 3 and 4 show the frequency-time spectrograms of two segments of high-rate waveform data obtained from Voyager 2 just prior to the period of enhanced ion acoustic wave activity shown in Figure 1. The ordinate and abscissa of the spectrogram are frequency and time, and the darkness at any given frequency-time point is proportional to the logarithm of the electric field spectral density, with black corresponding to the highest intensity and white to the lowest intensity. The line

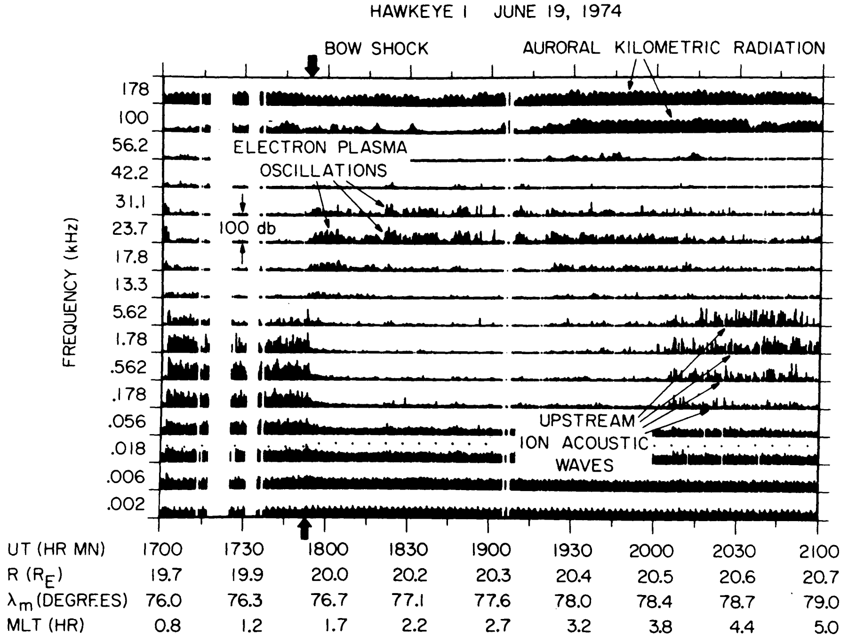

Fig. 6. An example of ion acoustic waves detected upstream of the earth's bow shock by the Hawkeye 1 satellite. The waves are at frequencies below the band of electron plasma oscillations at f_p^- seen in the 23.7-kHz channel.

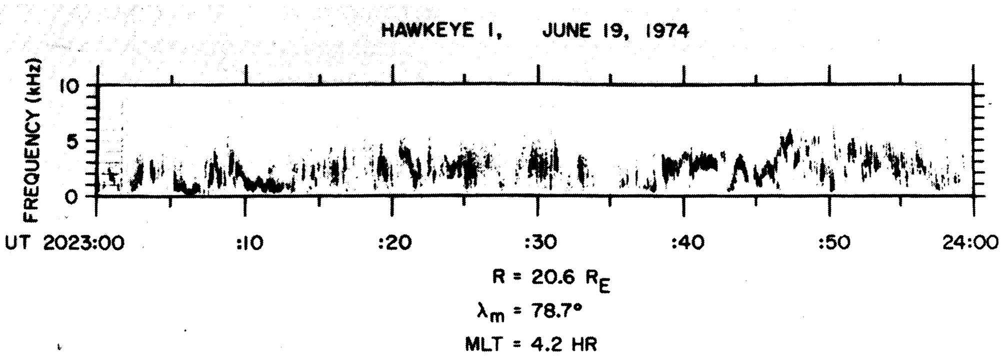

Fig. 7. A high-resolution spectrogram made from wideband data taken during the upstream ion acoustic wave event shown in Figure 6. The spectrum of the upstream waves are very similar to those of the waves shown in Figures 3, 4, and 5, detected in the distant solar wind.

at 2.4 kHz is interference from the spacecraft power supply. The intermittent monochromatic signals at about 400 Hz are also spacecraft-generated interference. Although the high-resolution spectrograms in Figures 3 and 4 were obtained prior to the main period of ion acoustic wave activity evident in Figure 1, a few weak bursts are clearly evident in these spectrograms. The spectrograms show that the ion acoustic waves consist of brief narrow-bandwidth bursts lasting only a few seconds. The center frequency of the emission varies rapidly in frequency, often starting at a frequency of about 3 kHz, increasing rapidly to a maximum frequency of about 6 kHz, and then decreasing rapidly back to the starting frequency. Characteristic inverted U-shaped bursts of this type are evident at 0233:58 UT in Figure 3 and at 0240:40 and 0240:48 UT in Figure 4. Because of the slow sampling rate of the step frequency receiver, these bursts do not appear in the step frequency receiver data in Figure 1. The duty cycle for detecting short impulsive bursts in a given channel of the step frequency receiver during this period of time is approximately $\frac{1}{80}$. Thus the relative occurrence of ion-acoustic waves in the solar wind is probably significantly higher than is indicated by the step frequency receiver data in Figure 1. At the present time only about 10 min of data exists in the high-rate mode from each of Voyager 1 and 2, and the frequency of occurrence of ion acoustic waves in the high resolution spectrograms is much higher than would have been expected from a survey of the step frequency receiver data. Continuously active filter channels with peak detection, such as those used on Helios, must be used to provide continuous detection of these waves.

Figure 5 shows another burst of ion acoustic wave activity which was detected by Voyager 1 at 1.73 AU. There is considerable evidence of ion acoustic turbulence throughout this entire frame of data, especially near 0222:10 UT. The frequency spectrum of the ion acoustic waves in this case is more nearly constant and at a significantly lower frequency than in Figures 3 and 4. The center frequency, ~ 1.5 kHz, is still well above the local ion plasma frequency, estimated to be about 250 Hz; this indicates that large Doppler shifts are necessary to explain the observed frequency spectrum.

4. Relationship to Waves Upstream of the Earth's Bow Shock

Now that high-resolution frequency-time spectrograms are available for studying ion acoustic waves in the distant solar

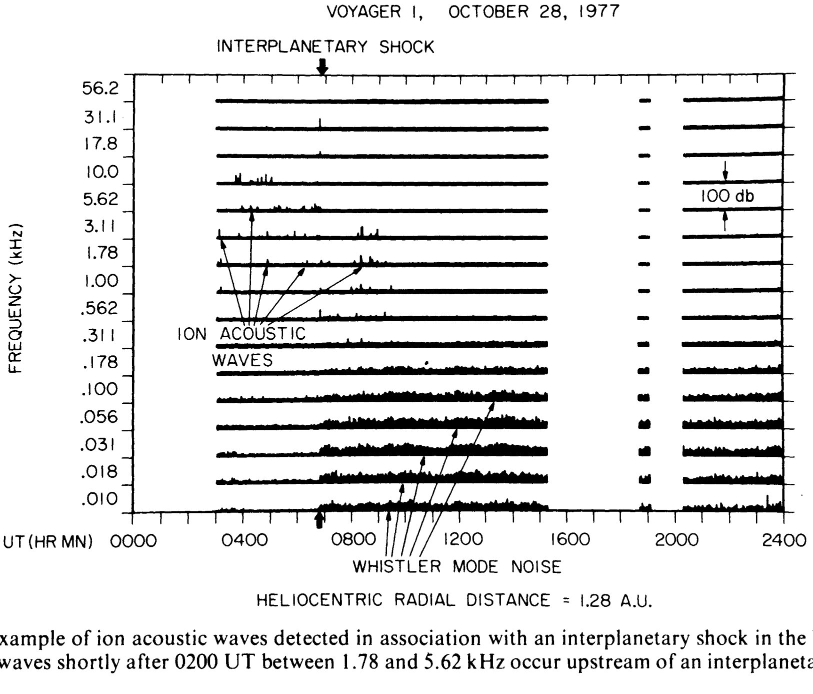

Fig. 8. An example of ion acoustic waves detected in association with an interplanetary shock in the Voyager 1 plasma wave data. The waves shortly after 0200 UT between 1.78 and 5.62 kHz occur upstream of an interplanetary shock detected at 0654 UT.

wind it becomes important to compare these with similar measurements of ion acoustic waves upstream of the earth's bow shock. Figure 6 is a display of data from the Hawkeye 1 plasma wave instrument with time and frequency scales similar to Figure 1. For a description of the Hawkeye 1 instrument, see *Kurth et al.* [1975]. Between about 2000 and 2100 UT Hawkeye 1 is in the solar wind upstream of the bow shock. During this period the plasma wave instrument detects strong waves between 562 Hz and 5.62 kHz. These waves are similar to events detected by Imp 6 and 8 published earlier in Figures 8, 9, 10, and 15 of *Gurnett and Frank* [1978]. A high-resolution wideband spectrogram taken simultaneously with the data in Figure 6 is shown in Figure 7. Although the ion acoustic turbulence is more intense and more nearly continuous in the region upstream of the bow shock than in the Voyager measurements in interplanetary space, the close similarity of the spectrums in the two regions is clearly evident. In both cases the waves consist of narrowband emissions from about 1 to 5 kHz, with rapidly varying center frequencies. Bursts with an inverted U shape, comparable to those in Figures 3 and 4, and intervals with a nearly constant emission frequency at about 1 kHz, comparable to Figure 5, can be seen in Figure 7.

As one might expect, it is also possible to detect ion acoustic waves upstream of interplanetary shocks. Figure 8 shows the plasma wave electric field intensities during October 28, 1977, when an interplanetary shock occurred. The shock passed Voyager 1 at 0654 UT but as is shown in Figure 8, an extensive ion acoustic wave 'storm' preceeded this shock by many hours. During this particular day, Voyager 1 was in a low data rate cruise mode (80 b/s). In this mode the step frequency receiver was cycling through all frequencies only once every 96 s. Although only a relatively small number of ion acoustic wave bursts are evident in Figure 8, the ion acoustic wave activity upstream of the shock is nevertheless fairly high, since the duty cycle for detecting an ion acoustic wave burst in a given channel at this low bit rate is only about 1/1920. Because the occurrence rate of the ion acoustic waves upstream of the shock is much higher than is normally detected in the solar wind it is almost certain that the ion acoustic waves in this case are directly associated with the approaching interplanetary shock. By analogy with similar events occurring upstream of the earth's bow shock, it seems reasonable to expect that similar mechanisms are responsible for the ion acoustic waves upstream of both interplanetary shocks and the earth's bow shock. The low-frequency electric field noise following the shock in Figure 8 is believed to be whistler mode turbulence, comparable to that observed by *Neubauer et al.* [1977*a*, *b*] in association with interplanetary shocks.

5. DISCUSSION

In this paper we have presented high-resolution frequency-time spectrograms of electrostatic waves detected by the Voyager 1 and 2 spacecraft in interplanetary space at frequencies between the electron and ion plasma frequencies. It is shown that these waves consist of brief narrowband bursts with rapidly varying center frequencies. Comparisons with similar spectrums obtained upstream of the earth's bow shock show that these waves have spectrums essentially identical to waves produced by suprathermal protons streaming into the solar wind from the bow shock. Observations are also presented showing that this same type of wave also occurs upstream of interplanetary shocks.

The high-resolution spectrograms from Voyager 1 and 2 now provide strong support for the conclusions of *Gurnett and Frank* [1978] that the electrostatic waves detected in interplanetary space between the electron and ion plasma frequencies are essentially identical to the waves detected upstream of the earth's bow shock in association with suprathermal protons streaming into the solar wind from the bow shock [*Scarf et al.*, 1970]. Following the conclusions of *Gurnett and Frank* [1978] we have referred to these waves as ion acoustic waves. The wave frequencies in the spacecraft frame appear to be nearly equal to the values expected for Doppler-shifted ion acoustic waves. Although these waves are ion-acoustic-like, the exact mechanism by which these waves are generated remains to be established. *Gurnett and Frank* [1978] have suggested the ion acoustic waves upstream of the earth's bow shock may often be driven by suprathermal protons streaming into the solar wind from the bow shock. Other events studied by Gurnett and Frank, believed to correspond to the interplanetary ion acoustic waves of the type detected by Helios and Voyager appear to have no clear correlation with suprathermal particles and may be generated by an electron heat flux instability as suggested by *Forslund* [1970] or by double-ion beams as suggested by *Gary* [1978]. In this paper we have shown the nearly identical spectral characteristics of the upstream waves and the waves detected in the distant interplanetary medium. The close similarity indicates that in some cases the driving mechanism may also be essentially the same.

Although ion acoustic wave turbulence has been observed upstream of an interplanetary shock it seems unlikely that all ion acoustic waves observed in the solar wind can be associated with interplanetary shocks, since these waves are often observed during periods for which no interplanetary shocks have occurred. Also, as typified by the event analyzed by *Gurnett et al.* [1979], we know that at least some interplanetary shocks do not have strong ion acoustic wave activity in the region upstream of the shock.

Acknowledgments. The authors express their thanks to James Sullivan and Herbert Bridge of the Massachusetts Institute of Technology for providing information on the interplanetary plasma parameters and to Norman Ness of Goddard Space Flight Center and the Voyager magnetometer team for providing measurements of the interplanetary field direction. We are also indebted to Paul Jepsen and the Image Processing Laboratory at the Jet Propulsion Laboratory for producing the Voyager high-resolution spectrograms used in this report. The research at the University of Iowa was supported by the National Aeronautics and Space Administration through contract 954013 with the Jet Propulsion Laboratory and contract NAS1-13129 with Langley Research Center, through grant NGL-16-001-043 with NASA Headquarters, and by the Office of Naval Research. The research at TRW was supported by the National Aeronautics and Space Administration through contract 954012 with the Jet Propulsion Laboratory.

The Editor thanks F. M. Neubauer and S. P. Gary for their assistance in evaluating this paper.

REFERENCES

Buneman, O., Instability, turbulence and conductivity in a current-carrying plasma, *Phys. Rev. Lett.*, *1*, 8, 1958.

Forslund, D. W., Instabilities associated with heat conduction in the solar wind and their consequences, *J. Geophys. Res.*, *75*, 17, 1970.

Gary, S. P., Ion-acoustic-like instabilities in the solar wind, *J. Geophys. Res.*, *83*, 2504, 1978.

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

Gurnett, D. A., and L. A. Frank, Ion acoustic waves in the solar wind, *J. Geophys. Res.*, *83*, 58, 1978.

Gurnett, D. A., F. M. Neubauer, and R. Schwenn, Plasma wave turbulence associated with an interplanetary shock, *J. Geophys. Res.*, *84*, 541, 1979.

Kurth, W. S., M. M. Baumback, and D. A. Gurnett, Direction-finding measurements of auroral kilometric radiation, *J. Geophys. Res., 80,* 2764, 1975.

Neubauer, F. M., G. Musmann, and G. Dehmel, Fast magnetic fluctuations in the solar wind: Helios 1, *J. Geophys. Res., 82,* 3201, 1977*a*.

Neubauer, F. M., H. J. Beinroth, H. Barnstorf, and G. Dehmel, Initial results from the Helios 1 search coil magnetometer experiment, *J. Geophys., 42,* 599, 1977*b*.

Scarf, F. L., Wave-particle interaction phenomena associated with shocks in the solar wind, in *Study of Travelling Interplanetary Phenomena,* edited by M. A. Shea et al., p. 259, D. Reidel, Hingham, Mass., 1977.

Scarf, F. L., and D. A. Gurnett, A plasma wave investigation for the Voyager mission, *Space Sci. Rev., 21,* 289, 1977.

Scarf, F. L., R. W. Fredricks, L. A. Frank, C. T. Russell, P. J. Coleman, Jr., and M. Neugebauer, Direct correlations of large-amplitude waves with suprathermal protons in the upstream solar wind, *J. Geophys. Res., 75,* 7316, 1970.

(Received May 2, 1978;
revised October 17, 1978;
accepted October 19, 1978.)