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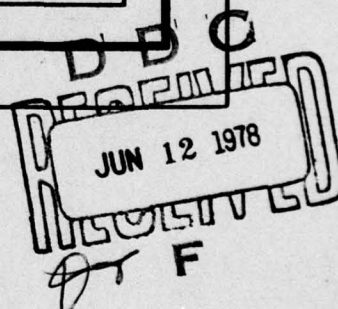
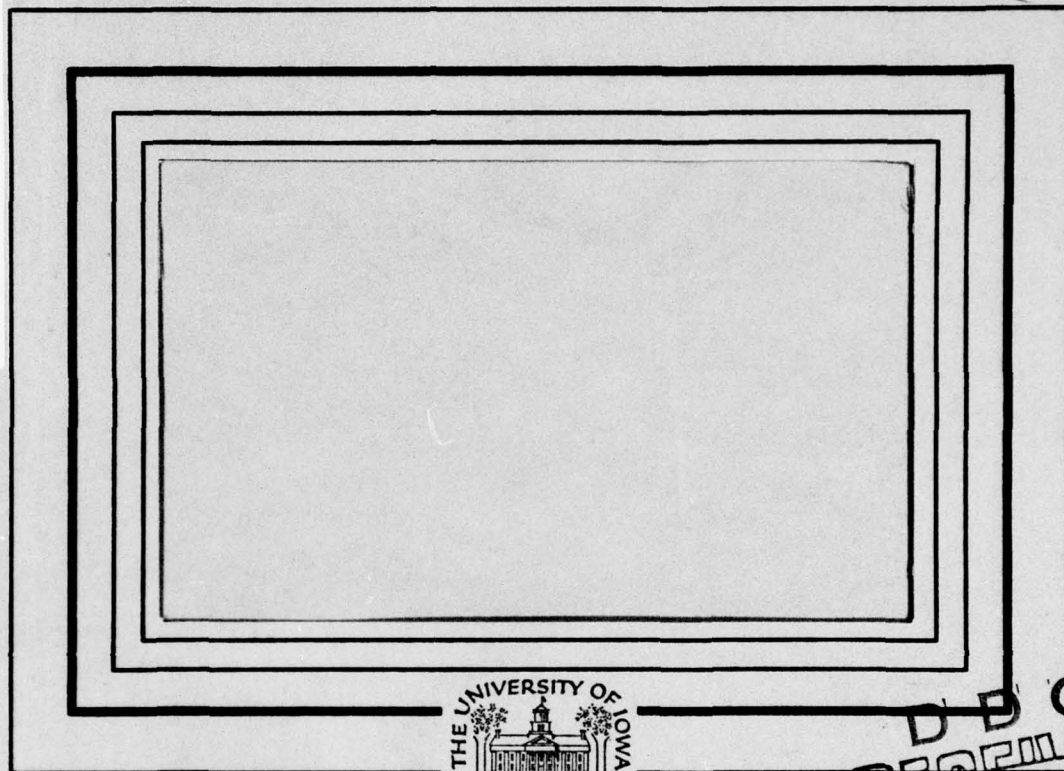
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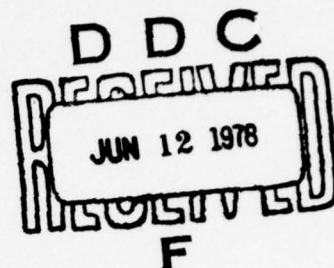
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High Resolution Spectrograms of
Ion-Acoustic Waves in the Solar Wind⁺

by

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March, 1978

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ABSTRACT

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 narrow-band 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.) $f_{sub p}(-)$

$f_{sub p}(+)$ 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 strongly suggests that the ion-acoustic waves detected in the solar wind by Helios and Voyager are driven by an ion beam instability, as has recently been suggested in a theoretical analysis by Gary.

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I. 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.

II. 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-meter 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 narrow-band 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 seconds for the highest possible telemetry rates. 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 sec. 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-second 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, using standard fast Fourier transform techniques.

III. 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 $1 \mu\text{V m}^{-1}$ to 100 mV m^{-1} . The vertical bars (solid black areas) give the average electric field intensity averaged over 24-second 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 in the 1.78 to 5.62 kHz channels from about 0250 to 0430 UT. (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 one or two days, similar to the event in Figure 1. 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.

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 to 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). Using the simplified ion-acoustic wave dispersion relation given by Scarf [1977] for $\lambda \approx 2\pi\lambda_D$, the maximum wave frequency in the spacecraft frame would approximately be

$$f_{\max} \simeq [V/(2\pi\lambda_D) + f_p^+/\sqrt{2}], \quad (1)$$

where V is the wind speed and f_p^+ is the rest frame proton plasma frequency. As an example, $f_{\max}$ can be computed for the data of Figure 2, using plasma parameters derived from the MIT Faraday cup on Voyager.

Specifically, during the 1200-1300 UT interval on December 13, 1977, the wind speed was 350 km/sec, the proton temperature was 5×10^4 °K, and the density was 3.7 cm^{-3} [J. Sullivan and H. Bridge, private communication), giving $f_p^+ = 400 \text{ Hz}$, $\lambda_D = 8 \text{ meters}$. Equation (1) then predicts $f_{\text{max}} \approx 7.2 \text{ kHz}$ 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 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 is approximately $1/80$. 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 minutes 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 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, which is estimated to be about 250 Hz, indicating that large Doppler shifts are necessary to explain the observed frequency spectrum.

IV. 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 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 narrow-band 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 shown in Figure 8, an extensive ion-acoustic wave "storm" preceded 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 seconds. 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 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] in association with interplanetary shocks.

V. 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 narrow-band 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 [Sarf 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. The close similarity of the

interplanetary ion-acoustic waves to the waves upstream of the earth's bow shock provides a strong inferential argument that the interplanetary ion-acoustic waves are driven by suprathermal ion streams in the solar wind. Gary [1978] has recently compared the threshold for electrostatic instabilities driven by electron and ion heat fluxes using parameters appropriate to the solar wind near 1 AU. Gary concludes that an electrostatic ion beam instability is the most likely source of the ion-acoustic-like waves observed by the Helios and Voyager spacecraft in interplanetary space. At the present time this conclusion has not been directly verified by comparisons with the solar wind plasma measurements, although attempts to establish this relationship are now in progress.

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. [1978], we know that many interplanetary shocks do not have strong ion-acoustic wave activity in the region upstream of the shock.

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

FIGURE CAPTIONS

- Figure 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 has been filtered to remove interference associated with attitude control jets firing.
- Figure 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.
- Figure 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.

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

Figure 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.

Figure 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.

Figure 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.

Figure 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.

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VOYAGER 2, DECEMBER 6, 1977

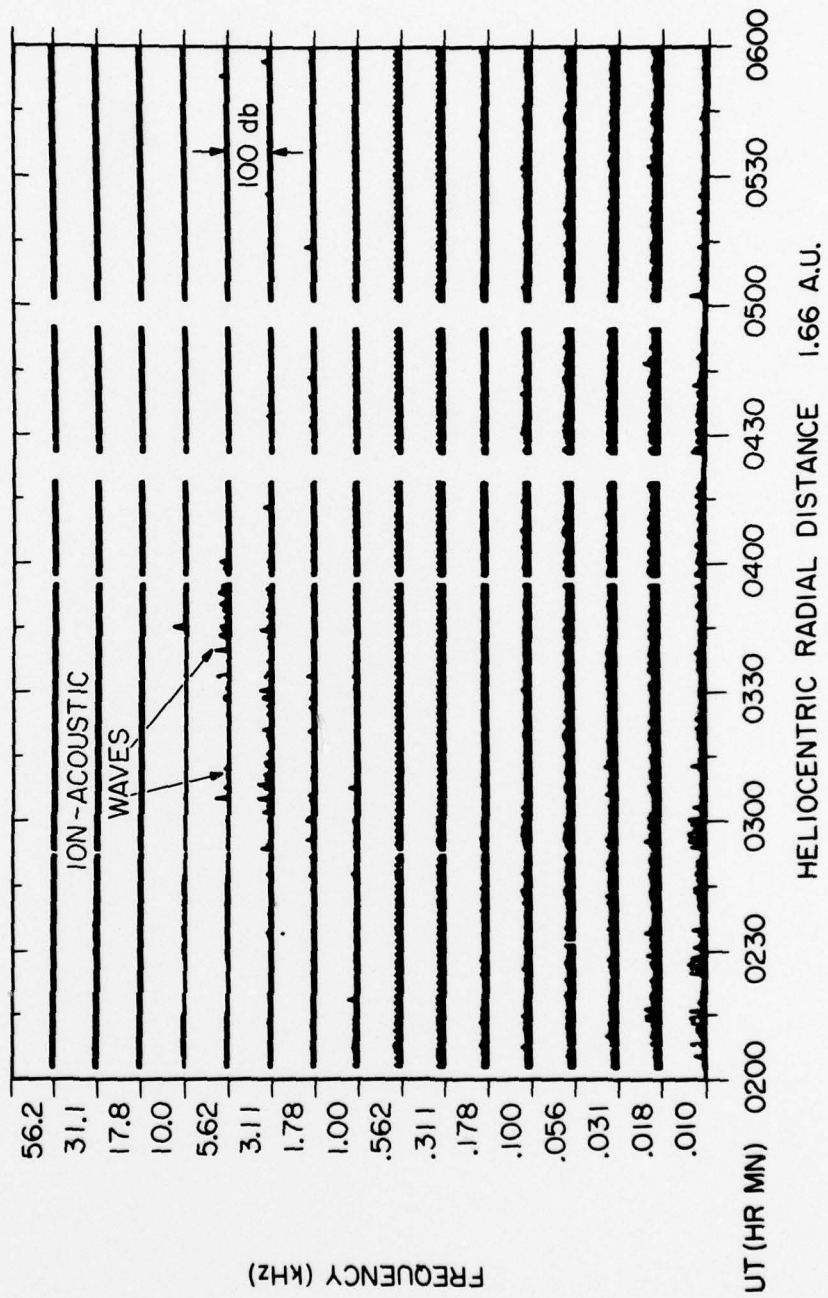


Figure 1

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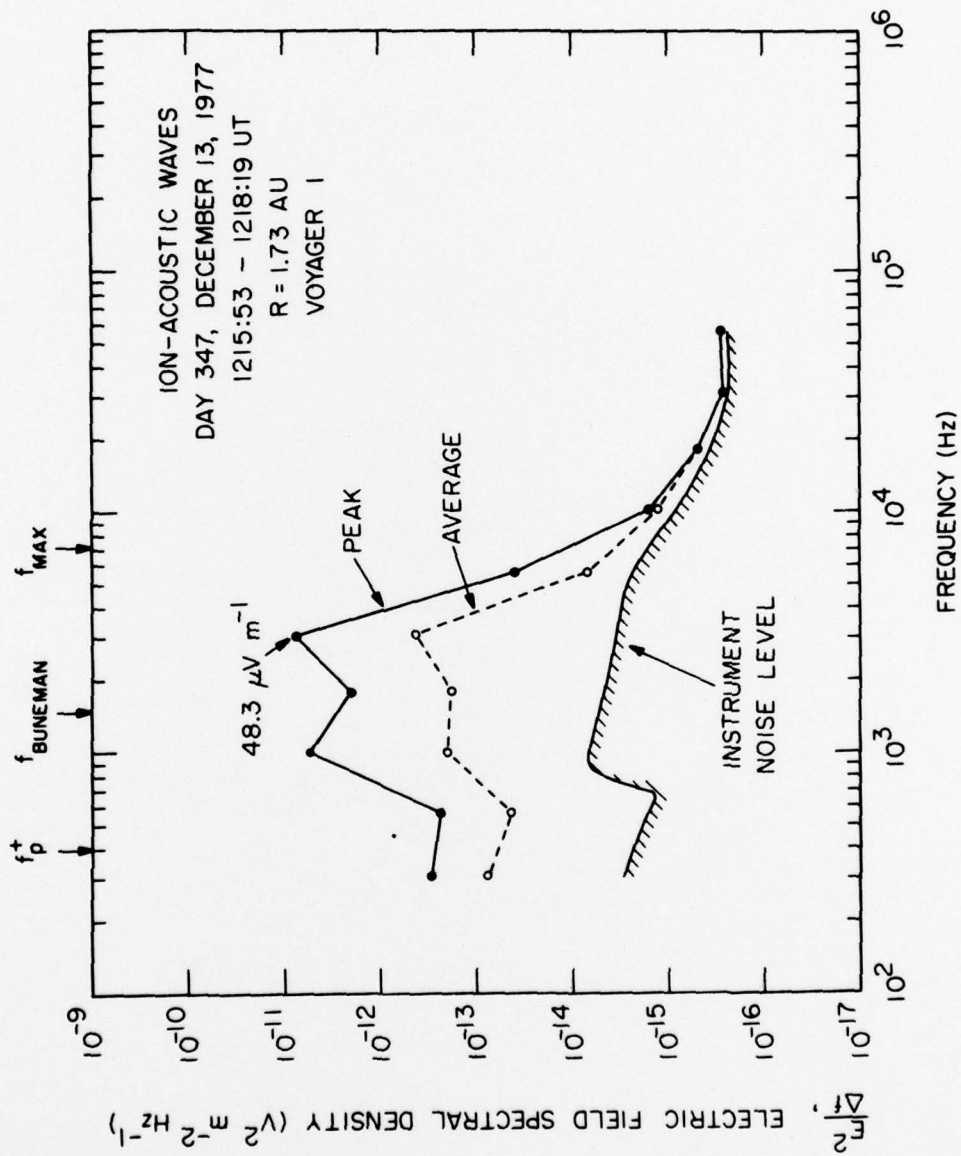


Figure 2

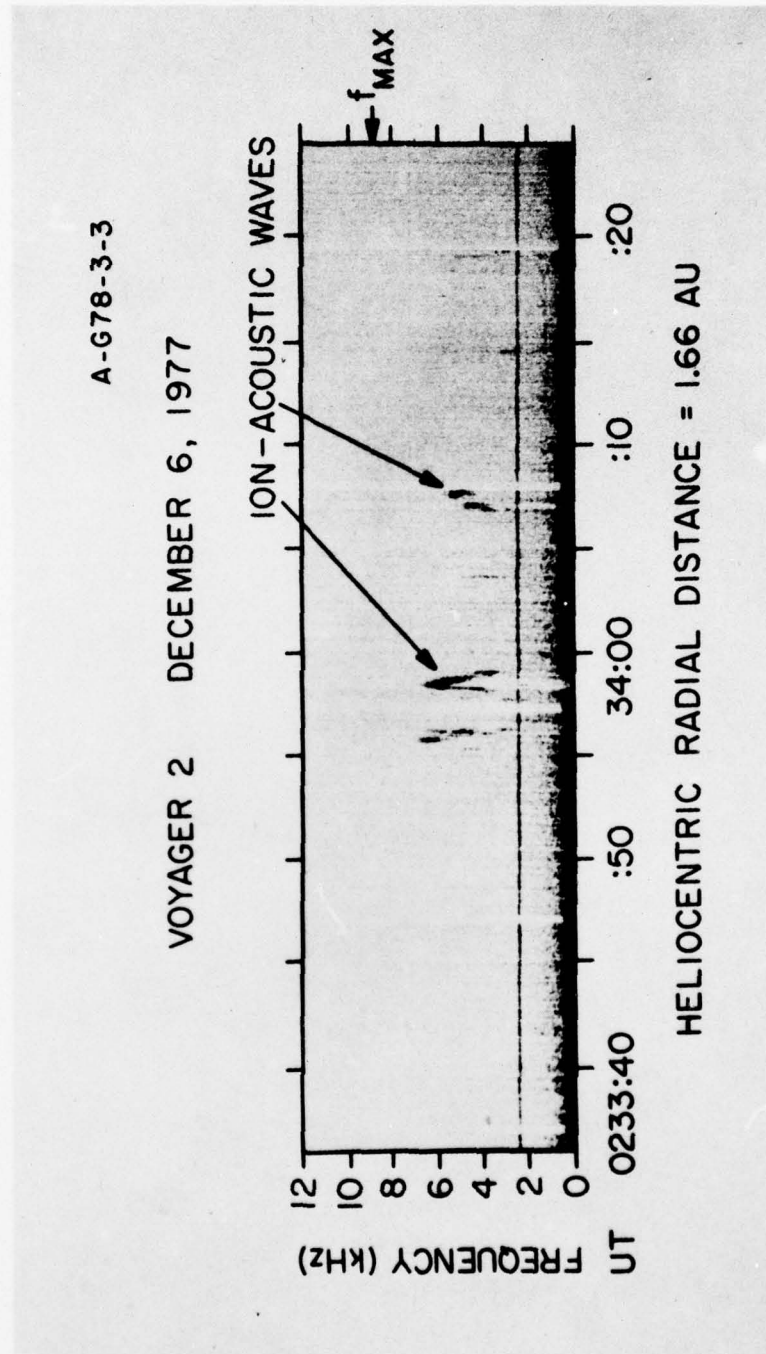


Figure 3

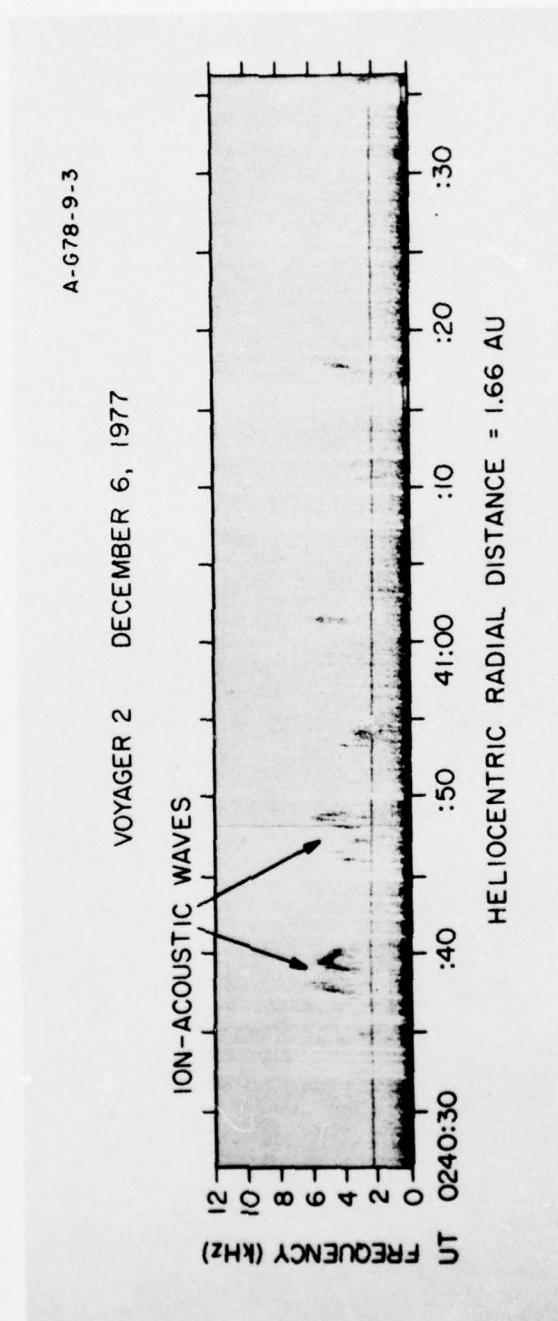


Figure 4

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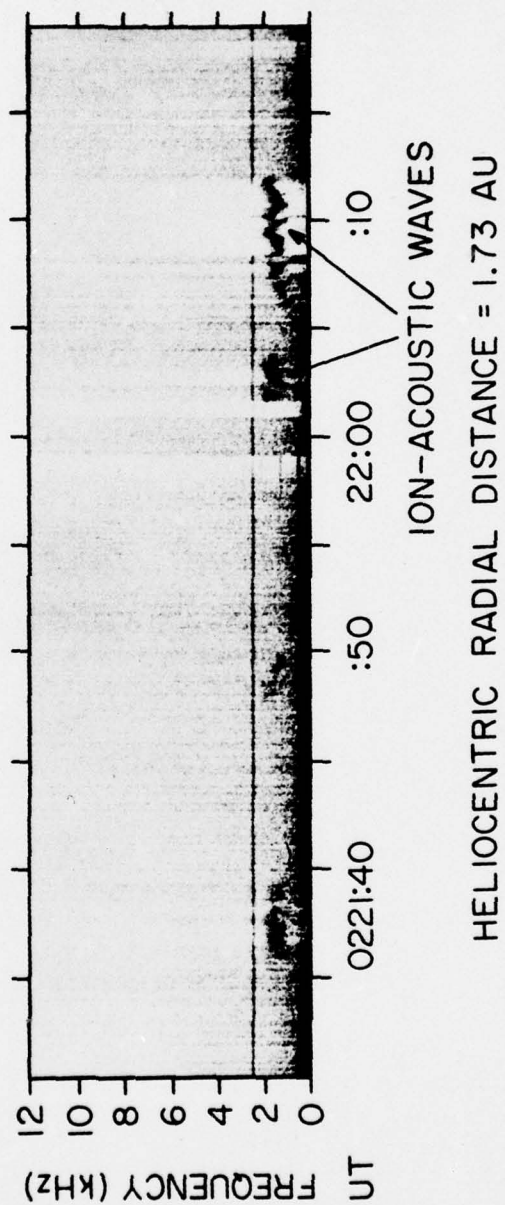


Figure 5

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HAWKEYE I JUNE 19, 1974

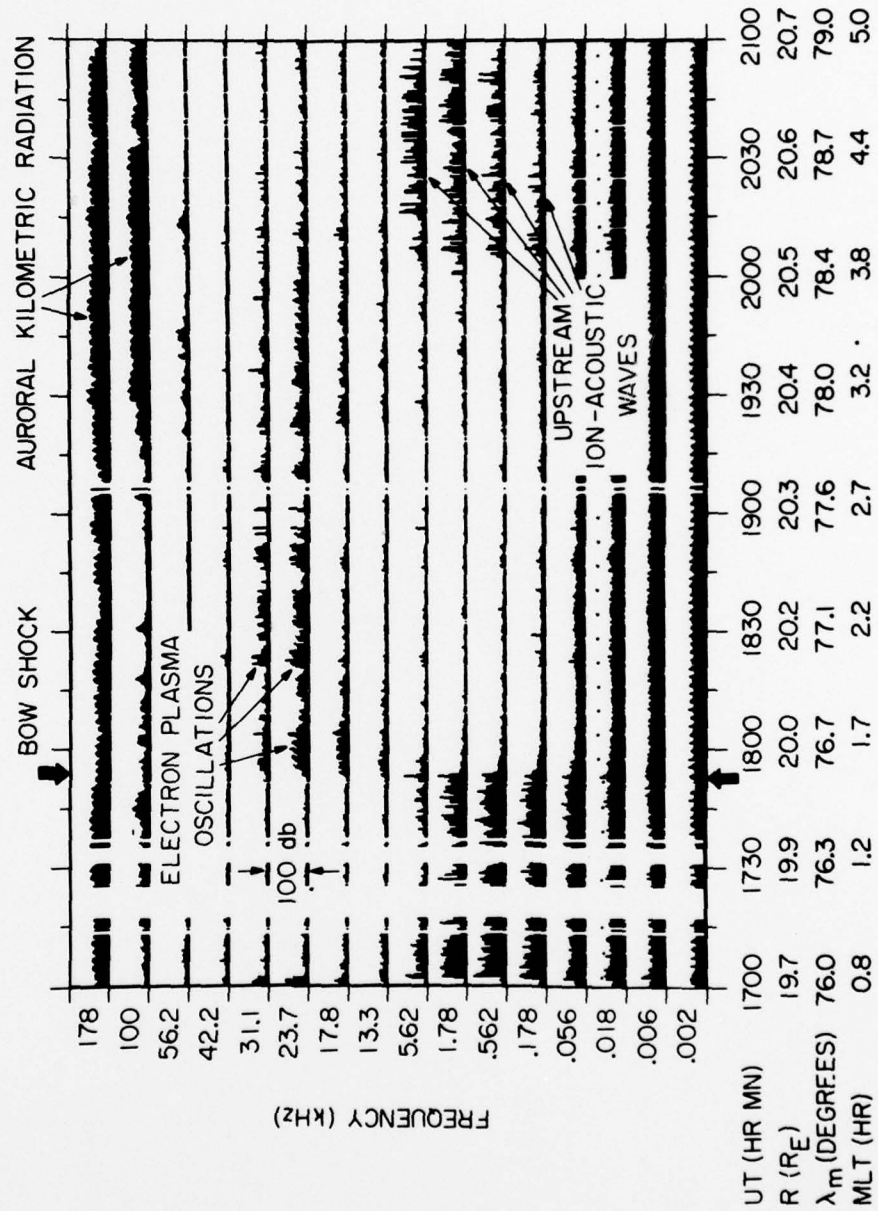


Figure 6

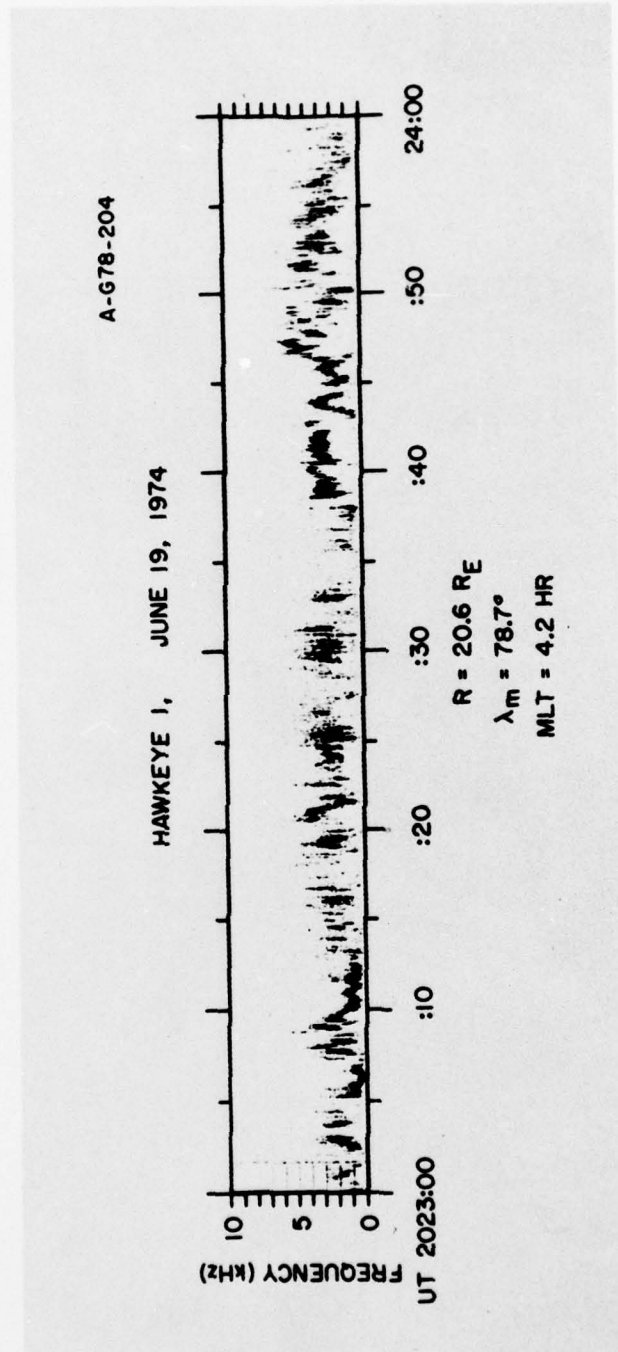


Figure 7

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VOYAGER 1, OCTOBER 28, 1977

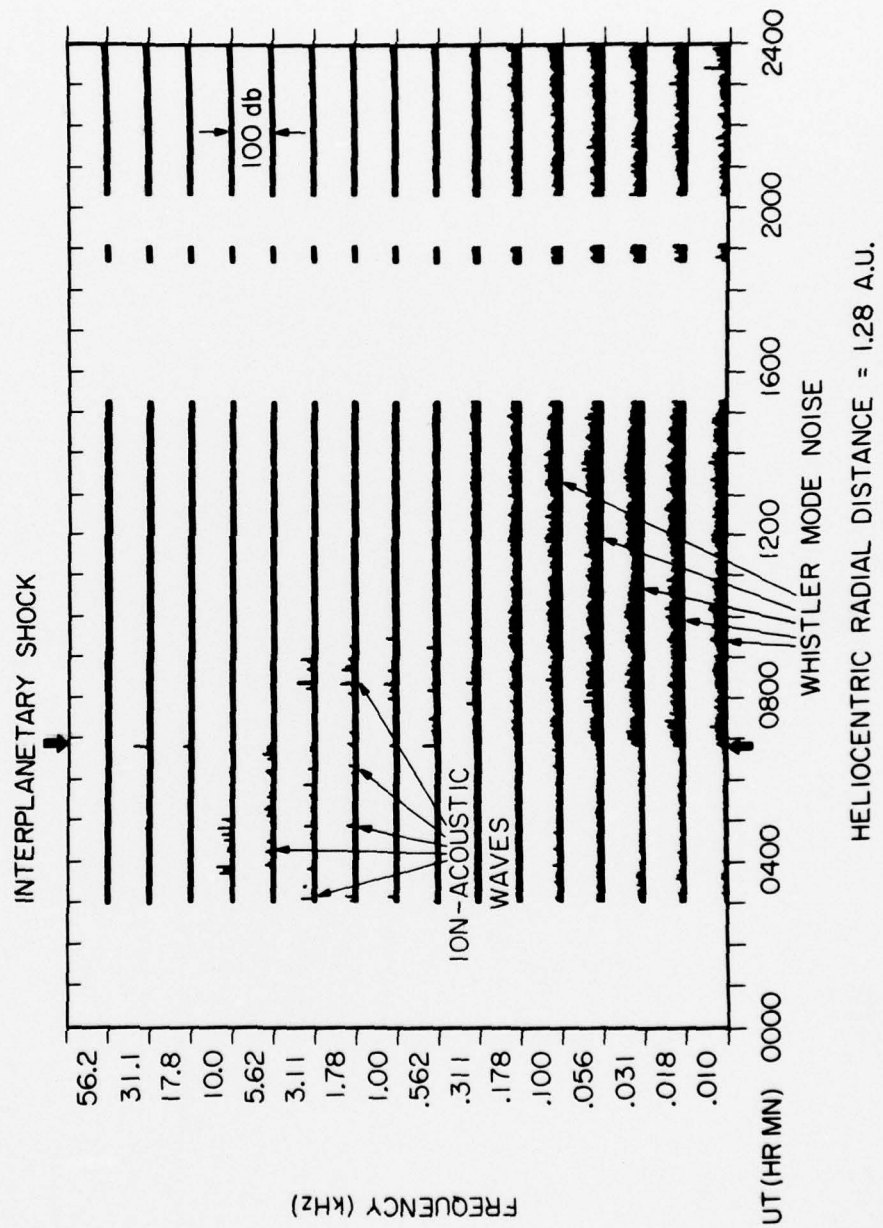


Figure 8