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PLASMA WAVES IN THE SOLAR WIND: A REVIEW OF OBSERVATIONS

D. A. Gurnett
Department of Physics and Astronomy, The University of Iowa
Iowa City, Iowa, USA

Abstract. A review is presented of the current experimental and theoretical understanding of plasma waves in the solar wind, with comments on the possible effect these waves may have on the macroscopic structure of the solar wind. Only short wavelength waves at frequencies above the magnetohydrodynamic regime are considered. These waves include electron plasma oscillations, ion-acoustic waves, whistler-mode waves, and ion-cyclotron waves. Waves associated with interplanetary shocks are also discussed.

I. INTRODUCTION

In the past few years significant advances have been made in our knowledge and understanding of plasma instabilities in the solar wind. The purpose of this paper is to survey the current status of solar wind plasma wave observations and to comment on the various plasma instability mechanisms which are thought to be responsible for these waves. To limit the scope of this review only short wavelength instabilities driven by microscopic, local processes in the solar wind are considered. For a review of long wavelength, Alfvén and magnetohydrodynamic (MHD) waves involving interactions on time scales comparable to the expansion time of the solar wind, see for example, Hollweg [1975]. Since this review covers all waves above the MHD range, the frequencies of interest extend across the entire range of local characteristic frequencies of the plasma, from the ion-cyclotron frequency to the electron plasma frequency.

Since the earliest work of Parker [1958], it has been thought that plasma instabilities play an important role in the dynamical evolution of the solar wind. As is well-known, waves generated by instabilities in a collisionless plasma play a role similar to collisions in an ordinary gas by providing the scattering and momentum transfer necessary to drive the plasma towards thermal equilibrium. Since the collisionless solar wind plasma can be described in many respects by fluid-like equations involving approximate local thermal equilibrium, wave-particle interactions must be involved in determining the equilibrium particle distributions. It has been suggested, for example, that wave-particle interactions play a role in controlling the heat flux in the solar wind [Forslund, 1970; Gary et al., 1975], in heating the solar wind protons [Fredricks, 1969], in thermalizing double-ion streams [Montgomery et al., 1975; Lemons et al., 1978], in accelerating alpha particles in the solar wind [Hollweg and Turner, 1978], and in controlling the evolution of energetic electrons emitted by solar flares [Papadopoulos et al., 1974; Magelssen and Smith, 1977].

Up to the present time the primary solar wind plasma wave measurements which are available for analysis are from the Pioneer 8 and 9 [Scarf et al., 1968], Helios 1 and 2 [Gurnett and Anderson, 1977; Neubauer et al., 1977] and Voyager 1 and 2 [Scarf and

Gurnett, 1978] spacecraft. Because of the low sensitivity, the early Pioneer 8 and 9 measurements are mainly confined to large amplitude electric fields associated with shocks and other solar wind discontinuities. The higher sensitivity measurements from the more recently launched Helios and Voyager spacecraft have in the meantime provided a comprehensive survey of all the plasma waves which occur in the solar wind from about 0.3 to 3 AU, even at very low intensities.

The main types of plasma waves observed in the solar wind are, in order of decreasing frequency (1) electron plasma oscillations (Langmuir waves) at the local electron plasma frequency, f_p^-, (2) ion-acoustic waves at frequencies below the ion plasma frequencies, f_p^+, (3) whistler-mode waves at frequencies below the electron gyrofrequency, f_g^-, and (4) ion-cyclotron waves at frequencies below the proton cyclotron frequency f_g^+. The approximate frequency range and radial variation of the characteristic frequency associated with each of these waves are shown in Figure 1. For future reference, Figure 2 shows the corresponding dispersion relation, phase velocity vs. frequency, for typical solar wind parameters at 1 AU. In this review, electrostatic and electromagnetic waves are discussed separately since the instability mechanism and interaction with the plasma tends to be quite different for these two cases. In addition, plasma waves associated with interplanetary shocks are discussed in a separate section since these events are of a somewhat specialized nature.

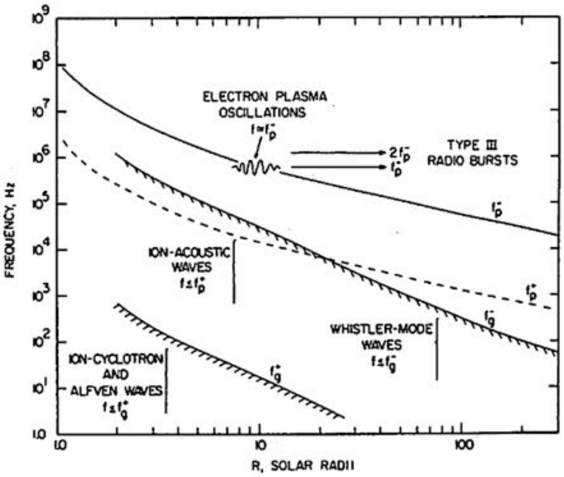

Figure 1. The radial variation of the most important characteristic frequencies of the solar wind plasma.

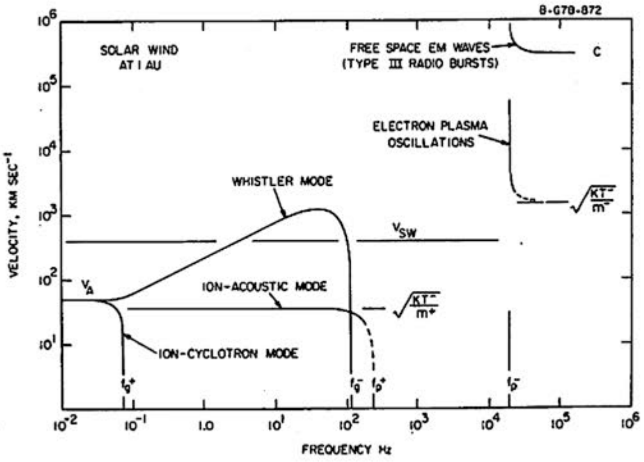

Figure 2. The phase velocity of the various plasma wave modes which occur in the solar wind at 1 AU.

II. ELECTROSTATIC WAVES

A. Electron Plasma Oscillations

Intense narrow-band electrostatic emissions near the electron plasma frequency, f_p^-, are occasionally detected by both the Helios and Voyager spacecraft. Polarization measurements with the Helios spacecraft [Gurnett and Anderson, 1977] show that the electric field of these waves is parallel to the static magnetic field, which together with the oscillation frequency, uniquely identifies these waves as electron plasma oscillations. Electron plasma oscillations usually occur in association with solar flares and type III radio bursts, although occasionally no relationship to solar activity is apparent. A typical example of electron plasma oscillations detected by Helios in association with a type III radio burst is shown in Figure 3, from Gurnett and Frank [1978]. The solid lines in this illustration give the peak electric field strengths and the vertical bars (solid black areas) give the average field strengths. The intensity scale for each frequency channel is logarithmic, with a dynamic range of 100 db, extending from about 1 μV m^{-1} to 100 mV m^{-1}. The local electron plasma frequency, f_p^-, at the time of the burst is indicated in Figure 3. As can be seen, the largest electric field strength occurs in the 31.1 kHz channel, in almost exact coincidence with the electron plasma frequency. Since the phase velocity of these waves is substantially larger than the solar wind velocity, V_{sw}, Doppler shifts due to the solar wind motion are small (see Figure 2). The very large ratio of peak-to-average field strengths, ~ 10^3, evident in Figure 3 indicates that the plasma oscillations consist of many short very intense bursts, with a relatively long dead time between bursts. As shown by Gurnett and Anderson [1977], the time scale for an individual burst is often extremely short, sometimes comparable to the time resolution (50 msec.) of the instrument. The observation of such spiky bursts has led to the suggestion that these waves may be involved in strong turbulence effects, such as the oscillating two-stream instability [Papadopoulos et al., 1974] and soliton collapse [Nicholson et al., 1978]. At the present time, however, support for such processes is only qualitative since the field strengths involved, $E^2/8\pi nkT \simeq 10^{-5}$, are only marginal for the onset of strong turbulence effects, and the time resolution is not adequate to resolve the intense fields associated with a collapsing soliton [Smith and Nicholson, 1978].

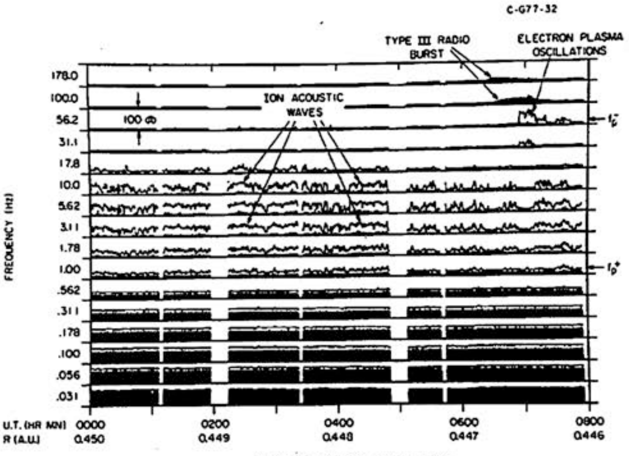

Figure 3. Typical examples of electron plasma oscillations and ion-acoustic waves detected by Helios 2 at 0.45 AU.

The Helios observations of electron plasma oscillations in direct association with type III solar radio bursts [Gurnett and Anderson, 1976] provides a convincing verification of the mechanism, first proposed by Ginzburg and Zheleznyakov [1958] nearly twenty years ago, that these radio bursts are caused by intense electron plasma oscillations generated by a two-stream instability. As indicated in Figure 1, nonlinear interactions can produce radio emission at both the fundamental, f_p^-, and second harmonic, $2f_p^-$, of the electron plasma frequency. The characteristic decreasing frequency with increasing time of a type III radio burst is produced by the decreasing electron plasma frequency excited by the solar flare electrons as they sweep outward away from the sun. Various techniques show that the dominant radio emission at low frequencies (≤ 1 MHz) is at the second harmonic [Fainberg et al., 1972; Kaiser, 1975; Gurnett et al., 1978a].

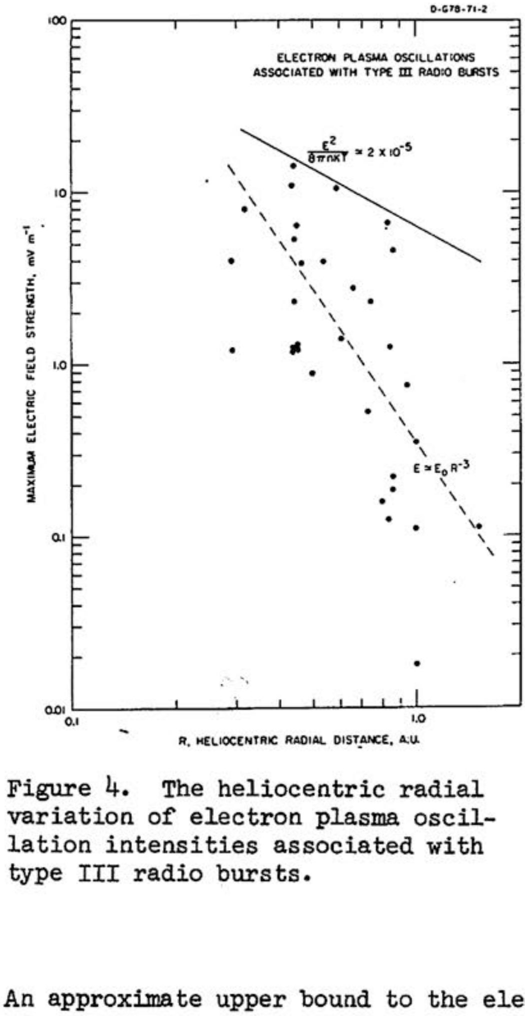

Figure 4. The heliocentric radial variation of electron plasma oscillation intensities associated with type III radio bursts.

When plasma oscillations are associated with a type III radio burst they are often very intense, as in Figure 3, and show a clear tendency for a saturation effect which limits the maximum field strength of the oscillations. Studies of numerous events at various radial distances from the sun show a systematic decrease in the saturation field strength with increasing radial distance. This radial dependence is illustrated in Figure 4, from Gurnett et al. [1978b], which shows the maximum plasma oscillation field strengths for all of the type III events detected to date with electron plasma oscillations. A best fit power law through all of the points indicates that the electric field amplitude varies approximately as $1/R^3$. Although the small number of events limits the accuracy to which the power law index can be determined, the general trend toward decreasing field strength with increasing radial distance from the sun is clearly evident. An approximate upper bound to the electric field to plasma energy density ratio, $E^2/8\pi nkT$, is approximately 2×10^{-5}, as indicated by the solid line in Figure 4.

B. Ion-Acoustic Waves

One of the early discoveries from the Helios plasma wave experiment was the observation of moderately intense electrostatic waves at frequencies between the ion and electron plasma frequencies, $f_p^+ < f < f_p^-$. These waves were initially referred to $f_p^+ < f < f_p^-$ noise [Gurnett and Anderson, 1977]. Subsequent investigations by Gurnett and Frank [1978] showed that these waves have very short wavelengths, $\lambda \simeq 2\pi\lambda_D$ where λ_D is the Debye length. Polarization measurements showed that the electric field is closely aligned along the direction of the static magnetic field. Considerations of the possible short wavelength electrostatic modes which can occur in a plasma strongly suggest that these waves are short wavelength ion-acoustic waves or waves with very similar characteristics.

An example of the ion-acoustic waves detected by Helios is shown in Figure 3. The ion-acoustic waves usually extend over a relatively broad range of frequencies and consist of many short impulsive bursts, as indicated by the large ratio of peak-to-average field strengths. The frequency spectrum of these bursts shows a systematic variation with radial distance from the sun, decreasing in intensity and frequency with increasing radial distance from the sun. This radial dependence is illustrated in Figure 5 which shows two typical spectrums from Helios at 0.47 and 0.98 AU and one spectrum from Voyager at 1.73 AU. The upper frequency cutoff of the spectrum is consistent with the maximum frequency expected for Doppler shifted ion-acoustic waves [Gurnett and Anderson, 1977],

$$f_{\max} \simeq f_p^+ + \left(\frac{V_{sw}}{2\pi\lambda_D}\right) \text{Cos } \theta_{kV} ,$$

where θ_{kV} is the angle between the wave vector and the solar wind velocity. As indicated in Figure 2, large Doppler shifts are expected for ion-acoustic waves, since the solar wind velocity is much larger than the ion-acoustic velocity, $\sqrt{kT^-/m^+}$. The radial variation in the upper frequency cutoff is mainly due to the radial variation in the Debye length which varies approximately as $\lambda_D \propto 1/R$. According to this interpretation the apparent relationship of the upper and lower cutoffs of the spectrum to f_p^+ and f_p^- is purely coincidental.

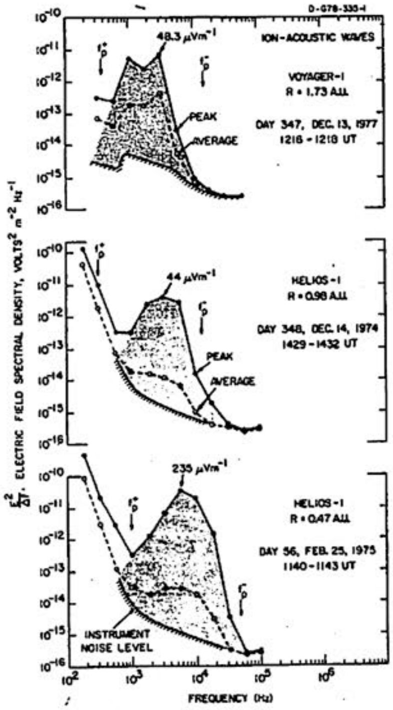

Figure 5. A sequence of ion-acoustic wave spectrums showing the decrease in the intensity and frequency with increasing radial distance from the sun.

High-time resolution spectrum measurements from the Voyager spacecraft, shown in Figure 6 from Kurth et al. [1979], provide very detailed information on the frequency-time structure of these waves. As can be seen from Figure 6, the ion-acoustic wave bursts consist of narrow-band emissions with a rapidly varying center frequency, sometimes displaying the inverted-U form evident in Figure 6. The rapid frequency variations explains why the peak field strength spectrums from Helios, as in Figure 3, appear so broad, since the frequency of a single burst usually sweeps through several channels. The duration of the bursts is usually very short, only a few tenths of a second to about one second.

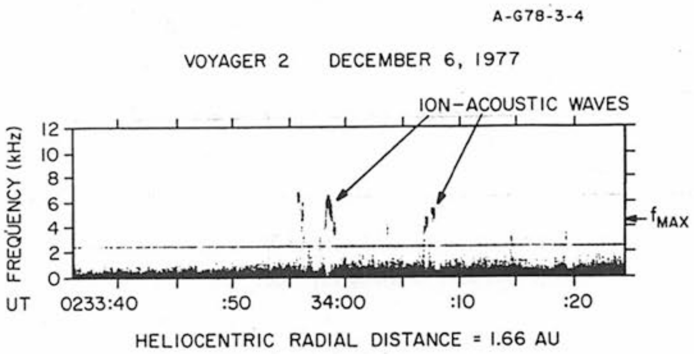

Figure 6. High-time resolution spectrogram of an ion-acoustic wave burst detected by Voyager 1.

The occurrence of ion-acoustic-like waves in the solar wind is not surprising, since at least two investigators predicted their occurrence before the Helios observations. Fredricks [1969] predicted that current-driven ion-acoustic waves should be observed in association with shocks and other discontinuities, and Forslund [1970] proposed that ion-acoustic waves should be generated by an electron heat flux instability whenever the electron-to-ion temperature ratio, T_e/T_i, is sufficiently large. More recent attempts to account for the detailed characteristics of the ion-acoustic waves detected by Helios and Voyager have concentrated on a double-ion beam instability proposed by Gary [1978] and on refinements of Forslund's electron heat flux mechanism [Dum et al., 1979]. At the present time the exact mechanism responsible for these waves, and even the precise identification of the waves as ion-acoustic waves, has not been definitely established. A thorough study of the relationship of these waves to the plasma parameters measured simultaneously by Helios has recently been given by Gurnett et al. [1979]. Im summary, both the electron heat flux and double-ion beam mechanisms have elements of support in the experimental data. The principal difficulty with the electron heat flux mechanism is that occasionally waves are observed at T_e/T_i ratios which are too small to predict instability. Similarly the proton distribution functions usually do not display a sufficiently separated double peak to produce an ion beam instability. Overall, the observed correlation of the wave intensity with T_e/T_i and the electron heat flux seem to favor the electron heat flux mechanism, although other mechanisms involving double-ion beams or suprathermal proton streams [which cannot be detected by Helios in the energy range from about 1.6 to 50 keV) cannot be ruled out.

III. ELECTROMAGNETIC WAVES

A. Whistler-Mode Waves

Measurements with high sensitivity search-coil magnetometers on Helios [Neubauer et al., 1977a] have shown that a weak background of low frequency magnetic field turbulence is nearly always present in the solar wind at frequencies extending up to approximately the local electron gyrofrequency. The upper frequency cutoff near the local electron gyrofrequency, f_g^-, provides substantial evidence that this turbulence is caused by electromagnetic whistler-mode waves. As shown in Figure 1, the whistler mode has an upper frequency cutoff at f_g^-. Fortunately, the phase velocity of the whistler mode (see Figure 2) is usually comparable or larger than the solar wind

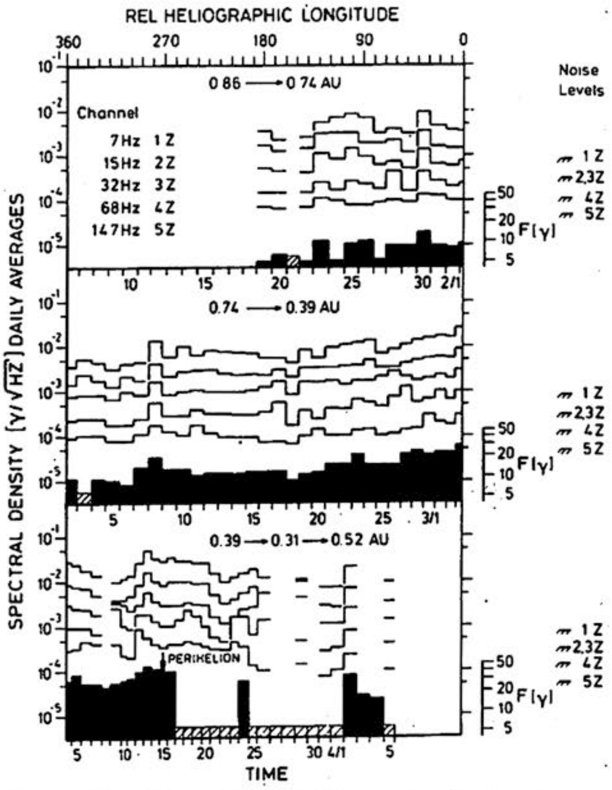

Figure 7. Magnetic field spectral densities of whistler-mode turbulence during the primary mission of Helios 1 [from Neubauer et al., 1977a].

velocity, so that the upper cutoff frequency is not strongly modified by Doppler shifts. A typical example of the magnetic field intensities associated with this whistler-mode turbulence is shown in Figure 7, from Neubauer et al. [1977a]. As can be seen, the intensity of this turbulence increases rapidly with decreasing frequency and with decreasing radial distance from the sun. Other types of discrete whistler-mode emissions have also been reported by Neubauer et al. in association with discontinuities in the solar wind.

Several possible mechanisms for generating unstable whistler-mode waves in the solar wind have been proposed, including thermal anisotropies in the ion distribution function [Scarf et al., 1967] and instabilities driven by the electron heat flux [Gary et al., 1975]. At the present time it seems most likely that the whistler-mode turbulence detected in the solar wind by Helios is produced by an electron heat flux instability, although other possibilities such as the nonlinear cascading of long wavelength large amplitude Alfvén waves cannot be entirely ruled out. Since whistler-mode waves can interact resonantly with electrons it is possible that this turbulence could play an important role in the pitch angle scattering of solar wind electrons or in controlling the thermal conductivity of the solar wind [Gary and Feldman, 1977]. For a review of these and other kinetic processes in the solar wind, see Feldman [1978].

B. Ion-Cyclotron Waves

As shown in Figure 1 electromagnetic ion-cyclotron waves are expected in the solar wind at frequencies below the proton cyclotron frequency, f_g^+. Because of the decreasing proton gyrofrequency with increasing radial distance from the sun, ion-cyclotron waves are generated as a natural consequence of the outward propagation of Alfvén waves from the sun, as in the "magnetic beach" model discussed by Stix [1962]. Ion-cyclotron waves can also be generated by a locally driven instability when $T_{||} > T_{\perp}$ [Gary et al., 1976].

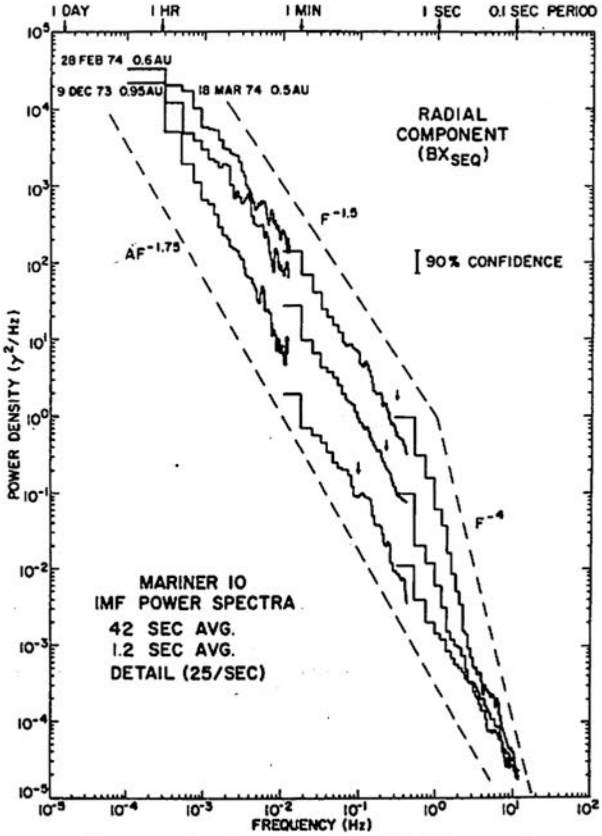

Figure 8. Typical magnetic field spectrums from Mariner 10 [Behannon, 1976] showing the break in the spectral slope near the proton gyrofrequency, possibly attributed to ion-cyclotron waves.

Because of the large Doppler shifts expected for the ion-cyclotron mode and the presence of whistler-mode turbulence in the same frequency range (see Figure 2), conclusive identification of ion-cyclotron waves in the solar wind is difficult. Magnetic field spectrum measurements such as in Figure 8, from Behannon [1976], consistently show a break in the spectral slope near the proton gyrofrequency which may indicate the presence of ion-cyclotron waves. Behannon has also reported nearly monochromatic left-hand polarized magnetic field oscillation at frequencies near the proton gyrofrequency which he tentatively identifies as ion-cyclotron waves. Further measurements with improved plasma diagnostics are needed to provide a firm identification of these waves as ion-cyclotron waves. Since ion-cyclotron waves can interact resonantly with protons, alpha particles and other heavy ions, it is thought that these waves may play an important role in the acceleration of solar wind ions [Hollweg and Turner, 1978].

IV. WAVES ASSOCIATED WITH INTERPLANETARY SHOCKS

As is the case for the earth's bow shock large plasma wave turbulence levels are expected in association with interplanetary shocks. This turbulence is necessary to provide the collisionless interactions required to heat the plasma at the shock boundary. The first observations of plasma wave electric fields associated with interplanetary shocks were obtained from Pioneer 7 and 8 [Scarf et al., 1968; Scarf and Siscoe, 1971; Siscoe et al., 1971]. Other shocks which have been investigated include measurements from IMP-7 [Scarf, 1977], Helios 1 and 2 [Neubauer et al., 1977b], Gurnett et al., 1979], and Voyager 1 [Kurth et al., 1979]. Because of the limited number of events which have been examined and the wide variability from event to event, it is difficult to summarize the characteristics observed, other than to comment that most of the wave modes discussed in the previous two sections are also present in association with shocks.

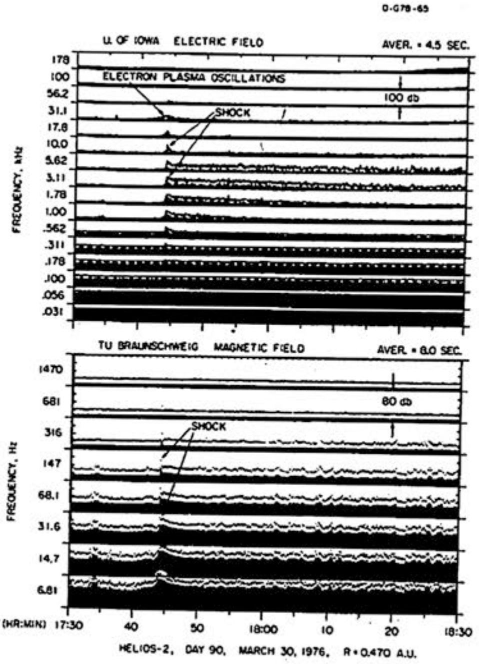

Figure 9. The electric and magnetic field intensities detected by Helios 2 for an interplanetary shock observed on March 30, 1976.

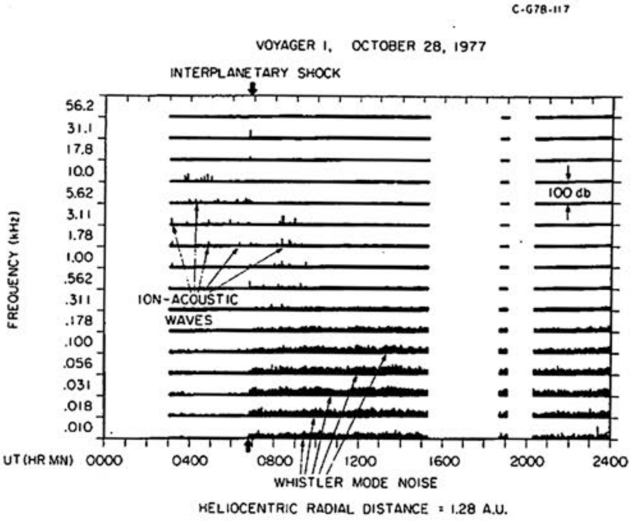

Figure 10. The electric field intensities detected by Voyager 1 for an interplanetary shock observed on October 28, 1977.

To illustrate the types of plasma wave turbulence usually observed, Figures 9 and 10 show two interplanetary shocks, one from Helios 2 [Gurnett et al., 1979] and the other from Voyager 1 [Kurth et al., 1979]. The shock in Figure 9 is a low Mach number, low beta, shock which has a very clearly defined enhancement in the electric and magnetic field intensities at the shock boundary. The electric field spectrum in the transition region and downstream from the shock is qualitatively similar to the spectrum of the ion-acoustic waves discussed in Section II. A weak burst of electron plasma oscillations can also be seen upstream of the shock. The magnetic field noise in and near the transition region is believed to be whistler-mode turbulence.

The Voyager 1 shock in Figure 10 differs from the shock in Figure 9 in several respects. In this case, only very small electric field intensities are observed in the transition region. Instead, a broad region of electrostatic wave turbulence similar to the ion-acoustic waves discussed in Section II is observed for several hours ahead of the shock. It seems likely that these upstream ion-acoustic-like waves are driven by suprathermal protons streaming out ahead of the shock, as occurs for the earth's bow shock. No electron plasma oscillations are observed in association with this shock. Whistler-mode turbulence qualitatively similar to Figure 9 is present in a broad region downstream of the shock.

These and other shocks studied show that there is a great deal of variability in the electrostatic noise intensities associated with shocks. Since so many parameters, such as the Mach number, the magnetic field direction with respect to the shock normal and the electron-to-ion temperature ratio, can affect the kinetic structure of a shock it is not possible with the limited number of events analyzed to give any general conclusions regarding the control which these parameters have on the plasma wave turbulence levels associated with a shock. Further studies are clearly needed.

V. CONCLUSION

This review has shown that considerable progress has been made in the experimental study and understanding of plasma waves in the solar wind during the past few years. Continued measurements by the Helios spacecraft during the solar maximum, by the Voyager spacecraft at large distances from the sun and by the ISEE-C spacecraft at the libration point upstream of the earth, promise to provide further improvements in our knowledge of solar wind plasma waves during the next few years. Although significant advances will be made, additional attention needs to be given to certain types of measurements. Of particular importance is the need for much higher time resolution, both for the plasma wave measurements and for the corresponding plasma distribution functions. As can be seen, many of the plasma wave phenomena observed in the solar wind occur on extremely short time scales, sometimes as short as a few tens of milliseconds or less. The reason why such impulsive fine structure occurs in, for example, electron plasma oscillations and ion-acoustic waves is not known, and probably cannot be fully resolved until higher time resolution measurements are available. Another area of particular importance is to extend these measurements in much closer to the sun. Essentially every plasma instability studied shows a clear tendency to increase rapidly in intensity with decreasing radial distance from the sun. This trend, along with various theoretical considerations, suggests that the most important microinstability processes which occur in the solar wind probably occur close to the sun, for example, near the sonic point in the solar wind flow and in the region of maximum solar wind heating. Direct in situ measurements close to the sun, such as may someday be obtained from a solar probe mission, are clearly needed to fully understand these processes.

ACKNOWLEDGEMENTS

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