Solar Wind Plasma Waves

Numerous types of waves exist in the SOLAR WIND. Since the solar wind is a plasma (i.e. an ionized gas) these waves are usually called plasma waves. Plasma waves play a fundamental role in determining the physical properties of the solar wind. In an ordinary gas, the gas is maintained in a state of thermal equilibrium by collisions. In thermal equilibrium the particle velocities have a universal isotropic form called a Maxwellian velocity distribution (see Haliday and Resnick 1981). Since the solar wind is very tenuous, collisions are extremely rare. An energetic particle from the Sun can reach the Earth without suffering a single large-angle collision. Under these conditions waves play a role similar to collisions. As the solar wind streams outward from the Sun, various dynamical effects cause the particle velocity distributions to deviate from a Maxwellian, often in the form of beams aligned along the magnetic field or various types of anisotropies. These non-equilibrium features eventually cause the growth of waves via various types of plasma instabilities. As the waves grow to large amplitudes, the waves interact with the particles in such a way as to eliminate the non-equilibrium feature that is responsible for the wave growth, thereby driving the velocity distributions toward thermal equilibrium, i.e. a role very similar to collisions. Waves also carry energy and momentum over long distances, and are believed to play a fundamental role in heating the solar CORONA and accelerating the solar wind. In this article we will describe the various types of waves that occur in the solar wind and discuss the role these waves play in determining the properties of the solar wind (see also SOLAR WIND: GLOBAL PROPERTIES; KINETIC PROPERTIES).

Plasma wave modes

Many types of waves can exist in a plasma. Figure 1 shows a plot of the propagation velocity, v, as a function of frequency, f, for the most commonly observed waves in the solar wind. This plot is representative of conditions at a radial distance of 1 AU (astronomical unit), near the orbit of the Earth. The propagation velocity is determined by a number of parameters, including the speed of light, c, the magnetic field strength, B, the particle number densities, N_s, of the various species in the plasma (s = e for electrons, and s = i for ions) and the temperatures, T_s, of these species. It is convenient to convert these parameters into a series of characteristic frequencies and speeds. The most important characteristic frequencies of a plasma are the electron cyclotron frequency, $f_{ce} = (1/2\pi)eB/m_e$, the ion cyclotron frequency, $f_{ci} = (m_e/m_i)f_{ce}$, the electron plasma frequency, $f_{pe} = (1/2\pi)(N_e e^2/\epsilon_0 m_e)^{1/2}$, and the ion plasma frequency, $f_{pi}(m_e/m_i)^{1/2}f_{pe}$. In these formulas e is the electronic charge, ϵ_0 is the permittivity of free space, m_e is the electron mass and m_i is the ion mass. The most important characteristic speeds of a plasma are the Alfvén speed, $V_A = B/(\mu_0\rho_m)^{1/2}$, the electron sound speed $V_e = (\gamma kT_e/m_e)^{1/2}$ and the ion sound speed $V_s = (\gamma kT_e/m_i)^{1/2}$, where μ_0 is the permeability of free space, ρ_m is the mass density and γ is the adiabatic compression factor. For a further discussion of these various quantities, see Stix (1992).

As can be seen in figure 1 the propagation velocity breaks up into a number of clearly defined branches, each of which corresponds to a well-defined mode of propagation. These modes are given specific names. Starting at the lowest frequencies, there are three modes of propagation called the magnetohydrodynamic (MHD) modes. These modes can be ordered according to the propagation velocity and are often called the fast magnetosonic mode, the Alfvén mode and the slow magnetosonic mode. The propagation velocities are given by

$$v_f^2 = \tfrac{1}{2}(V_A^2 + V_S^2) + \tfrac{1}{2}[(V_A^2 - V_S^2)^2 + 4V_A^2V_S^2\sin^2\theta]^{1/2} \qquad (1)$$

$$v_A^2 = V_A^2\cos^2\theta \qquad (2)$$

$$v_s^2 = \tfrac{1}{2}(V_A^2 + V_S^2) - \tfrac{1}{2}[(V_A^2 - V_S^2)^2 + 4V_A^2V_S^2\sin^2\theta]^{1/2} \qquad (3)$$

where v_f, v_A and v_s are the propagation velocities of the fast, Alfvén and slow modes. The angle θ, called the wave normal angle, is the angle between the direction of propagation and the magnetic field. As the name MHD implies, these modes involve a mixture of both magnetic and hydrodynamic (fluid) effects. The magnetic effects are represented by the Alfvén speed, V_A, which is proportional to the magnetic field strength, and the hydrodynamic effects are represented by the sound speed, V_s, which is proportional to the square root of the temperature. All three modes have electric and magnetic fields of the type that are usually associated with an electromagnetic wave. The fast and slow magnetosonic modes both have compressional motions of the type normally associated with sound waves (hence the dependence on the sound speed, V_S) and transverse motions of the type usually associated with electromagnetic waves (hence the dependence on V_A). The Alfvén mode on the other hand is a purely transverse mode and has no compressional motions (hence no dependence on the sound speed, V_S). The Alfvén mode was first discovered by Alfvén (1942) and is often called the shear Alfvén mode. For a discussion of MHD WAVES, see also Alfvén and Falthammer (1963). Under normal conditions the propagation velocities of all three MHD modes are substantially less than the solar wind velocity, V_{SW}, which is usually about 400 km s^{-1} (see figure 1).

Proceeding upward in frequency, one can see from figure 1 that as the frequency approaches the ion cyclotron frequency, f_{ci}, the propagation velocities of the fast magnetosonic mode and the Alfvén mode begin to deviate from the constant values given by equations (1) and (2). As the frequency approaches the ion cyclotron frequency the propagation velocity of the Alfvén mode begins to decrease rapidly, and it goes to zero at a frequency slightly below the ion cyclotron frequency. The exact frequency of the propagation cutoff depends on the wave

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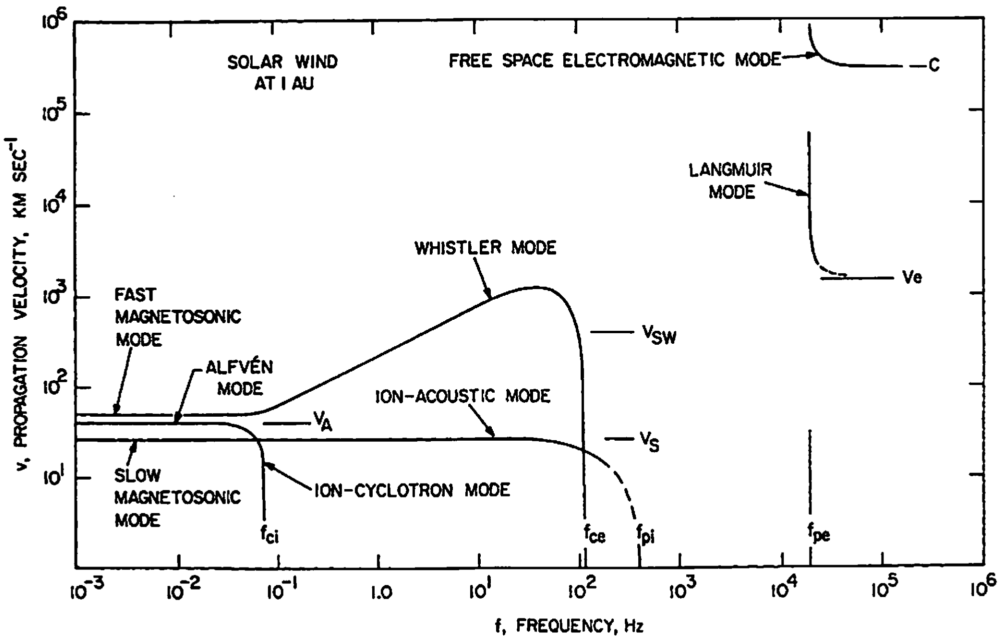

Figure 1. The propagation velocity of various plasma wave modes in the solar wind as a function of frequency for typical conditions at 1 AU.

normal angle. In this frequency range, near the ion cyclotron frequency, the Alfvén mode is usually called the ion cyclotron mode. Above the ion cyclotron frequency the Alfvén mode cannot propagate at any wave normal angle. For the fast magnetosonic mode, the propagation speed increases as the frequency crosses the ion cyclotron frequency, eventually varying as the square root of the frequency. This increase continues until the propagation velocity reaches a peak and then decreases rapidly, going to zero at a frequency slightly below the electron cyclotron frequency, f_{ce}. The exact frequency of this propagation cutoff depends on the wave normal angle. Above the electron cyclotron frequency the whistler mode cannot propagate at any wave normal angle. In the frequency range between the ion cyclotron frequency and the electron cyclotron frequency, the fast magnetosonic mode is usually called the whistler mode, after whistling signals generated by lightning that were discovered by Storey (1953). As the frequency of the slow magnetosonic mode increases the propagation velocity remains essentially unchanged as the frequency crosses the ion cyclotron frequency. Although the slow magnetosonic mode is an electromagnetic wave, at high frequencies, above the ion cyclotron frequency, the wave magnetic field becomes very weak and the wave takes on the properties of an electrostatic wave, with an electric field but no magnetic field. In this high-frequency regime the slow magnetosonic wave has many of the properties of an acoustic wave and is often called an ion acoustic wave. As the frequency approaches the ion plasma frequency, the propagation velocity of the ion acoustic mode goes to zero at the ion plasma frequency. The ion acoustic mode cannot propagate at frequencies above the ion plasma frequency. The ion acoustic mode is strongly damped by a collisionless damping process called Landau damping (Landau 1946). This damping arises because the propagation velocity is comparable with the ion thermal speed, which allows some of the wave energy to be absorbed by resonant interactions with ions moving at approximately the same velocity as the wave. The damping becomes particularly strong when the frequency is near the ion plasma frequency. This region of strong damping is shown by a dashed curve in figure 1. The damping is weak only if the electron temperature is substantially greater than the ion temperature, $T_e \gg T_i$, which raises the propagation speed of the wave well above the ion thermal speed (note that the ion sound speed, V_S, depends on the electron temperature and not on the ion temperature). The condition $T_e \gg T_i$ is only rarely satisfied in the solar wind.

At frequencies above the ion plasma frequency, no waves can propagate until the frequency reaches the electron plasma frequency, f_{pe}. At frequencies near and above the electron plasma frequency two modes of propagation occur, the free space electromagnetic mode and the Langmuir mode. The free space electromagnetic mode is a purely transverse wave with the electric and magnetic fields oriented perpendicular to each other and to the direction of propagation. The free space electromagnetic mode propagates at a speed given by $v = c/[1 - (f_{pe}/f)^2]^{1/2}$. Note that the propagation velocity

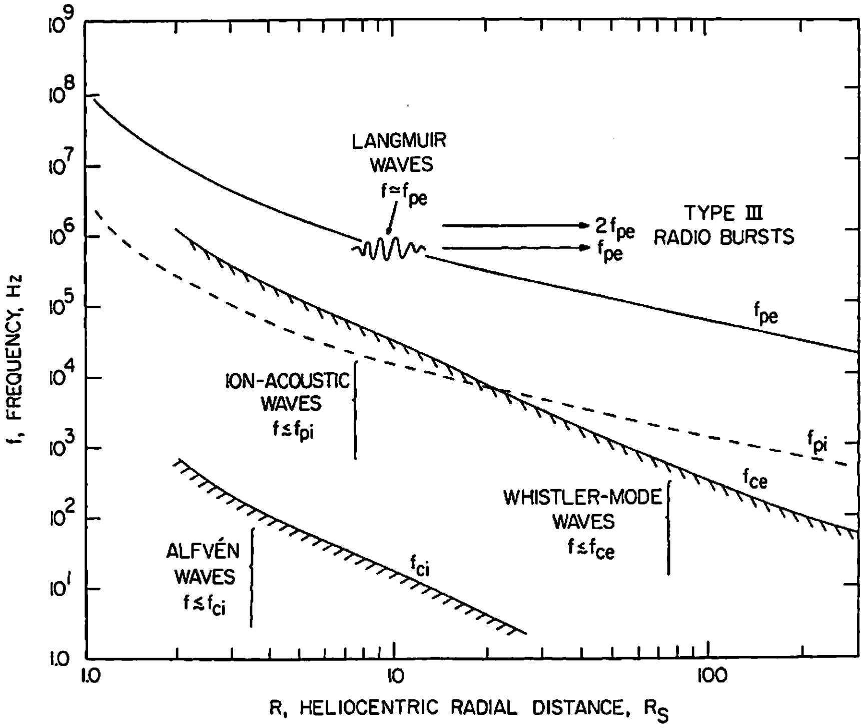

Figure 2. A plot of various characteristic frequencies of the solar wind plasma as a function of the heliocentric radial distance from the Sun in solar radii, R_S. The Earth is at a heliocentric radial distance (1 AU) of about $200R_S$.

of the free space electromagnetic mode goes to infinity at the electron plasma frequency and approaches the speed of light, c, at high frequencies. Since the propagation velocity is always greater than the velocity of any of the particles in the plasma, this mode cannot interact resonantly with the plasma particles and, therefore, does not experience Landau damping. The Langmuir mode is a purely longitudinal electrostatic wave (i.e. it has an electric field, but no magnetic field) and propagates at a speed given by $v = V_e/[1 - (f_{pe}/f)^2]^{1/2}$. Note that the propagation velocity of the Langmuir mode goes to infinity at the electron plasma frequency, and approaches the electron sound speed, V_e, at high frequencies. Since the characteristic propagation speed of this wave is near the electron thermal speed this wave is subject to strong Landau damping. The region of strong damping is indicated by a dashed curve in figure 1. The damping is small only for wave frequencies very close to the electron plasma frequency, $f \approx f_{pe}$, where the propagation speed goes to infinity. Thus, the Langmuir wave propagates with low damping only in a narrow frequency band around the electron plasma frequency, essentially a pure oscillation at the electron plasma frequency. The wave is also sometimes called an electron plasma oscillation.

To develop a complete understanding of the propagation of plasma waves in the solar wind we must consider the radial variation of the various characteristic frequencies of the plasma. Figure 2 shows a plot of the ion cyclotron frequency, the electron cyclotron frequency, the ion plasma frequency and the electron plasma frequency as a function of heliocentric radial distance. As one can see, all of the characteristic frequencies decrease with increasing radial distance from the Sun. To understand the detailed radial dependence we must discuss the radial variation of the magnetic field strength and the electron density. In the radial distance range from about $2R_S$ to $100R_S$, the magnetic field is directed almost radially outward from the Sun (Hundhausen 1972). Under these conditions conservation of magnetic flux shows that the magnetic field strength must vary approximately as $1/R^2$. Therefore, the cyclotron frequencies, f_{ci} and f_{ce}, vary as approximately as $1/R^2$ over this radial distance range. Because of strong multipole magnetic fields near the Sun, inside of about $2R_S$ it is not possible to give a specific prediction for the radial variation, except to say that it is likely to be steeper than $1/R^2$. Beyond about $100R_S$ the magnetic field develops a significant azimuthal component due to solar rotation, eventually varying as $1/R$ at large distances from the Sun. At radial distances beyond about $7R_S$ (Hundhausen 1972), where the solar wind is supersonic, conservation of particle flux shows that the electron density must vary as $1/R^2$. The ion and electron plasma frequencies, f_{pi} and f_{pe}, which

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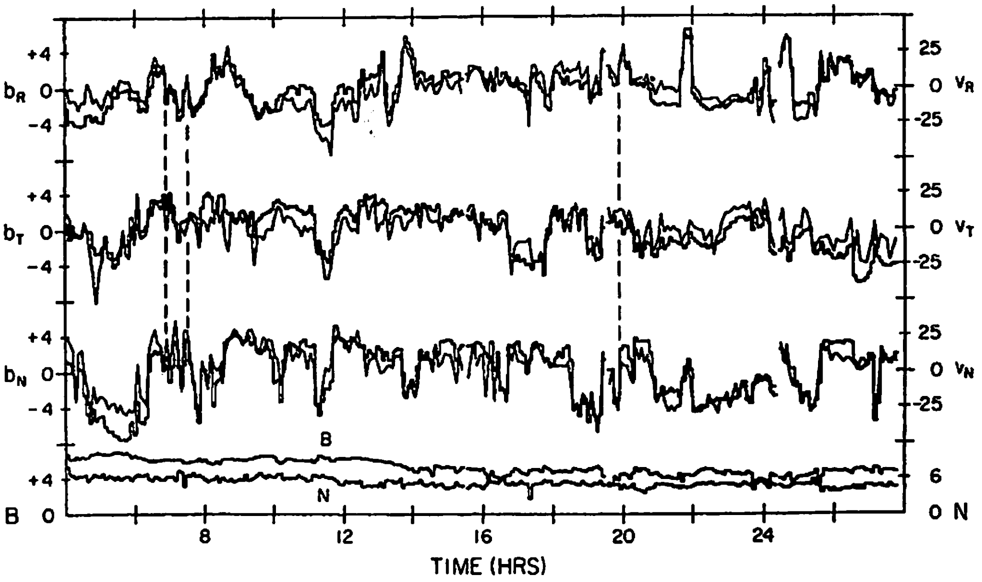

Figure 3. Alfvén waves in the solar wind as detected by the magnetic field and plasma instruments on the Mariner 5 spacecraft. From Davis (1972) with kind permission from Kluwer Academic Publishers.

are proportional to the square root of the electron density, must then vary as $1/R$ in this region. Inside of about $7R_S$, where the solar wind flow is subsonic, it is not possible to give a simple prediction for the radial variation of the plasma frequency, except to say that it is likely to be steeper than $1/R$.

Observations

To illustrate the types of plasma waves that are observed in the solar wind, we next show examples of each of the wave modes discussed in the previous section. To be consistent with the previous discussion, we start with the lowest frequencies and proceed to the highest frequencies.

Alfvén waves

Alfvén waves were first discovered in the solar wind by Unti and Neugebauer (1968) and Belcher *et al* (1969) using data from the Mariner 2 and 5 spacecraft. These waves are illustrated in figure 3, which is from Davis (1972). The top three plots shows three orthogonal components of the wave magnetic field, b_R, b_T and b_N. These components were obtained by subtracting the average background magnetic field from the measured field. Superposed on the same plots are the corresponding components of the plasma flow velocity fluctuation, u_R, u_T and u_N. The bottom plot shows the magnitude of the magnetic field, B, and the plasma density, N. The highly irregular variations in the magnetic field and flow velocity, on time scales ranging from a few hours to a few minutes, are Alfvén waves. Note that there is no evidence of corresponding variations in either the magnetic field magnitude or the plasma density. The absence of fluctuations in the magnetic field magnitude and in the plasma density indicates that the waves are non-compressional, thereby uniquely identifying the mode of propagation as the Alfvén mode. Note that the flow velocity variations are in phase (positively correlated) with variations in the corresponding magnetic field components. From the direction of the average background magnetic field during this event (directed inward, toward the Sun) and the positive correlation between the wave magnetic field and the flow velocity fluctuation, one can show that the waves are propagating outward, away from the Sun.

It is now widely believed that the Alfvén waves observed in the solar wind are excited by turbulent fluctuations near the Sun and that the waves propagate outward to great distances from the Sun, probably several AU or more. Although fast and slow magnetosonic waves are sometimes detected, the dominant wave energy is almost always in the shear Alfvén mode. The small amounts of energy in the fast and slow magnetosonic modes are most likely due to the fact that these modes are compressional, which leads to strong damping. In contrast, the Alfvén mode has very little damping, primarily because of the transverse (i.e. non-compressional) nature of this mode.

Ion cyclotron and whistler mode waves

As the Alfvén wave propagates outward from the Sun the ion cyclotron frequency decreases, eventually approaching the frequency of the wave (see figure 2). As the ion cyclotron frequency approaches the wave frequency the propagation velocity begins to decrease (see figure 2), and the wave becomes strongly damped

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by a process called ion cyclotron damping. Ion cyclotron damping occurs when the Doppler-shifted wave frequency seen in the frame of reference of an ion moving along the magnetic field matches the cyclotron frequency of the ion. The resulting interaction accelerates the ion and causes a loss of wave energy. The net effect is that the wave energy is absorbed as the ion cyclotron frequency approaches the wave frequency, thereby transferring the wave energy to the solar wind. This cyclotron resonant absorption process is believed to provide a significant heat input into the solar wind.

Evidence of this ion cyclotron absorption process is illustrated in figure 4, which shows a magnetic field spectrum observed by the Helios 2 spacecraft at a radial distance of about 0.3 AU. At the lowest frequencies, below about 10^{-2} Hz, the spectrum is mainly due to Alfvén waves. The intensity can be seen to vary as approximately f^{-1}. Proceeding upward in frequency a noticeable change in the spectral slope, from about f^{-1} to $f^{-1.7}$, can be seen as the frequency approaches the ion cyclotron frequency, f_{ci}, followed by a very abrupt decrease in intensity above the ion cyclotron frequency. The change in slope and the rapid decrease in the intensity near the ion cyclotron frequency are believed to be due to absorption of the Alfvén wave energy by either ion cyclotron damping or possibly Landau damping (Leamon *et al* 1998). Proceeding to higher frequencies, above the ion cyclotron frequency, a weak but persistent level of magnetic noise can be seen at frequencies extending up to about the electron cyclotron frequency. These frequencies are much too high to be caused by MHD waves and are almost certainly due to whistler mode waves (see figure 1). An alternative possibility, that they might be ion acoustic waves, is ruled out by the fact that, at these frequencies, the ion acoustic wave is almost purely electrostatic and would have no magnetic field. The origin of these whistler mode waves is poorly understood. Since whistler mode waves experience a significant level of cyclotron damping due to interactions with the relatively hot electrons ($T_e \simeq 10^5$ K) present in the solar wind, it seems unlikely that the waves could reach the spacecraft from a source near the Sun. The most likely explanation is that they are generated locally by anisotropies in the solar wind electron distribution. Anisotropic velocity distributions are known to be a free energy source for whistler mode waves (Kennel and Petschek 1966).

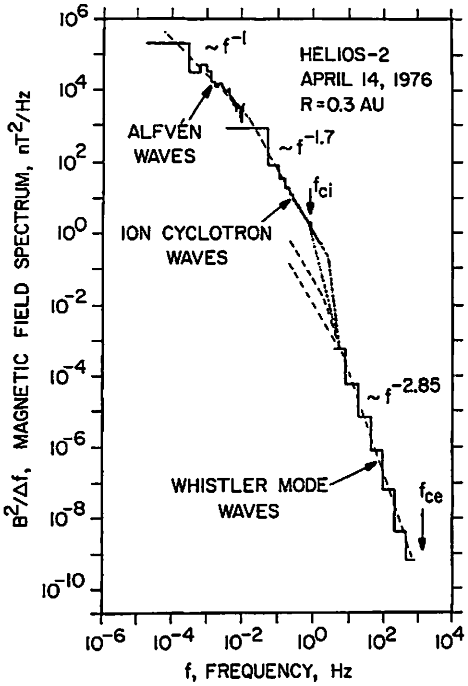

Figure 4. A magnetic field spectrum showing Alfvén waves, ion cyclotron waves and whistler mode waves detected by the Helios 2 spacecraft at a heliocentric radial distance of 0.3 AU. Illustration adapted from Denskat *et al* (1983).

Ion acoustic waves

Since the ion acoustic mode is normally very heavily damped by Landau damping, one would not expect to detect ion acoustic waves in the solar wind. Nevertheless, electrostatic waves have been detected in the solar wind that are believed to be ion acoustic waves. A frequency–time spectrogram showing a series of electrostatic bursts extending up to about 6 kHz that are believed to be ion acoustic waves is shown in figure 5. These waves were detected by the plasma wave electric field antenna on the Voyager 2 spacecraft at a heliocentric radial distance of 1.66 AU. The ion plasma frequency at this time is estimated to be about 300 Hz. Since the ion acoustic mode cannot propagate at frequencies above the ion plasma frequency, one may wonder how the frequencies could extend upward to frequencies as high as 6 kHz. The reason is that ion acoustic waves have very short wavelengths, which cause very large Doppler shifts. Under the conditions present in the solar wind near 1 AU, the frequency is almost entirely determined by Doppler shift, so there is no simple relationship to the ion plasma frequency. The Doppler shift is approximately $\Delta f = V_{SW}/\lambda$, where λ is the wavelength. The minimum wavelength of an ion acoustic wave is $2\pi\lambda_D$, where λ_D is the Debye length (Stix 1992), so the maximum frequency is approximately $f_{Max} = V_{SW}/2\pi\lambda_D$. For typical conditions at 1.66 AU the Debye length is about 10 m, which for a solar wind velocity of 400 km s^{-1} gives a maximum frequency of about 6 kHz, in good agreement with the observed upper frequency limit of the emissions in figure 5. Since the Debye length varies inversely with the square root of the electron density, the maximum frequency is predicted to increase inversely with radial distance from the Sun, in agreement with observations (Gurnett *et al* 1979).

At present the mechanism by which ion acoustic waves are produced in the solar wind is poorly understood. The intensity of these waves has been shown

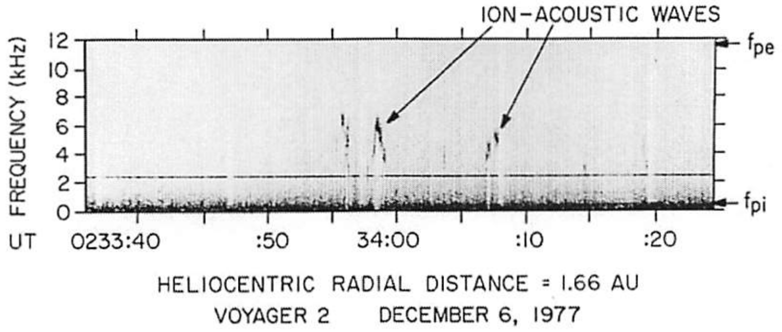

Figure 5. An electric field frequency–time spectrogram of ion acoustic waves detected in the solar wind by the Voyager 2 spacecraft at 1.66 AU.

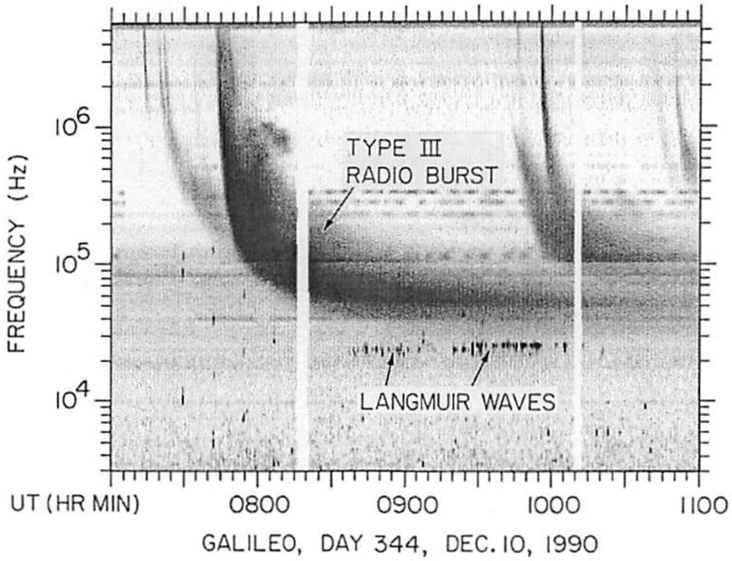

Figure 6. An electric field frequency–time spectrogram of a type III solar radio burst and associated Langmuir waves detected in the solar wind by the Galileo spacecraft at 0.98 AU.

by Gurnett *et al* (1979) to increase rapidly with decreasing distance from the Sun, which would seem to imply a solar origin. However, since the ion acoustic mode is strongly damped, it is highly unlikely that the waves could have propagated to the spacecraft from a source near the Sun. It is much more likely that they are produced locally. Both laboratory and theoretical studies show that the ion acoustic mode can be driven unstable by a shift between the average electron and ion velocities, such as occurs when a strong electrical current is present. The threshold current for the onset of the current-driven ion acoustic instability is very high when the electrons and ions have comparable temperatures, as it often is in the solar wind, but decreases rapidly as T_e/T_i increases. Although evidence exists that ion acoustic waves are more likely to be observed when T_e/T_i is large, electrical currents sufficiently strong to trigger the ion acoustic instability are usually not present in the solar wind. However, the heat flux carried outward from the Sun by solar wind electrons causes a similar shift between the core electron and ion velocities. Our present view is that the ion acoustic waves are probably driven by the solar wind heat flux. If so, ion acoustic waves could play a significant role in regulating the heat flux carried outward from the Sun. For a further discussion of ion acoustic waves in the solar wind, see Gurnett (1991).

Langmuir waves and type III solar radio bursts

For many years it has been known that a class of solar radio emissions called the type III radio bursts occurs in which the frequency drifts rapidly downward with increasing time (Wild 1950; see also SOLAR FLARES: RADIO

BURSTS). The time scale of the frequency drift varies from a few seconds at frequencies in the hundred MHz range to tens of minutes in the hundred kHz range. In a classic paper, Ginzburg and Zheleznyakov (1958) proposed that these radio bursts are produced by a two-step process in which (1) Langmuir waves are first excited by the energetic electrons emitted by a solar flare and (2) the Langmuir waves are converted to electromagnetic radiation at f_p and $2f_p$ by non-linear mode conversion processes. The downward frequency drift is caused by the decreasing electron plasma frequency encountered by the solar flare electrons as they stream outward from the Sun. The radiation at f_p is believed to be generated by a non-linear interaction between the Langmuir wave and a low-frequency wave such as an ion acoustic wave, and the radiation at $2f_p$ is believed to be generated by a non-linear interaction between two oppositely propagating Langmuir waves. The two-step generation process was confirmed by Gurnett and Anderson (1976) who made the first direct *in situ* observations of the Langmuir waves responsible for a type III radio burst using wave electric field measurements on the Helios 2 spacecraft.

A frequency–time spectrogram of a type III radio burst and its associated Langmuir wave emissions is shown in figure 6. This event was detected by wave electric field measurements on the Galileo spacecraft at a heliocentric radial distance of 0.98 AU. Although several type III radio bursts can be seen, the one of interest starts at 0745 UT (UNIVERSAL TIME). This event is associated with a solar flare that occurred at 0730 UT. As can be seen the type III radio burst associated with this flare was first detected at a frequency of about 6 MHz. The radio emission rapidly sweeps downward in frequency, eventually reaching a frequency of about 40 kHz after about 1 h. The Langmuir waves responsible for this radio emission can be seen from about 0835 to 1010 UT at a frequency of 23 kHz, which is the local electron plasma frequency. This onset time corresponds almost exactly to the arrival time of electrons with energies of about 100 keV from the solar flare, as determined from the energetic particle detector on Galileo; see Gurnett *et al* (1993). For this event the primary emission is believed to be at $2f_p$, which would produce radiation at a frequency of about 46 kHz. Note that the Langmuir waves responsible for radiation at frequencies higher (or lower) than 46 kHz cannot be detected, since these waves must occur closer to (or farther from) the Sun. Other studies have shown that both the intensity of the Langmuir waves and the emissivity of the type III radio events decrease rapidly with increasing radial distance from the Sun (Gurnett *et al* 1980), more or less in agreement with expectation for the $2f_p$ mode conversion process. However, the details of the mode conversion process, and the relative importance of emission at f_p and $2f_p$, remain poorly understood. For a discussion of the dynamics of Langmuir waves and the possible mode conversion processes that could be involved, see Robinson *et al* (1993).

Future research

In the sections above we have reviewed the basic characteristics of plasma waves in the solar wind. Although much is known about these waves at radial distances in the vicinity of the Earth's orbit, very little is known in the near vicinity of the Sun. The intensities of almost all the waves discussed increase rapidly with decreasing distance from Sun. Since many of the waves, such as whistler mode waves, ion acoustic waves and Langmuir waves, are locally generated, it is important that direct *in situ* measurements be made in the region close to the Sun, where the primary heating and acceleration of the solar wind are occurring. At present the closest measurements to the Sun are from the Helios 2 spacecraft, which approached to within 0.29 AU of the Sun. Hopefully, in the not-too-distant future a mission called the SOLAR PROBE will be sent much closer to the Sun, possibly to as close as $4R_S$, and will be instrumented to study plasma waves.

Acknowledgment

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