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# SOLAR SYSTEM PLASMA WAVES

Donald A. Gurnett

## Abstract

An overview is given of spacecraft observations of plasma waves in the solar system. In situ measurements of plasma phenomena have now been obtained at all of the planets except Mercury and Pluto, and in the interplanetary medium at heliocentric radial distances ranging from 0.29 to 58 AU. To illustrate the range of phenomena involved, we will discuss plasma waves in three regions of physical interest: (1) planetary radiation belts, (2) planetary auroral acceleration regions, and (3) the solar wind. In each region we will describe examples of plasma waves that are of some importance, either due to the role they play in determining the physical properties of the plasma, or to the unique mechanism involved in their generation.

## 1. Introduction

This overview of solar system plasma waves is presented in celebration of the 75th anniversary of the International Scientific Radio Union (URSI).The study of naturally occurring plasma waves is an old subject that has its origins in early ground-based investigations of very-low-frequency (VLF) radio signals. The first known report of VLF radio signals of natural origin was by Preece [1894], who detected a variety of unusual audio frequency electrical signals while experimenting with a long-distance telephone line. Based on his description, the signals that he detected were probably spherics, which are lightning-generated signals that propagate in the Earth-ionosphere waveguide, and a type of VLF radio emission now known as chorus. Some years later, during World War I, Barkhausen [1919] described unusual whistling signals lasting several seconds that he detected while attempting to intercept enemy telephone communications using a rudimentary vacuum-tube amplifier. Initial progress on the understanding of these whistling signals, which soon came to be called whistlers, was slow. After several years of investigation, including detailed analyses of their frequency-time characteristics, Eckersley [1935] correctly postulated that whistlers were produced by lightning. However, the mechanism that caused the dispersion, and the long propagation paths required to achieve the several-second travel time were unknown. It was not until the 1950s that Storey [1953] was able to provide a satisfactory explanation of whistlers. He showed that the dispersion occurred as the signal propagated along the magnetic field line from one hemisphere to the other in a plasma mode of propagation now known as the whistler mode.

In addition to whistlers, which are produced by lightning, a number of other unusual VLF signals were discovered in this early era that were clearly not due to lightning. The best known of these are "chorus" and "hiss." The term chorus was introduced by Storey[1953] because the signals sounded like the early morning chorus from a colony of birds. The hiss signals produced a hiss-like sound in the audio output of the receiver. At high latitudes, hiss was soon found to be associated with the aurora, and this type of emission came to be know as "auroral hiss." Among the early investigators, Ellis [1957] had the distinction of being the first to propose a theory for the generation of these emissions. He suggested that auroral hiss was produced by Cerenkov radiation from the charged particles responsible for the aurora. As will be discussed later, elements of his ideas still exist in modern theories of auroral hiss. For a more extensive review of early ground-based observations, see Helliwell [1965].

The launch of the first Earth-orbiting satellites in the late 1950s opened up an entirely new era in the study of space plasma wave phenomena. VLF receivers on Earth-orbiting spacecraft soon revealed an extremely complex variety of plasma waves in the ionosphere and in the hot magnetized plasma surrounding the Earth known as the magnetosphere. Many of these waves had never been seen in laboratory plasmas. Because of the ideal conditions that

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existed in space, with negligible collisions and no walls, the study of space plasma waves soon became an important element of modern plasma research. The growth of plasma waves was found to play a crucial role in establishing an equilibrium in a plasma, in much the same way that collisions in an ordinary gas play a role in achieving thermal equilibrium. Plasma waves and radio emissions also often provided a useful diagnostic tool for determining various plasma properties, such as the electron density and magnetic field strength. Because of the importance of these measurements, radio and plasma wave instruments were soon routinely included on missions to other planets. Now, nearly forty years after the launch of the first Earth-orbiting satellite, in situ measurements of plasma waves and radio emissions have been obtained at all of the planets except Mercury and Pluto, and in the interplanetary medium at heliocentric radial distances from 0.29 to 58 AU (astronomical units). Since this subject covers such a broad area of research, this overview must necessarily be limited. To restrict the scope of this review, we will concentrate on three regions of physical interest: (1) planetary radiation belts, (2) planetary auroral acceleration regions, and (3) the solar wind. In each region, we will describe certain selected examples of some importance, either due to the role they play in determining the physical properties of the plasma, or to the unique mechanism involved in their generation.

## 2. Planetary radiation belts

A radiation belt consists of energetic electrons and ions that are trapped in the magnetic field of a planet. The Earth's radiation belt was discovered by Van Allen [1959] using Explorer 1, which was the first U.S. satellite. Since then radiation belts have been discovered at five other planets, Mercury, Jupiter, Saturn, Uranus, and Neptune, all of which have substantial magnetic fields. The energies of the radiation belt particles vary considerably from planet to planet, but are generally in the range from a few keV to several MeV. Jupiter has by far the most intense and energetic radiation belt. In situ measurements of plasma waves and radio emissions have been made in all of the known radiation belts, except for Mercury. A summary of the various types of plasma waves that have been observed is given in Table 1. Of these, we will describe two that are of particular importance. These are (1) whistler-mode

| Type of Plasma Wave | Venus | Earth | Mars | Jupiter | Saturn | Uranus | Neptune |
|---|---|---|---|---|---|---|---|
| Whistlers (lightning) | X | X |  | X |  |  | X |
| Whistler-mode hiss |  | X |  | X | X | X | X(?) |
| Whistler-mode chorus |  | X |  | X | X | X |  |
| Auroral hiss |  | X |  | X |  |  |  |
| Cyclotron maser radiation |  | X |  | X | X | X | X |

*Table 1*

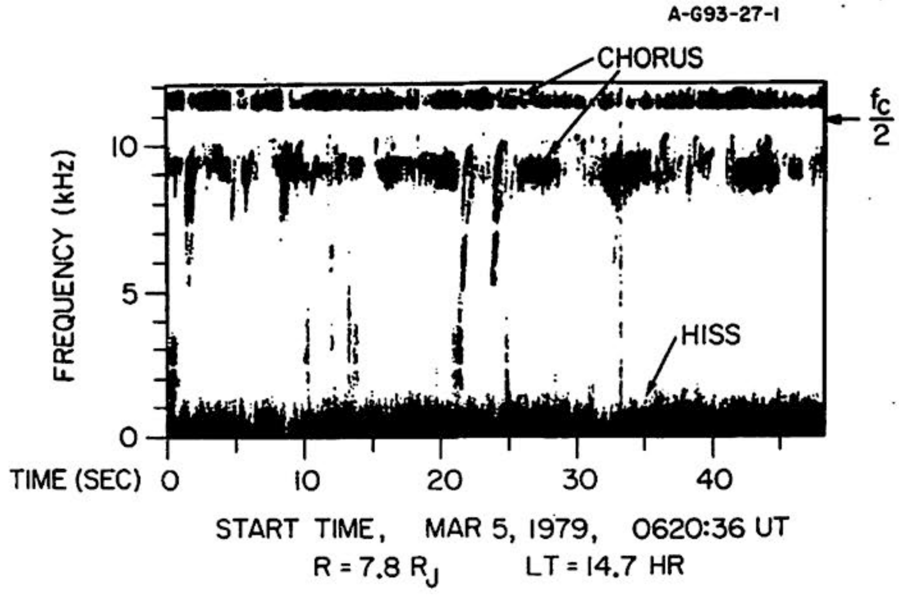

*Fig. 1 - A frequency-time spectrogram showing whistler-mode chorus and hiss detected by Voyager 1 in the radiation belt of Jupiter. Chorus consists of the many discrete narrow band emissions, usually rising in frequency on time scales of a few seconds, and hiss consists of the nearly steady spectrum of band-mimited noise. In this case, the chorus occurs from about 8 to 12 kHz, and the hiss occurs below about 1 kHz.*

emissions, and (2) electromagnetic ion cyclotron emissions.

### *A. Whistler-mode emissions*

The whistler mode is an electromagnetic mode that propagates at frequencies below the electron cyclotron frequency, $f_c = eB/m_e$, where e and $m_e$ are the charge and mass of an electron, and B is the magnetic field strength. The whistler mode is right-hand polarized with respect to the magnetic field. Two types of whistler-mode emissions, chorus and hiss, are commonly observed in planetary radiation belts. Chorus consists of numerous discrete narrow band emissions, usually rising in frequency on time scales of a few seconds. Hiss consists of a nearly steady level of band-limited noise, usually below the frequencies at which chorus is observed. A frequency-time spectrogram of chorus and hiss in the Jovian radiation belt is shown in Figure 1. These emissions were observed during the Voyager 1 flyby of Jupiter [Scarf et al., 1979], and are remarkably similar to the terrestrial chorus and hiss emissions detected during the early era of ground-based VLF studies.

Chorus and hiss are both believed to be generated by a cyclotron resonant interaction with radiation belt electrons. Cyclotron resonance occurs when the wave frequency in a frame of reference moving along the magnetic field with the particle matches the cyclotron frequency of the particle. The wave field in the moving frame of reference must also be rotating around the magnetic field in the same sense as the particle. Cyclotron resonance can occur for both electrons and ions. However, for the whistler mode the most important cyclotron resonance interactions occur with the electrons. In a classic paper on the subject, Kennel and Petschek [1966] showed that the parallel energy at which electrons are in cyclotron resonance with a whistler-mode wave is given by

$$W_{\parallel} = \frac{B^2}{2\mu_o N}\left(1 - \frac{f}{f_c}\right)^3 \frac{f_c}{f}$$

where $B^2/2\mu_o$ is the magnetic field energy density, N is the electron number, and f is the wave frequency. Whistler-mode waves grow spontaneously if the electron velocity distribution is anisotropic in such a way that there is a deficit in the number of resonant electrons moving at small angles to the magnetic field. In a planetary radiation belt, this type of anisotropy always occurs, since any particle with a pitch angle within a cone of directions called the "loss-cone" will strike the planet and be lost from the system.

Although the whistler mode is always unstable due to the presence of the loss cone, the question of whether the wave grows to a large amplitude depends on the gains and losses along the ray path. Kennel and Petschek showed that the growth rate is proportional to the number of electrons in resonance with the wave. Therefore, the growth rate increases as the radiation belt intensity increases. Since the highest radiation belt intensities usually occur near the magnetic equator, the highest growth rates tend to be near the magnetic equatorial plane. Various types of losses exist. One of the main losses is simply due to the propagation of the wave out of the system. Because of the anisotropic nature of the propagation, whistler-mode waves tend to be guided along the magnetic field lines toward the planet, where they can escape through the base of the ionosphere. However, if the initial wave normal angle is sufficiently large, the wave tends to reflect as soon as the lower-hybrid-resonance frequency, $f_{LHR} = \sqrt{m_e/m_i f_c}$, exceeds the wave frequency. A typical ray path is shown in Figure 2.

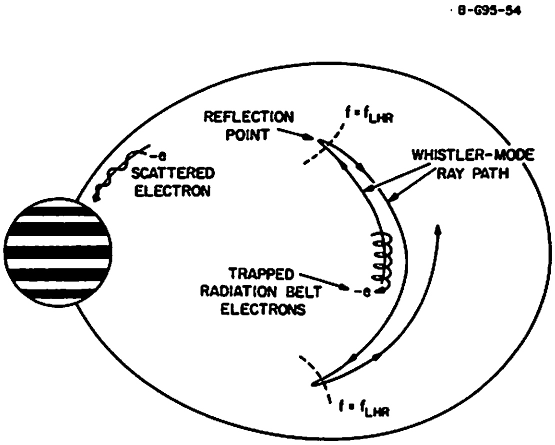

*Fig. 2 - A sketch of whistler-mode ray paths in the Jovian radiation belt. For sufficiently large wave normal angles, whistler-mode waves reflect as soon as the lower-hybrid-resonance frequency, $f_{LHR}$ exceeds the wave frequency. The resulting ray paths are then similar to a laser, with repeated passes through the equatorial plane where wave growth occurs via cyclotron resonant interactions with energetic radiation belt electrons. These interactions then scatter the electrons into the loss cone, causing them to hit the planet.*

This reflection process causes the waves to bounce back and forth along the magnetic field line from one hemisphere to the other. Reflections not only minimize the losses, but they also cause repeated passes through the equatorial region where the maximum growth rate occurs. From Figure 2, one can see that the growth of whistler-mode waves in a planetary radiation belt is similar to a laser, with the anisotropy in the trapped electrons providing the free energy source, and the reflections near $f = f_{LHR}$ playing the role of the mirrors.

The generation of whistler-mode waves would be relatively unimportant except for the effect these waves have on the radiation belt electrons. Since whistler-mode waves are right-hand polarized, these waves carry away right-hand angular momentum. The angular momentum must come from the resonant electrons. Since electrons rotate in the right-hand sense with respect to the magnetic field, the effect of the wave generation is to lower the pitch angle of the electrons, thereby driving them toward the loss cone. Those electrons that are scattered into the loss cone collide with the planet and are lost from the system. The growth of whistler-mode waves therefore leads directly to the loss of radiation belt electrons. This pitch-angle scattering mechanism is believed to be the primary mechanism that limits the intensity of energetic electrons in a planetary radiation belt. Whenever some process acts to increase the trapped electron intensity, whistler-mode waves grow, which increases the loss of electrons, thereby establishing a new equilibrium.

Before closing the discussion of whistler-mode emissions, it is worth commenting on the differences between chorus and hiss. Since chorus usually occurs at higher frequencies than hiss, one can see from the frequency dependence in Equation 1 that chorus resonates with lower electron energies than hiss. This difference is illustrated in Figure 3, which shows the spectrums of the chorus and hiss emissions in the top panel, and the corresponding resonance energies in the bottom panel. As can be seen, chorus resonates with electrons in the few keV range, and hiss resonates with electrons in the several hundred keV range.

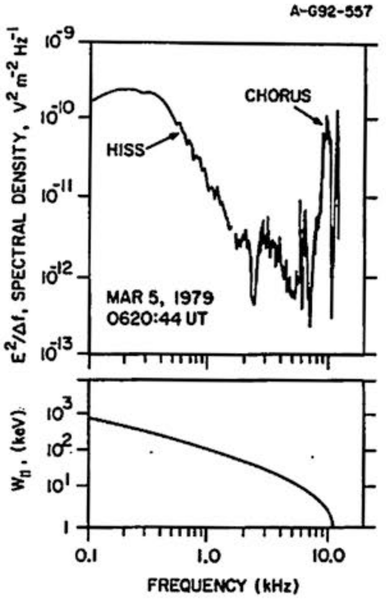

*Fig. 3 - The top panel shows the spectrum of the whistler-mode chorus and hiss in Figure 1 and the bottom panel shows the parallel energy of electrons that are in cyclotron resonance with these waves. Chorus tends to resonate with relatively low energies, typically a few keV, whereas hiss resonates with much higher energies, typically several hundred keV or more.*

Since there are more resonant electrons at lower energies, chorus has higher growth rates than hiss. The higher growth rate causes nonlinear saturation effects to occur sooner, before the wave has even reached the first reflection point in Figure 2. These nonlinear effects are thought to cause the wave to evolve into the nearly monochromatic wave packets that are characteristic of chorus. Hiss on the other hand has much lower growth rates, leading to many reflections from one hemisphere to the other. The superposition of these many reflected waves and the absence of strong nonlinear effects is believed to cause the emission to evolve into the nearly steady band-limited spectrum that is characteristic of hiss. It may be worth noting that the above views on the origin of hiss are not universally accepted. Recently, Draganov et al. [1993] have proposed that the hiss in the Earth's radiation belt (called plasmaspheric hiss) may not be due to an instability at all, but rather due to the superposition of many lightning-generated whistlers that have become trapped near the equatorial plane via reflections similar to those illustrated in Figure 2. This mechanism was first suggested by H.C. Koons [see Storey et al., 1991].

### *B. Electromagnetic ion cyclotron emissions*

The electromagnetic ion cyclotron mode is an electromagnetic mode that propagates at frequencies below the ion cyclotron frequency, $f_{ci} = eB/m_i$. This mode is left-hand polarized with respect to the magnetic field. Since positively charged ions rotate in the left-hand sense with respect to the magnetic field, the ion cyclotron mode interacts primarily with positively charged ions. Kennel and Petschek [1966] have shown that the ion cyclotron mode can be driven unstable by a process very similar to the whistler mode, except that the ion anisotropy is responsible for the instability rather than the electron anisotropy. Since the ion cyclotron frequency is a factor of $m_e/m_i$ smaller than the electron cyclotron frequency, ion cyclotron emissions occur at much lower frequencies than whistler emissions. Whereas whistler-mode emissions are usually at frequencies in the few kHz range, ion cyclotron emissions are usually at frequencies of a few Hz or less. Because of their extremely low frequency, ion cyclotron waves are difficult to detect. At present, electromagnetic ion cyclotron waves have only been observed in the radiation belts of two planets, Earth and Jupiter, and possibly in the radiation belt of Neptune (see Table 1). Although electromagnetic ion cyclotron emissions are weak and difficult to detect, they are still of considerable importance. At Earth, a mid-latitude type of aurora known as a stable red arc is believed to be due to the precipitation of radiation belt ions by electromagnetic ion cyclotron waves [Cornwall, 1970]. Similar processes are also believed to cause auroral ion precipitation at Jupiter [Thorne, 1983]. Thus, electromagnetic ion cyclotron waves play a role in the loss of radiation belt ions similar to the role that whistler-mode waves play in the loss of radiation belt electrons.

## 3. Planetary auroral acceleration regions

The aurora consists of light produced by energetic charged particles impinging on the upper levels of a planetary atmosphere. Five planets, Earth, Jupiter, Saturn, Uranus, and Neptune, are known to have auroras. At Earth, the aurora is usually confined to a narrow region from about 65 to 75° magnetic latitude known as the auroral zone. Strong electrical currents, known as field-aligned currents, flow along the magnetic field lines linking the auroral zones with the outer regions of the magnetosphere. These currents are carried primarily by electrons. For reasons that are not completely understood, large potential differences develop along the magnetic field lines in regions of strong field-aligned currents. These potential differences accelerate some of the electrons to high energies; typically several keV, thereby forming field-aligned electron beams. Both upgoing and downgoing electron beams are observed. The auroral light is produced when a downgoing beam strikes the atmosphere. Although relatively little is known about auroral processes at planets other than Earth, there are good reasons to believe that the processes are basically similar.

Many types of plasma waves and radio emissions are known to be generated in planetary auroral acceleration regions. Of these, we will focus on two in particular, (1) auroral hiss, and (2) cyclotron maser radiation.

### *A. Auroral hiss*

Auroral hiss is a whistler-mode emission that is produced by auroral electron beams. Auroral hiss has been observed at Earth and Jupiter, and possibly Neptune (see Table 1). The absence of adequate high-latitude observations at Saturn and Uranus makes it impossible to say whether auroral hiss occurs at these planets. A frequency-time spectrogram illustrating auroral hiss observed during a high-latitude pass over the Earth's auroral zone is shown in Figure 4. The auroral hiss is the funnel-shaped emission that can be seen extending from about 100 Hz to 50 kHz. A sharp upper frequency cutoff can be seen at the electron cyclotron frequency, which is what one would expect, since the whistler mode cannot propagate at frequencies above the electron cyclotron frequency. Both upgoing and downgoing auroral hiss has been observed. The upgoing auroral hiss is associated with upgoing electron beams, and the downgoing auroral hiss is associated with downgoing electron beams. Upgoing auroral hiss is mainly observed at high altitudes, 1 to 3 $R_E$ or more, as in Figure 4. Downgoing auroral hiss is only observed at low altitudes, 1 $R_E$ or less. The funnel-shaped feature in Figure 4 is a propagation effect. At higher frequencies, the radiation propagates at larger angles to the magnetic field lines, thereby increasing the latitudinal region over which that radiation is observed.

Whistler-mode auroral hiss is believed to be generated by a Cerenkov-like radiation process similar to that proposed by Ellis [1957]. However, the radiated power cannot be accounted for by simply summing the Cerenkov power emitted from the individual electrons in the beam. Instead, a collective process that organizes the phase of emitting electrons must be involved so that the radiated power is increased. Using modern plasma theory, it can be shown that electrons of velocity $v_b$ interact resonantly with the whistler-mode radiation if the frequency w and wave number k satisfy the condition $v_b \cong \omega/k_\parallel$, where the symbol $\parallel$ represents the component along the magnetic field. This condition is called the Landau resonance. The Landau resonance is essentially identical to the Cerenkov condition encountered in single particle radiation theory. It can also be shown that the growth rate is proportional to $\partial f/\partial v_\parallel$, where f is the electron velocity distribution. A beam always has a range of velocities where $\partial f/\partial v_\parallel$ is positive, so that wave growth will occur. This instability is often called the two-stream instability.

Auroral hiss is a very common plasma wave emission. Almost every pass over the Earth's auroral zones has intense auroral hiss. The interaction of the auroral hiss with the auroral electron beam has been extensively studied by Maggs [1976]. As the auroral hiss grows in amplitude,

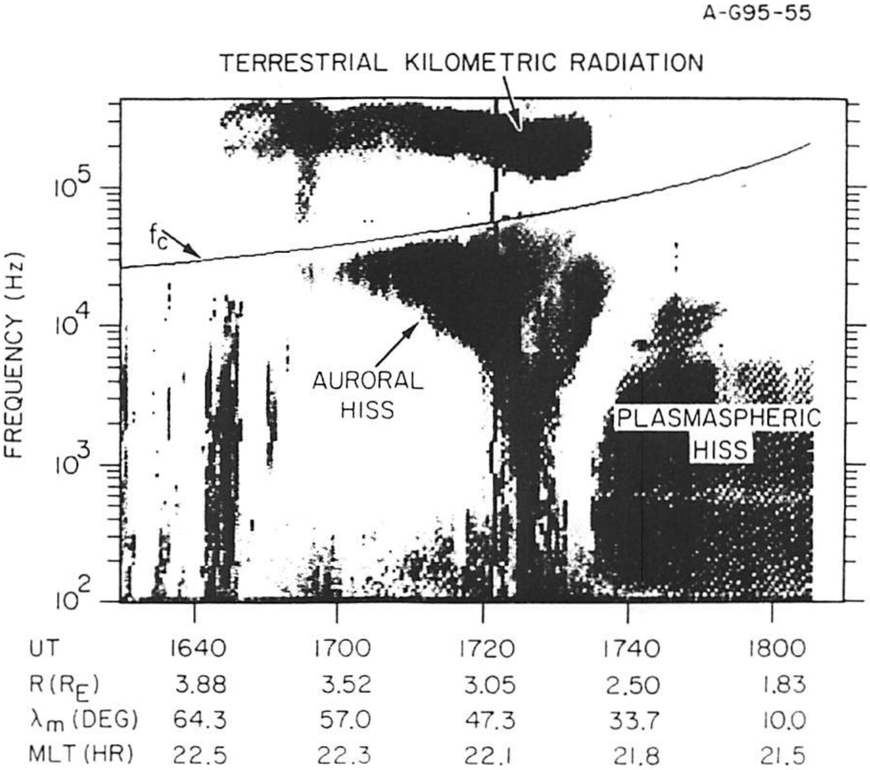

*Fig. 4 - A frequency-time spectrogram from a pass of the DE-1 spacecraft over the Earth's northern polar cap. Two types of auroral radio emissions can be seen: (1) auroral hiss, and (2) terrestrial kilometric radiation. Auroral hiss is a whistler-mode emission, and terrestrial kilometric radiation is a free-space radio emission that propagates freely away from the Earth.*

wave-particle interactions tend to flatten the electron velocity distribution function in the region where $\partial f / \partial v_{\parallel}$ is positive, thereby driving $\partial f / \partial v_{\parallel}$ to zero. Whistler-mode waves therefore act to drive the electron distribution toward a stable equilibrium. The presence of this stabilization process is confirmed by the fact that well-defined "beams" are seldom observed in the auroral zones. As soon as a beam starts to develop, whistler-mode wave-particle interactions quickly spread the beam into a flat distribution.

### *B. Cyclotron maser radiation*

During the late 1960s and early 1970s, an entirely new type of terrestrial radio emission was discovered by eccentric Earth-orbiting satellites. This radio emission was first detected by Benediktov et al. [1965] using data from the Elektron 2 and 4 satellites. A few years later, Gurnett [1974] showed that this radiation, which has its peak intensity in the frequency range from about 100 to 500 kHz, was closely correlated with the occurrence of discrete auroral arcs. Gurnett also showed that the total radiated power was very large, up to $10^9$ Watts. The high power levels came as a surprise, since this radiation had not been previously detected on the ground. The reason, of course, is the radiation cannot propagate downwards through the ionosphere. The Earth was therefore found to be an intense planetary radio source, comparable in some respects to Jupiter, which had been known for many years to be an intense radio emitter [Burke and Franklin, 1955]. Since the terrestrial radiation occurs in the kilometer wavelength range, this radio emission soon became known as "terrestrial kilometric radiation" or "auroral kilometric radiation". An example of terrestrial kilometric radiation can be seen in the upper part of Figure 4, at about 100 to 400 kHz, slightly above the electron cyclotron frequency. It is now known that this same basic type of radio emission occurs at five planets, Earth, Jupiter, Saturn, Uranus, and Neptune. A comparison of the radio emission spectrums from these five planets is shown in Figure 5. The characteristic features in all cases are that the radiation is (1) very intense, (2) right-hand polarized, and (3) generated at frequencies near the electron cyclotron frequency.

Since it is relatively easy to obtain in situ measurements of plasmas and radio emissions over the Earth's auroral zones, the discovery of the terrestrial kilometric radiation provided an unprecedented opportunity to investigate an astronomical radio emission mechanism of considerable significance. Now, after many years of study, we have a very good understanding of how this radio emission is produced. The basic mechanism is called the cyclotron maser instability. The cyclotron maser mechanism was first discussed by Melrose [1973], and later analyzed in more detail by Wu and Lee [1979] in connection with the terrestrial kilometric radiation. The basic instability is similar to the whistler loss-cone instability in that it involves an electron cyclotron resonance. However, the mode of propagation is the free space R-X mode rather than the whistler mode. One unusual feature is that relativistic effects are fundamentally involved in the resonance condition and cannot be omitted even though the electron energies are non-relativistic (i.e., only a few keV). The free energy source that drives the instability has been the subject of considerable debate. Originally, Wu and Lee [1979] proposed that it was the loss cone in the electron distribution that provided the free energy for the instability. However, more recent studies by Louarn et al. [1989] indicated that electrons trapped in the auroral acceleration region by magnetic mirror and electrostatic forces provide the primary free energy source. Once generated, the radiation escapes freely away from the Earth, following ray paths more or less as shown in Figure 6.

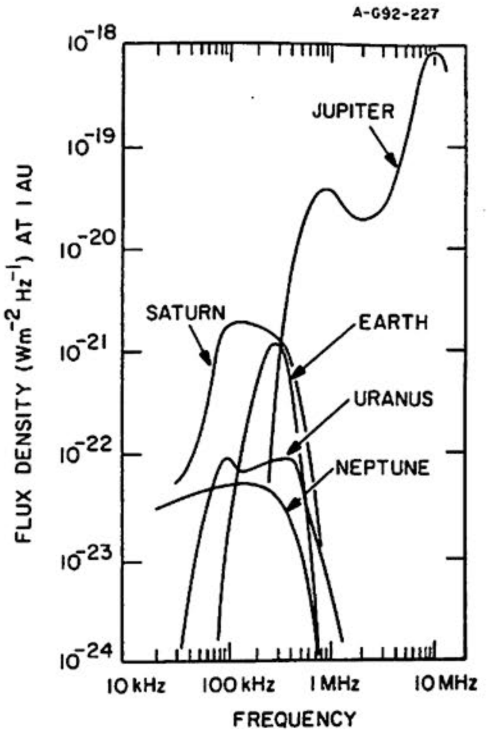

*Fig. 5 - A comparison of the spectrums of cyclotron maser radiation from five planets. The spectrums are all referenced to a distance of 1 AU.*

Although very detailed in situ measurements are available in the region where the cyclotron maser radiation is generated at Earth, comparable measurements are not available at the other planets. Even though the Voyager spacecraft flew by Jupiter, Saturn, Uranus, and Neptune, the trajectory did not pass through the source region, which in almost all cases is located at high latitudes. Thus, the only information that can be obtained about the cyclotron maser radiation mechanism at these planets is what can be gleaned from the radio emission spectrum. The Jovian cyclotron maser radiation (called decametric radiation) has one unusual feature that is worth noting. The intensity of the Jovian decametric radiation has been shown by Bigg [1964] to be strongly controlled by Jupiter's moon, Io. As Io moves through the Jovian magnetosphere, it induces a field-aligned current loop that closes in the auroral zone. This current system then causes electron acceleration, auroral light emission, and other effects comparable to the aurora at Earth. Recent pictures from the Hubble Space Telescope show that Jupiter also has an auroral zone that appears to be driven by a magnetospheric current system. Thus, at least two energy sources are probably involved in the generation of cyclotron maser radiation at Jupiter.

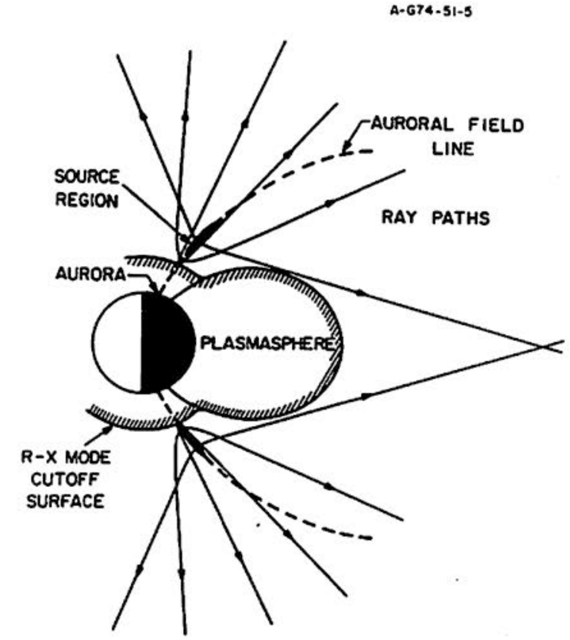

*Fig. 6 - A sketch of typical ray paths of terrestrial kilometric radiation. This radiation is generated in the auroral acceleration region by an electron cyclotron maser mechanism. The radiation propagates away from the Earth in a broad conical beam, the axis of which is aligned along the magnetic field in the source region.*

## 4. The solar wind

The solar wind is a hot, fully ionized gas that flows outward from the Sun at a supersonic speed. At the orbit of Earth, the solar wind density is approximately 5 cm$^{-3}$, and the speed is approximately 400 km/s. In situ measurements of plasma waves and radio emissions have been made in the solar wind as close to the Sun as 0.29 AU, and as far from the Sun as 58 AU. To illustrate the range of plasma wave and radio emission processes that can occur in the solar wind, we will focus on two examples: (1) Langmuir waves associated with type III solar radio bursts, and (2) heliospheric 2-3 kHz radio emissions.

### *A. Langmuir waves associated with type III solar radio bursts*

Langmuir waves are electrostatic oscillations that occur in a plasma at the electron plasma frequency, $f_p = 9\sqrt{N}$ kHz, where N is the electron density in cm$^{-3}$. Langmuir waves are excited by electron beams and are of considerable importance in the theory of certain types of solar radio emissions. In a classic paper, Ginzburg and Zheleznyakov [1958] proposed that type III solar radio bursts are produced by a two-step process in which (1) electrons from a solar flare excite Langmuir waves at $f_p$ via a two-stream instability, and (2) the Langmuir then decay into electromagnetic radiation at $f_p$ and $2f_p$ via nonlinear wave-wave interactions. The two-step type III generation process has now been confirmed by a variety of space plasma wave measurements [see Gurnett and Anderson, 1976; and Lin et al., 1981]. An example of a type III radio burst detected in the solar wind near 1 AU is shown in Figure 7. Type III radio bursts are characterized by an emission frequency that decreases with increasing time. The downward frequency drift is caused by the decreasing electron plasma frequency encountered by the solar flare electrons as they move outward from the Sun. This process is illustrated in Figure 8, which shows a typical radial variation of the plasma frequency in the solar wind. Although the type III radiation can propagate great distances, the Langmuir waves, which are a locally generated oscillation, cannot be detected until the electron beam reaches the spacecraft.

In Figure 7, the type III solar radio burst is associated with a solar flare that occurred at about 0730 UT. The Langmuir waves excited by the energetic electrons arriving from this solar flare can be seen at the local electron plasma

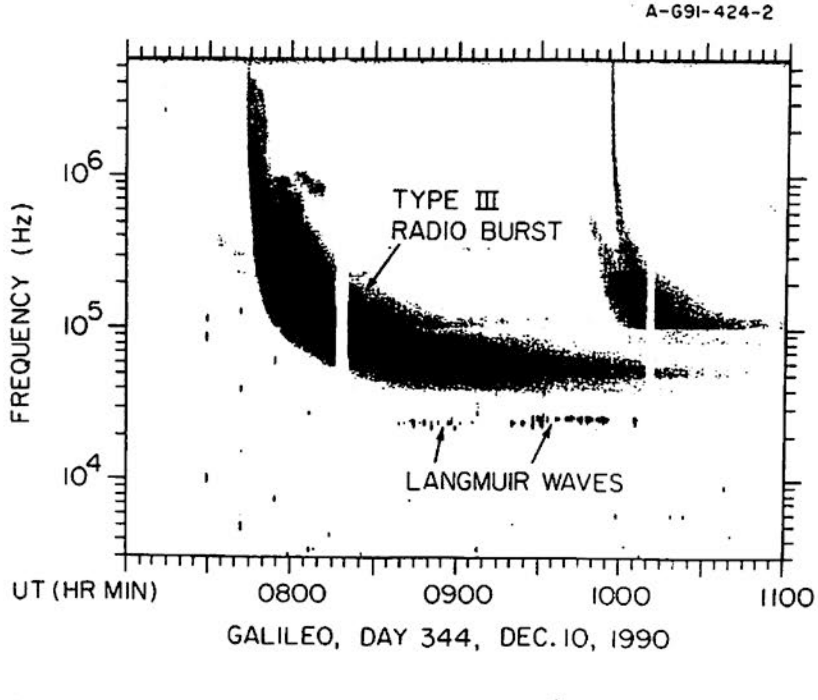

*Fig. 7 - An example of a strong solar type III radio burst detected by the Galileo spacecraft at a heliocentric radial distance of about 0.98 AU. The Langmuir waves responsible for the radio emission can be seen at the local electron plasma frequency, which in this case is about 23 kHz. These waves are driven by electrons arriving from a solar flare that occurred at about 0730 UT.*

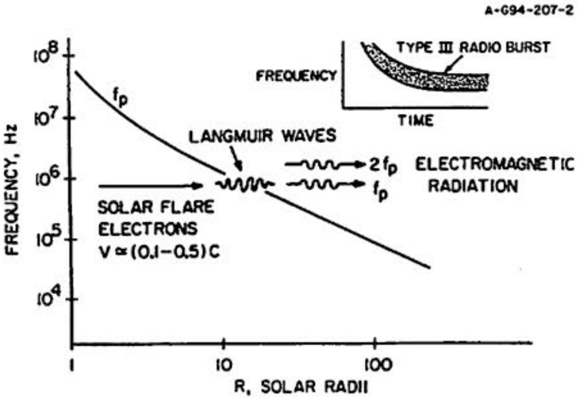

*Fig. 8 - In the two-step mechanism believed to be responsible for type III radio bursts, electrons arriving from a solar flare excite Langmuir waves at the local electron plasma frequency, $f_p$. The Langmuir waves then generate radiation at $f_p$ and $2f_p$ via nonlinear wave-wave interactions. The downward frequency drift of the radio burst is caused by the decreasing electron plasma frequency encountered by the solar flare electrons as they move outward from the Sun.*

frequency ($f_p \approx 23$ kHz) starting at about 0835 UT and continuing to about 1020 UT. In this case the type III radio emission is generated at the harmonic $2f_p$. Harmonic radiation is believed to result from the interaction of two Langmuir waves, L and L', such that the emitted frequency is $f_{pL} + f_{pL'} = 2f_p$. Since the emitted transverse electromagnetic wave, T, has a wave number much smaller than the Langmuir waves, conservation of momentum ($k_L + k_L' = k_T$) requires that the Langmuir waves, L and L', must be propagating in opposite directions. The origin of the oppositely propagating Langmuir wave is still a subject of debate. The current view is that this wave is produced by parametric decay from the original beam-driven Langmuir wave. Radiation at the fundamental, which is rare at these low frequencies, is believed to occur when a beam-driven Langmuir wave interacts with another low-frequency wave, such as a sound wave, to produce emission at $f = f_p + f_s$. Since $f_s << f_p$, the radiation occurs slightly above the plasma frequency.

### *B. Heliospheric 2-3 kHz radio emissions*

In the early 1980s, as the Voyager 1 and 2 spacecraft were moving outward from the Sun beyond the orbit or Saturn, they began to detect an unusual radio emission in the frequency range from about 2 to 3 kHz. In the approximately twelve years since this radio emission was first detected, two particularly strong events have occurred, the first in 1983-84 [Kurth et al., 1984] and the second in 1992-93 [Gurnett et al., 1993]. A twelve-year frequency time spectrogram from Voyager 1 illustrating these two events is shown in Figure 9. Since the solar wind electron plasma frequency varies roughly as $f_p = 20\ (1/R)$ kHz where R is the heliocentric radial in AU, the source of these radio emissions must be located far from the Sun, at least R 10 AU. Initially, several possible sources were considered, including (1) planetary, (2) heliospheric, and (3) stellar. Based on the most recent 1992-93 event, Gurnett et al. [1993] have estimated that the total radiated power is at least $10^{13}$ W, which effectively rules out planetary sources (also see Gurnett and Kurth [1994]). Because of the great distance to the nearby stars, stellar sources are also considered unlikely, since they would require extremely high power levels (>$10^{20}$ Watts) to account for the observed intensities. A heliospheric source has recently been given strong support by the fact that the 1983-84 and 1992-93 events each followed a period of intense solar activity, the first in July 1982 and the second in May-June 1991. The delay time between the peak of the solar activity and the onset of the radio emission in both cases was approximately 400 days.

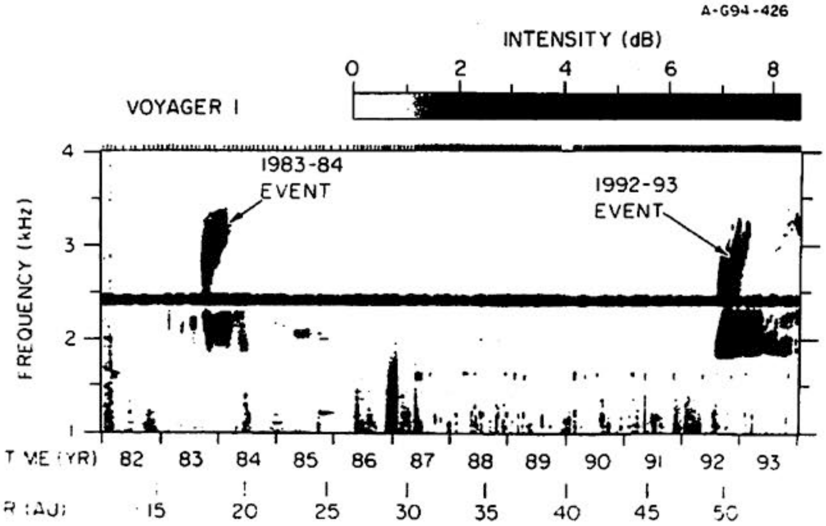

*Fig. 9 - A 12-year frequency-time spectrogram showing the two intense heliospheric 2-3 kHz radio emission events detected by the Voyager 1 and 2 spacecraft in the outer regions of the solar system. These two events each occurred about 400 days after intense periods of solar activity, the first in July 1982 and the second in May-June 1991.*

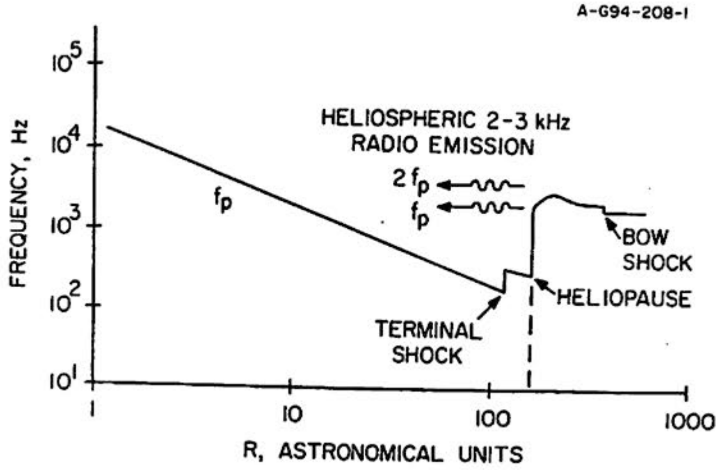

*Fig. 10 - The heliospheric 2-3 kHz radio emissions are believed to be produced in the vicinity of the heliopause by an interplanetary shock wave moving outward from the Sun. The radiation is believed to be produced by a two-step process involving Langmuir waves generated by an electron beam accelerated by the shock.*

The best current explanation of the 2-3 kHz radio bursts is that they are produced in the outer regions of the heliosphere by an interaction involving a shock wave or system or shock waves propagating outward from the Sun. There are two obvious boundaries where this interaction could occur, (1) the termination shock, where the solar wind undergoes a transition from a supersonic to a subsonic flow, and (2) the heliopause, where the solar wind is held off by the pressure of the interstellar medium. Because the Sun is moving through the local interstellar medium at a speed of about 26 km/s, the heliopause is expected to form a bullet-shaped boundary around the Sun [Axford, 1990]. Since the pressure in the local interstellar medium is poorly known, the distances to the terminal shock and heliopause are difficult to estimate. Pioneers 10 and 11, and Voyagers 1 and 2 are currently at 61.3, 42.2, 58.1, and 44.7 AU (as of January 1, 1995), and none have yet reach either the termination shock or the heliopause.

The most likely mechanism for generating the heliospheric 2-3 kHz radio emissions is thought to be similar to the two-step Langmuir wave mechanism, except that the electron beam is produced by an interplanetary shock. This is the mechanism by which type II radio bursts are believed to be produced. The radiation would then be generated at $f_p$ or $2f_p$. If a two-step Langmuir wave mechanism is responsible for the radiation, then it is unlikely that the radio emission is produced at the termination shock, since the plasma frequency is too low. At Voyager 1 the plasma frequency in the solar wind is already down to about 350 Hz, so it must be even lower at the termination shock. At the heliopause, the situation is much better. Since the heliopause is a contact discontinuity, the plasma density can increase by whatever factor is necessary to maintain pressure balance with the interstellar medium. Current best estimates of the electron density in the interstellar medium [Lallement et al., 1993], indicate that the plasma frequency is in the range from 2.2 to 2.8 kHz. Thus, the plasma densities in the vicinity of the heliopause are in a suitable range to account for the 2-3 kHz radio emissions. A representative plasma frequency profile through the outer regions of the heliosphere is shown in Figure 10. If the radio emission is generated by the interaction of an interplanetary shock with the heliopause, then the distance to the heliopause can then be estimated from the travel time and speed of the shock. From the 400-day travel time, and the speeds of the interplanetary shocks (550 to 800 km/s), the distance to the heliopause can be computed, and is in the range from about 106 to 177 AU [Gurnett et al., 1995].

## 5. Conclusions

In the nearly forty years since the launch of the first Earth-orbiting satellites, considerable progress has been made in the understanding of solar system plasma processes. Measurements of space plasma waves and radio emissions have played an essential role in achieving this understanding. However, much remains to be done. Although our knowledge of the plasma environment of the Earth is very good, our knowledge of plasma processes at other planets is very limited. There is a strong need to obtain plasma and plasma wave measurements in the auroral acceleration regions at Jupiter, where strong radio emissions are generated over the high-latitude polar regions, most likely in association with the aurora. There is also a strong need to explore plasma wave processes much closer to the Sun, in the region where strong radio emissions are produced in response to flares and other energetic solar processes. In the meantime, most future space plasma wave research will probably focus on measurements obtained in the vicinity of Earth. At Earth there are still many avenues of research that remain to be explored. Although the linear growth phase of most plasma wave instabilities is well understood, the nonlinear mechanisms that limit the growth and saturate the instability are poorly understood. The continued pursuit of these and other areas of space plasma wave research is likely to continue well into the 21st century.

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