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SOLAR SYSTEM PLASMA WAVES

by

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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.

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 known 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 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

II. 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 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 narrowband emissions, usually 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. 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 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.

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

III. 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.

that electrons of velocity v_b interact resonantly with the whistler-mode radiation if the frequency ω and wave number k satisfy the condition $v_b \cong \omega/k_{\|}$, where the || symbol 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 $\partial f/\partial v_{\|}$, where f is the electron velocity distribution. A beam always has a range of velocities where $\partial f/\partial v_{\|}$ 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, wave-particle interactions tend to flatten the electron velocity distribution function in the region where $\partial f/\partial v_{\|}$ is positive, thereby driving $\partial f/\partial v_{\|}$ 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, 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.

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

IV. 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

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 $R \gtrsim 10$ 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.

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 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].

V. 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.

Acknowledgements

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Table 1

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

FIGURE CAPTIONS

Figure 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 narrowband emissions, usually rising in frequency on time scales of a few seconds, and hiss consists of the nearly steady spectrum of band-limited noise. In this case, the chorus occurs from about 8 to 12 kHz, and the hiss occurs below about 1 kHz.

Figure 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.

Figure 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.

burst is caused by the decreasing electron plasma frequency encountered by the solar flare electrons as they move outward from the Sun.

Figure 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.

Figure 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.

A-G93-27-1

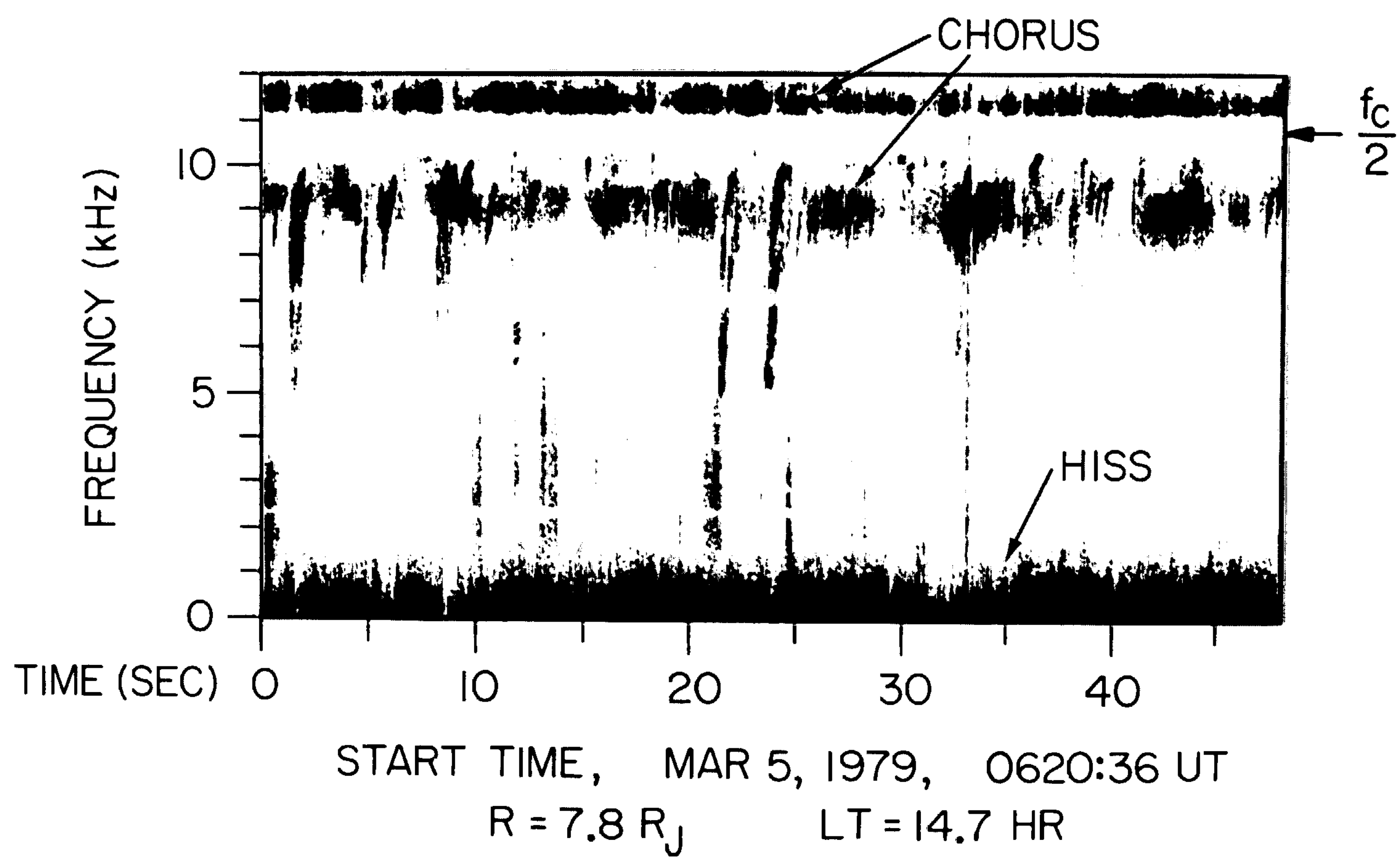


Figure 1

B-G95-54

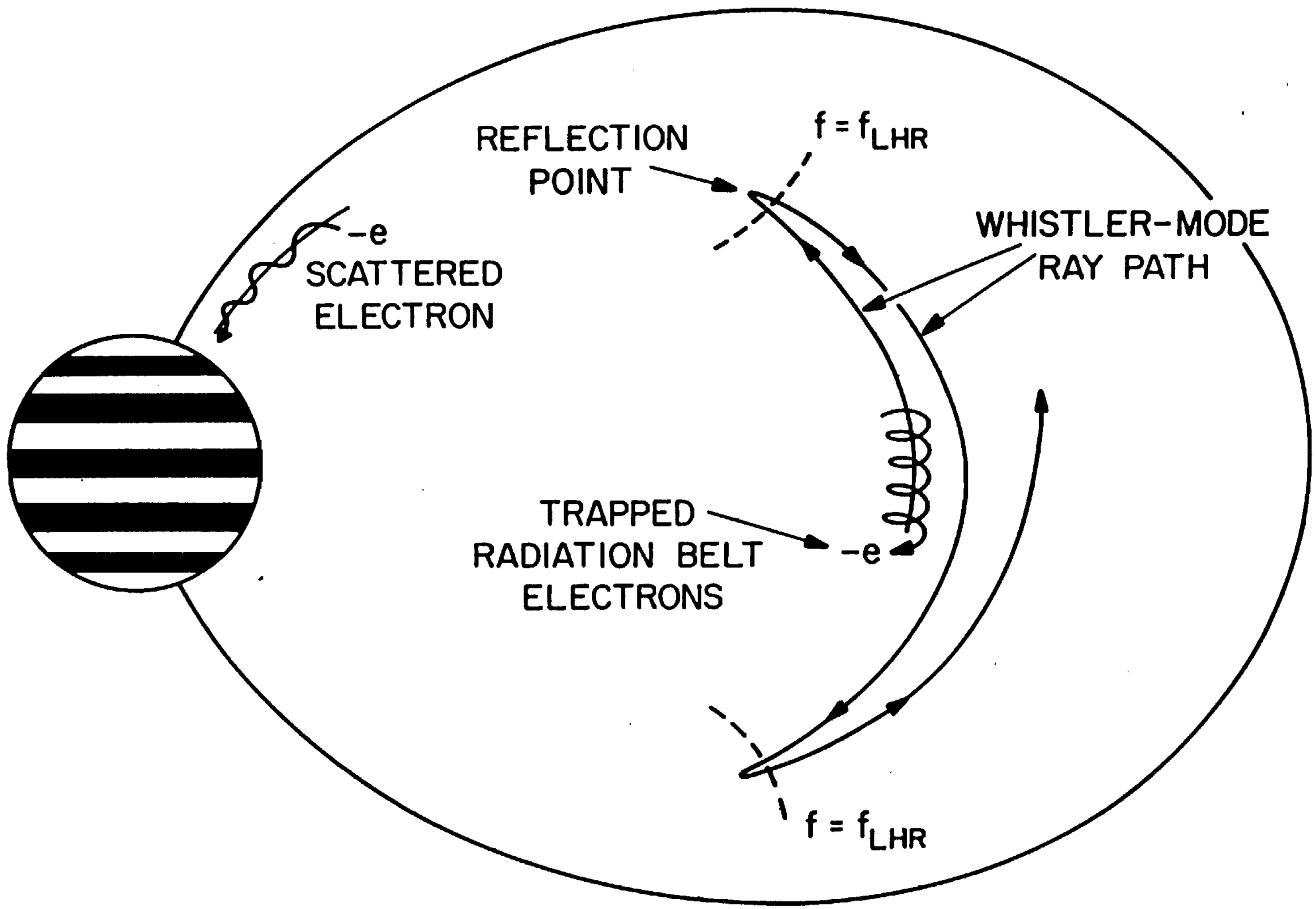


Figure 2

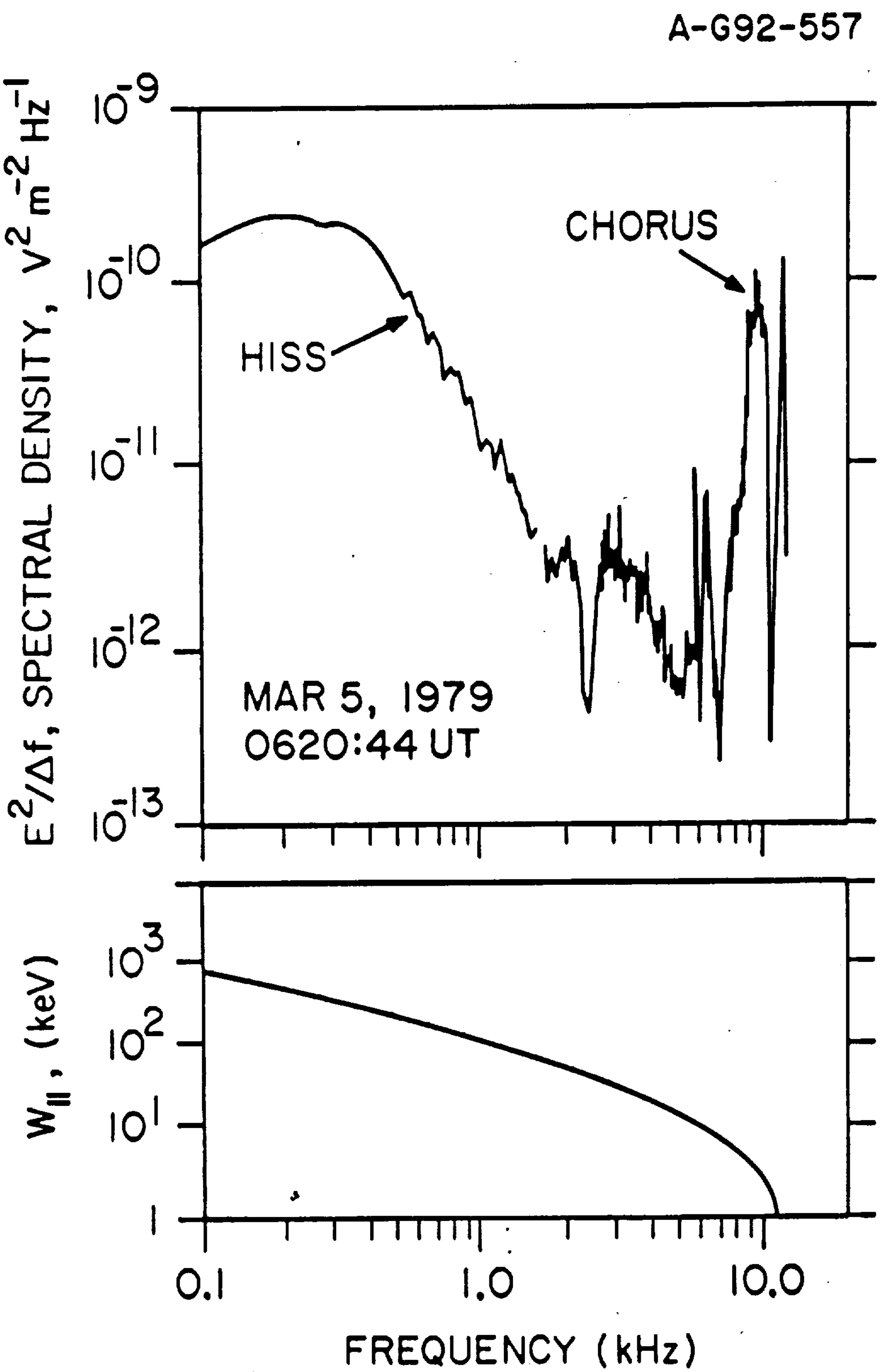

A-G92-557
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
$E^2/\Delta f$, SPECTRAL DENSITY, $V^2 m^{-2} Hz^{-1}$
CHORUS
HISS
MAR 5, 1979
0620:44 UT
10^3
10^2
10^1
1
$W_{\parallel}$, (keV)
0.1
1.0
10.0
FREQUENCY (kHz)

Figure 3

A-G95-55

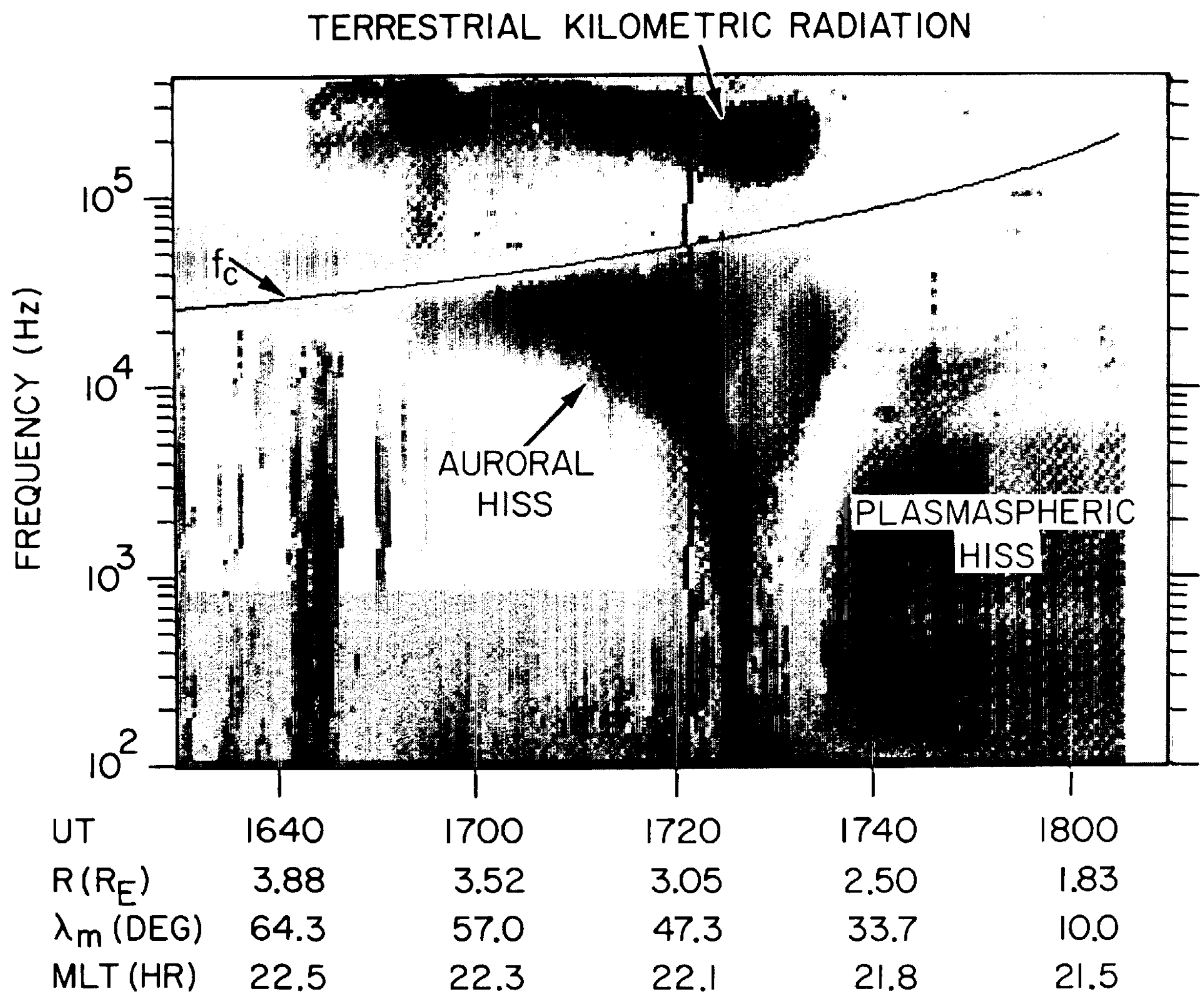


Figure 4

~~38~~ 35

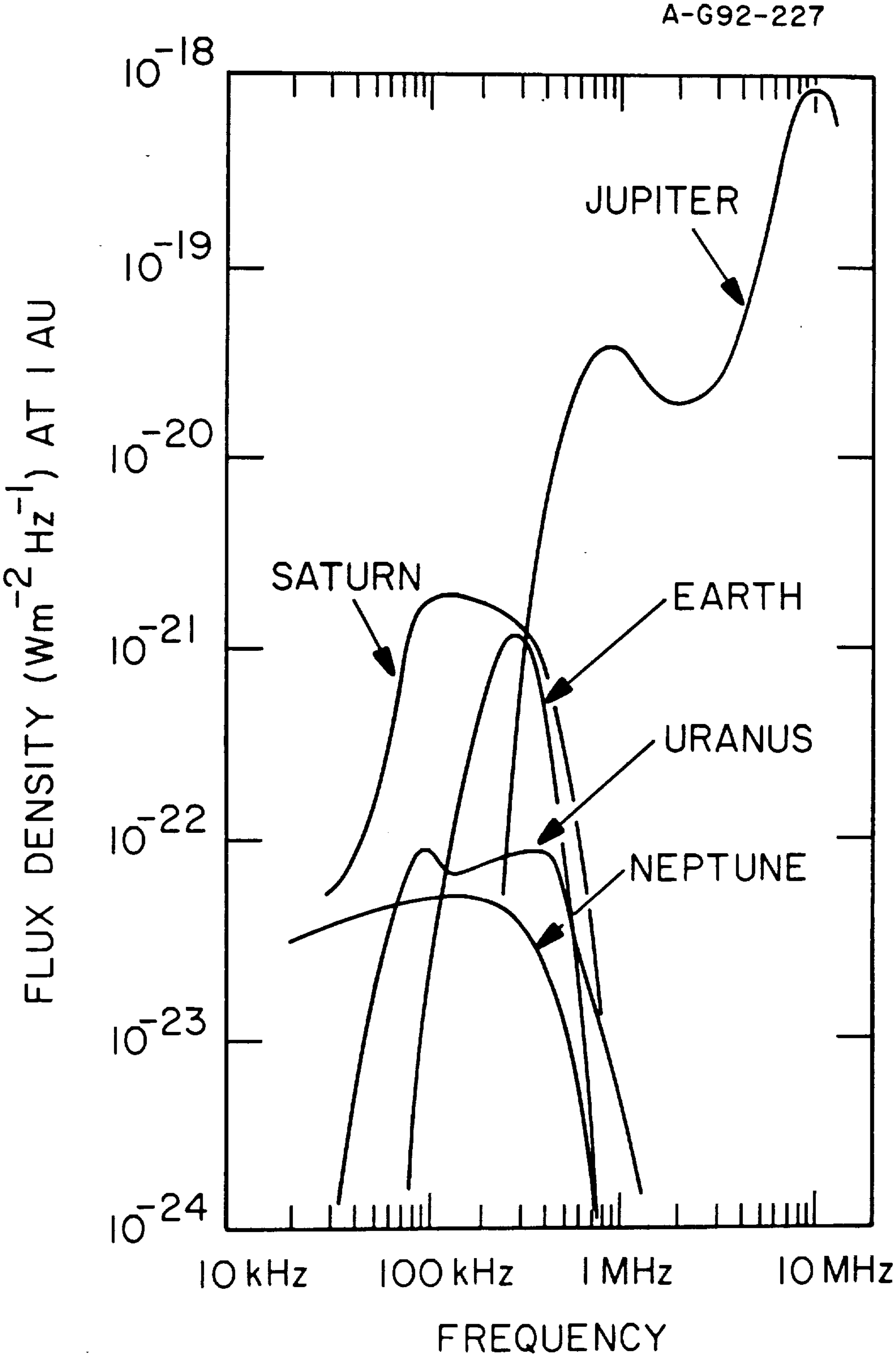

A-G92-227
JUPITER
SATURN
EARTH
URANUS
NEPTUNE
FLUX DENSITY (Wm^{-2} Hz^{-1}) AT 1 AU
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10 kHz
100 kHz
1 MHz
10 MHz
FREQUENCY

Figure 5

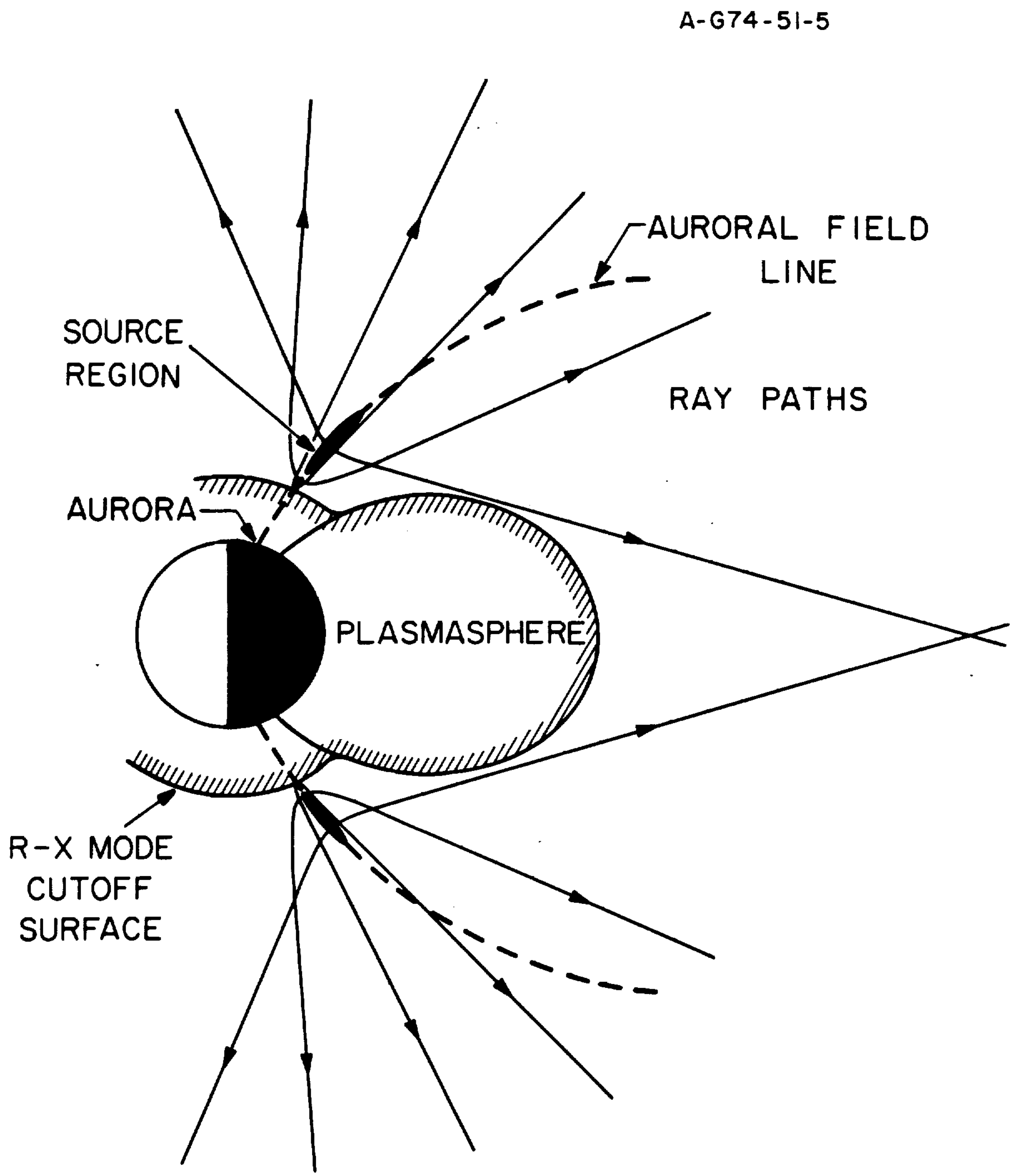

A-G74-51-5
AURORAL FIELD LINE
SOURCE REGION
RAY PATHS
AURORA
PLASMASPHERE
R-X MODE CUTOFF SURFACE

Figure 6

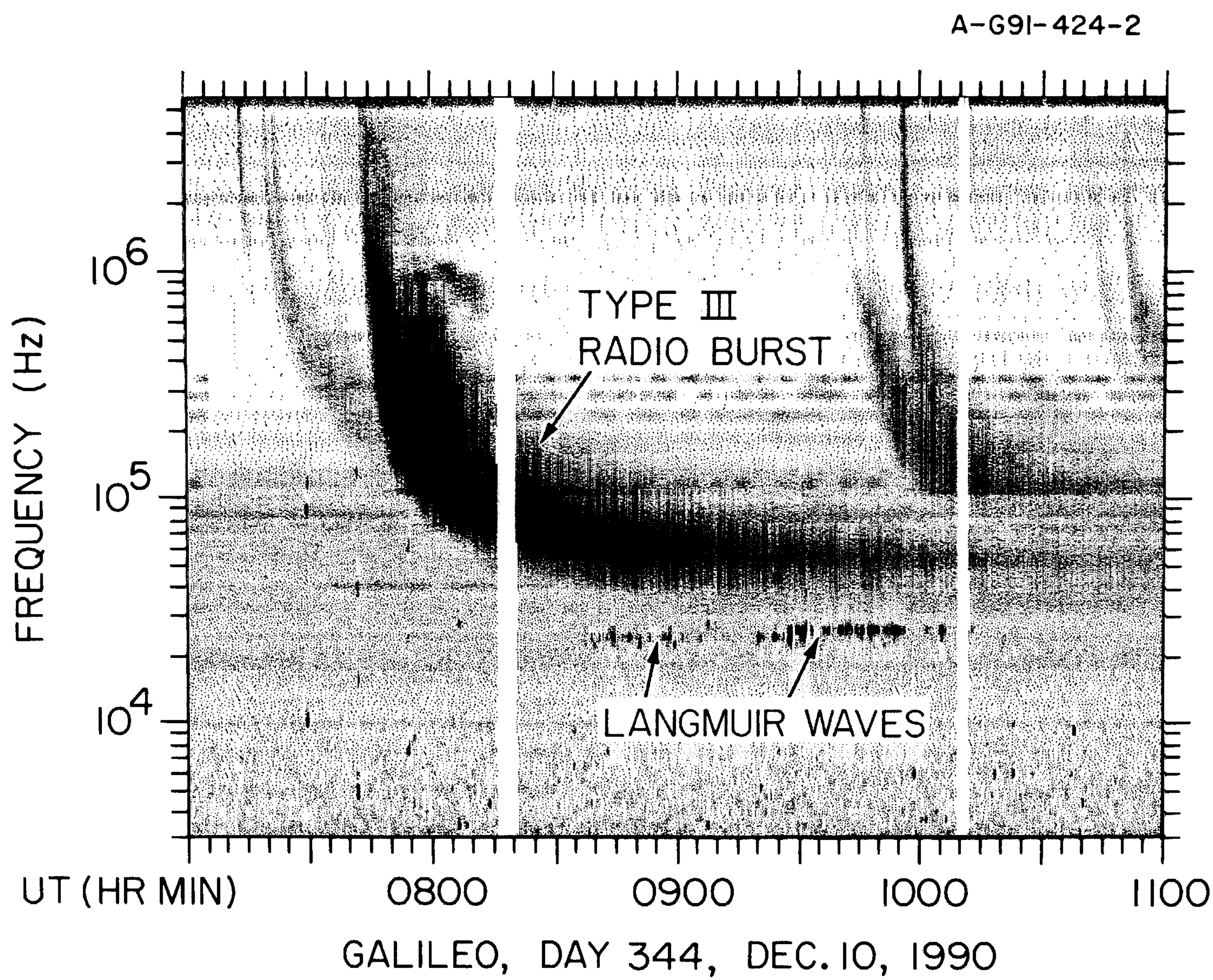

A-G91-424-2
FREQUENCY (Hz)
10^6
10^5
10^4
TYPE III
RADIO BURST
LANGMUIR WAVES
UT (HR MIN)
0800
0900
1000
1100
GALILEO, DAY 344, DEC. 10, 1990

Figure 7

A-G94-207-2

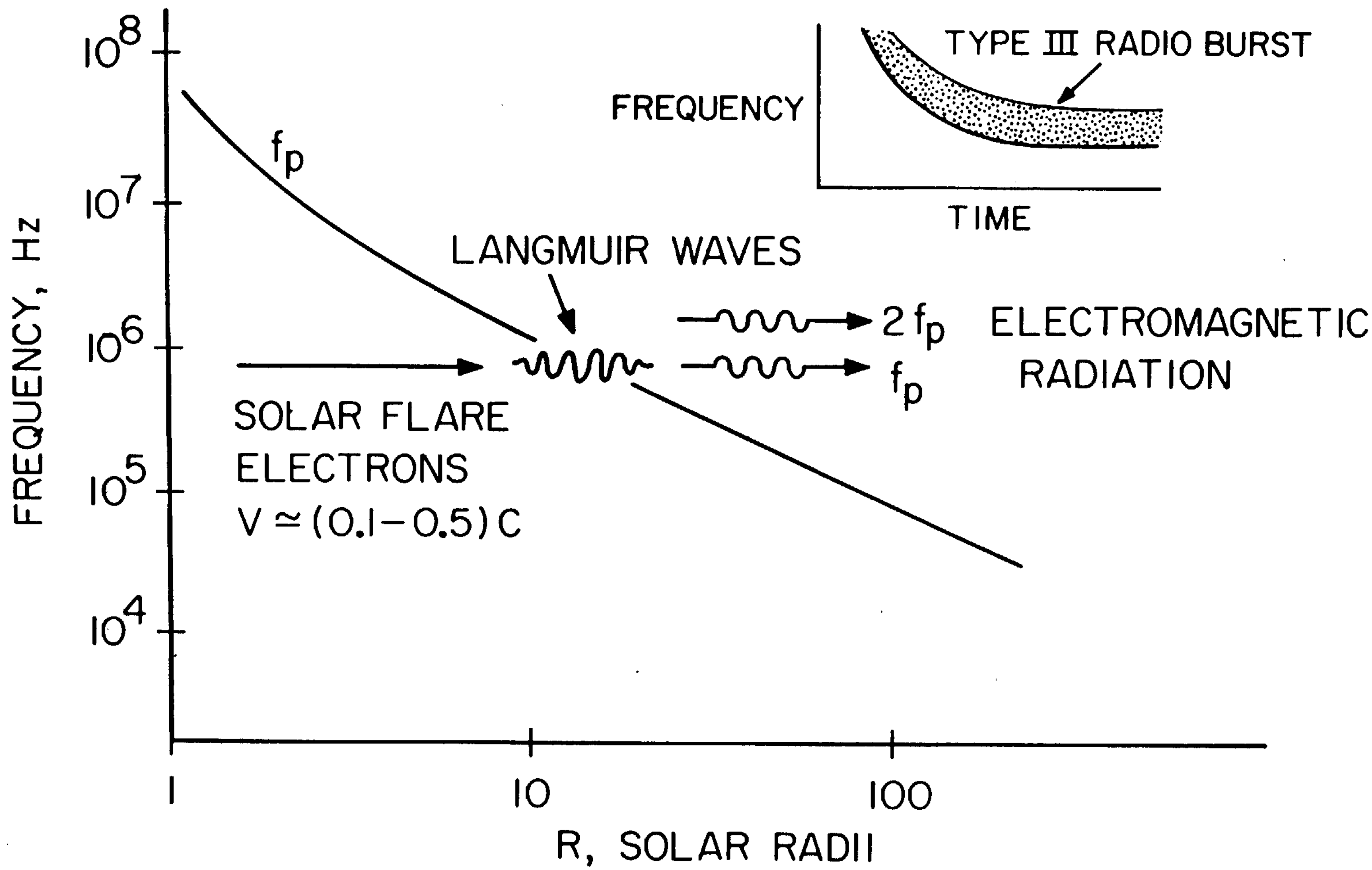
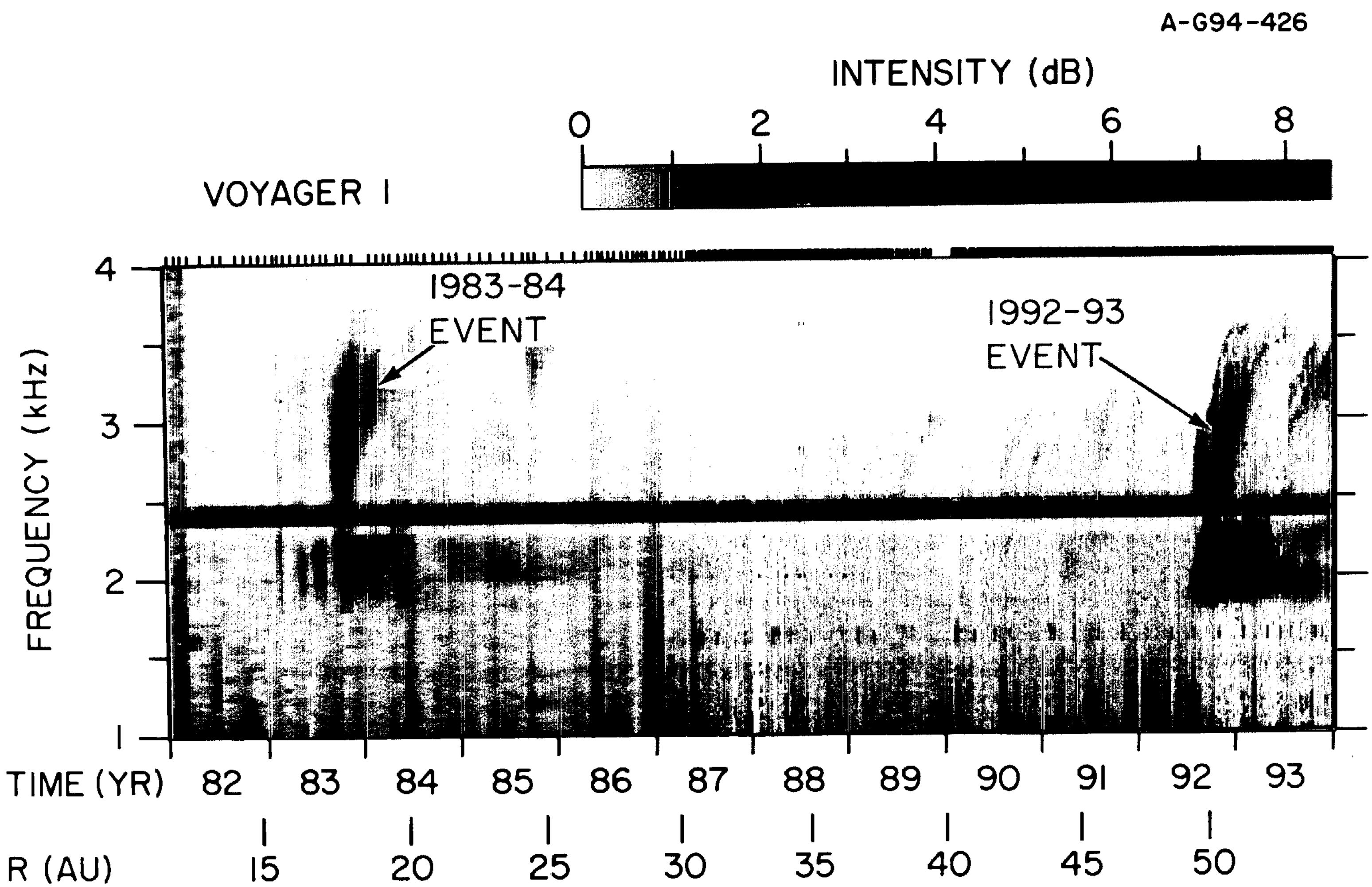


Figure 8



A-G94-426
INTENSITY (dB)
0
2
4
6
8
VOYAGER I
1983-84
EVENT
1992-93
EVENT
FREQUENCY (kHz)
1
2
3
4
TIME (YR)
82
83
84
85
86
87
88
89
90
91
92
93
R (AU)
15
20
25
30
35
40
45
50

Figure 9

A-G94-208-1

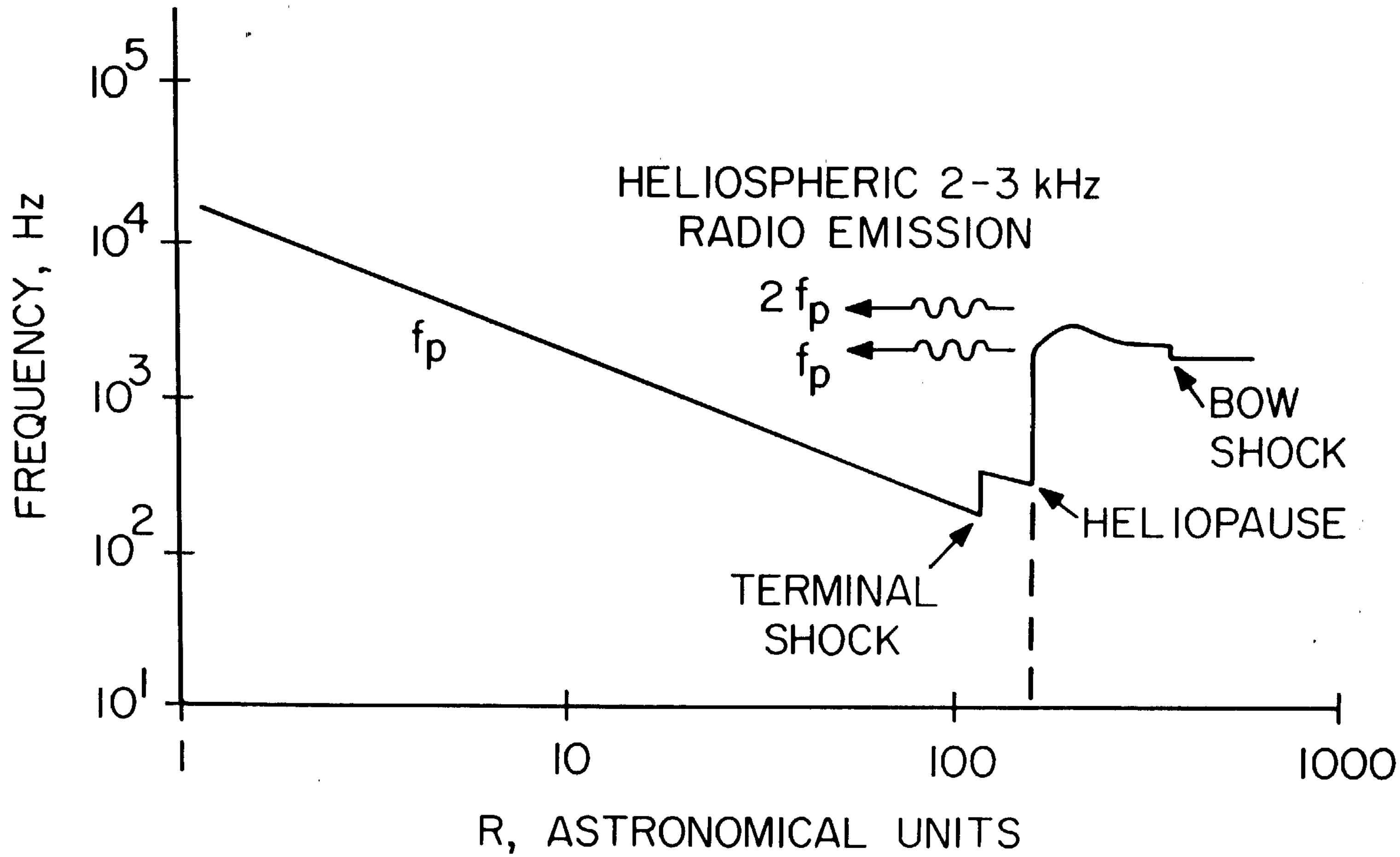


Figure 10

~~41~~
41