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Department of Physics and Astronomy
THE UNIVERSITY OF IOWA
Iowa City, Iowa 52242

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Narrowband Electromagnetic Emissions
from Saturn's Magnetosphere

by

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May, 1981

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ABSTRACT

During the Voyager 1 flyby of Saturn a series of narrowband electromagnetic emissions were detected by the plasma wave instrument coming from the inner region of the magnetosphere in the frequency range from 3 to 30 kHz. These emissions have many close similarities to continuum radiation detected in the Earth's magnetosphere and narrowband kilometric radiation (nKOM) detected in the Jovian magnetosphere. Based on the close similarity to the terrestrial continuum radiation the Saturn narrowband emissions are interpreted as being generated by mode conversion from intense electrostatic waves at half-integral harmonics of the electron gyrofrequency. The observed frequency spacing suggests that the emissions are being generated near the moons Tethys, Dione and Rhea, probably in regions of large plasma density gradients associated with boundaries of the plasma sheet.

- A -

I. INTRODUCTION

Among the numerous results from the Voyager 1 plasma wave instrument during the Saturn flyby on 12-13 November 1980 was the observation of a series of narrowband electromagnetic emissions at frequencies ranging from 3 to 30 kHz [(1)]. These bands are remarkable because of their extremely complex spectral structure, consisting of a large number of nearly monochromatic emissions. Frequency spacings can be identified between the various bands which correspond to the equatorial electron gyrofrequencies near the moons Tethys, Dione and Rhea. Because of the possible association of the radio emissions with the moons of Saturn, we have undertaken a detailed analysis of these emissions in order to determine the origin of the radiation and to explore similarities to other planetary radio emissions. This article describes the characteristics of the narrowband electromagnetic emissions detected in the vicinity of Saturn, and discusses various models which have been developed to explain the generation of these emissions. For a description of the plasma wave instrumentation on Voyager 1, see the description given by Scarf and Gurnett[(2)].

II. OBSERVATIONS

The strongest and best resolved examples of the narrowband electromagnetic emissions occur in the inner region of the magnetosphere, near closest approach. The electric field intensities in this region are shown in Fig. 1. Each channel gives the electric field intensity on a logarithmic frequency scale at the center frequencies indicated on the left of the plot. For reference the electron gyrofrequency, f_g, and plasma frequency, f_p, are shown by the solid and dashed lines. The electron gyrofrequency ($f_g = 28B$ in Hz, where B is the magnetic field in gammas) was determined from the Voyager 1 magnetic field instrument[3], and the plasma frequency ($f_p = 9000 \sqrt{n_e}$ in Hz, where n_e is the electron number density in cm^{-3}) was obtained from the Voyager 1 plasma instrument[4]. The narrowband electromagnetic emissions consist of a series of smooth enhancements in the 3.11-to 31.1-kHz channels from about 2100 SCET (spacecraft event time in hours and minutes) on 12 November to 0100 on 13 November. These enhancements all occur at frequencies above the electron plasma frequency as determined by the plasma experiment. The sharp cutoffs evident in the 5.62-and 10.0-kHz channels shortly after closest approach appear to be directly associated with the local electron plasma frequency. It can also be seen that the enhanced intensities extend across the electron gyrofrequency with no obvious propagation effect. These characteristics uniquely identify the mode of propagation as the free-space left-hand polarized ordinary

(L,O) mode. A well-known characteristic of this mode is that propagation occurs for all frequencies $f > f_p$, and that no resonance or cutoff occurs at the electron gyrofrequency.

From Fig. 1 it is seen that another type of very intense narrowband emissions occurs in the 31.1 kHz channel at about 0130 on November 13, coincident with the cutoff of the electromagnetic radiation. At peak intensity this narrowband burst has a field strength approximately 60 db larger than the adjacent electromagnetic radiation. On the basis of similar observations in the Earth's magnetosphere[5-7] and at Jupiter[8-10] this burst is identified as an electrostatic emission at the local upper-hybrid resonance (UHR) frequency, $f_{UHR} = \sqrt{f_p^2 + f_g^2}$. The fact that the observed emission frequency is higher than the upper hybrid resonance frequency computed from the measured plasma frequency and gyrofrequency is attributed to uncertainties in the determination of the electron number density by the plasma instrument. Most likely the electron density and electron plasma frequency are somewhat higher than shown by the plasma instrument at this particular time.

Because the intensity of the electromagnetic radiation is comparable in adjacent frequency channels, Fig. 1 gives the impression that the spectrum is nearly continuous, possibly comparable to the continuum radiation detected in the Earth's magnetosphere[5]. Fortunately, one 48-second frame of wideband waveform data was obtained in this region which provides greatly improved frequency resolution. A high-resolution frequency-time spectrogram of these data is shown in Fig. 2. As can be seen the spectrum is not continuous, but rather consists of many narrowband emissions, some with bandwidths less than 100 Hz. The spectrum is illustrated in greater detail in Fig. 3, which shows the electric field spectral density as a function of frequency. Three main bands can be identified, one at a frequency of about 1 kHz, a second at about 6 kHz, and a third at about 9.7 kHz. Because the low frequency band at 1 kHz is below the electron plasma frequency, whereas the others are all above the electron plasma frequency, this band cannot be propagating in the same mode as the higher frequency bands. For $f < f_p$ the only possible modes are the whistler-mode and the Z-mode. Based on the similarity to whistler-mode hiss emissions observed in the higher density regions of the plasma sheet, we have previously concluded that this low frequency (~ 1 kHz) band is propagating in the whistler mode[1].

The most definitive evidence that the high frequency bands are propagating in the free-space electromagnetic mode is given in Fig. 4, which shows a series of wideband spectrograms obtained over a three-day period near and after closest approach. A single persistent band of emission can be seen at about 5 kHz extending over a range of radial distances from at least 3.26 to 58.3 R_S. Because the plasma parameters change over a wide range it is difficult to see how this band of emission could be observed over such a large range of radial distance without being a freely propagating electromagnetic wave. The last observation, labelled F in Fig. 4, is in the magnetosheath where the local plasma frequency is about 3.8 kHz [personal communication, J. Scudder]. Although the electromagnetic bands can be detected in the wideband data over a several day period, the intensity and detectability vary considerably. The meridian plane plot in Fig. 5 summarizes the regions in which the bands were detected. The locations of the wideband frames in Fig. 4 are indicated by the circles labelled A through F, and intervals during which the emissions could be identified in the 16-channel survey plots (as in Fig. 1) are indicated by the solid black areas. Except for the brief interval near closest approach all of the observations of narrowband emissions were confined to high latitudes on the outbound pass. No examples were found on the inbound leg. The absence of observations on the inbound leg is almost certainly due to the fact that the spacecraft was passing through the high density central region of the plasma sheet where the electron density is sufficiently high to refract the radiation away from the equatorial region. In contrast, for the outbound pass ($R \gtrsim 10\ R_S$) at high latitudes the electron density(4) is always low enough to allow direct line-of-sight propagation to the spacecraft at frequencies above a few kHz. The strongest emissions were observed at position A near closest approach, with substantially reduced intensities at larger radial distances, thereby suggesting that the radiation originates in the inner region of the magnetosphere at $R \lesssim 10\ R_S$.

Examination of the 16-channel survey plots shows evidence of a periodic modulation of the narrowband emission intensities at the 10 hour 40 minute rotation period of Saturn. Typically, the narrowband emission events last for about three or four hours and tend to repeat at intervals of about 11 hours. The three intervals containing B, C-D, and E, in Fig. 5 show this periodicity. Maximum intensity occurs when the Saturn Longitude System (SLS) longitude of the subsatellite point is near 290°. Event F in Fig. 5 is also in phase with this general rotational modulation, however, one cycle seems to have been missed between E and F, possibly owing to the very low intensity and difficulty of detecting these emissions far from the planet.

III. RELATIONSHIP TO OTHER PLANETARY RADIO EMISSIONS

Although at first glance the complex narrowband structure of these Saturn radio emissions appears somewhat unusual, in fact very similar types of radio emissions have been identified in the magnetospheres of Earth and Jupiter. At Earth it has been known for many years that a relatively weak type of broadband radio emission called continuum radiation is generated within the magnetosphere [5,11,12]. This radiation has a relatively smooth steady temporal structure, and when analyzed with spectral resolution comparable to that obtained from the Voyager 16-channel spectrum analyzer, the overall appearance is very similar to the electromagnetic emissions shown in Fig. 1. As with the Saturn observations, when the terrestrial continuum radiation is analyzed with better frequency resolution it becomes apparent that the frequency spectrum is not continuous, but instead consists of a series of discrete narrowband emissions[13]. The detailed characteristics of the continuum spectrum depend on the frequency range. At frequencies below the solar wind plasma frequency, where the radiation is trapped in the low density magnetospheric cavity, the frequency spectrum tends to be nearly continuous with only occasional evidence of narrowband structure[11]. At frequencies above the solar wind plasma frequency, where the radiation can freely escape from the magnetosphere, the frequency spectrum often shows considerable narrowband structure. Typically, the spectrum consists of one or more relatively broad emission bands, with

$\Delta f/f \sim 20\%$, consisting of numerous narrowband features, some of which have harmonic frequency spacings[13]. The spectral characteristics of the terrestrial narrowband emissions are remarkably similar to the narrowband emissions observed at Saturn.

At Jupiter narrowband electromagnetic emissions with somewhat similar characteristics have been reported by Kaiser and Desch[14]. This radiation is referred to as nKOM, which stands for narrowband kilometric radiation. Although the frequency resolution available for the Jovian nKOM observations is not sufficient to reveal the extraordinary fine structure evident in the terrestrial and Saturnian emissions, the overall characteristics consisting of a relatively smooth narrowband emission with $\Delta f/f \sim 20\%$ are quite similar. An even closer similarity is the fact that the Jovian nKOM intensity is controlled by the rotation of Jupiter, very similar to the rotational control of the narrowband emissions observed at Saturn. The period of the nKOM is in fact slightly slower than the rotation period of Jupiter, and corresponds to the rotation period of the plasma in the outer region of the Io plasma torus, at a radial distance of about 10 R_J.

The close similarities between the narrowband electromagnetic emissions at Earth, Jupiter, and Saturn strongly suggest that the same basic emission mechanism is operative at all three planets. Before exploring possible models for explaining the Saturnian narrowband emissions, it is useful to review the currently accepted ideas for generating the corresponding radio emissions at Earth and Jupiter. At Earth it is now widely believed that continuum radiation is generated by mode conversion from electrostatic waves generated by low energy electrons near the plasmapause and in the outer regions of the magnetosphere. This general mechanism has a long history of experimental and theoretical development(5,7,15,16), including the observation of enhanced radiation intensities when low energy electrons are injected into the magnetosphere(17). The electrostatic wave involved is an electrostatic mode which occurs near the upper hybrid resonance frequency, $f_{UHR} = \sqrt{f_p^2 + f_g^2}$. One of the specific conditions which must be satisfied for this mode to be unstable is that $(n + 1/2)f_g \approx f_{UHR}$(6,7,18). The physical situation which occurs in the Earth's magnetosphere is illustrated in Fig. 6, which shows a representative radial profile of f_{UHR} and f_g near the plasmapause. Intense electrostatic emissions occur whenever f_{UHR} crosses a half-integral harmonic of f_g (shown by the dashed lines). Recent measurements by Kurth et al.(13) demonstrate that the electrostatic emissions are directly converted to electromagnetic radiation with little or no frequency shift. The radiation is believed to be generated in the free space (L,O) mode. The resulting radio emission spectrum therefore consists of a series of lines with a frequency spacing characteristic of the electron gyrofrequency in the source region. Kurth et al.(13) have proposed that the Jovian nKOM radiation can be explained by essentially this same mechanism, with the density gradient in the outer region of the Io plasma torus playing the same role as the plasmapause at the Earth. Large plasma density gradients are an essential element of some theories for the electrostatic to electromagnetic mode conversion(19).

IV. INTERPRETATION OF THE SATURN OBSERVATIONS

Because of the close observational similarities between the narrowband radio emissions at Earth, Jupiter and Saturn, it seems likely that the electrostatic to electromagnetic mode conversion mechanism described in the previous section can also account for the narrowband emissions at Saturn. This viewpoint is strengthened by the fact that intense upper hybrid waves are observed at Saturn in the region where the narrowband electromagnetic radiation is most intense (see Fig. 1). Also, at Saturn the narrowband electromagnetic emissions are known to be propagating in the free space (L,O) mode, which is the favored mode for mode conversion. The principal uncertainties which remain have to do with the exact source location and the physical processes which lead to the generation of intense electrostatic waves.

Unfortunately, because of the absence of any appreciable tilt in the magnetic dipole axis of Saturn, it has not been possible to utilize geometry dependent propagation effects to help determine the source location. Probably the best clue to the source position is the frequency spectrum. If the mode conversion model is correct then the frequency spacing between the lines gives the electron gyrofrequency in the source region. From Fig. 3 it is evident that several half-integral harmonic frequency spacings can be identified in the radio emission spectrum. If we identify the main emissions at 6.0 and 9.7 kHz as a harmonic pair, then the gyrofrequency is 3.7 kHz. A second set of lines can be identified at 3.1, 4.7 and 6.1 kHz, which gives a gyrofrequency of 1.50 kHz. Finally, a third set of lines can be identified at 8.7, 9.6, 10.4 and 11.4 kHz, which gives a gyrofrequency of 870 Hz. Assuming that the source is located near the equatorial plane (as at Earth and Jupiter) the corresponding radial distances for these gyrofrequencies are 5.4, 7.3 and 8.8 R_S, based on a dipole moment of 0.21 gauss R_S^3[3]. Since the emission frequency is not necessarily at a half-integral harmonic and the source may not be located exactly at the magnetic equator these radial distances should be regarded as only a rough indication of the source position. It is interesting to note that the radial distances obtained are in the vicinity of the moons Tethys, Dione and Rhea. Since at least one of Saturn's moons, Dione, is already thought to play an important role in controlling the kilometric radio emissions from Saturn[1,20,21], this comparison strongly suggests that one or more of these moons is involved in generating the narrowband electromagnetic emissions.

The most likely way a moon could be controlling nonthermal radio emission processes in the inner region of Saturn's magnetosphere is by injecting plasma, much as Jupiter's moon, Io, controls radio emissions by injecting plasma into the Jovian magnetosphere. Already evidence exists from the Pioneer 11 and Voyager 1 plasma instruments[4,22] suggesting that plasma production by Tethys and Dione may be the source of the extended disk-shaped plasma sheet observed near the equatorial plane of Saturn. If nonequilibrium processes associated with the plasma injection are responsible for the narrowband electromagnetic emissions, then the analogies with Earth and Jupiter would suggest that the source is associated with a steep plasma density gradient near the edge of the plasma sheet. Fig. 8(A) and 8(B) show two extreme models which have been considered for the source positions. In Fig. 8(A) the source is located near the north-south boundaries of the plasma sheet, and in Fig. 8(B) the source is located near the sharp field-aligned inner boundary of the plasma sheet described by Bridge et al.[4].

If the source is located at the north-south boundary of the plasma sheet, as in Fig. 8(A), then the source would have to be tightly confined to a specific L-shell to produce the narrow emission spectrum. Such a localization could, for example, be cause by a field-aligned current system flowing along the Dione L-shell. A source located on the Dione L-shell at the north-south boundary of the plasma sheet 2 R_S from the equatorial plane would have an electron gyrofrequency in close agreement with the 3.7 kHz major frequency spacing evident in Fig. 3. On the other hand, if the source is located along a field-aligned inner boundary of the plasma sheet, as in Fig. 8(B), then the narrowband characteristic of the source would be easily explained since the gyrofrequency is, to first order, constant along the magnetic field line near the equator. This situation would be closely analogous to the generation of continuum radiation near the plasmapause at the Earth, except that the decreasing density gradient is facing toward rather than away from the planet. It is interesting to note that the 7.3 R_S radial distance identified for the 1.5 kHz frequency spacing in Fig. 3 is in very close agreement with field-aligned boundary identified by Bridge et al.[4] at L=7. This boundary occurs slightly beyond the orbit of Dione. Because of the uncertainties which still exist concerning the plasma density distribution in the inner region of the magnetosphere, it is probably too early to try to decide which of these, or other similar models, can best account for the characteristics of the narrowband emissions.

V. CONCLUSION

The Voyager 1 flyby of Saturn has revealed the presence of a series of narrowband electromagnetic emissions originating from the inner region of the magnetosphere in the frequency range from 3 to 30 kHz. At closest approach the broadband electric field strength of these emissions is about 50 $\mu V\ m^{-1}$, which corresponds to a total radiated power of about 2.5×10^6 watts, assuming an isotropic source. Although this power is small compared to the power radiated by Saturn at kilometric wavelengths, $\sim 10^8$ to 10^9 watts [20], these emissions are still of considerable interest because of the close similarity to narrowband radio emissions from Earth and Jupiter, and because of the possible information these emissions may be able to provide on nonequilibrium processes in the magnetosphere of Saturn.

On the basis of comparisons with similar narrowband emissions in the Earth's magnetosphere, a strong case can be made that these emissions are produced by mode conversion from electrostatic waves near the upper hybrid resonance. Because essentially the same type of narrowband radiation has been observed at Earth, Jupiter and Saturn, it appears that this radio emission mechanism may be of universal importance. This same mechanism has also been proposed to explain certain types of solar radio emissions[23]. Although the basic mechanism has been identified, the conditions under which the radiation can occur are poorly understood. Observations at all three planets suggest that distinct "hot spots" occur, usually associated with a plasma density gradient, from which the radiation is preferrentially emitted. The association with a plasma density gradient is probably a requirement of the mode conversion process, as suggested by Jones[19]. Unfortunately, the requirements for generating the electrostatic waves are complicated and not completely understood. The generation of these waves probably involves the presence of large fluxes of low energy (100 eV to 1 keV) electrons with a pronounced loss-cone or $\partial f/\partial v_\perp > 0$ feature and a suitably large cold to hot electron density ratio[18,24,25]. Hopefully, future studies of these emissions at Earth and by Voyager 2 at Saturn will further clarify the physical conditions required for generating the electromagnetic radiation.

One final puzzle is worth noting. At Saturn no evidence was found for trapped continuum radiation comparable to the continuum radiation trapped in the low density magnetospheric cavities of Earth and Jupiter. Since the Voyager 1 plasma measurements[4] demonstrate the existence of a low density cavity at Saturn with an electron plasma frequency well below the solar wind plasma frequency, it is surprising that no radiation is trapped in this cavity. Apparently the radio emission source at Saturn does not extend down to sufficiently low frequencies to illuminate the cavity. The reasons for this marked difference in the radio emission spectrum are not understood.

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FIGURE CAPTIONS

Figure 1 The plasma wave electric field intensities in the region near closest approach. The narrowband electromagnetic emissions are confined to the low density region outside of the plasma sheet at $f > f_p$ (dashed lines). The plasma sheet is entered at about 0000 to 0100, as the spacecraft approaches the magnetic equator (see the sketch of the trajectory).

Figure 2 A frequency-time spectrogram showing that the electromagnetic radiation at $f > f_p$ in Fig. 1 consists of a series of narrowband emissions.

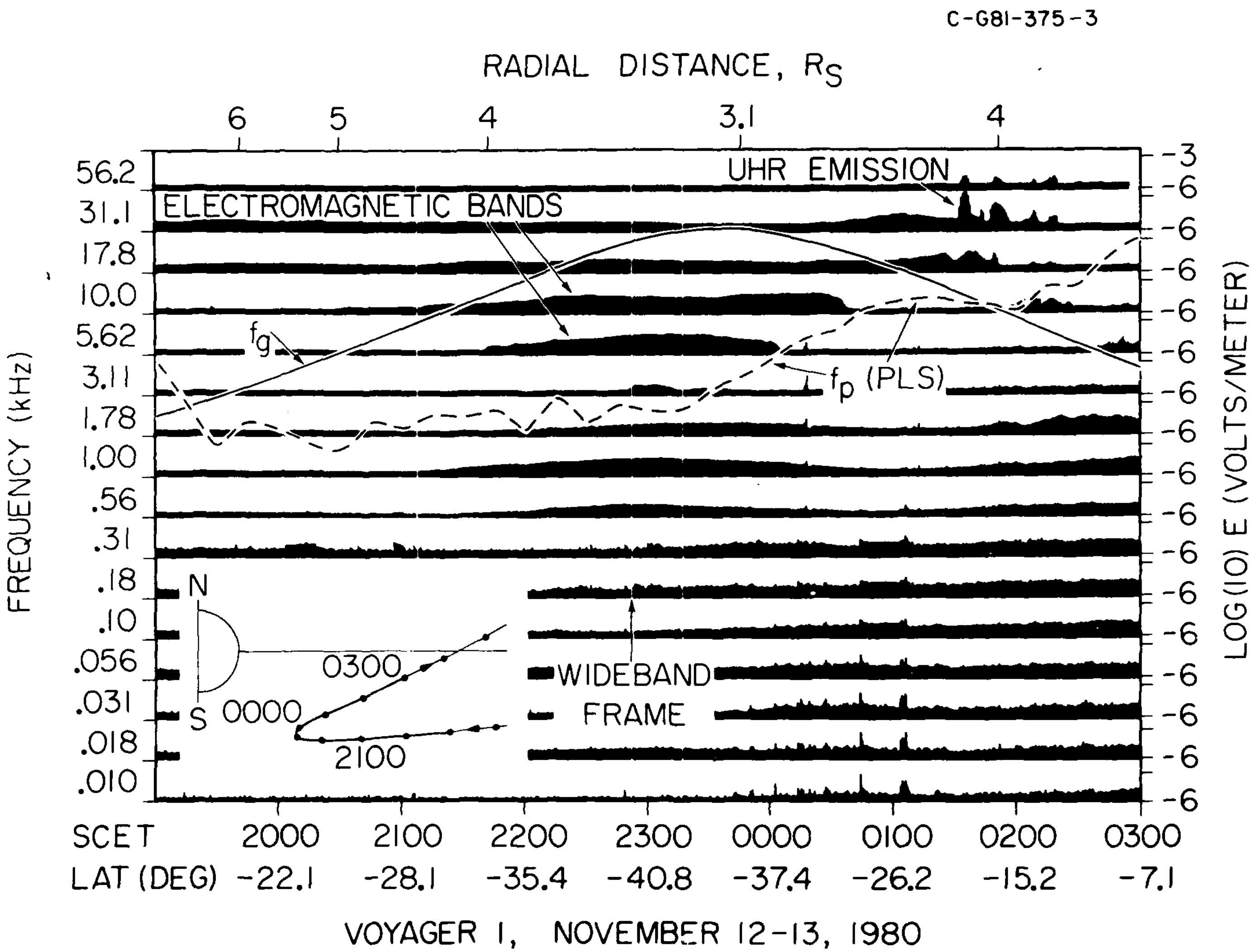
Figure 3 A detailed frequency spectrum of the emission in Fig. 2, showing the occurrence of numerous bands with approximately harmonic frequency spacings.

Figure 4 A series of frequency-time spectrograms obtained in various regions of the magnetosphere demonstrating that the band at ~ 5 to 6 kHz can be detected over a large range of radial distances. This series of observations provides the best evidence that the noise consists of freely propagating electromagnetic radiation.

Figure 5 A summary of all the regions where narrowband electromagnetic emissions were observed. The black bands indicate detections in the 16-channel spectrum analyzer data, and the circles correspond to the wideband spectrograms shown in Fig. 4.

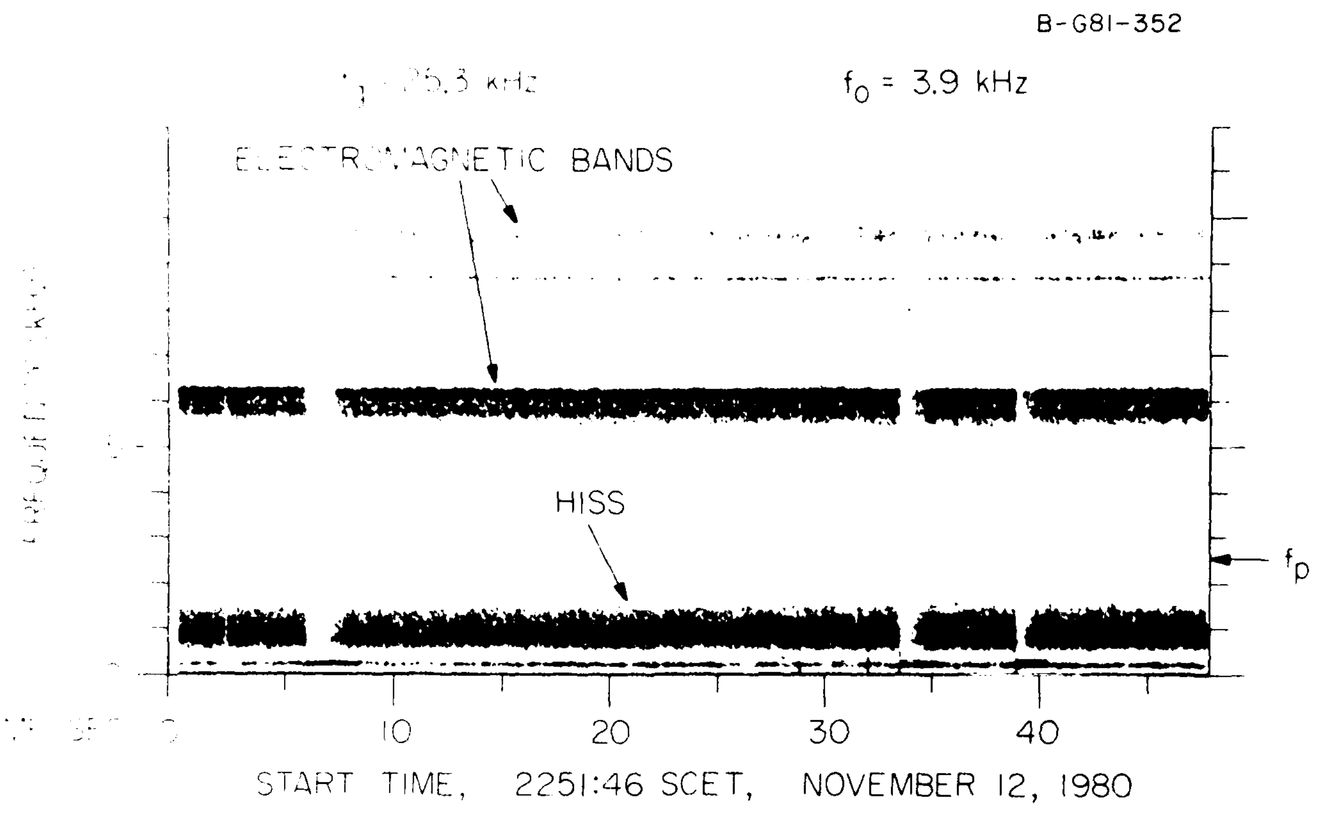
Figure 6 A model illustrating the mechanism for generating narrowband electromagnetic emissions (continuum radiation) in the Earth's magnetosphere. Intense electrostatic upper hybrid resonance (UHR) emissions at $(n + 1/2)f_g \simeq f_{UHR}$ are believed to be converted to electromagnetic emissions in regions with steep plasma density gradients, such as near the plasmapause.

Figure 7 Two possible models for generating narrowband electromagnetic emissions in Saturn's magnetosphere. In model (A) the emissions are generated at the density gradient which exists at the north and south boundaries of the plasma sheet, and in model (B) the emissions are generated along the field-aligned boundaries of the plasma sheet reported by Bridge et al.[4].



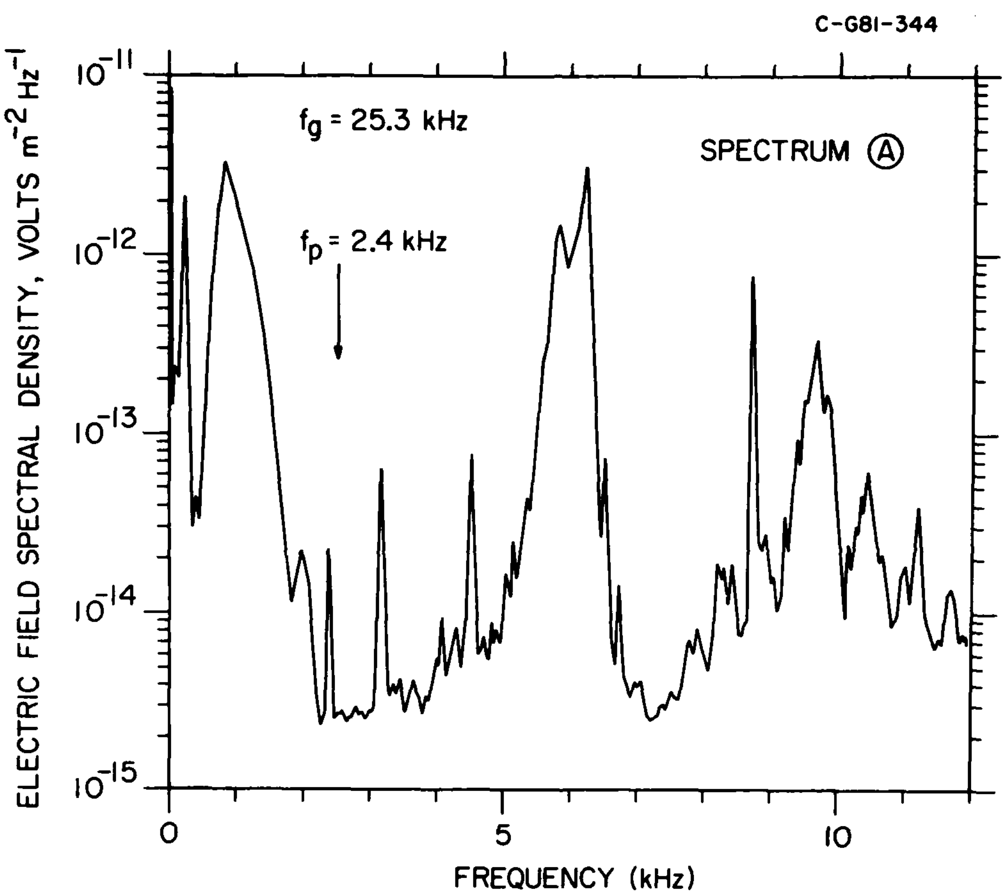
C-G81-375-3
RADIAL DISTANCE, R_S
6
5
4
3.1
4
UHR EMISSION
ELECTROMAGNETIC BANDS
56.2
31.1
17.8
10.0
5.62
3.11
1.78
1.00
.56
.31
.18
.10
.056
.031
.018
.010
FREQUENCY (kHz)
f_g
f_p (PLS)
N
S
0300
0000
2100
WIDEBAND
FRAME
-3
-6
LOG(10) E (VOLTS/METER)
SCET 2000 2100 2200 2300 0000 0100 0200 0300
LAT (DEG) -22.1 -28.1 -35.4 -40.8 -37.4 -26.2 -15.2 -7.1
VOYAGER 1, NOVEMBER 12-13, 1980

Figure 1



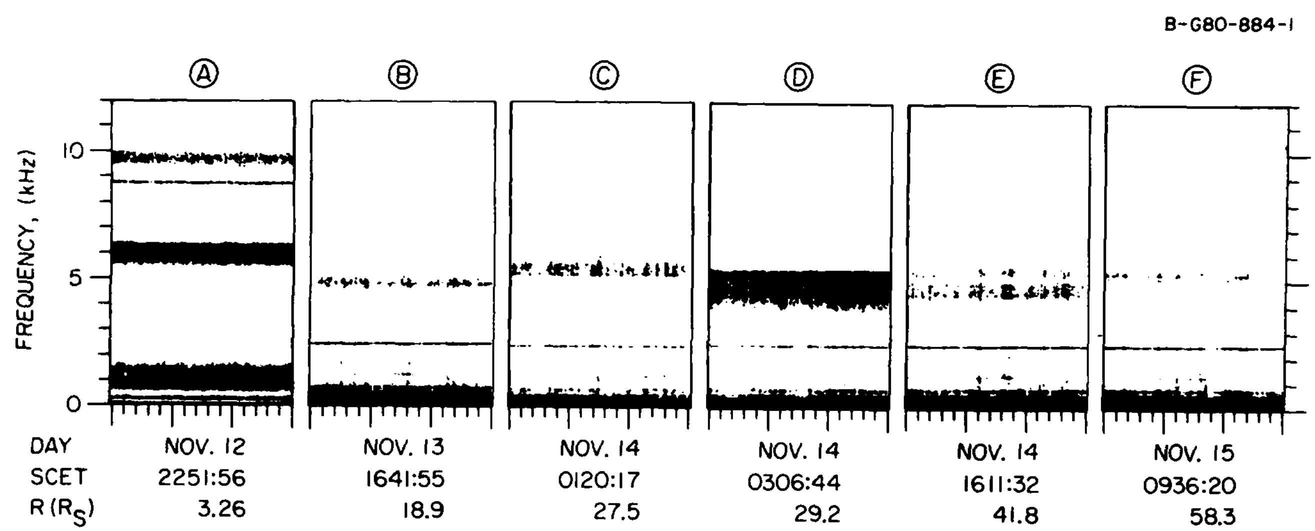
B-G81-352
f_o = 3.9 kHz
ELECTROMAGNETIC BANDS
HISS
f_p
0
10
20
30
40
START TIME, 2251:46 SCET, NOVEMBER 12, 1980

Figure 2



START TIME, 2251:58 SCET, NOVEMBER 12, 1980
AVERAGING INTERVAL, 18 SEC.

Figure 3



B-G80-884-1
A
B
C
D
E
F
FREQUENCY, (kHz)
10
5
0
DAY
SCET
R (R_S)
NOV. 12
2251:56
3.26
NOV. 13
1641:55
18.9
NOV. 14
0120:17
27.5
NOV. 14
0306:44
29.2
NOV. 14
1611:32
41.8
NOV. 15
0936:20
58.3

Figure 4

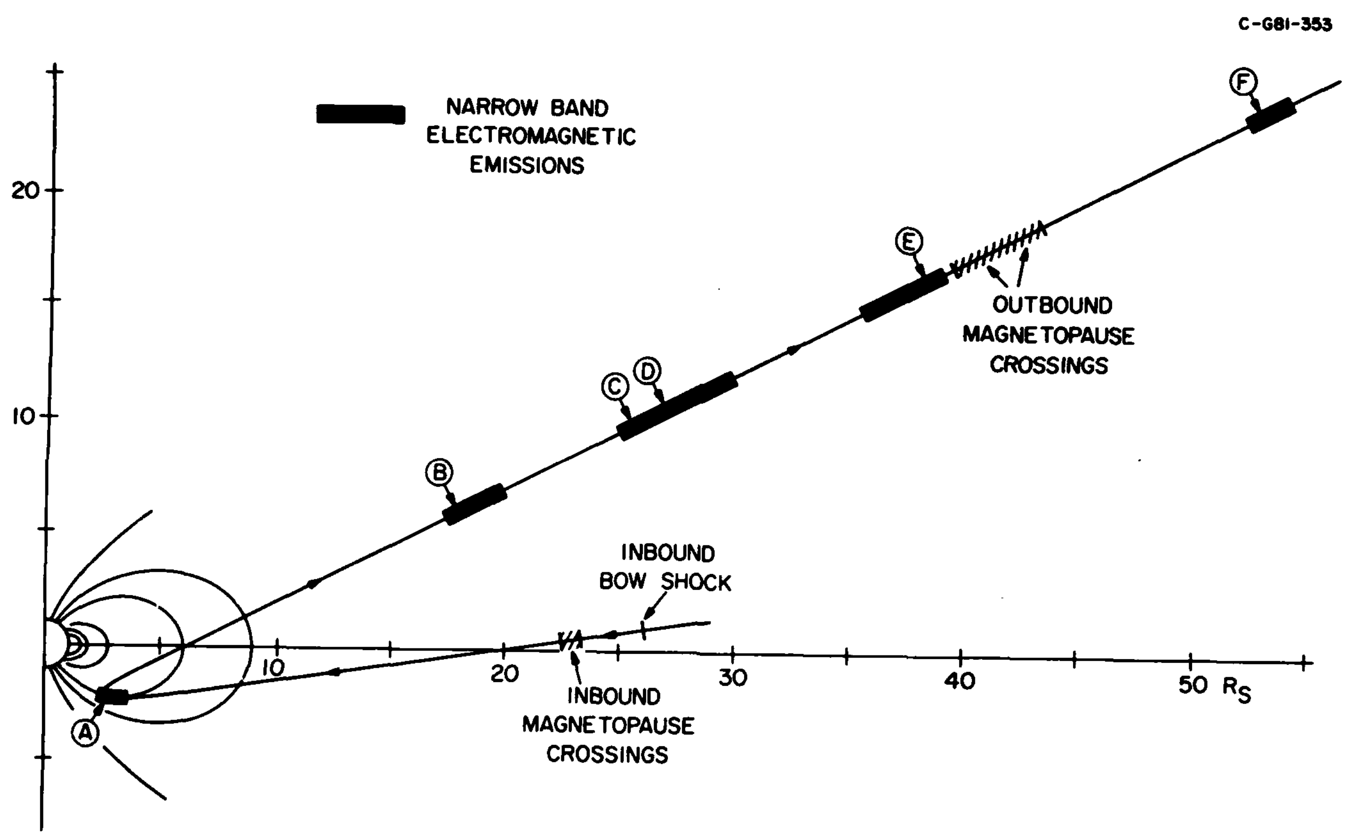

C-G81-353
NARROW BAND
ELECTROMAGNETIC
EMISSIONS
20
10
A
B
C
D
E
F
OUTBOUND
MAGNETOPAUSE
CROSSINGS
INBOUND
BOW SHOCK
INBOUND
MAGNETOPAUSE
CROSSINGS
10
20
30
40
50 R_S

Figure 5

A-G81-355

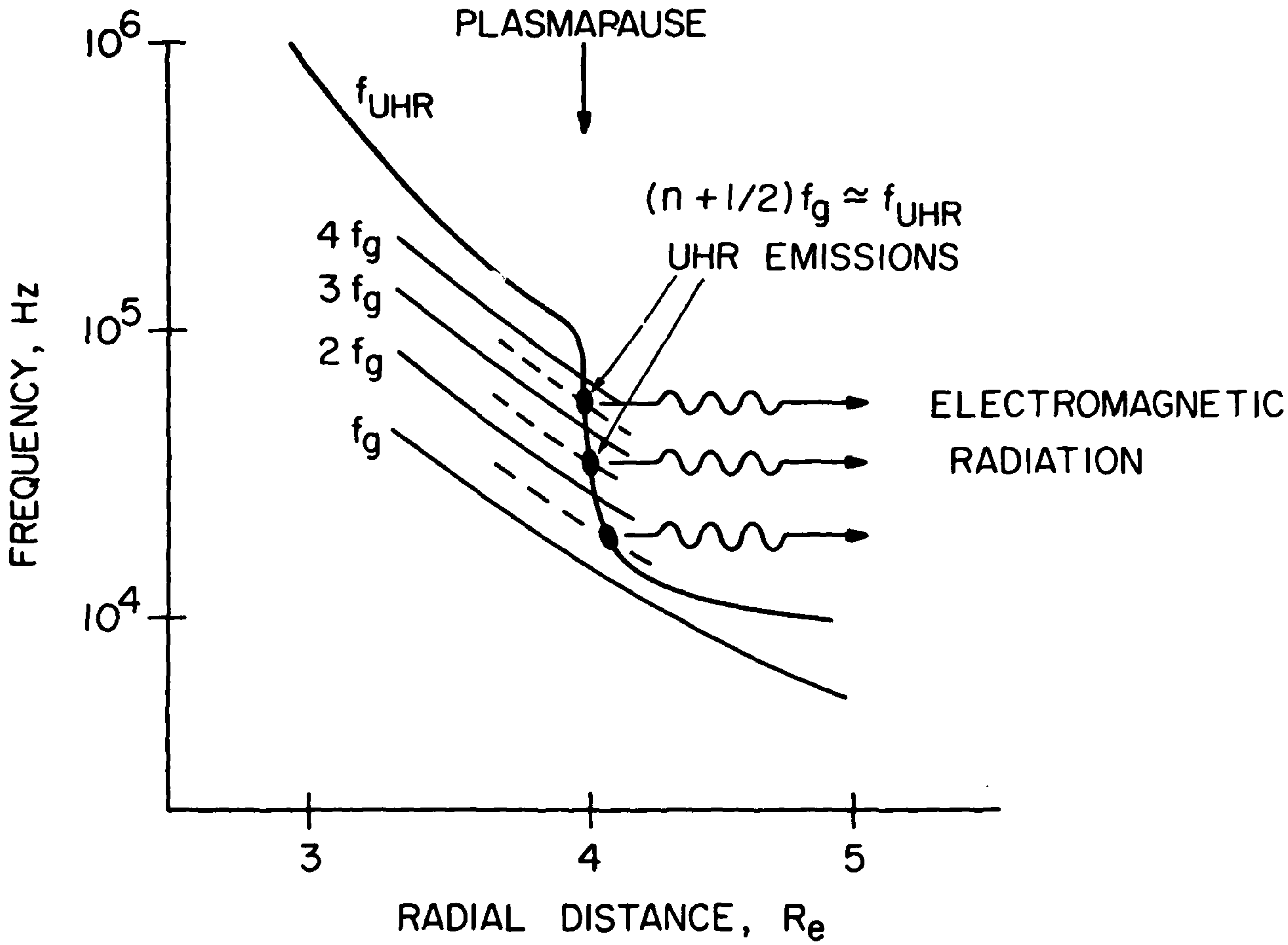


Figure 6

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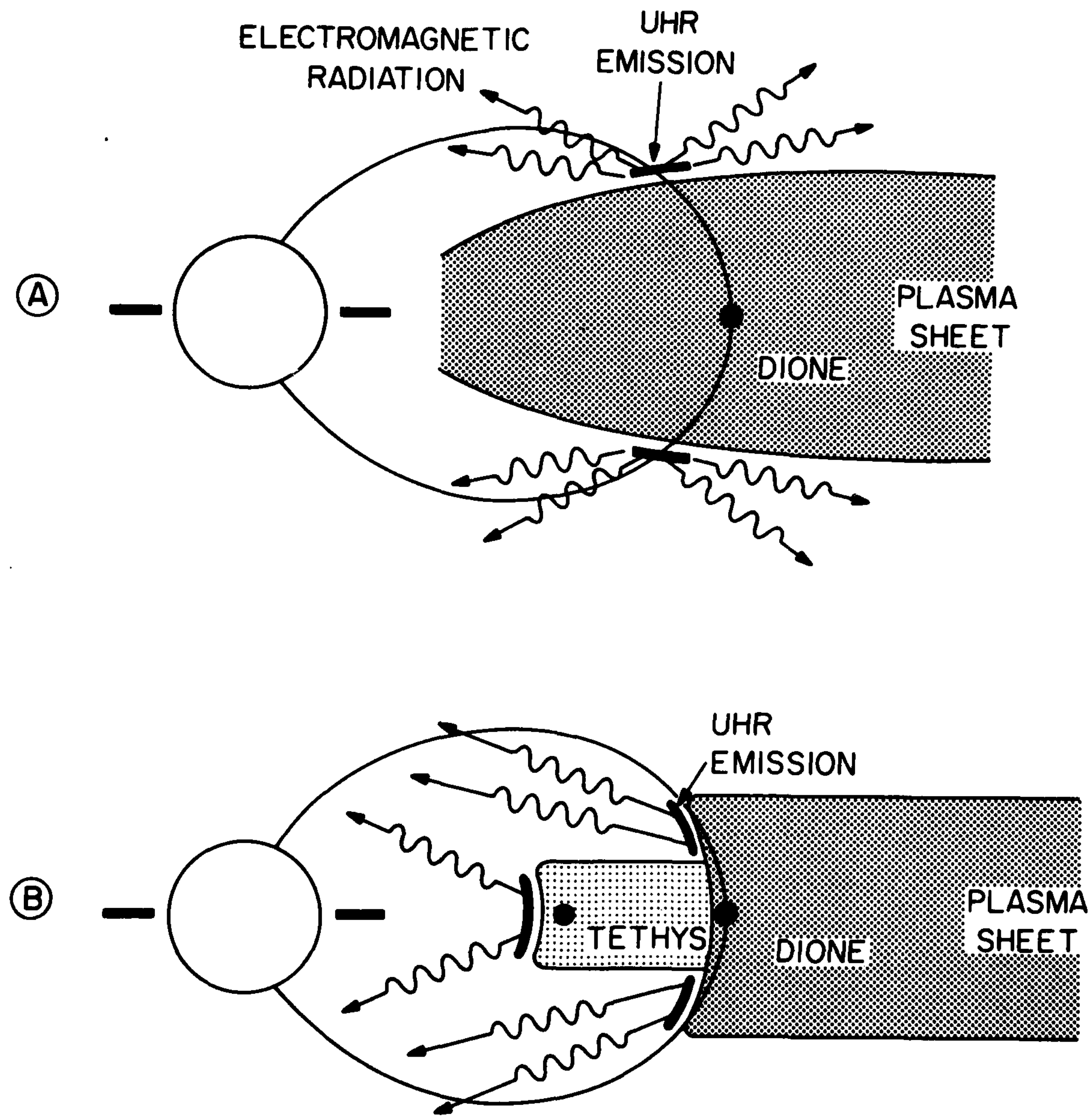

Figure 7