



La Jolla International School of Physics
The Institute for Advanced Physics Studies

RESEARCH TRENDS IN PHYSICS

Nonlinear Space Plasma Physics

R. Z. Sagdeev
Editor-in-Chief

AIP

American Institute of Physics

New York

Nonlinear Radio Emission Processes in Planetary Magnetospheres

D.A. Gurnett

Department of Physics and Astronomy
The University of Iowa
Iowa City, IA 52242

ABSTRACT

Rapid advances have been made in the observations and understanding of radio emissions from planetary magnetospheres. It is now known that there are two primary types of coherent planetary radio emissions: (1) cyclotron maser radiation and (2) mode conversion radiation. In recent years the primary emphasis has been on linear analyses of these radio emission mechanisms. In this paper we review evidence of nonlinear processes in the generation of planetary radio emissions. In the case of the cyclotron maser radiation, the spectrum shows an extremely complex fine structure, including narrowband emissions with extremely rapid temporal variations, and emission lines at harmonics of the ion cyclotron frequency. This fine structure strongly suggests that nonlinear processes, such as particle trapping, play an important role in the generation of this radiation. For the mode conversion radiation, which involves the conversion of electrostatic wave energy to electromagnetic radiation, recent estimates show that linear conversion has an efficiency that is three orders of magnitude too small to explain the observed intensities. A nonlinear mode conversion processes, such as wave-wave coupling, must therefore be responsible for generating the radiation. However, at the present time the exact mechanism involved has not been identified.

I. INTRODUCTION

Plasma waves in planetary magnetospheres can be divided into two types, those that are internally confined, and those that can escape. The waves that can escape to great distances from the planet are usually called radio emissions. These waves are necessarily electromagnetic, since electrostatic waves always have substantial damping and cannot propagate great distances. The first evidence of radio emissions from planetary magnetospheres was obtained by Burke and Franklin [1955] who discovered strong bursty emissions from Jupiter at a frequency of 22 MHz. Since this early discovery, radio emissions of various types have been detected from the magnetospheres of five planets: Earth, Jupiter, Saturn, Uranus, and Neptune. At the outer planets most of these observations have been obtained from the Voyager spacecraft. For a review of planetary radio emissions, including a discussion of the Voyager results, see Gurnett [1992].

If we omit synchrotron radiation, which is not a collective plasma process, it appears that there are only two basic mechanisms involved in the generation of magnetospheric radio emissions. These mechanisms are (1) the cyclotron maser instability, and (2) mode-conversion from electrostatic waves. Both of these mechanisms can generate intense radio emissions, much more intense than incoherent processes such as synchrotron radiation, and both involve nonlinear interactions, not all of which are adequately understood. In this paper we describe various observations that indicate nonlinear processes play an important role in the generation of planetary radio emissions.

II. CYCLOTRON MASER RADIATION

The cyclotron maser mechanism is a process by which electromagnetic radiation is directly generated in one or both of the two free space modes via a loss-cone type of free energy source. Cyclotron maser radiation has been observed from the magnetospheres of Earth, Jupiter, Saturn, Uranus, and Neptune. A comparison of the spectrums of cyclotron maser radiation from these five planets is shown in Figure 1. Although Jupiter is by far the most powerful radio emitter, the primary developments in the theory and understanding of the cyclotron maser mechanism have come from terrestrial radio emission studies, where the radiation is called auroral kilometric radiation. Although first discovered by Benediktov et al. [1965], the main advances in the understanding of auroral kilometric radiation occurred in the 1970s as detailed measurements became available from space-borne radio receivers. Among the early studies, Gurnett [1974] showed that the radiation was generated at altitudes of about $1R_E$ along the auroral zone field lines and was closely associated with the energetic electrons responsible for the auroral light emissions. A sketch of the source region and some typical ray paths are shown in Figure 2. The frequency range of the auroral kilometric radiation extends from 100 to 500 kHz and the peak power can be as high as 10^9 Watts. This power is nearly 1% of the total electrical power dissipated in the auroral zones. The high radiated power level means that the Earth is a powerful radio emitter, comparable in many respects to the giant planets (see Figure 1). Auroral kilometric radiation is strongly polarized, with a right-hand polarization relative to the magnetic field in the source region, and the emission frequency is very close to the electron

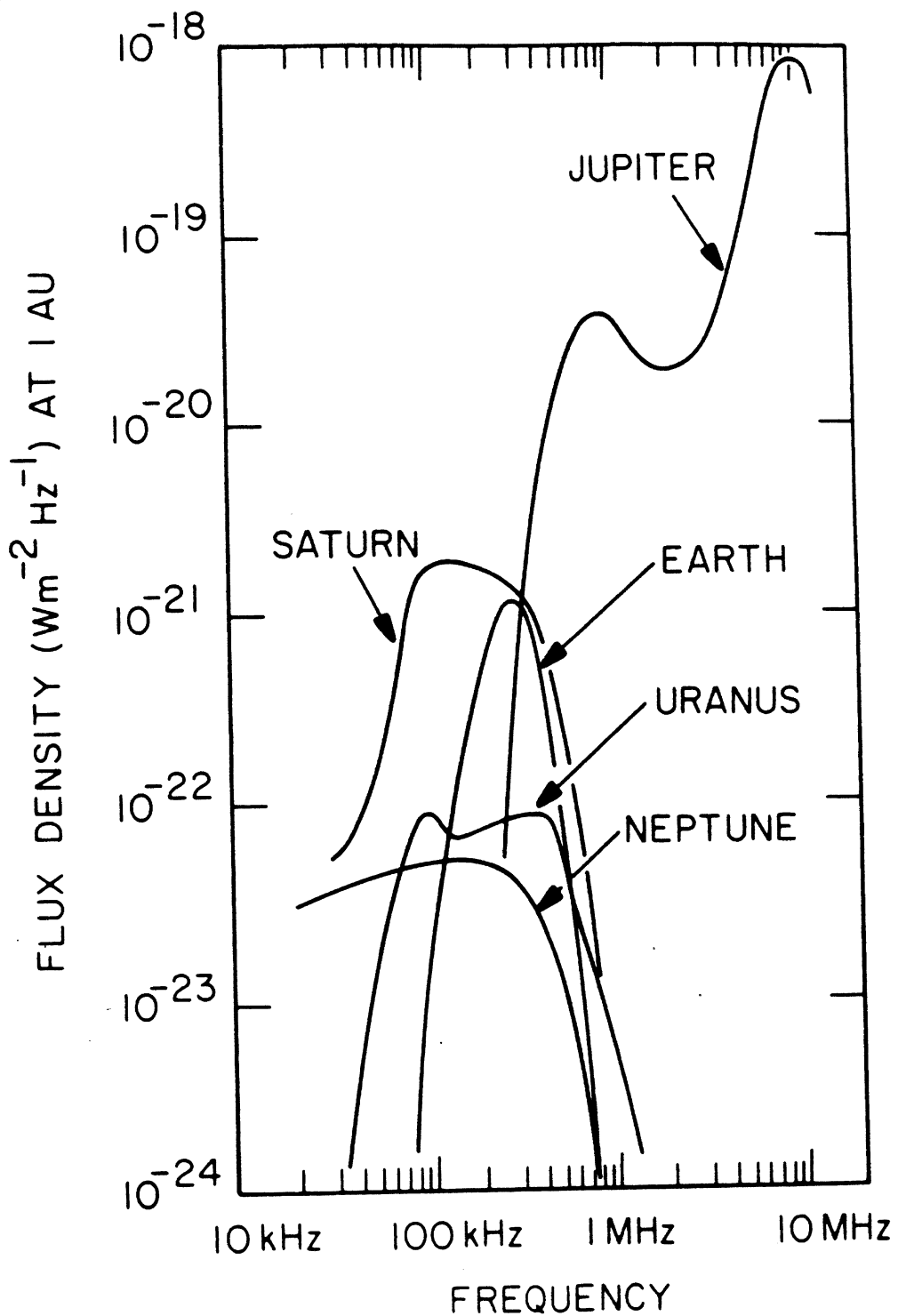


Figure 1

A comparison of the radio emission spectrums of five planets that are known to be intense radio emitters.

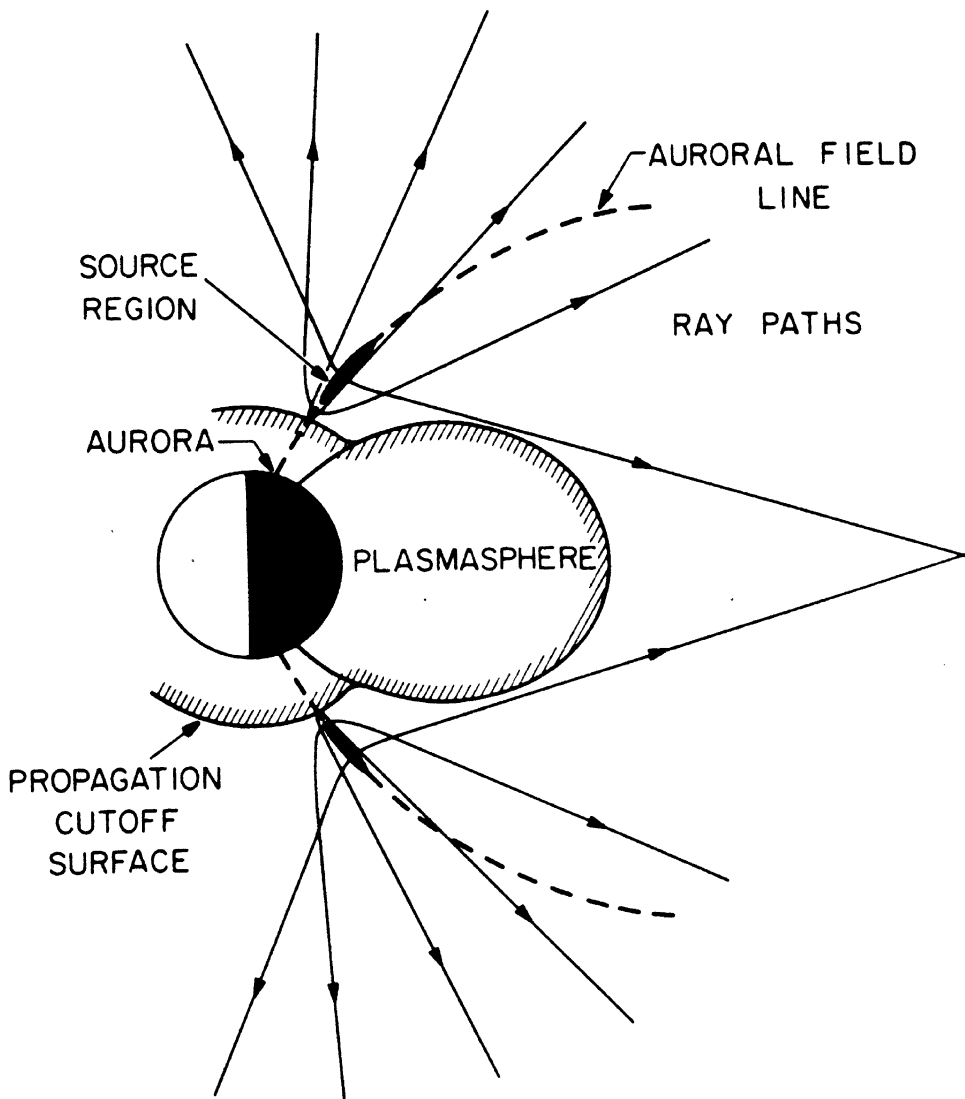


Figure 2

Terrestrial auroral kilometric radiation is generated by the cyclotron maser mechanism at altitudes of about $1 R_E$ along the auroral field lines. The free energy for this radiation comes from the loss-cone in the auroral electron distribution.

cyclotron frequency. These characteristics, high radiation efficiency, right-hand polarization, and generation near the electron cyclotron frequency, are the identifying features of the cyclotron maser mechanism.

Shortly after the basic characteristics of the terrestrial auroral kilometric radiation became known, Wu and Lee [1979] developed the mechanism now known as the cyclotron maser instability. This theory used the loss-cone in the energetic (1 to 10 keV) auroral electron distribution as the free energy source for generating the radiation. A unique aspect of Wu and Lee's theory was the fact that relativistic effects must be considered in the cyclotron resonance condition, even though the electron energies are non-relativistic. The relativistic cyclotron resonance condition was also previously discussed by Melrose [1973]. For the cyclotron maser instability to have a positive growth rate several conditions must be satisfied: (1) the electron distribution function must have a loss-cone, (2) the plasma frequency must be well below the electron cyclotron frequency ($f_p \ll f_c$), (3) the wave normal angle with respect to the magnetic field must be large (i.e., near 90°), and (4) the wave frequency must be near the electron cyclotron frequency. The theory also predicts that the strongest radiation should be produced in the right-hand polarized extraordinary (R-X) mode, although under some circumstances left-hand polarized ordinary (L-O) mode radiation can also be generated. This prediction is in agreement with observations, which show that although the right-hand polarized component is dominant, occasionally a left-hand component is observed [Mellott et al., 1984].

Based on the success of the cyclotron maser theory for explaining the terrestrial auroral kilometric radiation, this mechanism is now widely accepted as the explanation for the intense, strongly polarized radio emissions observed at the outer planets. Although the linear theory is

considered highly successful, several aspects of the observations cannot be addressed with a linear theory. Most striking is the fine structure. Using wideband measurements, Gurnett et al. [1979] discovered that the spectrum is not smooth and continuous, as one might expect from a simple linear amplification theory, but rather has an extremely complex structure consisting of many narrowband tones, some of which display temporal variations on time scales as short as a fraction of a second. An example of a high resolution frequency-time spectrogram illustrating some of these effects is shown in Figure 3. Somewhat similar fine scale structure effects have also been observed in the spectrum of Jovian decametric radiation [Carr et al., 1983], but on even shorter time scales (millisecond), suggesting that these fine structure effects are universal. Another remarkable feature is the discovery by Grabbe [1982] that the auroral kilometric radiation sometimes has imbedded harmonic emission lines with a frequency spacing that corresponds to the proton cyclotron frequency in the source region. A spectrum illustrating this cyclotron harmonic structure is shown in Figure 4.

Complex spectral features, such as illustrated in Figures 3 and 4, are strongly indicative of nonlinear effects. In particular, the short duration bursts, as in Figure 3, suggest that some nonlinear effect, such as trapping of resonant particles in the high frequency wave field, acts to saturate the instability. Somewhat similar fine structure effects have been observed for many years in discrete whistler-mode emissions and are widely regarded as being due to the trapping of resonant electrons [Helliwell and Crystal, 1973; Karpman et al., 1974; Matsumoto and Omura, 1981; Nunn, 1986]. Of course, whistler-mode emissions propagate in the whistler mode rather than in one of the free space modes. Nevertheless, there are close similarities. Whistler-mode emissions are generated by a cyclotron resonance interaction somewhat similar to the

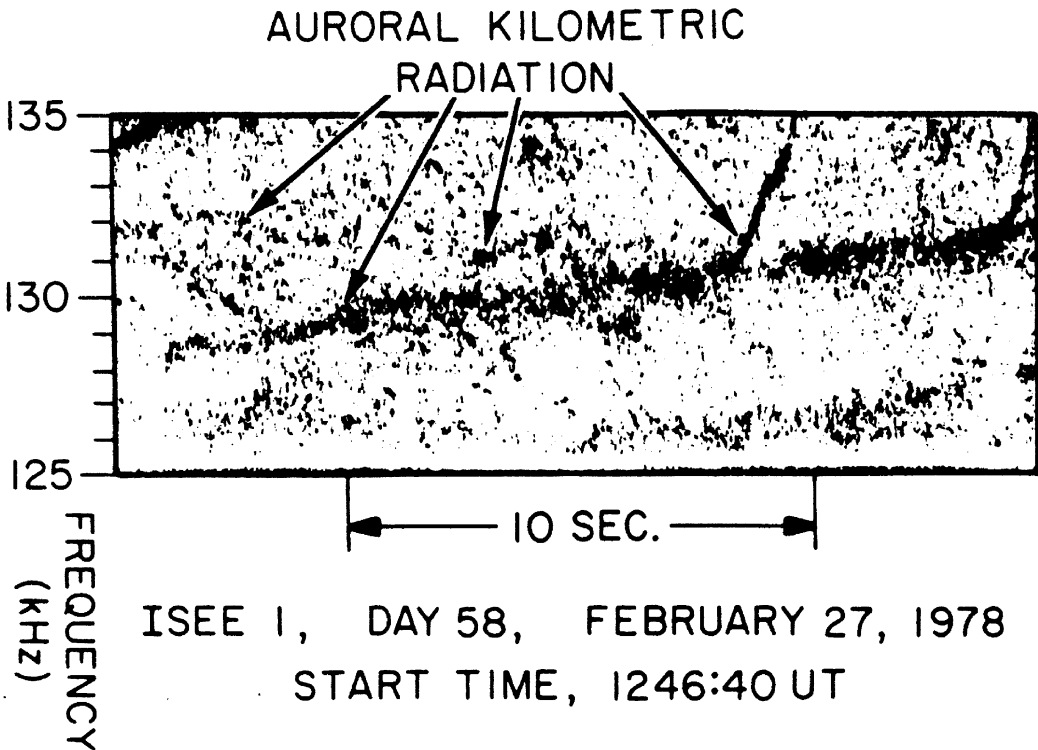


Figure 3

A high resolution frequency time spectrogram showing the fine structure of the auroral kilometric radiation. The extremely complex fine structure of this radiation strongly suggests that a nonlinear saturation process limits the growth of the cyclotron maser instability. Note that the frequency scale is greatly expanded to show the fine structure.

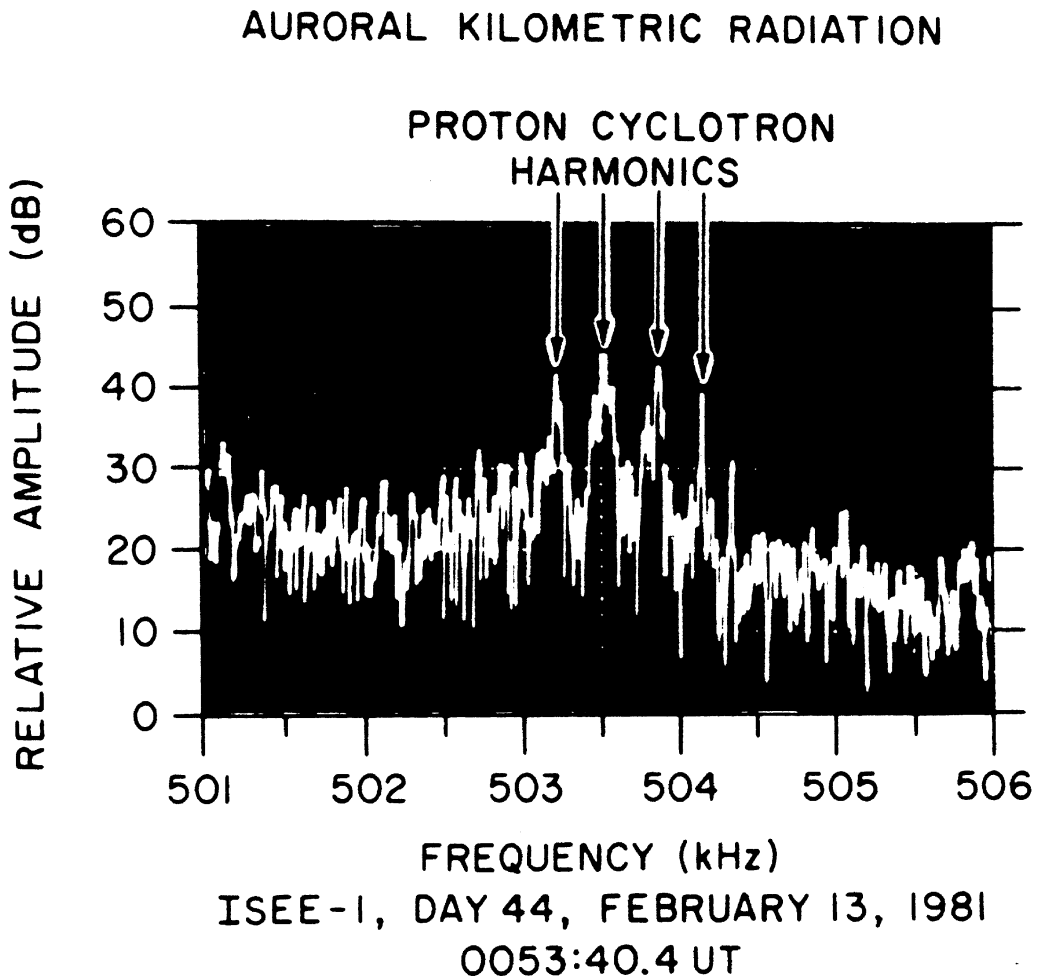


Figure 4

An example of proton cyclotron harmonics in the auroral kilometric radiation spectrum. The harmonic structure suggests that the cyclotron maser radiation is involved in non-linear interactions with low frequency electrostatic ion cyclotron waves.

cyclotron maser instability, and derive their free energy from a loss-cone in the resonant electron distribution. Therefore, it is not surprising that both types of emissions display somewhat similar fine structure effects.

The presence of ion cyclotron harmonics in the auroral kilometric radiation spectrum provides added evidence of nonlinear effects. These harmonic bands are most likely produced by a wave-wave interaction between the high frequency cyclotron maser instability and a low frequency ion cyclotron mode. Interactions of this type are entirely plausible, since electrostatic ion cyclotron waves are frequently observed [Kintner et al., 1978] in the same region that the auroral kilometric radiation is generated.

Relatively little theoretical attention has been given to the fine structure of cyclotron maser radiation. Calvert [1982], using a wave feedback mechanism similar to a laser, has proposed a model to explain drifting narrowband features in the spectrum of auroral kilometric radiation. His model is essentially linear and most likely cannot account for the very complex temporal variations that are often observed. Melrose [1986] has attempted to apply the particle trapping mechanism developed by Helliwell for whistler-mode emissions to the fine structure of the terrestrial auroral kilometric radiation and the Jovian kilometric radiation. His model can account for several important characteristics of the observed cyclotron maser radiation, such as the extremely narrow bandwidths. However, certain other key characteristics, such as the frequency drift rates, differ somewhat from the observations. Various computer simulations have also been performed to investigate the nonlinear aspects of the cyclotron maser instability [Wu, 1985; Pritchett and Strangeway, 1985; Winglee and Pritchett, 1986]. However, none of the computer simulations have specifically addressed the origin of the complex fine structure.

III. MODE CONVERSION RADIATION

Mode conversion radiation is generated whenever the energy of internally trapped electrostatic waves is converted to escaping electromagnetic radiation. In planetary magnetospheres electrostatic waves near the upper hybrid resonance frequency, $f_{\text{UHR}} = (f_c^2 + f_p^2)^{1/2}$, are the primary type of wave involved in this mode conversion process. The basic mechanism is shown in Figure 5, which illustrates the generation of continuum radiation in the Earth's magnetosphere [Gurnett, 1975; Gurnett and Frank, 1976; Kurth et al., 1981], also sometimes called myriametric radiation [Jones, 1982]. Somewhat similar types of radio emission have also been observed at Jupiter [Warwick et al., 1979; Birmingham et al., 1981; Gurnett et al., 1983], Saturn [Gurnett et al., 1981], and possibly at Uranus [Kurth et al., 1990a] and Neptune [Kurth et al., 1990b]. At Earth it is known that low energy electrons injected into the magnetosphere generate intense electrostatic waves near half-integral harmonics of the electron cyclotron frequency. These waves are particularly intense near the upper hybrid resonance frequency (i.e., when $(n + 1/2)f_c = f_{\text{UHR}}$), and are known as upper hybrid resonance (UHR) waves. Upper hybrid resonance waves are observed to decay into electromagnetic radiation, either in narrow bands, or in the presence of spatial gradients into an essentially continuous spectrum (hence the term "continuum radiation"). A high resolution frequency-time spectrogram illustrating the conversion of locally generated UHR waves into escaping electromagnetic radiation is shown in Figure 6. The free energy source for the UHR waves is believed to be a loss-cone anisotropy in the low energy (10 to 100eV) electron distribution [Abdalla and Kennel, 1978; Rönmark et al., 1978]. Highly

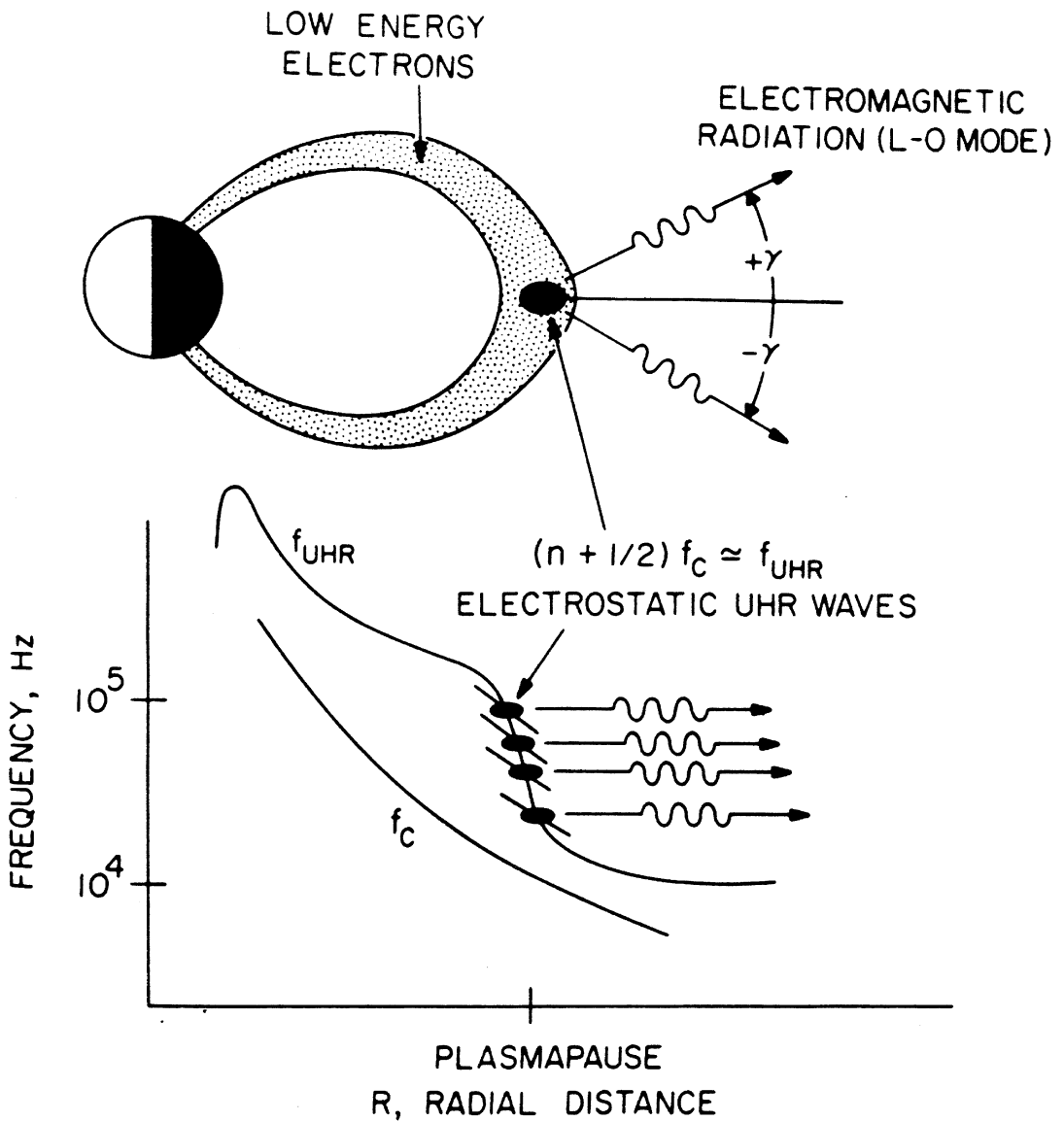
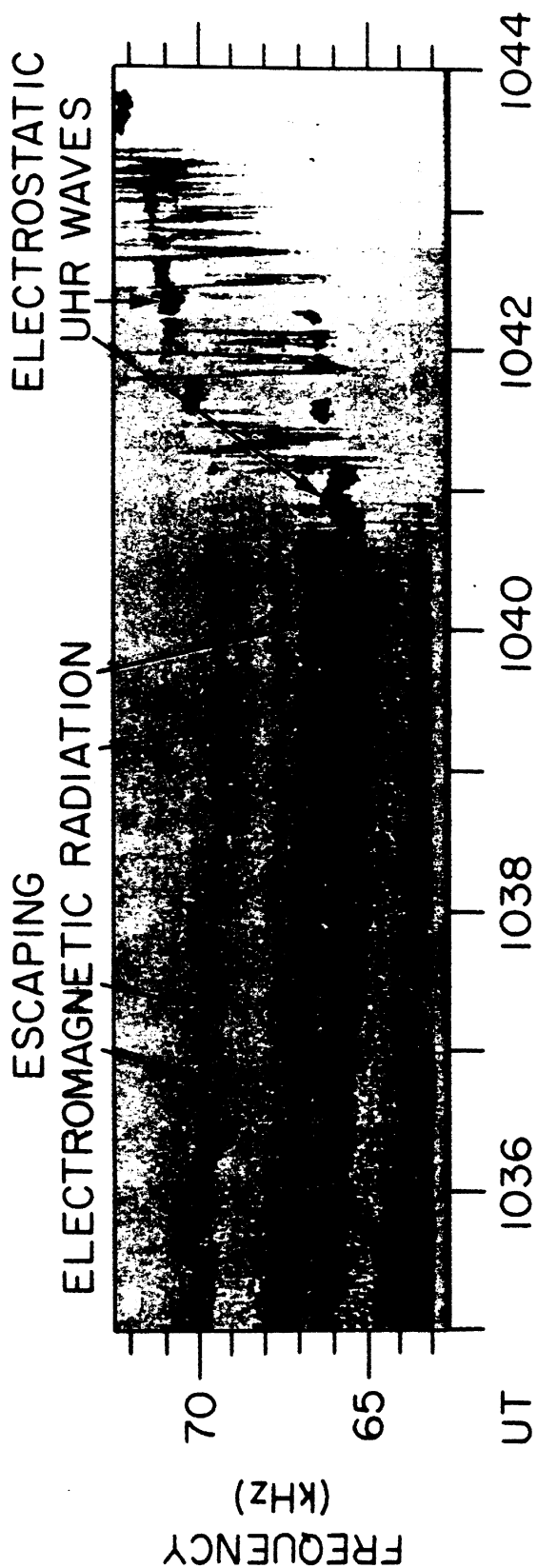


Figure 5

A sketch showing the conversion of electrostatic $(n + 1/2)f_c$ electron cyclotron waves to escaping electromagnetic radiation at frequencies near the upper hybrid resonance, f_{UHR} . The electrostatic waves are strongly enhanced when $(n + 1/2)f_c \approx f_{UHR}$, where n is an integer.



ISEE 1, DAY 362, DECEMBER 28, 1977

$R = 6.4 R_E$ $MLT = 9.3$ HR $\lambda_m = 7.1^\circ$

Figure 6 A high resolution spectrogram showing a series of electrostatic UHR waves (to the right) and the associated escaping electromagnetic radiation produced by mode conversion (to the left). From Kurth et al. [1981].

anisotropic electron distributions, sharply peaked at pitch angles of 90° , are frequently observed near the magnetic equator in planetary magnetospheres. The conversion of the electrostatic wave energy into escaping electromagnetic radiation is believed to be more efficient in regions with large density gradients. This may explain why the radiation originates from the plasmapause in the Earth's magnetosphere [Gurnett, 1975], and from the outer edges of the Io torus at Jupiter [Kaiser and Desch, 1980].

Two mechanisms, linear and nonlinear, have been proposed for converting the electrostatic wave energy into electromagnetic radiation. For reviews of the various conversion mechanisms, see Melrose [1981] and Barbosa [1982]. The leading proponent of the linear conversion theory has been Jones [1976; 1980; 1982]. Although Jones first proposed his theory to explain terrestrial continuum radiation, the basic idea has its origins in early work on ionospheric radio propagation and is discussed in various radio propagation books, such as Budden [1961]. In the linear conversion mechanism the electrostatic UHR waves are assumed to be propagating in a mode known as the "Z-mode", which becomes quasi-electrostatic near the upper-hybrid resonance frequency. In the presence of density gradients Z-mode waves can "tunnel" across the evanescent region between the Z-mode and the free space L-O mode. In the ionospheric radio propagation literature this tunnelling process is known as the "radio window". The process is linear because the intensity of the L-O mode radiation is directly proportional to the intensity of the Z-mode waves. For the linear conversion mechanism the polarization of the escaping radiation is predicted to be left-hand (i.e., the L-O mode), in agreement with the observations of Gurnett et al. [1988]. Jones also predicted that the radiation should be beamed outward in two directions at an angle $\gamma = \pm \text{Arctan}(f_c/f_p)^{1/2}$ with respect to the magnetic

equator, as illustrated in Figure 5. Although symmetrical double beaming patterns, comparable to Figure 5, are occasionally found [Jones et al., 1987], an extensive study of the beaming of terrestrial continuum radiation by Morgan and Gurnett [1991] shows that the typical radiation pattern consists of a single broad beam (40° - 60° half angle) directed outward along the magnetic equator.

Although the linear conversion mechanism of Jones can account for many aspects of the mode conversion radiation, the single greatest difficulty with the linear theory is the conversion efficiency. A recent study by Rönmark [1989] shows that the conversion efficiency is at least three orders of magnitude too small to explain the observed intensities of terrestrial continuum radiation. Faced with the failure of the linear mode conversion theory, we have no alternative but to consider various non-linear mechanisms. The possibilities for a non-linear conversion process have been discussed in general terms by Melrose [1981], and various computer simulations have been performed by Abdalla and Okuda [1984]. However, relatively few detailed studies have been carried out. The main constraint on a nonlinear theory is that the frequency of the escaping electromagnetic radiation must be essentially the same (within a few percent) as the frequency of the electrostatic wave. Proof of this relationship is shown in Figure 6, where it can be seen that the frequency of the escaping electromagnetic radiation is within a few percent of the frequency of the associated UHR waves. If the conversion involves a wave-wave coupling process, for which the frequency of the interacting waves must be related by $\omega_{EM} = \omega_{UHR} \pm \omega_L$, it follows that the frequency of the low frequency wave, ω_L , must be very low, less than a few percent of the upper hybrid resonance frequency. Christiansen et al. [1978] have noted that low frequency waves, with frequencies much less than f_{UHR} , are often present in

244 Nonlinear Radio Emission Processes

regions where the intense UHR bands are observed. Whether these low frequency waves are involved in the mode conversion process is simply not known, and will require further study.

CONCLUSION

This review has presented strong evidence that nonlinear processes are an essential aspect of the generation of radio emissions from planetary magnetospheres. Up to the present time very little attention has been given to these nonlinear effects. To some extent the slow rate of progress in studying nonlinear effects is due to the difficulties of obtaining suitable observation. The investigation of planetary radio emission processes is inherently difficult, because the radio emissions are almost always observed outside of the source region, whereas the phenomena of interest occur within the source. Often it is extremely difficult to know when the spacecraft is actually in the source region. Furthermore, most of the nonlinear phenomena of interest occur on extremely fast time scales, which requires full waveform measurements to conduct a detailed analysis. Although wideband waveform measurements are available, they suffer from various problems. They are usually analog measurements with minimal dynamic range and poor signal to noise ratios. Future plasma wave instruments, involving very high rate digital waveform measurements from multiple spacecraft, such as the European Cluster Mission [Schmidt and Goldstein, 1988], may eventually overcome some of these observational difficulties. In the meantime we will have to rely on theoretical predictions and plasma simulations to assist in the interpretation and analyses. Here, the picture looks very good, since there are now many powerful computer codes that can simulate various nonlinear effects. More effort should be made to compare the results of these simulations with existing measurements.

ACKNOWLEDGEMENTS

The author wishes to thank Prof. C. S. Wu for reviewing this manuscript and making several helpful suggestions.

The research at The University of Iowa was supported by the Jet Propulsion Laboratory through contracts 958779 and 959193, and by NASA Goddard Space Flight Center through contracts NAG5-1093 and NAG5-310.

REFERENCES

- Abdalla, M., and C. F. Kennel, Nonconvective and convective electron cyclotron harmonic instabilities, J. Geophys. Res., **83**, 1531, 1981.
- Abdalla, M., and H. Okuda, Generation of ordinary mode electromagnetic radiation near the upper hybrid frequency in the magnetosphere, J. Geophys. Res., **89**, 9125, 1984.
- Barbosa, D. D., Low level VLF and LF radio emissions observed at Earth and Jupiter, Rev. Geophys., **20**, 316, 1982.
- Birmingham, T. J., J. K. Alexander, M. D. Desch, R. F. Hubbard, and B. M. Pedersen, Observations of electron gyroharmonic waves and the structure of the Io torus, J. Geophys. Res., **86**, 8497, 1981.
- Budden, K. G., Radio Waves in the Ionosphere, Cambridge Univ. Press, New York, 1961.
- Burke, B. F., and K. L. Franklin, Observations of a variable radio source associated with the planet Jupiter, J. Geophys. Res., **60**, 213, 1955.
- Calvert, W., A feedback model for the source of auroral kilometric radiation, J. Geophys. Res., **87**, 8199, 1982.
- Carr, T. D., M. D. Desch, and J. K. Alexander, Phenomenology of magnetospheric radio emissions, Physics of the Jovian Magnetosphere, ed. by A. J. Dessler, Cambridge Press, London, 226, 1983.
- Grabbe, C. L., Theory of the fine structure of auroral kilometric radiation, Geophys. Res. Lett., **9**, 155, 1982.

- Gurnett, D. A., The Earth as a radio source: Terrestrial kilometric radiation, *J. Geophys. Res.*, **79**, 4227, 1974.
- Gurnett, D. A., The earth as a radio source: The nonthermal continuum, *J. Geophys. Res.*, **80**, 2751, 1975.
- Gurnett, D. A., Planetary radio emissions, *The Astronomy and Astrophysics Encyclopedia*, Ed. by S. Maran, Van Nostrand Reinhold, N.Y., 535, 1992.
- Gurnett, D. A., R. R. Anderson, F. L. Scarf, R. W. Fredricks, and E. J. Smith, Initial results from the ISEE-1 and -2 plasma wave investigation, *Space Sci. Rev.*, **23**, 103, 1979.
- Gurnett, D. A., W. Calvert, and R. L. Huff, The polarization of escaping terrestrial continuum radiation, *J. Geophys. Res.*, **93**, 12,817, 1988.
- Gurnett, D. A., and L. A. Frank, Continuum radiation associated with low-energy electrons in the outer radiation zone, *J. Geophys. Res.*, **81**, 3875, 1976.
- Gurnett, D. A., W. S. Kurth, and F. L. Scarf, Narrowband electromagnetic emissions from Saturn's magnetosphere, *Nature*, **292**, 733, 1981.
- Gurnett, D. A., W. S. Kurth, and F. L. Scarf, Narrowband electromagnetic emissions from Jupiter's magnetosphere, *Nature*, **302**, 385, 1983.
- Helliwell, R. A., and T. L. Crystal, A feedback model of cyclotron interaction between whistler-mode waves and energetic electrons in the magnetosphere, *J. Geophys. Res.*, **78**, 7357, 1973.
- Jones, D., Source of terrestrial nonthermal radiation, *Nature*, **260**, 686, 1976.
- Jones, D., Latitudinal beaming of planetary radio emissions, *Nature*, **288**, 225, 1980.
- Jones, D., Terrestrial myriametric radiation from the Earth's plasmopause, *Planet. Space Sci.*,

30, 399, 1982.

Jones, D., W. Calvert, D. A. Gurnett, and R. L. Huff, Observed beaming of terrestrial myriametric radiation, Nature, 328, 391, 1987.

Kaiser, M. S., and M. D. Desch, Narrow-band Jovian kilometric radiation: A new radio component, Geophys. Res. Lett., 7, 389, 1980.

Karpman, V. I., J. N. Istomin, and D. R. Shklyar, Nonlinear theory of a quasi-monochromatic whistler-mode packet in an inhomogeneous plasma, Planet. Space Sci., 22, 859, 1974.

Kintner, P. M., M. C. Kelley, and F. S. Mozer, Electrostatic hydrogen cyclotron waves near one Earth radius altitude in the polar magnetosphere, Geophys. Res. Lett., 5, 139, 1978.

Kurth, W. S., D. D. Barbosa, D. A. Gurnett, R. L. Poynter, and I. H. Cairns, Low-frequency radio emissions at Neptune, Geophys. Res. Lett., 17, 1649, 1990b.

Kurth, W. S., D. A. Gurnett, and R. R. Anderson, Escaping nonthermal continuum radiation, J. Geophys. Res., 86, 5519, 1981.

Kurth, W. S., D. A. Gurnett, and M. D. Desch, Continuum radiation at Uranus, J. Geophys. Res., 95, 1103, 1990a.

Matsumoto, H., and Y. Omura, Cluster and channel effect bunching by whistler waves in the nonuniform geomagnetic field, J. Geophys. Res., 86, 779, 1981.

Mellott, M. M., W. Calvert, R. L. Huff, and D. A. Gurnett, DE-1 observations of ordinary mode and extraordinary mode auroral kilometric radiation, Geophys. Res. Lett., 11, 1188, 1984.

Melrose, D. B., Coherent gyromagnetic emission as a radiation mechanism, Aust. J. Phys., 26, 229, 1973.

250 Nonlinear Radio Emission Processes

- Melrose, D. B., A theory for the nonthermal radio continuum in the terrestrial and Jovian magnetospheres, J. Geophys. Res., **86**, 30, 1981.
- Melrose, D. B., A phase-bunching mechanism for fine structures in auroral kilometric radiation and Jovian decametric radiation, J. Geophys. Res., **91**, 7970, 1986.
- Morgan, D. D., and D. A. Gurnett, The source location and beaming of terrestrial continuum radiation, J. Geophys. Res., **96**, 9595, 1991.
- Nunn, D., A nonlinear theory of sideband stability in ducted whistler mode waves, Planet. Space Sci., **34**, 429, 1986.
- Pritchett, P. L., and R. J. Strangeway, A simulation study of kilometric radiation generation along an auroral field line, J. Geophys. Res., **90**, 9650, 1985.
- Rönmark, K., Myriametric radiation and the efficiency of linear mode conversion, Geophys. Res. Lett., **16**, 731, 1989.
- Rönmark, K., H. Borg, P. S. Christiansen, M. P. Gough, and D. Jones, Banded electron cyclotron harmonic instability - a first comparison of theory and experiment, Space Sci. Rev., **22**, 401, 1978.
- Schmidt, R., and M. L. Goldstein, Cluster - A fleet of four spacecraft to study plasma structures in three dimensions, ESA SP-1103, European Space Agency, Paris, 7, 1988.
- Warwick, J. W., J. B. Pearce, A. C. Riddle, T. D. Carr; S. Gulkis, A. Boischot, C. C. Harvey, and B. M. Pedersen, Voyager 1 planetary radio astronomy observations near Jupiter, Science, **204**, 995, 1979.
- Winglee, R. M., and P. L. Pritchett, The generation of low-frequency electrostatic waves in association with auroral kilometric radiation, J. Geophys. Res., **91**, 13,531, 1986.

Wu, C. S., Kinetic cyclotron and synchrotron maser instabilities: Radio emission processes by direct amplification of radiation, Space Sci. Rev., 41, 215, 1985.

Wu, C. S., and L. C. Lee, A theory of terrestrial kilometric radiation, Astrophys. J., 230, 621, 1979.