JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 99, NO. A12, PAGES 23,541–23,546, DECEMBER 1, 1994

# Correlation between terrestrial myriametric and kilometric radio bursts observed with Galileo

P. Louarn, A. Hilgers ,[1] A. Roux, and C. de Villedary

Centre d'étude des Environnements Terrestre et Planétaires, Velizy, France

D. A. Gurnett and W. S. Kurth

Department of Physics and Astronomy, University of Iowa, Iowa City

**Abstract.** Data from the Galileo plasma wave system recorded during an investigation of the Earth magnetotail on December 8, 1990, are analyzed in both the myriametric and the kilometric wavelength range. In the far tail, between 80 and 30 Earth radii, two components are observed in the myriametric range (frequencies between 6 and about 30 kHz): (1) the "classical" trapped continuum radiation with a smoothly varying intensity in time and (2), superposed on this component, bursts of waves with typical spectral densities of $10^{-15}$ $V^2m^{-2}Hz^{-1}$. These bursts of myriametric waves are shown B to correlate with bursts of intense auroral kilometric radiation (AKR) with typical spectral density of $10^{-12}$ $V^2m^{-2}Hz^{-1}$. This bursty myriametric radiation is the analog of the low frequency radiation (LFR) reported by Filbert and Kellog (1989). Its close correlation with the kilometric radiation suggests the existence of a direct relationship between these two radiations. A generation mechanism that explains this correlation and the frequency gap between the AKR and the LFR is proposed.

## 1. Introduction

For more than two decades the Earth has been known to be a powerful nonthermal radio source [*Benediktov et al.*, 1965; *Dunckel et al.*, 1970; *Brown*, 1973]. Several components have been observed (see a review by *Barbosa* [1982]). Among them, the auroral kilometric radiation (AKR) is the most intense. It is sporadic and originates in the night sector on auroral field lines between 1.5 and 3 Earth radii of altitude [*Gurnett*, 1974; *Kurth et al.*, 1975] at frequencies close to the local electron cyclotron frequency [*Gurnett and Green*, 1978; *Benson and Calvert*, 1979]. The nonthermal continuum [*Gurnett*, 1975] has a component trapped inside the magnetospheric cavity, with frequencies below the plasma frequency of the magnetosheath, and an escaping component at higher frequencies. The trapped component has a rather smooth spectrum and has been observed at frequencies as low as 5 kHz. The escaping component consists of several narrow-banded spectral structures [*Kurth et al.*, 1981; *Etcheto et al.*, 1982]. It has been observed at frequencies as high as 200 kHz [*Kurth et al.*, 1981] and seems to originate in a broad region between 4 and 14 MLT at distances between 5 and 8 $R_E$ [*Gurnett*, 1975; *Morgan and Gurnett*, 1991].

Some recent studies have also provided evidence of other types of myriametric radiations. One can mention the continuum enhancement (CE) and the low-frequency radiation (LFR). While the former lasts for about 1 hour and seems to originate in the midnight local time sector, close to the equator [*Gough*, 1982; *Filbert and Kellog*, 1989] the latter is more impulsive and is correlated with AKR bursts within a minute [*Filbert and Kellog*, 1989].

In this paper we report observations made with the Galileo plasma wave system in the far tail, between 80 to 30 $R_E$ from the Earth. This crossing of the magnetotail offers the interesting possibility of a simultaneous detection of the AKR and of the myriametric radiation over several hours, during periods of high magnetospheric activity (substorm development) and quiet periods. We are going to show that the myriametric radiation is almost continously emitted, at a level that increases with the magnetospheric activity. However, as already demonstrated by *Filbert and Kellog* [1989], it seems possible to distinguish two components in the myriametric range: (1) the classical continuum radiation (which is here, the trapped component) and (2) a bursty emission very closely related to bursts of AKR (LFR, hereafter). The close correlation between the AKR and the LFR suggests that these two emissions are produced on the same field lines. The problem is then to explain why a frequency gap exists between them. An explanation, based on the cyclotron maser mechanism, will be proposed.

## 2. Observation of Radioelectric Waves

In plate 1 the electric component of waves recorded between 0400 and 2000 UT is displayed. Galileo entered

---

[1] Now at ESTEC, Noordwijk, The Netherlands.

Paper number 94JA00922.
0148-0227/94/94JA-00922$05.00.

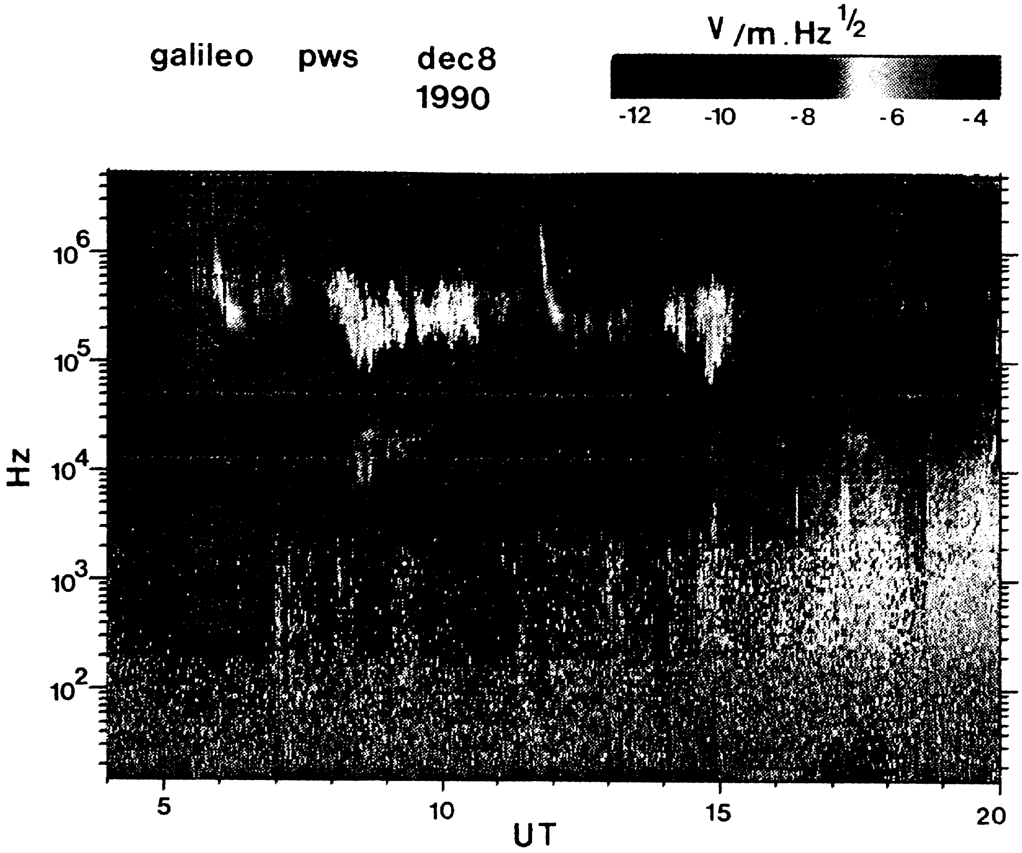

**Plate 1.** Dynamic spectrum of the wave electric component measured with Galileo in the Earth magnetotail.

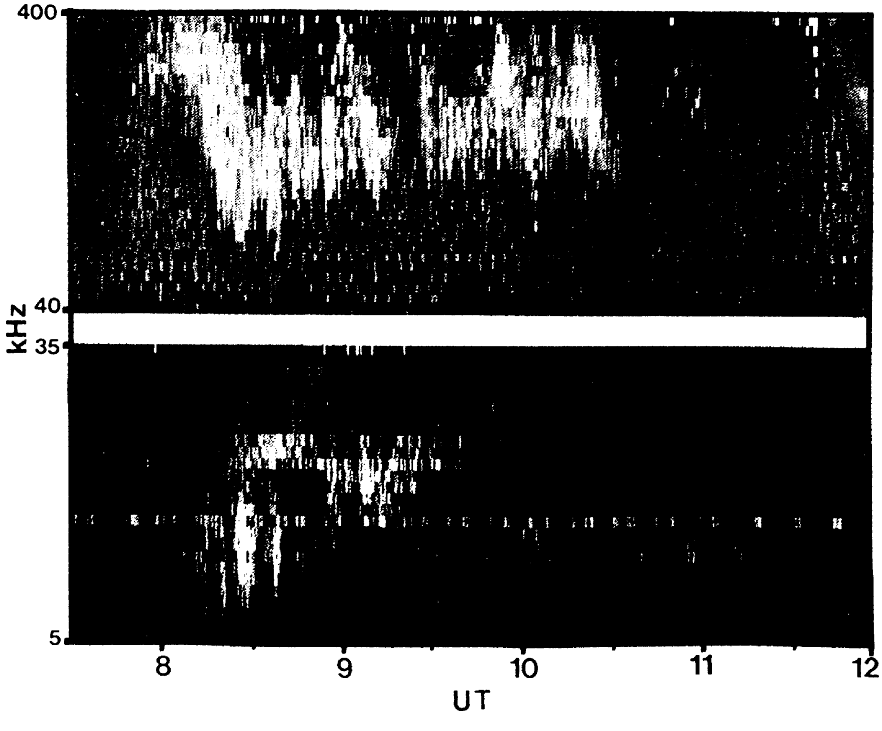

**Plate 2.** Same as Plate 1 but restricted to the band 5-300 kHz

the Earth magnetotail at about 0300 UT and a radial distance of about 87 $R_E$ and remained in the tail, close to the plasma sheet in the midnight sector, until close encounter with Earth at 2034 UT. For a description of the wave instrument, see *Gurnett et al.* [1992].

At high frequencies (above 50 kHz) one observes very clear signatures of type III solar radio bursts and AKR bursts. At lower frequencies (from a few kilohertz to a few tens of kilohertz) one observes a weaker noise whose intensity is just above the background noise level, especially between 0800 and 1500 UT. The level of this noise is too low to be detectable with the magnetic antenna, so that its electromagnetic nature cannot be directly ascertained. However, the large bandwidth of this emission suggests that it is an electromagnetic mode. Given the very low value of the local electron gyrofrequency, this noise cannot be in the whistler mode, and it is reasonable to interpret it as myriametric radio waves. This emission is also observed after 1500 UT (bumps in the spectra at frequencies close to 20 kHz around 1600 and 1730 UT). However, during this period the spacecraft entered regions of higher plasma densities which result in an increased noise level on the antenna. The low-frequency radio emission is then less clear.

For all this period a description of the global magnetospheric context can be found in the work by *Kivelson et al* [1993]. Three substorms are reported: 0440-0730 UT; 0755-0930 UT; and 1034-1140 UT. As expected, one can check in Plate 1 that each of these disturbed periods corresponds also to an AKR event. Concerning the myriametric radiation, two facts can be noticed: (1) It is detected irrespective of the magnetospheric activity and, in particular, when no AKR is emitted (after 1500 UT, for example). This is a characteristic of the classical continuum radiation, always observed if the instrumental sensitivity is good enough. (2) On the other hand, its level is, in some way, linked to the AKR level. For example, the two peaks of activity (near 0830 and 1445 UT) correspond also to an intensification of the myriametric emission. Following the work of *Filbert and Kellog* [1989], this can be interpreted as a particular type of myriametric radiation, correlated with the AKR.

In Plate 2 one shows the dynamic spectrum of the myriametric radiation, in the frequency range (5 to 40 kHz) and of the AKR (40 to 300 kHz) in the time period (0730, 1200). On the "AKR" upper panel, five time intervals can be distinguished: (1) before 0755 UT: very low-level AKR activity; (2) between 0755 and 0918 UT: intense AKR activity characterized by bursty emissions lasting 3 to 5 min (for instance, at 0827, 0837, 0845, and 0858 UT); (3) between 0920 and 0927 UT: quiet period with a corresponding low-level AKR activity; (4) between 0927 and 1035 UT: second active and quite bursty period with AKR slightly less intense than during period 2; (5) between 1035 and 1135 UT: low level AKR activity, but bursts are nevertheless observable.

The myriametric radiation is generally smoother. There are, however, three bursts observed around 0830 UT. The sharp decrease of the AKR intensity at 1030 UT does not correspond to anything special in the myriametric radiation intensity. The period 0920-0927 UT where there is little AKR activity is not associated with any reduction of myriametric activity. This, together with the fact that myriametric waves are observed between 1530 and 2000 UT without AKR, leads to the conclusion that a component of the myriametric radiation is continuously emitted. This component is the "classical" continuum radiation.

Let us now return to the observation of bursts of myriametric radiation. The key observation can be made just before 0840 UT. The myriametric radiation seems to have split into two components. The high-frequency part (above 20 kHz) is smooth and can be interpreted as continuum radiation. The low-frequency part is well organized in three bursts that seem to be correlated to AKR bursts. Using the terminology of Filbert and Kellog, this component will be now called LFR. After 0840 UT these two components merge in frequency.

When it was possible to separate in frequency the two myriametric radiations (from 0810 to 0900 UT), we have computed the cross-correlation coefficient between the AKR and the LFR amplitudes for a time shift varying from -5 to 5 min (Figure 1). The maximum of the cross-correlation factor (0.72) is obtained for a time delay of 72 s (equal to the duration of two spectra), the AKR being systematically observed before the LFR.

In conclusion, during more than 6 hours of observation, while the spacecraft approached the Earth from 70 $R_E$ to less than 30 $R_E$, AKR and two types of myriametric radiations were observed. One type of myriametric radiation has smooth variations and is quasi-continuously detected, independently of the presence of the AKR. The other type, bursty and correlated with AKR, is similar to the LFR described by Filbert and Kellog. Let us now discuss some possible interpretations of these Galileo observations.

## 3. Possible Interpretations

### 3.1. On the Continuum Radiation Seen by Galileo

The observations of the smooth component of the myriametric radiation made by Galileo are consistent with previous studies. This component can be inter-

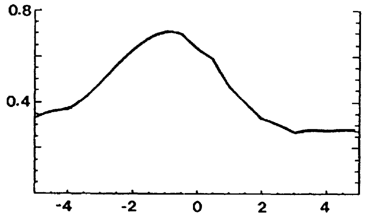

**Figure 1.** Correlation factor between the low frequency radiation and the auroral kilomatric radiation intensities, as a function of the time delay expressed in minutes.

preted as the trapped continuum and nothing can be deduced in favor or against the existing models and theories of generation of this emission. It is just possible to notice that, not surprisingly, periods of activity of the magnetosphere (substorm developments) correspond to an enhanced level of the continuum radiation.

Without more precise informations and depending on the choice of the generation mechanism, several reasonable scenarios may account for this relationship. However, one must note that a large part of the magnetospheric activity is concentrated in the midnight sector (substorm developments, acceleration of particles in the auroral zone, generation of AKR, ...) while the source of the trapped continuum is located near the morning plasmapause. These two regions are certainly not simply and directly connected. A global correlation between the magnetospheric activity and the intensity of the continuum radiation can be easily understood as a consequence of the increase of the electrostatic turbulence close to the plasmapause during active periods (this turbulence being further converted linearly [*Jones*, 1988] or nonlinearly [*Melrose*, 1981; *Rönmark*, 1985]. However, the observation of a direct correlation between the LFR and the AKR is much more puzzling if one retains the idea of a dayside generation for this component too. This favors the hypothesis of two different sources for the continuum and the LFR. Let us now discuss some possibilities.

### 3.2. Possible Scenarios for the Generation of LFR

In order to explain its close correlation with the AKR, the simplest hypothesis is to assume that it is generated on field lines connected to the AKR sources. If we only retain reasonably well known and established generation mechanisms for radio waves, there are two possibilities: (1) a generation near the local electron gyrofrequency ($F_c$) (or its first harmonics) by the cyclotron maser instability (as it is the case for the AKR) or (2) a generation at the plasma frequency ($F_p$) or at its second harmonic by a linear or nonlinear conversion of Langmuir turbulence (as it is the case for the continuum).

**Generation at $F_c$.** This hypothesis implies that the source of the LFR is a few thousands kilometers above the sources of AKR, at a typical altitude of 25,000 km. Provided that enough free energy exists in the electron distribution function (positive "perpendicular" slopes in the electron distribution function: $\partial f/\partial w_\perp > 0$), the cyclotron maser instability can, in principle, develop and produce radio waves at such high altitudes. However, at these radial distances the ratio $F_p/F_c$ is hardly very small. As already discussed in numerous papers (see the review by *Wu* [1985]), X mode waves cannot be generated near $F_c$ under such plasma conditions. Nevertheless, it is still possible to generate X mode at $\sim 2F_c$ and O mode at $\sim F_c$ via the maser cyclotron instability. Typical values for the corresponding growth rates are [*Melrose et al.*, 1984; *Winglee*, 1985]

$$\gamma^x_{2\omega_c} \sim \gamma^o_{\omega_c} \sim 10^{-4}\omega_c$$

with the restriction that $\omega_p/\omega_c$ must be lower than 1 for the amplification of the O mode and lower than $\sqrt{2}$ for that of the second harmonic X mode.

For a gyrofrequency of the order of 10 kHz, a simple numerical calculation shows that the amplification length is much too large (a few $10^4$ km) unless the group velocity of the waves is considerably reduced ($v_g \sim 10^{-2}$ to $10^{-3} \times c$). Efficient generation is then possible only close to the cut-off of the O mode near $\omega_p$ (and thus $\omega_p/\omega_c \simeq 1$) or to the cut-off of the X mode near $2\omega_c$ (and $\omega_p/\omega_c < \sqrt{2}$). Above the acceleration region which corresponds to the source of AKR, one expects to find loss cone distribution functions. In that case the growth rate of second harmonic X mode can be too low to account for efficient generation [*Winglee*, 1985] so we only consider the possibility of O mode generation. Along an auroral field line, the ratio $\omega_p/\omega_c$ probably increases continuously and owing to the previous remarks, in the altitude range where $0.3 < \omega_p/\omega_c < 1$ no radio waves can be efficiently produced ($\omega_p/\omega_c$ is too large for a production of X mode at $F_c$ and too low for reducing the group velocity of the O mode near $F_c$). It is only at higher altitudes (i.e., where $\omega_p/\omega_c$ becomes very close to unity) that radio waves are efficiently produced, predominantly on O mode. Thus a continuous increase of the ratio $\omega_p/\omega_c$ along the field line can give rise to a frequency gap in the auroral radio spectrum between the myriametric component and the kilometric one.

Using some simple considerations on the properties of the cyclotron maser instability, it is possible to quantize this gap. Indeed, as shown by *Le Queau and Louarn* [1989], two parameters are essential for the generation of the AKR: (1) the normalized plasma energy: $\delta = (v_0/c)^2/2$ where $v_0$ is the typical electron velocity and (2) the ratio $\epsilon = (\omega_p/\omega_c)^2$. In an idealized case it can be shown that if $\delta < \epsilon/4$ then, the X mode is not amplified. Assuming an electron energy of 5 keV and a plasma frequency of 10 kHz (these values are typically those observed inside the AKR sources by the VIKING spacecraft [*Louarn et al.*, 1990], one then obtains a minimum value for the electron gyrofrequency: 50 kHz, below which it is no more possible to generate the AKR. This value must be considered as an order of magnitude. It is, however, interesting to note that it corresponds to the low-frequency AKR cutoff as seen on Plate 2. If one then assumes that the LFR is emitted near the O mode cutoff (at $F_p/F_c \sim 1$, then near 10 kHz), a typical gap of 40 kHz is obtained between the two types of emissions, which is not too far from the observations.

In this context, one can relate the systematic time delay between occurrence of AKR and myriametric bursts to characteristic timescales of auroral phenomena. The knowledge on the dynamic of auroral acceleration structure is still in a very uncomplete stage, yet AKR is known to consist of narrow-banded drifting emissions that one can relate to small-scale individual sources.

The frequency drift rate of these emissions suggests then that the triggering agent of AKR generation (the formation of the free energy source for instance) propagates upward with a velocity of the order of 10 to 100 km $s^{-1}$. The time delay that we have measured in section 2 fits with the time necessary for such a phenomenon to propagate over a distance of 1 $R_E$ (order of the altitude difference between AKR and the supposed LFR sources).

**Generation from electrostatic turbulence (at $F_p$ or 2 $F_p$).** The hypothesis of a generation at $F_p$ leads to less precise deductions. Along an auroral field line, $F_p$ can be of the order of 10 kHz over a wide altitude range so that the source cannot be precisely located. Using Viking data, we have tried to check whether the strong electrostatic turbulence detected inside the sources of AKR could be converted into electromagnetic waves (O mode close to $F_p$ or at 2 $F_p$). The idea is that the acceleration region that corresponds to the AKR source could emit two kinds of radio emissions; the AKR itself and a myriametric component as a by-product of the Langmuir turbulence. The experimental problem is that the level expected for such an O mode emission is extremely low compared to the level of the turbulence. The magnetic component of these radio waves would be below the noise level. Thus, in the sources the eventual emission of O mode at $F_p$, if it exists, would be difficult to confirm. The problem is different at 2 $F_p$, in a frequency range where a nonlinear generation of radio waves from the turbulence is expected to be the most efficient. Here, there is no problem of noise. With the sensitivity of the VIKING experiment, no emission has been observed at 2 $F_p$ inside the AKR sources.

From this lack of evidence of a generation related to the Langmuir turbulence inside or near AKR sources, we will favour the hypothesis of a generation of the LFR linked to the cyclotron maser mechanism.

## 4. Conclusion

Observations presented here provide evidence of a bursty component of the myriametric radiation, correlated with bursts of AKR. This component is usually superposed on the classical trapped continuum. Its close correlation with the AKR and the observation of a frequency gap between the bursty and the continuous component suggest that these two radiations have different origins. This is consistent with previous observations. As a matter of fact, *Filbert and Kellog* [1989] have observed from IMP 6 data a low-frequency lobe of the auroral radiation down to about 10 kHz in the magnetotail. They also observed a depletion of the spectral energy between the low- and the high-frequency emissions, but they did not comment on it. However, the threshold of the IMP 6 experiment being lower than the Galileo one, they could perform an analysis of the direction of propagation and of the signal modulation factor. They concluded that the source of the low-frequency component is close to that of the AKR and is likely to be located at a higher altitude.

We have tested two hypotheses for the generation of the LFR: (1) source in the auroral region and generation at $F_c$ and (2) source in the auroral region and generation at $F_p$. Two factors have been taken into account for the choice between these different hypotheses: (1) the generation mechanism for the bursty component must be one of the already well-known mechanisms used for the AKR or the continuum and (2) the sources of the bursty component must be easily connected to the sources of AKR. From a theoretical point of view, these two hypothesis are plausible. From a reexamination of the data obtained by Viking we would propose that the first hypothesis is the most plausible. In any case the observation of a systematic delay between two types of radio emissions indicates that they are not generated at the same place or by the same mechanism. This time delay could give a typical timescale for the exchange of information between two regions of the magnetosphere. This can be considered as a particular example of the use of radio wave observations for remote sensing of the magnetospheric activity.

**Acknowledgments.** The Editor thanks Kjell Rönnmark and Jean-Louis Steinberg for their assistance in evaluating this paper.

## References

Barbosa, D. P., Low-level VLF and LF radio emission observed at Earth and Jupiter, *Rev. Geophys.*, *20*, 316, 1982.

Benediktov, E. A., G. G. Gemantsev, Yu. A. Sazonov, and A. F. Tarasov, Preliminary results of measurement of the intensity of distributed extraterrestrial radio-frequency emission at 72 and 1525 kC frequencies by the satellite Electron 2, *Cosmic Res.*, *3*, 492, 1965.

Benson, R. F., and W. Calvert, ISIS 1 observations at the source of AKR, *Geophys. Res. Lett.*, *6*, 479-482, 1979.

Brown, L. W., The galactic radio spectrum between 130 and 2600 kHz, *Astrophys. J.*, *180*, 3590, 1973.

Dunckel, N., B. Ficklin, L. Rorden, and R. A. Helliwell, Low frequency noise observed in the distant magnetosphere with OGO 1, *J. Geophys. Res.*, *75*, 1854, 1970.

Etcheto, J., P. J. Christiansen, M. P. Gough, and J. G. Trotignon, Terrestrial continuum radiation observed with GEOS-1 and ISEE-1, *Geophys. Res. Lett.*, *9*, 1239, 1982.

Filbert, P. C., and P. J. Kellog, Observations of low-frequency emissions in the Earth's magnetosphere, *J. Geophys. Res.*, *94*, 8867, 1989.

Gough, M. P., Non-thermal continuum emissions associated with electron injections: Remote plasmapause sounding, *Planet. Space Sci.*, *30*, 657, 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., and J. L. Green, On the polarization and origin of the auroral kilometric radiation, *J. Geophys. Res.*, *83*, 689, 1978.

Gurnett, D. A., W. S. Kurth, R. R. Shaw, A. Roux, R. Gendrin, C. F. Kennel, F. L. Scarf, and S. D. Swawhan, The Galileo plasma wave investigation, *Space Sci. Rev.*, *60*, 341, 1992.

Jones, D., Planetary radio emissions from low latitudes: Observations and theories, in *Planetary Radio Emissions II*, edited by H. O. Rucker, S. J. Bauer and B. M. Pedersen, p. 255, Austrian Academy of Sciences Press, Vienna, 1988.

Kivelson, M., et al , The Galileo Earth encounter: Magnetometer and allied measurements, *J. Geophys. Res.*, *98*, 11299, 1993.

Kurth, W. S., M. M. Baumback, and D. A. Gurnett, Direction finding measurement of auroral kilometric radiation, *J. Geophys. Res.*, *80*, 2764, 1975.

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

Le Quéau, D., and P. Louarn, Analytical study of the relativistic dispersion: Application to the generation of the AKR, *J. Geophys. Res.*, 94, 2605, 1989.

Louarn, P., A. Roux, H. de Feraudy, D. Le Quéau, M. André, and L. Matson, Trapped electrons as a free energy source for the auroral kilometric radiation, *J. Geophys. Res.*, *95*, 5983, 1990.

Melrose, D. B., A theory for the nonthermal continua in the terrestrial and Jovian magnetospheres *J. Geophys. Res.*, *86*, 30, 1981.

Melrose, D. B., R. G. Hewitt, and G. A. Dulk, Electron cyclotron maser emission: Relative growth and damping rates for different modes and harmonics, *J. Geophys. Res.*, *89*, 897, 1984.

Morgan, D. D., and D. A. Gurnett, The source location and beaming of terrestrial continuum radiation, *J. Geophys. Res.*, *96*, 9595, 1991.

Rönmark, K., Emission of myriametric radiation by coalescence of upper hybrid waves with low frequency waves, *Ann. Geophys.*, *1*, 187, 1983.

Winglee, R. M., Fundamental and harmonic electron cyclotron maser emission, *J. Geophys. Res.*, *90*, 9663, 1985.

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

C. de Villedary, P. Louarn, A. Roux, CNET-CNRS/CRPE, 38-40 rue du General Leclerc, 92131 Issy-les-Moulineaux, France.

A. Hilgers, ESA/ESTEC/WMA, PO box 299, 2200 AG Noordwijk, The Netherlands.

D. A. Gurnett and W. S. Kurth, Dept. of Physics and Astronomy, University of Iowa, Iowa City, IA 52242.

(Received December 21, 1993; revised March 16, 1994; accepted March 29, 1994.)