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# Nonlinear emission mechanism for continuum radiation in Jupiter's magnetosphere

Wiesław M. Macek

Space Research Centre, Polish Academy of Sciences, Warsaw, Poland

**Abstract.** The question of how continuum radiation trapped in Jupiter's magnetosphere might be generated is considered. It is shown that the efficiency of the linear conversion is not sufficient to account for the observed intensity of the emission. We discuss nonlinear processes that can more easily provide the required conversion efficiency. The field strengths of upper hybrid waves required to generate the fundamental harmonic emissions are $\sim 0.5 \div 4$ mV m$^{-1}$. Comparison of the results of the discussed model with electric fields reported in the Jovian magnetosphere shows that the model adequately explains the generation of continuum radiation trapped in the planetary cavity.

## 1. Introduction

There are two primary types of coherent radio emissions observed from planetary magnetospheres. The most intense emissions are associated with the cyclotron maser instability while weaker emissions result from mode conversion from electrostatic waves. Here we consider this latter type of radiation, which usually has a smooth monotonic frequency spectrum extending over a frequency range of several octaves and is often referred to as nonthermal continuum radiation [e.g., *Kurth*, 1992].

Continuum radiation has been observed from the magnetospheres of Earth, Jupiter, Saturn, Uranus, and Neptune. Naturally, most of what we understand about continuum radiation is derived from terrestrial observations. In an early study, *Gurnett* [1975] recognized the trapped and escaping components of the emission and suggested a source region associated with the intense electrostatic waves near the upper hybrid resonance frequency. Many subsequent Earth-based studies of continuum radiation have been done, some having a direct bearing on the question of nonlinear generation mechanism. It has been pointed out that continuum radiation appears to emerge from regions where the upper hybrid resonance and the half-integral harmonics of the electron cyclotron appear to converge in frequency [e.g., *Kurth*, 1982]. In fact, further observational evidence has shown that intense electrostatic emissions at the upper hybrid resonance frequency are the source of the continuum radiation trapped inside the magnetospheric cavity [e.g., *Gurnett and Scarf*, 1983; *Gurnett et al*., 1989; *Kurth*, 1992].

It is still not clear, however, how the energy in the electrostatic waves is converted into electromagnetic waves, which can escape from the source region. Admittedly, a linear wave conversion mechanism can explain some observable features of the radiation [cf. *Jones*, 1988, and references therein]. In addition, Jones's theory had the advantage that it made some very specific predictions about beaming angles and polarization, which could be measured experimentally. In fact, in several examples the polarization was found to be consistent with this theory, and naturally, the linear mechanism can contribute to some portion of the observed spectrum. On the other hand, it is not clear from the observations that the linear theory explains the entire continuum spectrum, as discussed by *Kurth* [1992]. Moreover, some specific predictions about beaming angles seem to be, in part, discounted by observations [*Morgan and Gurnett*, 1991]. Generally speaking, the primary criticism of the linear theory is based on the grounds that it cannot account for the entire continuum spectrum at any of or all the planetary magnetospheres. Basically, the efficiency of the linear conversion is not sufficient to account for the observed intensity of the emissions [*Rönnmark*, 1989]. The possibility that nonlinear processes may play an important role in the generation of planetary continuum radiation has been suggested by a number of authors [e.g., see *Gurnett and Scarf*, 1983; *Gurnett et al*., 1983]. After reviewing a number of mechanisms at both Earth and Jupiter, *Melrose* [1981] concluded that the most likely process for generating the continuum radiation involves a nonlinear interaction between the upper hybrid emissions and a low-frequency mode. Following *Melrose* [1980a, 1980b, 1981], we therefore discuss nonlinear processes that can more easily provide the required conversion efficiency.

The various theoretical models for the generation mechanism can also be distinguished by whether they depend on direct or indirect emission processes. Direct mechanisms refer to particle-generated electromagnetic waves in which free energy is directly converted into photons. Indirect mechanisms consist of two steps. Free energy is first used to generate electrostatic waves by particle-wave interactions, and these electrostatic waves are then converted into photons by (nonlinear) wave-wave interactions or scattering (mode conversion) processes [*Goldstein and Goertz*, 1983].

It is argued here that for the low-frequency, low-amplitude emissions detected in the Jovian magnetosphere the indirect mechanism applies and that the upper hybrid waves are generated by a loss cone distribution. The excess free energy in velocities perpendicular to the magnetic field is first transformed into electrostatic waves. The nonlinear interactions of these waves which can produce electromagnetic waves are then treated in the semiclassical formalism. The frequency of these emissions is above the local electron plasma frequency, $f_p = \omega_p/(2\pi)$, which is directly related to the electron number density $n_e$: $f_p = 8.98\ n_e^{1/2}$, where $f_p$ is in kilohertz and $n_e$ is in cm$^{-3}$. More precisely, the emissions are at the upper hybrid



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frequency $f_{UH} = (f_p^2 + f_B^2)^{1/2}$, where $f_B$ is the electron cyclotron frequency [e.g., *Krall and Trivelpiece*, 1973]. Far from the planet we have $f_{UH} \approx f_p$. We also argue that these nonlinear interactions take place in the region of the magnetopause where the gradient is strong, and transverse waves in a frequency range $\Delta f$ can be generated over a range of distances $\Delta r = 2L_n(\Delta f/f)$, where $L_n = n_e/|dn_e/dr|$ is the characteristic distance over which the plasma density $n_e$ varies.

*Macek et al.* [1991a, 1991b] have presented a simple model for the generation mechanism of plasma waves by the electron beam near the heliospheric shock, and they have considered kinematic constraints on the emission processes involving electrostatic longitudinal waves. In this way, they have estimated the wave amplitude expected to be measured by the plasma wave instrument in the heliospheric foreshock. In the limiting case of saturation of these emission processes the minimum value of the wave electric field has been obtained. Later, a more realistic field strength of electrostatic waves required to generate the observed radiation was also calculated [*Macek*, 1994, 1996; *Macek et al*., 1995]. The same mechanism was also discussed for the Earth's bow shock [e.g., *Macek*, 1996], suggesting that this mechanism is also a candidate for the terrestrial case.

In this paper we use the same approach toward understanding the generation mechanism of the nonthermal (low-frequency and low-amplitude) continuum radiation in the planetary magnetosphere. Since the space mission to the giant planets has probably contributed most to our expanding knowledge of space plasma waves, we focus on Jupiter's magnetosphere. Admittedly, we only use a rough quantitative method to explore the possibility of nonlinear coupling but not necessarily excluding applicability of a linear theory to explain certain features of the radiation. Hence we study the plausibility of nonlinear coalescence-decay processes being the generation mechanism of continuum radiation. Measurements of longitudinal electric wave amplitudes are then used to determine whether there is enough energy in such waves to power the process strongly enough to create the observed electromagnetic waves. We hope that the application of that nonlinear method constitutes a progress in the search for the generation mechanism of continuum radiation. In section 2 we first explain how the interaction between electrostatic waves in the source leads to electromagnetic radiation. Section 3 is devoted to the main results of our calculations. In particular, on the basis of the observed flux of the photons the average value of the brightness temperature of the source is obtained. Then the value of the strength of the electrostatic oscillations as being a source of the continuum radio emissions trapped in Jupiter's magnetosphere is estimated for the case of saturation. It is shown that this value is consistent with the Voyager observations. Finally, in section 4 a possible extension of the model for nonsteady state (nonsaturation) conditions is also briefly considered. The main conclusions are summarized in section 5.

## 2. Model

### 2.1. Generation of Photons

In the semiclassical formalism, waves are regarded as a collection of wave quanta (photons and plasmons). Emission, absorption, and scattering of waves are discussed; both stimulated and spontaneous emissions can be included in a straightforward way. In a low-frequency Rayleigh-Jeans approximation the occupation number for a mode $\sigma$ with wave vectors $\mathbf{k}^\sigma$ is related to the wave spectral density $\kappa T^\sigma(\mathbf{k}^\sigma)$ by [*Melrose*, 1980a, 1980b, 1981]:

$$N_k^\sigma \equiv \frac{W_\mathbf{k}^\sigma}{\hbar\omega^\sigma} = \frac{1}{\exp(\hbar\omega^\sigma/\kappa T^\sigma) - 1} \approx \frac{\kappa T^\sigma}{\hbar\omega^\sigma} = N^\sigma(\mathbf{k}^\sigma), \quad (1)$$

where $\kappa$ is Bolzmann's constant, $\hbar = h/(2\pi)$ denotes Planck's constant, and $T^\sigma$ is called the effective temperature. The wave energy density is

$$W^\sigma = \int W_k^\sigma\, d^3\mathbf{k}^\sigma/(2\pi)^3 \approx \int \kappa T^\sigma(\mathbf{k}^\sigma)\, d^3\mathbf{k}^\sigma/(2\pi)^3. \quad (2)$$

### 2.2. Three-Wave Interactions

One can consider up-conversion coalescence ($\rightarrow$) and decay ($\leftarrow$) processes ($\sigma_1 + \sigma_2 \leftrightarrow \sigma$) and invoke the energy ($E_1 + E_2 = E \equiv \hbar\omega$; $\omega_1 + \omega_2 = \omega$) and momentum ($\mathbf{p}_1 + \mathbf{p}_2 = \mathbf{p} \equiv \hbar\mathbf{k}$; $\mathbf{k}_1 + \mathbf{k}_2 = \mathbf{k}$) conservation laws.

Assuming a basic probability $u^{\sigma\sigma_1\sigma_2}(\mathbf{k}, \mathbf{k}_1, \mathbf{k}_2)$ to be the same for coalescence and decay processes, the rates of transition are $u^{\sigma\sigma_1\sigma_2}(1 + N^\sigma)N^{\sigma_1}N^{\sigma_2}$ for the coalescence process and $u^{\sigma\sigma_1\sigma_2}N^\sigma(1 + N^{\sigma_1})(1 + N^{\sigma_2})$ for the decay process, correspondingly. In the classical limit one obtains [*Melrose*, 1980a]

$$\frac{dN^\sigma(\mathbf{k})}{dt} = \int \frac{d^3\mathbf{k}_1}{(2\pi)^3}\frac{d^3\mathbf{k}_2}{(2\pi)^3}\, u^{\sigma\sigma_1\sigma_2}[N^{\sigma_1}N^{\sigma_2} - N^\sigma(N^{\sigma_1} + N^{\sigma_2})]. \quad (3)$$

If the number of photons is not decreasing in time, $dN^\sigma(\mathbf{k})/dt \geq 0$, then

$$N^\sigma \leq \frac{(N^{\sigma_1}N^{\sigma_2})}{(N^{\sigma_1} + N^{\sigma_2})}. \quad (4)$$

Examples of nonlinear processes involving longitudinal electrostatic oscillations ($L$, $L'$) or plasmons are given below, where $S$ is the low-frequency (e.g., ion sound, lower hybrid, or ion cyclotron) wave and $t$ is the transverse electromagnetic plasma wave or the photon [*Melrose*, 1970, 1980a, 1980b]:

| | | | |
|---|---|---|---|
| $\sigma_1$ | $L$ | $L$ | $L$ |
| $\sigma_2$ | $S$ | $S$ | $L'$ |
| $\sigma$ | $t$ | $L'$ | $t$ |

For the processes of coalescence and decay of longitudinal waves with low-frequency waves, $L \pm S \leftrightarrow t$, one has (superscript $\sigma$ is omitted for $\sigma = t$)

$$N \leq \frac{(N^L N^S)}{(N^L \pm N^S)}. \quad (5)$$

An interesting limiting case of the coalescence and decay processes is when one high-frequency wave emits or absorbs a low-frequency wave, i.e., for $\omega^S \ll \omega^L \approx \omega$. If $T^L/\omega^L \ll T^S/\omega^S (N^L \ll N^S)$, then (4) simply reads [*Melrose*, 1980a, 1980b]

$$T \leq T^L. \quad (6)$$

### 2.3. Brightness Temperature and Photon Flux

The effective temperature of photons, $T$, is also called the brightness temperature of the radiation. The value of $T$ is related to the energy flux of photons per unit frequency, $F$, by the equation

$$T \approx \frac{c^2}{2\kappa f^2} \frac{F}{\Delta\Omega_S}, \qquad (7)$$

where $\Delta\Omega_S$ is the angular extent of the observed source, $f$ is the wave frequency, and $c$ is the speed of light. The measured flux $F$ may be used to constrain the brightness temperature of the radiation.

Let us also assume that in the source photons of energy density $W$, frequency $f = \omega/(2\pi)$ and wave vector $\mathbf{k}$ (superscript is omitted for the photons) are produced by a conversion process from electrostatic longitudinal waves of the energy density $W^L = \varepsilon_0(E^L)^2$. According to (1) and (2), this energy density is related to the effective temperature $T^L$ by

$$W^L \sim \kappa T^L \Delta\Omega^L (\Delta k^L/k^L)/(\lambda^L)^3. \qquad (8)$$

Here $\Delta k^L/k^L = |\Delta\lambda^L/\lambda^L|$ is the relative bandwidth of longitudinal waves with the central wavelengths $\lambda^L = 2\pi/k^L$, and $\Delta\Omega^L$ is the range of propagation solid angles [*Melrose*, 1980a]. This means that $\kappa T^L$ is simply the energy density per unit volume in the phase space of longitudinal waves. Taking $\lambda^L = v_e/f$, where $v_e = (\kappa T_e/m_e)^{1/2}$ is the thermal speed of electrons of mass $m_e$ and a typical temperature $T_e \sim 3 \times 10^8$ K [*Krimigis et al.*, 1979], one can now estimate electrostatic wave electric fields $E^L$ from (8) for the saturation steady state condition, $T \approx T^L$ in (6).

## 3. Results

In Jupiter's magnetospheric cavity the energy flux falls as $F \approx 10^{-10} \, (f/10^2)^{-3.5}$ W m$^{-2}$ Hz$^{-1}$. Taking the maximum density flux observed, $F \approx 10^{-10}$ W m$^{-2}$ Hz$^{-1}$ at $f_p \sim 10^2$ Hz [*Gurnett and Scarf*, 1983], one obtains from (7) the brightness temperature of the source, $T \approx 3.3 \times 10^{25}$ K/$\Delta\Omega_S$ (sr). Because obviously $\Delta\Omega_S \leq 4\pi$ sr, this value of $F$ implies $T \geq 2.6 \times 10^{24}$ K. The minimum flux of the trapped component is expected at the plasma frequency of the ambient solar wind at Jupiter's orbit. With $f \approx f_p \sim 5$ kHz and $F \sim 10^{-16}$ W m$^{-2}$ Hz$^{-1}$, one has $T \approx 1.3 \times 10^{16}$ K/$\Delta\Omega_S$ (sr) $\geq 10^{15}$ K. Because $\kappa T \gg m_e c^2$, one sees that the radiation is really nonthermal. Consequently, nonlinear interactions should be considered [*Melrose*, 1970].

Of course, one also has to make an assumption about the wave vector spectrum of electrostatic longitudinal waves. In order to estimate the value of $E^L$ we take the terrestrial values for the foreshock region, $\Delta k^L/k^L = 0.08$, and the range of the propagation solid angle of the longitudinal waves to be of $\Delta\Omega^L \sim 0.2$ sr [*Gurnett*, 1975; *Filbert and Kellogg*, 1979]. Using the maximum value of the estimated brightness temperature, the resulting value of the longitudinal electric field in Jupiter's magnetosphere required to generate the observed continuum flux is rather small, $E^L = 0.5$ mV m$^{-1}$. However, even for the spectral parameters as large as $\Delta k^L/k^L = 1$ and $\Delta\Omega^L = 1$ sr, one obtains $E^L = 3.6$ mV m$^{-1}$. *Scarf et al.* [1979] reported electric fields up to 4 mV m$^{-1}$ in the Jovian magnetosphere. This shows that the model adequately explains the generation of continuum radiation trapped in planetary cavities and possibly in the heliospheric cavity [*Fahr et al.*, 1986; *Macek et al.*, 1991a, 1991b; *Gurnett et al.*, 1993; *Macek*, 1994, 1996].

## 4. Discussion

For the fundamental harmonic emission from electrostatic waves the observed flux density $F$ with a reasonable guess for the parameter $\zeta = (\Delta\Omega_S/\Delta\Omega^L)/(\Delta k^L/k^L)$ implies values of the average field strength of the longitudinal waves required in the source of $E^L \approx 0.5 \div 4$ mV m$^{-1}$. With a possible uncertainty of 2 orders of magnitude in the phase space volume of the longitudinal waves (or $\zeta$), the resulting minimum electric fields obtained by *Macek et al.* [1991b] assuming saturation, i.e., $T = T^L$, would vary by only 1 order of magnitude ($E^L \propto \zeta^{-1/2}$). Without assuming saturation, i.e., $T < T^L$, the results are even less sensitive to the assumed volume in the phase space [*Macek*, 1994].

For a given photon flux $F$ the energy density of longitudinal waves $W^L$ is proportional to the ratio of the longitudinal waves' spectral density to the photon spectral density, $T^L/T$ [*Macek et al.*, 1991b, equation (2)]. Since according to (6), $T \leq T^L$, nonsaturated waves lead to higher average field strengths than those in the limit of saturation. The continuum radiation can probably escape down the Jovian magnetotail [*Gurnett and Kurth*, 1994]. This argues against a steady state being reached. In this case the calculated steady state level of $E^L$ is an average lower limit.

Admittedly, several points have to be clarified before one could consider the scheme described in this paper to represent a physical mechanism in the planetary magnetospheres. The most important point seems to be the question of the "seed population" of electrons with excess free energy in velocities perpendicular to the magnetic field and the actual size of the source.

In (7) we have taken the effective angular extent of a source associated with the density gradients of $\Delta\Omega_S = 4\pi$ sr. One can, in fact, expect that the angular size of the source associated with the density gradient is large. One should, however, remember that the data can only poorly constrain the direction of the incoming radio waves and hence the source location. The resulting field strengths are not very sensitive to the assumed angular size of the source ($E^L \propto \Delta\Omega_S^{-1/2}$). The value of $E^L$ is more sensitive to the characteristic of the electron distribution function, which substantially depends on the local direction of the magnetic field relative to the source of the radiation.

In a nutshell, the saturation condition, $T \sim T^L$ in (6), is hardly satisfied, and a steady state is probably never actually reached. However, in this case the calculated steady state level of required $E^L$ would simply be an average lower limit [cf. *Macek et al.*, 1991a, 1991b; *Macek*, 1996]. For Jupiter's magnetosphere the obtained saturated values are $0.5 \div 3.6$ mV m$^{-1}$. Even though with no saturation these values could be somewhat higher, they should be comparable to those measured in situ by the Voyager spacecraft, 4 mV m$^{-1}$. Hence the nonlinear processes could still be a plausible explanation of the intensity of the observed continuum radiation from Jupiter's magnetosphere.

## 5. Conclusions

The suggested mechanism of the emission is due to nonlinear interaction between upper hybrid waves generated by an electron loss cone distribution in the magnetosphere at the fundamental (or possibly multiples) of the local plasma frequency. The intensity of the radio emissions at $10^2$ Hz can also be explained provided that the electron distribution generating upper hybrid waves exists on density gradients in the magnetospheric plasma. Admittedly, this is one possible explanation of the observations. The field strengths of upper hybrid waves required to generate the fundamental emissions are approximately of 0.5 ÷ 4 mV $m^{-1}$. Comparison of the discussed results with electromagnetic radiation trapped in Jupiter's magnetosphere shows that the model adequately explains the generation of plasma waves in the planetary cavities.

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W. M. Macek, Space Research Centre, Polish Academy of Sciences, Bartycka 18A, PL-00716, Warsaw, Poland. (macek@cbk.waw.pl)

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