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# ELECTROSTATIC WAVES IN THE JOVIAN MAGNETOSPHERE

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*Abstract.* Observations by the plasma wave receivers on Voyagers 1 and 2 show that a wide variety of electrostatic waves are present within the Jovian magnetosphere and that the Jovian electrostatic waves are for the most part very similar to those observed in the terrestrial magnetosphere. Bands of emission near the upper hybrid resonance frequency in the dayside outer magnetosphere are detected between higher harmonics of the electron gyrofrequency. Inside of about 23 $R_J$, electron cyclotron harmonic emissions appear to be durable features of the inner Jovian magnetosphere and are extremely well confined to the Jovian magnetic equator. The cyclotron emissions extend from just above the local electron gyrofrequency to the upper hybrid resonance frequency.

## Introduction

Electrostatic waves are conspicuous features of the terrestrial magnetosphere and have been the subject of numerous observational and theoretical studies (see for example *Kennel et al.* [1970], *Shaw and Gurnett* [1975], *Ashour-Abdalla and Kennel* [1978], *Hubbard and Birmingham* [1978], *Rönnmark et al.*, [1978], and *Kurth et al.* [1979]). In particular the electron cyclotron harmonic emissions are thought to play an important role in scattering electrons into the loss cone, thereby forming the diffuse aurora. Now observations provided by plasma wave and radio astronomy receivers onboard Voyagers 1 and 2 have revealed the existence of similar electrostatic emissions in the Jovian magnetosphere [*Scarf et al.*, 1979; *Warwick et al.*, 1979; *Gurnett et al.*, 1979].

In general the Voyager observations indicate most of the Jovian wave phenomena have direct terrestrial analogs, however, some details of the regions of occurrence differ between the Earth and Jupiter. The electrostatic waves observed in the Jovian magnetosphere are all of the electron cyclotron harmonic (ECH) class lying between harmonics of the electron gyrofrequency, $f_g^-$, ranging up to the upper hybrid resonance frequency, $f_{UHR}$. In this paper we summarize the initial Voyager observations of the electrostatic emissions by enumerating the various types of phenomena, their intensities, and their regions of occurrence. Finally, using our understanding of the terrestrial emissions, we shall comment on the implications the presence of the ECH waves has on the distribution of plasmas in the Jovian magnetosphere.

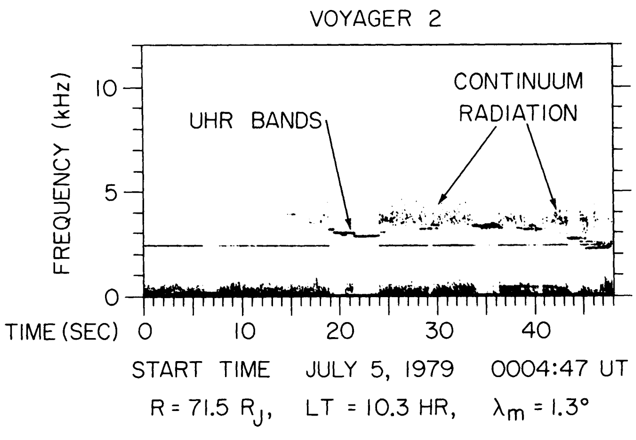

Fig. 1. A frequency-time spectrogram showing narrowband emissions near $f_{UHR}$ in the outer magnetosphere. The bands change frequency in discrete steps approximately equal to $f_g^-$.

Before proceeding, we note that the Voyager plasma wave receivers have only a non-spinning electric dipole antenna and no magnetic sensor, hence, it is not possible to directly determine whether a particular wave phenomenon is electrostatic or electromagnetic nor can we directly ascertain the wave-normal direction. However, based on analogy with electrostatic waves observed extensively in the Earth's magnetosphere, we are reasonably confident of our identification of these emissions. In particular, we emphasize the strong $(n + \frac{1}{2})f_g^-$ dependence of these waves. At the Earth, electron cyclotron harmonic waves, $(n + \frac{1}{2})f_g^-$ emissions, very similar to those seen at Jupiter, all have large electric-to-magnetic field ratios [*Shaw and Gurnett*, 1975; *Kurth et al.*, 1979]. Therefore, the electron cyclotron harmonic emissions are commonly referred to as electrostatic waves and the gyroharmonic nature of the waves indicates wave-normal angles perpendicular to the ambient magnetic field.

## Observations of Jovian Electrostatic Waves

The observations presented in this section are selected from the plasma wave measurements from Voyagers 1 and 2 [*Scarf and Gurnett*, 1977] to serve as a representative sample of the various electrostatic wave phenomena present in the Jovian magnetosphere. As a natural ordering scheme, we choose to begin with observations at the magnetopause and work towards the inner magnetosphere.

Just inside the dayside magnetopause, bands of emission near the upper hybrid resonance frequency ($f_{UHR}^2 = (f_p^-)^2 + (f_g^-)^2$) are occasionally observed. This region is dominated by the presence of nonthermal continuum radiation trapped by the higher magnetosheath densities [*Scarf et al.*, 1979; *Gurnett et al.*, 1979]. In the L-O mode the electromagnetic continuum radiation can propagate down to the P=0 cutoff at the electron plasma frequency, $f_p^-$. Continuum radiation propagating in the R-X mode can propagate down to the R=0 cutoff and these two cutoffs cannot be uniquely differentiated without polarization measurements. In this case, however, $f_p^- \gg f_g^-$ and the

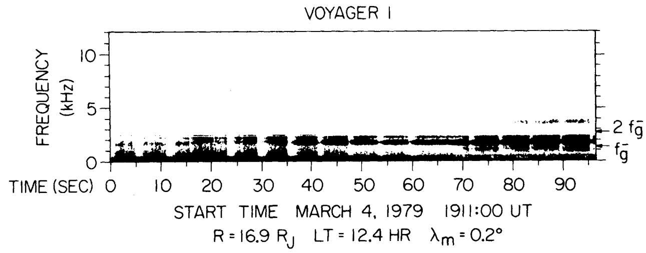

Fig. 2. An example of $3f_g^-/2$ and $5f_g^-/2$ emissions observed near the magnetic equator during the Voyager 1 encounter. The periodic signal dropouts are an AGC effect due to interference from a stepper motor on the spacecraft.

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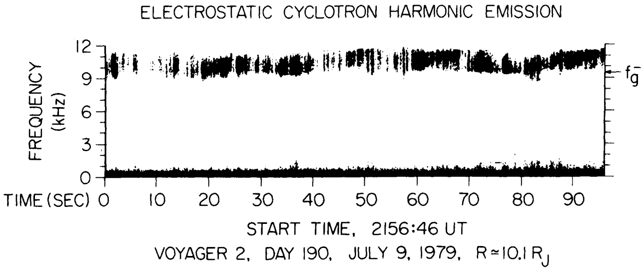

Fig. 3. An example of $3f_g^-/2$ emission just above $f_g^-$ observed near the Voyager 2 periapsis.

R=0 cutoff is very close to $f_p^-$. Hence, the lower cutoff of the continuum provides an accurate measure of the local electron density. As shown in Figure 1, narrowband emissions occur very close to the lower frequency cutoff of the continuum radiation. Plotted are the relative intensities of waves as a function of frequency and time with the darker regions representing the most intense waves. The continuum radiation which appears in Figure 1 as diffuse wave activity above about 3 to 4 kHz seems to disappear when the more intense UHR bands appear because of the characteristics of the automatic gain control (AGC) receiver. When the more intense upper hybrid waves are present, the gain of the AGC receiver is set lower and the weaker continuum radiation falls below the receiver threshold. The dynamic range of the receiver is ~ 20 db for a fixed gain, hence, the electrostatic waves are at least 20 db above the intensity of the continuum radiation. Therefore, since the continuum radiation has a spectral density of $1.2 \times 10^{-13}$ $V^2m^{-2}Hz^{-1}$ as determined using the plasma wave receiver's spectrum analyzer, the narrowband emissions must have amplitudes $\gtrsim 60$ μV $m^{-1}$.

The most interesting aspect of the narrowband features in Figure 1 is that the band does not change frequency continuously, but changes in discrete steps of about 200 Hz. The magnetic field at this time is about 6.5 nT [N. F. Ness, personal communication, 1979] corresponding to a gyrofrequency of about 180 Hz. Hence, the spacing between two steps is approximately the local electron gyrofrequency. Since the band frequency is very close to the lower cutoff of the continuum radiation, the tendency for the emission to occur in discrete steps of $f_g^-$ provides virtually unmistakable evidence that the bands are perpendicularly propagating waves in the upper hybrid mode between higher harmonics of the gyrofrequency and not, for example, Langmuir waves travelling along the magnetic field. Similar emissions occurring just beyond the terrestrial plasmapause have been described in detail by *Kurth et al.* [1979], and *Hubbard et al.* [1979] have studied emissions near $f_p^-$ in the outer dayside magnetosphere of the Earth. The simultaneous occurrence of upper hybrid resonance bands and continuum radiation is common at the Earth. In fact, emissions near $f_{UHR}$ are thought to be a source of terrestrial nonthermal continuum radiation (see, for example, *Kurth et al.* [1979] and references therein).

A major difference in the occurrence of electrostatic waves at Jupiter and at Earth is the lack of emissions at the lower $(n + \frac{1}{2})f_g^-$ bands in the outer dayside magnetosphere of Jupiter. The Earth is characterized by relatively intense $3f_g^-/2$ and multiharmonic emissions in this region of the magnetosphere, but there is little or no evidence of $(n + \frac{1}{2})f_g^-$ emissions in the outer Jovian magnetosphere except for those near $f_{UHR}$ discussed above. Wave amplitudes at the lower frequencies are slightly greater than magnetosheath levels, but neither the spectrum analyzer channels or waveform receiver of the plasma wave instrument shows the presence of banded emissions near the lower harmonics of $f_g^-$.

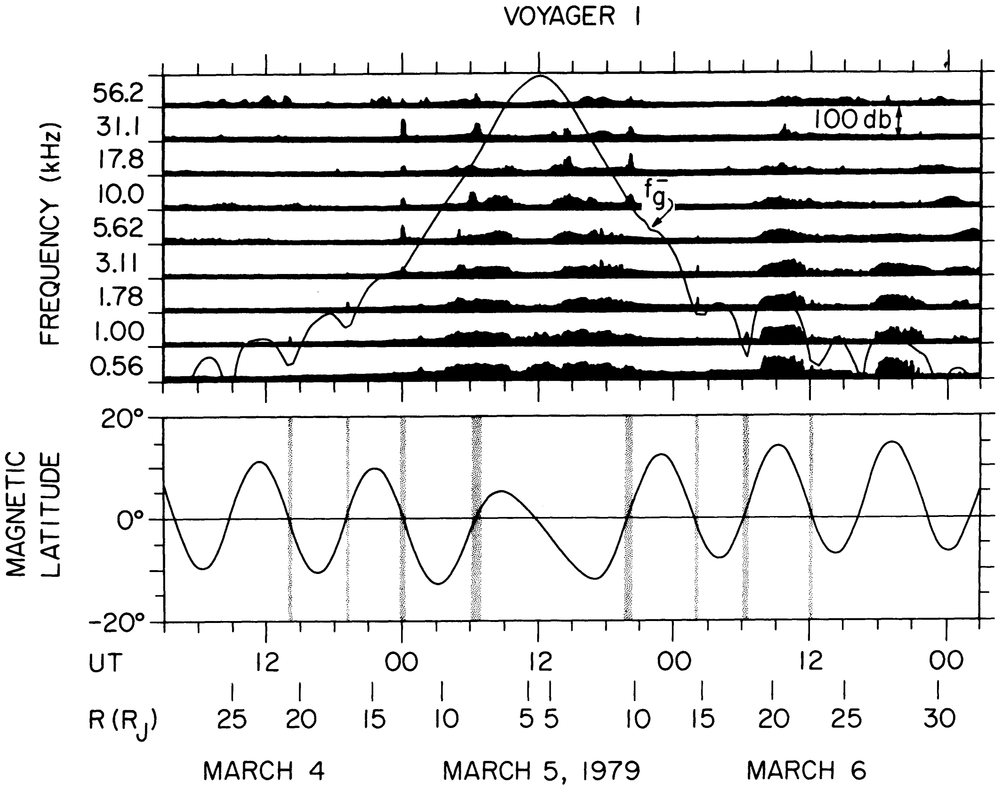

Fig. 4. Average electric field strengths are plotted as a function of time in the upper panel for 9 step frequency receiver channels to illustrate the occurrence of electron cyclotron harmonic emissions in the inner Jovian magnetosphere. The vertical grey strips in the lower panel mark the position and duration of the emissions. Notice that the electrostatic waves are observed within a few degrees of the magnetic equator on every equatorial crossing within 23 $R_J$. The $f_g^-$ contour is based on the onboard magnetometer measurements [Ness et al., 1979].

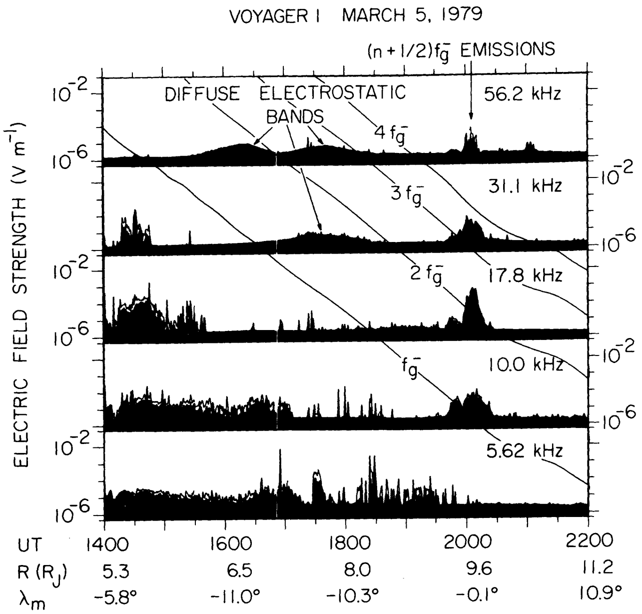

Fig. 5. Step frequency receiver data showing the weak, smoothly varying character of diffuse electrostatic bands between harmonics of $f_g^-$ near the Voyager 1 periapsis.

As the Voyager spacecraft approached the inner magnetosphere the plasma wave receivers detected emissions at odd, half-harmonics of $f_g^-$ on virtually every crossing of the magnetic equator within ~ 23 $R_J$. Figure 2 is a frequency-time spectrogram illustrating one of the first events detected by the Voyager 1 instrument on its inbound leg. A band of emission is present between $f_g^-$ and $2f_g^-$ for the entire period of time shown with a $5f_g^-/2$ emission appearing toward the end of the interval. The values of $f_g^-$ and $2f_g^-$ indicated in Figure 2 are derived from the magnetic field strength as measured by the onboard magnetometer [N. F. Ness, personal communication, 1979]. This event lies only about 1° from the magnetic equator based on the D4 magnetic field model [*Smith et al.,* 1975] which we use throughout this paper.

The $(n + \frac{1}{2})f_g^-$ emissions shown in Figure 2 are somewhat more complex than those usually detected at the Earth in that those illustrated appear to consist of a relatively intense, narrowband emission near 1.5 $f_g^-$ with weaker emission covering much of the range from ~ $f_g^-$ to $2f_g^-$. (The gap near 2.4 kHz is a notch filter in the receiver designed to reduce interference from the spacecraft power supply. The semi-regular interruption of the signal is an AGC effect due to strong, periodic interference from the low energy charged particle instrument's stepper motor.)

A second example of a $3f_g^-/2$ emission within the inner magnetosphere is shown in Figure 3. This example is from the Voyager 2 closest approach ($R \simeq 10\ R_J$, $\lambda_m = -1.3°$). Notice that this band extends almost down to $f_g^-$ as determined by magnetic field measurements [N. F. Ness, personal communication, 1979]. Terrestrial $3f_g^-/2$ emissions often occur very close to $f_g^-$ as in Figure 3 [*Shaw and Gurnett,* 1975]. Step frequency receiver data for this time period indicate higher harmonics are also present, extending up to $f_{UHR}$ [*Gurnett et al.,* 1979].

As mentioned above, the $(n + \frac{1}{2})f_g^-$ emissions are observed near the magnetic equator on virtually every equator crossing in the inner magnetosphere. Figure 4 summarizes this effect as seen in the Voyager 1 encounter data. The upper panel shows 288-second electric field strength averages as a function of time for the upper 9 step frequency receiver channels. The solid black areas are approximately proportional in height to the logarithm of the electric field strength with a dynamic range of 100 db below ~ 100 mV $m^{-1}$. The magnetic latitude is plotted in the lower panel. The vertical shaded regions indicate times when electrostatic waves are being detected as shown in the upper panel. Inside of ~ 23 $R_J$ every crossing of the equatorial plane is accented by emissions between $f_g^-$ and $f_{UHR}$. The gyrofrequency is out of the frequency range at closest approach, but electrostatic emissions at $(n + \frac{1}{2})f_g^-$ harmonics are reported by *Warwick et al.* [1979] during this time. Notice that each event is confined to within a few degrees of the equator. We can estimate the half-thickness, Z, of the region containing the waves by assuming the events occur right at the D4 equator and are symmetric above/below the equator occurring within ± λ degrees of it. If R is the spacecraft radial distance at the crossing, we have approximately

$$Z \simeq R \tan \lambda \qquad (1)$$

We find that the largest latitude achieved for the eight events is $\lambda_{max} = 1.9°$ (for the fifth crossing) and the largest half-thickness is $Z_{max} \simeq 0.44\ R_J$ for the seventh event. The averages over the eight events are $\lambda_{avg} \simeq 1.1°$ and $Z_{avg} \simeq 0.28\ R_J$. Hence, electrostatic electron cyclotron harmonic waves in the inner Jovian magnetosphere are very tightly confined to the magnetic equator. Furthermore, the more distant regions are confined to even smaller latitudes than those near closest approach and this may indicate that the diamagnetic depressions in the magnetic field have some effect on the containment of these waves at greater distances. Note also that there appears to be a tendency for the events to lag the D4 equatorial plane crossing by a small amount. This may be indicative of a heavier inner magnetosphere observed by Voyagers 1 and 2 than by Pioneers 10 and 11 because of volcanic activity on Io during the interim.

There is evidence that the terrestrial electron cyclotron emissions are found primarily at the magnetic equator [*Kennel et al.,* 1970; *Fredricks and Scarf,* 1973], but there are numerous exceptions to this trend. At Jupiter, however, there is no question that the emissions are tightly confined to the magnetic equatorial plane. It is also apparent that at Jupiter the electron cyclotron harmonic emissions are durable features of the inner magnetosphere since the emissions are prominent in all crossings of the magnetic equatorial plane. The apparent permanence of the electrostatic waves near the equator, however, does not imply a steady-state existence of large amplitude waves. On the contrary, during an individual event, the amplitude is observed to fluctuate over more than an order of magnitude on time scales of several seconds. The high temporal variability suggests the presence of a microscopic plasma instability since localization and propagation effects common to instabilities often result in such fluctuations even without rapid, gross changes in the particle distribution function.

The average amplitudes of the emissions in the inner magnetosphere show distinct trends. First, close examination of the events in Figure 4 shows that maximum amplitudes are usually seen in the band just above $f_g^-$, that is, the $3f_g^-/2$ band and at the highest frequency of emission which, by analogy with emissions at the Earth, we believe to be at or near $f_{UHR}$. Second, the intensities of the emissions are greatest at smaller radial distances and decrease with increasing distance. The maximum amplitudes observed are in the range of a few mV $m^{-1}$.

Figure 4 also shows evidence of day-night asymmetries in the amplitudes of the cyclotron harmonic emissions. For example, near 0000 UT 5 March 1979, when Voyager was near 13 hours local time, the $3f_g^-/2$ emission in the 56.2 kHz channel is more than an order of magnitude more intense than the event near 0200 UT on March 6 when Voyager was at a similar radial distance, but at 2 hours local time. Also note the dayside event exhibits an intense emission at $f_{UHR}$ (31.1 kHz), which is not present in the nightside event.

Figure 5 illustrates another type of electrostatic emission common at the Earth and also of the $(n + \frac{1}{2})f_g^-$ genre. The smoothly varying low amplitude emissions in the 56.2- and 31.1-kHz channels are nearly identical to diffuse electrostatic bands seen just beyond the terrestrial plasmapause [*Shaw and Gurnett*, 1975; *Kurth et al.*, 1979]. These bands are found at magnetic latitudes off the equatorial plane, not far from the higher density Io plasma torus. As shown in Figure 5, the diffuse electrostatic bands lie between harmonics of $f_g^-$ which are indicated by solid lines in the illustration. The values of $f_g^-$ are based on magnetometer measurements [*Ness et al.*, 1979]. The diffuse electrostatic bands are significantly weaker than the emissions confined to the equatorial plane with typical amplitudes near 10 $\mu$V m$^{-1}$.

## Discussion

Voyager observations of electrostatic waves in Jupiter's magnetosphere have afforded the opportunity for a penetrating look into plasma-physical processes occurring there. A detailed body of knowledge concerning these emissions in the Earth's magnetosphere is rapidly growing and we have already made use of that knowledge in identifying characteristic features in the wave data. The similarity of these emissions at Jupiter to their terrestrial cousins has demonstrated the general nature of ECH waves for magnetospheric and astrophysical environments that are not too dissimilar. However, we stress that there are significant morphological differences and we believe this information not only can teach us something about Jupiter's magnetosphere but also deepen our understanding of the terrestrial emissions.

The Jovian data have underscored the magnetic equator as a particularly important location for an electron cyclotron instability and effective wave-particle interactions which, at the Earth, are thought to precipitate diffuse auroral electrons. While equatorial confinement of electrostatic emissions has been observed at Earth, the effect is much stronger at Jupiter. At $R \simeq 7.5\ R_J$, the latitudinal extent is only ± 1.7° for a moderately intense [0.2 mV m$^{-1}$] "3/2's" emission. This region of the magnetosphere is dominated by the Io plasma torus with its cool 50 - 100 eV plasma and relatively undistorted magnetic field. The ratio $f_p^-/f_g^- \simeq 10$ for this event [*Warwick et al.*, 1979]. In addition to the cool plasma there is evidence suggesting significant fluxes of nonrelativistic ~ keV electrons pervade the torus [*Coroniti et al.*, 1980] based on the presence of VLF chorus emissions at $f \simeq f_g^-/2$ [cl., the fourth event in Figure 4]. Electrostatic waves also interact strongly with $\gtrsim$ few keV electrons. Thus, both the dramatic equatorial confinement of the waves together with the association with odd half-harmonics of the gyrofrequency lead us to think that an anisotropic loss cone-like distribution of keV electrons exists with a cool background ($n_h/n_c \ll 1$) providing a situation for electrostatic wave instability. The outer portion of the magnetosphere at Jupiter ($\gtrsim 20\ R_J$) is made up of predominantly hot plasma [*Barbosa et al.*, 1979] and isotropic electrons [*Sentman and Van Allen*, 1976], a situation not unlike the Earth's tail plasma sheet [*Frank et al.*, 1980]. It follows that the emissions will probably not be conspicuous features of the Jovian magnetosphere beyond about 20 $R_J$ as we have observed. The results of a theoretical analysis with these guidelines will be reported shortly.

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