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Radio emissions observed by Galileo near Io

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Abstract. The Galileo spacecraft observed spin modulation of radio wave emissions near Io in the frequency range from about 600 kHz to about 1.2 MHz. Assuming transverse EM radiation, we have used the modulation of the high-frequency sweep-frequency receiver signals of the electric dipole antenna over many spins to estimate the plane through the source. The emission has a range of frequencies close to the local upper hybrid frequency of the plasma near Io. We conclude that the emission may be associated with either the plasma torus or magnetic flux tubes in the wake of Io (the Alfvén current system). We postulate this emission may be associated with a free-energy source such as density gradients, energetic plasma beams and/or an electron distribution with a temperature anisotropy. All of these free-energy sources are observed or expected in the torus near Io. The observations are the first in the hectometric frequency range that have a source associated with Io or in the Io torus.

1. Introduction

Data returned by the Galileo spacecraft in orbit around Jupiter since December 1995 has continued to reveal remarkable new facts about the magnetosphere of the giant planet [cf. *Science 274*, Oct. 18, 1996]. The plasma wave instrument (PWS) on board has detected high plasma densities near Io and the Io wake and has been continuously returning plasma and radio emission data in the frequency range from 5.6 Hz to 5.6 MHz. Direction finding using spin modulation of radio wave data has been used by numerous satellites [cf. Fainberg et al., 1972; Kurth et al., 1975; Morgan and Gurnett, 1991] and more recently from interplanetary probes [cf. Reiner et al., 1993a,b; Ladreiter et al., 1994]. In the latter studies, data from the Unified Radio and Plasma Wave (URAP) experiment on the Ulysses spacecraft were used to produce the first direction-finding studies of radio emissions from Jupiter using an instrument designed in part for this purpose. Jovian hectometric emission (HOM) exists in the approximate frequency range 200 kHz $< f <$ 2 MHz [cf. Carr et al., 1983; Ladreiter and Leblanc, 1991]. This emission is now believed to have a source either in the auroral region at $L > 6$ [cf. Ladreiter et al., 1994] or near the foot of the magnetic field lines located in the range $3 < L < 10$ [Reiner et al., 1993a,b; Menietti and Reiner, 1996]. Most recently, Kurth et al. [1997] have used the occultation of radio emission observed by Galileo during the first flyby of Ganymede to determine the source of HOM in the frequency range 700 kHz to 5.6 MHz. Their results suggest a source along an $L \gtrsim 7$ magnetic field line, consistent with a Ganymede or Europa flux tube. Until now, there have been no reported observations of HOM radio emission that have a source at or near Io.

In this paper we analyze some of the radio emission data returned by PWS on board Galileo just after the flyby of Io and before the Jovian orbit injection. We restrict ourselves to observations obtained from the plasma wave high-frequency receiver (101 kHz $< f <$ 5.6 MHz) and in particular to emissions near 1 MHz. We will show that direction finding can be used to determine the approximate source location of the radio emissions, and indicates that the plasma in the vicinity of Io is the most likely source. This puts a number of constraints on the source mechanism as will be discussed in Section 4.

2. Instrumentation

The plasma wave receiver on board Galileo consists of 4 different sweep frequency receivers that cover the frequency range from 5.6 Hz to 5.6 MHz for electric fields and 5.6 Hz to 160 kHz for magnetic fields. For this study only electric field data obtained by the high-frequency receiver (HFR) will be analyzed, covering the frequency range from about 101 kHz to 5.6 MHz. The single electric dipole antenna with a tip-to-tip length of 6.6 m is connected to each electric receiver. A complete set of electric field measurements is obtained every 18.67 seconds with a frequency resolution of about 10 % [cf. Gurnett et al., 1992]. The antenna is attached to the end of a boom and extends perpendicular to the spin axis.

3. Direction-Finding Analysis and Observations

A freely propagating transverse EM wave will be received with maximum intensity if the antenna is perpendicular to the wave vector of the incoming wave. In other words, we determine the plane containing the source and the spin axis of the spacecraft. Let us assume a discrete radio emission source with constant power and location. If this source lies close to the spin plane of a rotating dipole antenna, the radio receiver should measure power as a function of time that varies smoothly with a peak intensity when the electric plane of the antenna is perpendicular to the wave propagation vector. Difficulties with the technique are many in practice because the spacecraft is moving and the source regions vary in size, frequency, and intensity with time, and the source is in general not in the spin plane of the spacecraft. Some direction information out of spin plane is possible, however, using the modulation index [cf. Fainberg et al., 1972; Morgan and Gurnett, 1991], which we discuss below. In this work we assume the radio emission is not elliptically polarized, which is a good assumption for Jovian hectometric emission [cf. Reiner

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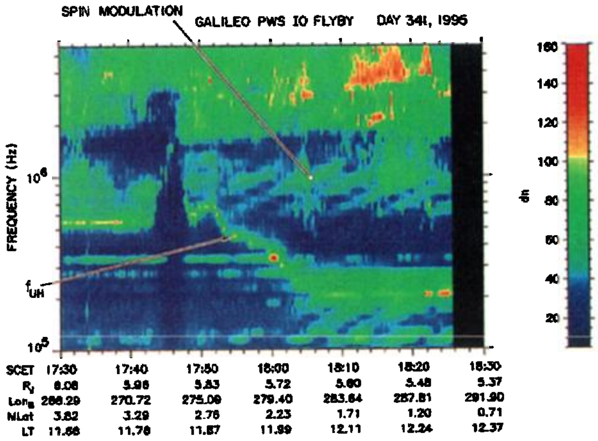

Figure 1a. Frequency-vs-time spectrogram of PWS data for a brief period on day 341 of 1995, during and just after the Io flyby. The spin modulation is seen after about 17:54 for frequencies in the approximate range 600 kHz < f < 1.2 MHz.

et al., 1993b, 1995]. If, however, this is not the case (i.e., a large longitudinal component), then our calculated directions to the source could be significantly in error.

Since the spacecraft spin axis points essentially at the Earth, Galileo was in a favorable position to see spin modulation from a source in the vicinity of Io near closest approach (CA) on day 341 of 1995. The spacecraft at this time was not in a favorable orientation to observe spin modulation of radio emission from a source near Jupiter, because the direction to Jupiter was nearly perpendicular (89.3°) to the spin plane of the spacecraft. The top panel of Figure 1 is a frequency-vs-time spectrogram of the data obtained near CA. Seen in the figure is the rather discrete upper hybrid emission, which is an indicator of the local plasma density [cf. Gurnett et al., 1996]. Also indicated is spin modulation (diagonal bands) in the frequency range from about 600 kHz to about 1.2 MHz observed immediately following CA in the time period from about 17:55 to 18:25 spacecraft event time (SCET). The modulation is produced by a "beating" of the plasma wave instrument (PWS) frequency cycling period (18.67 sc) against the spin period of the spacecraft (~ 19.0 sc). It disappears if the source signal strength decreases sufficiently or if the spacecraft orientation relative to the source is not favorable (i.e., if the source lies far from the spin-plane of the satellite).

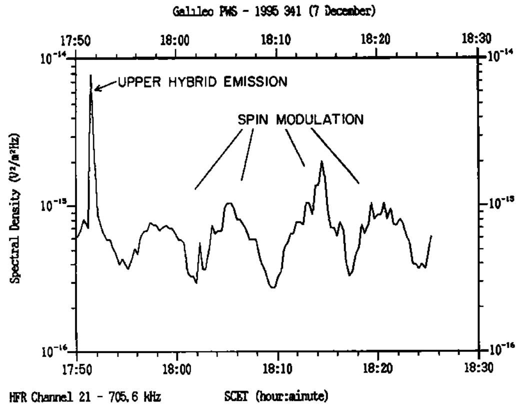

Figure 1b. Electric field intensity versus time at a frequency of 705.6 kHz indicating the spin modulation (sinusoidal curve).

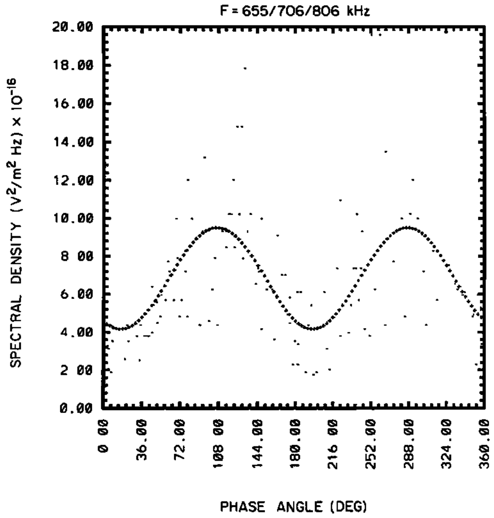

Figure 2. Spectral density ($\times 10^{-16}$) versus spin angle for 17:54 < t < 18:25. To improve statistics, the plot includes data for 3 adjacent frequency channels: 655.2 kHz, 705.6 kHz, and 806.0 kHz.

The electric field intensity for a frequency of 705.6 kHz for 17:50 < t < 18:25 is shown in Figure 1b. The spin modulation (roughly sinusoidal shape) is seen for t > 17:54. The emission spectral density versus satellite spin angle, ϕ, for an extended period of time for 3 adjacent frequency channels is plotted in Figure 2. The curve has a period of π instead of 2π because the spacecraft antenna is properly oriented for optimum reception twice each spin period. Thus, the source direction could be in one of two directions separated by 180 degrees.

We have performed a least squares fit of this data to the functional form A + B cos(2ϕ-d), where d/2 is the phase shift or direction to the source in the spin plane of the satellite, and A and B are offset and amplitude fitting parameters. The data of Figure 2 yields a spin-plane source direction of ~ 16° to the north of Io (the

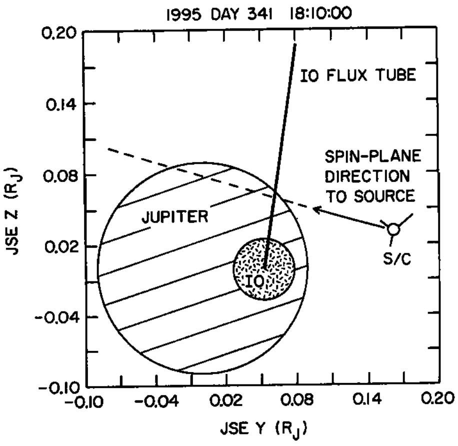

Figure 3. Direction to the source region projected into the spin-plane of the satellite (y-z plane). The direction is determined from the data of Figure 2.

direction of Io's center is 0°). Alternatively the direction could be -147 degrees in the direction away from and to the south of Io. This direction is shown with Io projected into the spin plane of the spacecraft (JSE Y-Z plane) in Figure 3. Due to the scatter of the data points we estimate the statistical error of this propagation direction to be ±4°. The estimate of the statistical error was obtained by varying the phase angle until χ^2 changed by an amount corresponding to one standard deviation. Refractive effects have not been considered in this analysis. For information out of the spin plane we have calculated the modulation index defined as M = B/A, which essentially is a measure of the depth of the nulls (valleys) of the modulated signal. To interpret the index it is necessary to make assumptions about the nature of the source and the background unmodulated signal. If we assume that the source is a point source out of the spin plane, it can be shown that $\cos\theta = \sqrt{2M/(1+M)}$ where θ is the azimuthal angle measured from the spin plane to the source. We give two values for θ depending upon two different assessments of the background emission. First we determine the background by calculating the average of the highest and lowest signal strengths observed near the null points. For this case we obtain $\theta \sim 18°$. If we assume the background is the lowest signal strength received during the time of observations, then $\theta \sim 35°$. These angles are shown in Figure 4. The calculated direction to the source is consistent with a source region that is located in the Io torus or along magnetic flux tubes in the wake of Io.

4. Discussion

The particularly interesting spin-modulated radio emission in the HOM frequency range observed near Io, while Galileo was within the dense region of the Io torus, is consistent with a source that lies along a recently visited Io flux tube (in the wake of Io) or within the Io torus. The spacecraft orientation was not favorable to receive spin modulation from a Jovian source at this time. Since the local gyrofrequency near Io (~ 40 kHz) is much less than the observed spin-modulated emission (600 kHz < f < 1.2 MHz), the cyclotron maser instability is not a viable wave generation mechanism. We postulate that electron beams may be an alternative free-energy source for this emission. Candidate wave generation mechanisms include both linear and nonlinear wave conversion mechanisms [Jones, 1985, 1986; Melrose, 1981; Rönnmark, 1983] or the temperature anisotropic beam instability (TABI) [Wong and Goldstein, 1990; Winglee et al., 1992]. In the linear wave conversion mechanism (LWCM), electrostatic waves near the upper hybrid frequency and in the presence of a density gradient can mode-convert into radio waves in the ordinary mode. In the nonlinear wave conversion mechanism, intense upper hybrid waves coalesce with low-frequency electrostatic waves to generate O-mode waves. These mechanisms have been proposed as a source of left-hand polarized kilometric radiation observed at Jupiter. In the TABI mechanism, an electron distribution including an electron beam and a temperature anisotropy ($T_\perp > T_\parallel$) is unstable to radio emission that can be left-hand circular polarized (LCP) if $\omega_{pe}/\omega_{ce} \gtrsim 1$ or RCP if $\omega_{pe}/\omega_{ce} \lesssim 1$. The spin-modulated radio emission is observed well above both ω_{pe} and ω_{ce} and can be either right-hand extraordinary or left-hand ordinary mode emission, but unfortunately the wave polarization is not directly obtainable from the PWS measurements.

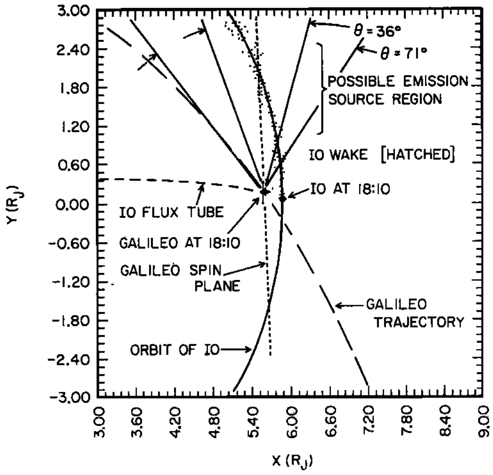

Figure 4. The positions of the spacecraft and Io in the x-y plane are shown at the time 18:10, near the midpoint of the spin-modulation observations. The spin plane of Galileo and two out-of-spin-plane angular ranges are shown intersecting a possible source region of the emission in the Alfven current system of the Io wake. The smaller angular range is determined assuming a higher unmodulated background signal level.

Near Io, upper hybrid emissions were clearly observed as indicated in Figure 1a and discussed by Gurnett et al. [1996]. In addition, electron beams with energies greater than 15 keV have been observed near Io [cf. Williams et al., 1996]. Also, density gradients and temperature anisotropic particle distributions (at least in the ions) are expected in the Io torus [cf. Bagenal, 1994; Schneider et al., 1997; Thomas and Lichtenberg, 1997]. It is significant that the electron density in the vicinity of Io has been reported to be as large as 5300 cm^{-3} [cf. Gurnett et al., 1996]. This means the local plasma and upper hybrid frequency in this region would be ~ 700 kHz, comparable to the range of frequencies observed with spin modulation just after the Io closest approach.

Gurnett and Goertz [1981] have postulated that a current is carried by Alfven waves that propagate along the Alfven wings and are reflected in the ionosphere, and partially reflected and refracted in the Io torus. Goldstein and Goertz [1983] have further suggested that the kinetic Alfven waves could accelerate electrons along the Io flux tube. Therefore, in a second scenario, we postulate that the spin-modulated radio emission detected by PWS near Io may have a source in the downstream wake of Io in flux tubes of the reflecting Alfven wave current system, as indicated in Figure 4. Published theories of HOM suggest source regions near Jupiter, either in the auroral regions or at the foot of the Io flux tubes [cf. Ladreiter et al., 1994]. The spin-modulated observations obtained near Io by Galileo are thus the first reported emissions in the HOM frequency range that have a possible source in the Io plasma torus or along magnetic flux tubes in the Io wake.

5. Summary and Conclusions

The Galileo PWS observed spin-modulated emission shortly after the flyby of Io in the frequency range from about 600 kHz to about 1.2 MHz. This spin modulation is produced by a beating of the spacecraft spin period and the cycling period of the frequency channels of the PWS instrument. This allows a determination of the direction to the source in the spin plane of the satellite. Our results indicate that the source of the emission is most likely the Io torus or magnetic flux tubes in the wake of Io (the Alfven wing current system). Spin modulation from a source near Jupiter is not likely due to the orientation of the spacecraft at the time. Plasma wave refraction due to the dense Io plasma torus undoubtedly occurs [cf. Menietti and Reiner, 1996], however, such effects are relatively small and will not alter the general conclusions derived here. The emission frequency is near the local upper hybrid frequency in the vicinity of Io, and we suggest some possible candidate wave generation mechanisms. First is the LWCM proposed as a source of some Jovian kilometric emission [Jones, 1986; 1987]. This mechanism requires intense electrostatic emissions (such as upper hybrid emission) in the presence of strong density gradients, both of which are known to exist near Io [cf. Gurnett et al., 1996; Bagenal, 1994]. Nonlinear mode conversion due to coalescence of intense upper hybrid waves and low-frequency electrostatic waves has also been proposed as a source of Jovian kilometric O-mode emission by Melrose [1981] and Rönnmark [1983]. Another possible emission mechanism is the TABI [Wong and Goldstein, 1990; Winglee et al., 1992], which requires electron beams and a plasma distribution with an electron temperature anisotropy ($T_\perp/T_\parallel > 1$). Electron beams have been observed near Io [Williams et al., 1996], and temperature anisotropies for electrons are not unlikely in the Io torus and indeed are expected for the ions [cf. Bagenal, 1994].

The observations presented represent the first in the HOM frequency range from a source or sources near Io. The emissions suggest a very dynamic and unstable plasma environment in this region which will be of much interest in future detailed studies of the plasma distribution.

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