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Control of Jovian radio emission by Ganymede

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Abstract. Galileo has been in orbit around Jupiter since December 1995. We present the results of a survey of the data for the frequency range 3.2 MHz to 5.6 MHz, the low-frequency decametric (DAM) emissions. While the control of a portion of the radio emission by the moon Io is well-known, we report that a small but significant portion of low-frequency DAM emission is seen to be correlated with the orbital phase of Ganymede. This result is in agreement with other recent results indicating a significant interaction of the magnetosphere of Ganymede with that of Jupiter.

Introduction

Decametric radiation ($3 < f < 40$ MHz) has been perhaps the most actively studied Jovian radio emission. Ground based observations date from Burke and Franklin [1955], revealing the power of the Jovian transmitter. The exciting discovery of the correlation between the orbital phase of Io and the occurrence of DAM storms [Bigg, 1964] marked the beginning of an increasingly intense study of the source location and generation mechanism for DAM emission. Ground-based observations were responsible for the eventual development of the Jovian longitude-Io phase plots and the initial identification of the now standard Io-A, Io-B, Io-C, and Io-D "sources". In addition, the discovery of an 11.9 year periodicity of the DAM (equal to the sidereal period of Jupiter) was believed due to changes in the declination of the observer. The purpose of this paper is to report the discovery of control of a portion of the DAM radio emission by Ganymede.

The Voyager missions finally opened the radio window to broadband observations extending from a few kHz to 40 MHz. Continuous monitoring at high resolution revealed a dynamic spectrum characterized by vertex-early and vertex-late "arcs" [cf. Carr et al., 1983]. The occurrence of emission for ranges of Io orbital phase centered near ~ 240° and ~ 90° is believed to be due to cyclotron resonant emission at large wave normal angles in a hollow emission cone [cf. Goldstein and Goertz, 1983; Green, 1984; Menietti et al., 1987; Wilkinson, 1989].

Gurnett and Goertz [1981] proposed that the decametric arcs are caused by the multiple reflections of a standing Alfvén wave current system excited by Io, as it interrupts the corotational flow of plasma around Jupiter. Others, such as Staelin [1981] have suggested the arcs are due to the dependence of the wave normal angle on frequency, in turn a result of the cyclotron maser instability [Wu and Lee, 1979]. For a review of these and other explanations of the arc structure of DAM see Goldstein and Goertz [1983]. Excellent descriptions of the Voyager PRA observations can be found in Warwick et al. [1979], Boischot et al. [1981], and a thorough review of the spectral phenomenology was presented by Carr et al. [1983].

The Galileo mission is unique in two major ways. First it is an orbiter instead of a "flyby" mission, and second it has made multiple close approaches to each of the Galilean satellites. The data from this mission can thus greatly complement and extend that of the Voyager and Ulysses flyby missions. The Galileo mission has provided a unique opportunity to contribute to this investigation of DAM and hectometric (HOM) sources. Based on ground observations, Kaiser and Alexander [1973] first reported that only the Jovian moon Io showed a correlation of orbital phase with DAM radio emission. The Voyager and Ulysses flyby missions have also not shown any clear satellite control of radio emission other than Io. Because of the continuous sampling of the radio emission data and the proximity of the spacecraft to Jupiter, however, Galileo has been able to improve the statistics of the investigation, and a number of new and exciting discoveries have been made regarding Ganymede.

Kivelson et al. [1996; 1997] have reported the possible discovery of an intrinsic magnetic field at Ganymede. Gurnett et al. [1996] have reported a magnetosphere with a relatively high-density ionosphere. Frank et al. [1997] have reported strong hydrogen outflows from the polar region of Ganymede. Kurth et al. [1997b] and Menietti et al. [1998] have shown that Galileo radio emission direction finding measurements can be interpreted as suggesting that the instantaneous Ganymede flux tube may be a source of HOM/DAM emission. Most recently, analysis of Galileo high energy plasma data from the Energetic Particle Detector (EPD) data has led Eviatar et al. [1998] to conclude that the deceleration of corotational flow of Jovian plasma near Ganymede requires an Alfvén wing type of current interaction. Such studies indicate that the interaction of Ganymede's own magnetosphere with that of Jupiter is much more complex and interesting than previously believed. The observations reported in this paper support this developing understanding.

Instrumentation/Observations

The Galileo plasma wave instrument (PWS) provides excellent spectral frequency resolution over a range extending from a few Hz to almost 6 MHz, covering the low-frequency portion of the decametric emission. Since Galileo is an orbiter, in contrast to past flyby missions, it provides unique local time information and continuous sampling of the equatorial magnetosphere in the radial distance range from about 9 R_j to over 140 R_j. The magnetic latitude of Galileo varies between -10° and +10° for the duration of the mission, i.e., the Jovicentric latitude is near 0 and both magnetic poles are alternately seen by the spacecraft each Jovian rotation. Figure 1 shows a plot of portions of the orbits for which the data was sampled. For this study, no data was included for radial distances less than 25 R_j, in other words inside the orbits of Io and Ganymede.

The plasma wave receiver on board Galileo consists of 4 different swept-frequency receivers that cover the frequency range from 5.6 Hz-5.6 MHz for electric fields and 5.6 Hz to 160 kHz for magnetic fields. We will concentrate in this study on the electric field measurements obtained by the high-frequency receiver,

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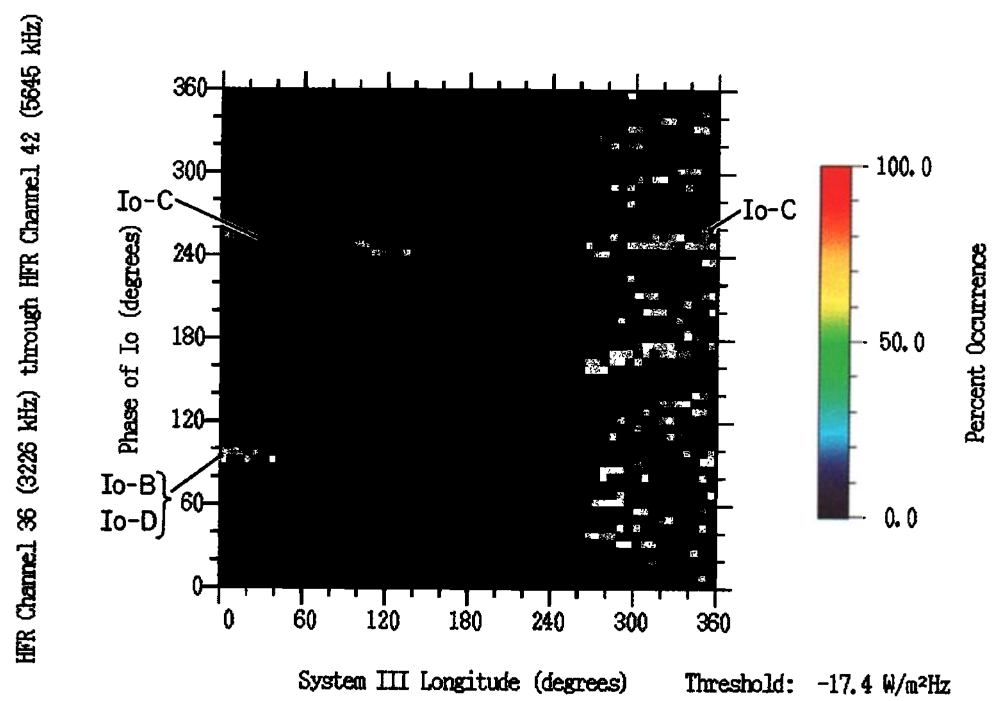

Plate 1. Percent occurrence probability of decametric radiation as a function of orbital phase of Io and system III longitude showing the expected regions of Io-dependent and Io-independent emission. The percent occurrence of the emission is color-coded according to the color bar at the right.

which covers the frequency range from 100.8 kHz to 5.6 MHz. A 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].

We have conducted a survey of the Galileo data set in the frequency range 3.2 MHz $< f <$ 5.6 MHz for portions of the time interval from day 341 of 1995 to day 314 of 1997. This is in the lower frequency range of DAM, a range that was not well-resolved by the Voyager Planetary Radio Astronomy instrument (PRA) due to spacecraft interference. All the intensity values are normalized to a distance of 100 R_J. The data have been sorted in 6° x 6° bins of Jovian satellite orbital phase (γ_I or γ_G) versus system III longitude, λ_{III}. This bin size was chosen to provide a large number of data points per bin and a more easily readable plot. The orbital phase is defined in a counter clockwise sense from superior conjunction. Both the emission intensity and occurrence probability are determined for each bin, with occurrence probability defined to be the total number of occurrences of emission above a threshold value ($P_0 = 10^{-17.4}$ W/m^2 - Hz) relative to the total number of occurrences within each bin. After analyzing instrument intensity levels for many spacecraft orbits, the value P_0 was determined to be above background noise levels. These plots can be directly compared, therefore, to similar plots obtained for the Voyager 1 and 2 data [cf. Alexander et al., 1981; Carr et al., 1983]. The unique aspects of this current study are that the data has been accumulated in Jovian orbit at high frequency resolution for more than a year (over 10 orbits).

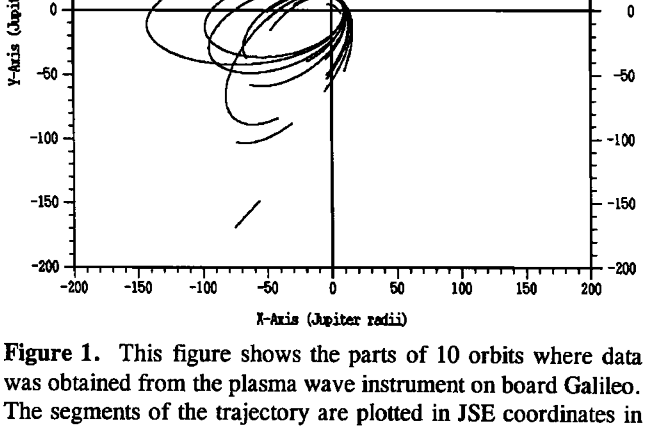

Figure 1. This figure shows the parts of 10 orbits where data was obtained from the plasma wave instrument on board Galileo. The segments of the trajectory are plotted in JSE coordinates in the x-y plane.

In Plate 1 we show the results of sorting the relative occurrence in the frequency range (3.0 MHz $< f <$ 5.6 MHz) in a typical format of Io orbital phase versus central meridian system III longitude. A plot similar to Plate 1 is shown in Figure 7.15 of Carr et al. [1983]. In Plate 1 we see the Io-dependent emissions Io-B and Io-D as indicated, but the Io-A emissions are not clearly discernable for this low-frequency range of DAM. In addition, for $\lambda_{III} <$ 240°, our results show some differences compared to those for f ~ 20 MHz discussed by Carr et al. [1983] in their Figure 7.15 and Table 7.4. There is a general increase in the relative occurrence for emission centered near $\gamma_I \sim$ 90° and $\gamma_I \sim$ 240° as seen at higher frequencies, but after an apparent gap near λ_{III} = 120°, emissions extend to $\lambda_{III} \sim$ 160°, which is greater than the value of $\lambda_{III} \sim$ 60° observed at higher frequencies [cf. Carr et al., 1983]. However, the Voyager data did show a general trend of emission at larger values of λ_{III} for lower frequencies of DAM emission, similar to the Galileo observations [Thieman, private communication, 1998]. PWS does not measure the polarization, so it is not possible to distinguish Io-B from Io-D emissions, for instance, which typically have opposite polarities.

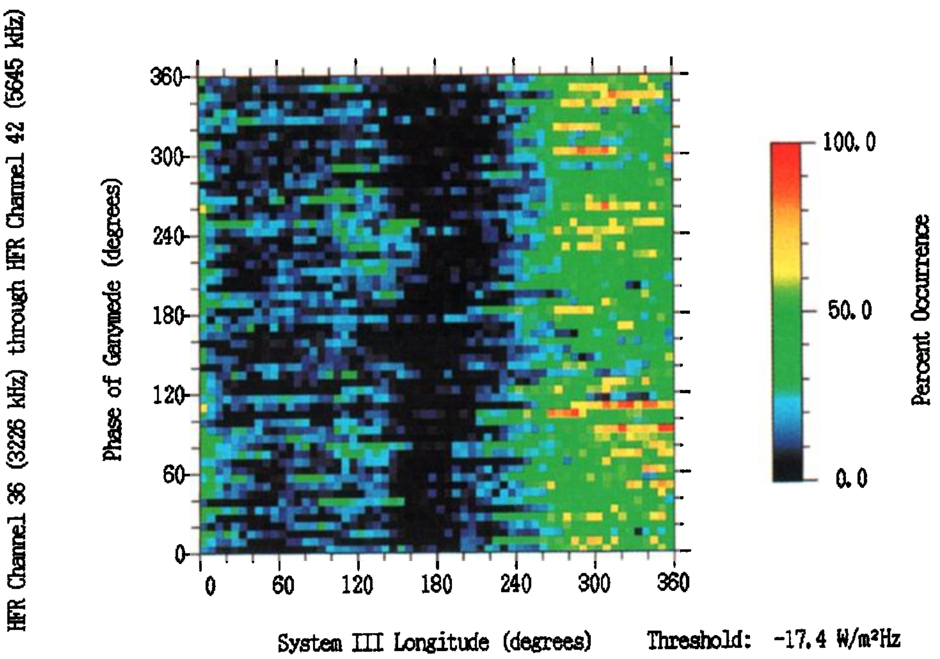

Plate 2. Percent occurrence probability of DAM radiation as a function of Ganymede orbital phase, γ_G, and system III longitude. Enhanced emission occurrence is apparent centered near orbital phases of 80° and 240°. This is most noticeable in the range of system III longitudes $100° < \lambda_{III} < 160°$, but also in the range $290° < \lambda_{III} < 360°$, especially for $\gamma_G \approx 80°$.

The range of Io orbital phases for our results are consistent with those listed by Carr et al. [1983] in their Table 7.4 for f ~ 20 MHz.

Even more interesting results are obtained, however, when the data in the same frequency range is plotted versus Ganymede orbital phase as we show in Plate 2. There is evidence of enhanced relative occurrence for orbital phases centered at approximately 80° and 245°. This is evident for $0 < \lambda_{III} < 180°$, but also in the range $290° < \lambda_{III} < 360°$, especially centered near $\gamma_G = 80°$. The extent of each region in orbital phase is not clear, but appears largest near $\lambda_{III} \sim 130°$. The number of occurrences of emission in each bin near Ganymede orbital phase of ~80° or 245° was typically in the range of $75 < N < 225$. We have eliminated data from this plot whenever the orbital phases of Ganymede and Io are within 6° (bin size) of each other. In addition, we have eliminated data when the orbital phase of Io lay within the range $85° < \gamma_I < 100°$ or $220° < \gamma_I < 225°$. In Figure 2 we show a plot of the occurrence probability (relative occurrence) versus orbital phase of Ganymede. In this plot we have limited the range of system III longitudes to a window of width $100° < \lambda_{III} < 160°$. There are two zones of emission due to Ganymede seen centered near Ganymede phases of 80° and 245°. A more quantitative description of the results is obtained by statistical analysis. In Figure 3 we plot the occurrence probability in each bin of phase for the data of Figure 2. Superimposed on the data is a least-squares fit to the function $Y = A + B \sin(2\theta + \phi)$, where θ is the phase of Ganymede. This fit of the 60 data points yields peaks at phases of 64° and 244°, with $\chi^2 = 45.4$ and a standard deviation of $\sigma = 6.7$. In analogy to Io-dependent emission, these results suggest that radio emission occurs at large wave normal angles from a cyclotron resonant source along the magnetic field line that passes through or near Ganymede.

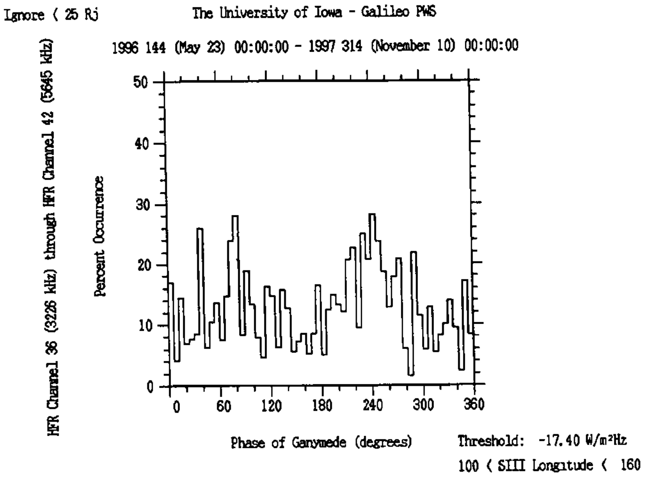

Figure 2. A plot of percent occurrence (relative occurrence) versus orbital phase of Ganymede showing two broad peaks above the more general background emission. This plot was constructed by calculating the percent occurrence above a threshold for a window of system III longitudes in the range $100° < \lambda_{III} < 160°$.

Summary and Conclusions

The Galileo spacecraft is the first orbiting man-made satellite of Jupiter, and consequently provides a unique data set. For the first time the Jovian magnetosphere is being mapped in a systematic way. In this paper we have reported the results of a survey of the plasma wave data for a period of time extending from day 341 of 1995 until day 091 of 1998, thus covering parts of 10 orbits at most local times. Because of the eccentricity of the orbits, the sample ranges over radial distances from about 9 R_j to over 140 R_j and magnetic latitudes that range from about -10° to +10°.

An important result of our survey of the plasma wave instrument data is that not only is a portion of the emission controlled by Io, but also Ganymede, albeit to a smaller extent. Past studies have not reported this correlation [cf. Kaiser and Alexander, 1973], which is apparent in the Galileo data because of the large sampling times in orbit and sensitivity of the plasma wave instrument. In light of past studies of the Io-dependent emission mechanisms [cf. Gurnett and Goertz, 1981], we suggest that field-aligned currents in the form of Alfvén waves as suggested by Eviatar et al. [1998] are indirectly responsible for radio emission

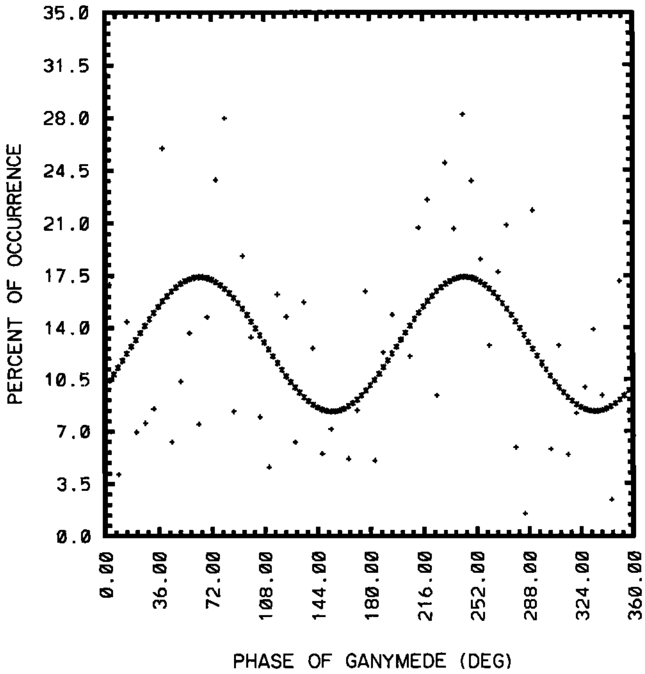

Figure 3. A plot of the percent occurrence in each 6° bin of Ganymede orbital phase versus system III longitude. The power threshold and system III longitude range are the same as in Figure 2. Superimposed on the data is a least-squares fit to the functional form $Y = A + B \sin(2\theta + \phi)$ as described in the text.

with a source near the footprint of a magnetic field line that passes through Ganymede. A number of recent observations and related studies all suggest that such an interpretation is reasonable. Galileo observations have already suggested that Ganymede may have an intrinsic magnetic field [Kivelson et al., 1996; 1997]. Gurnett et al. [1996] have reported a magnetosphere with a relatively high-density ionosphere. Frank et al. [1997] have reported dense, supersonic hydrogen outflows from the polar region of Ganymede. Kurth et al. [1997a] have reported the first direct observations of non-thermal emission, in this case continuum emission in the frequency range 15 kHz $< f <$ 50 kHz, from Ganymede. Kurth et al. [1997b] and Menietti et al. [1998] have shown that Galileo radio emission direction finding measurements can be interpreted as suggesting that the foot of the instantaneous Ganymede flux tube may be a source of HOM/DAM emission. Analysis of Galileo Energetic Particles Detector data has led Eviatar et al. [1998] to conclude that the deceleration of corotational flow of Jovian plasma near Ganymede requires an Alfvén wing type of current interaction. The control of a portion of the Jovian radio emissions by Ganymede, similar to but not as strong as the control by Io, is consistent with these other observations, and indicates a more complex and interesting interaction of the Ganymede magnetosphere with that of Jupiter than previously realized.

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