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Control of Jovian Radio Emission by Callisto

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Abstract. Galileo has been in orbit around Jupiter since December 1995 and a large database has been collected. We present the results of a survey of the plasma wave data for the frequency range 2.0 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, and Ganymede control has been more recently indicated, we report that a small but significant portion of DAM emission is seen to be correlated with the orbital phase of Callisto. While the occurrence rate of emission controlled by Ganymede and Callisto is considerably less than for Io, the power levels can be nearly the same. We estimate the power of the Callisto-dependent emission to be ~70% of the Io-dependent radio emission and about the same as the Ganymede-dependent radio emission. This result indicates an Alfvén current system associated with Callisto, and thus a significant interaction of the magnetosphere of Callisto with that of Jupiter as is believed to exist for both Io and Ganymede.

I. Introduction

Because of their powerful nature and ability to be observed even from ground-based observatories (dating from *Burke and Franklin* [1955]), decametric radiation ($3 < f < 40$ MHz) has been the most studied Jovian radio emission. 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. Subsequent studies have led to the eventual development of the Jovian longitude-Io phase plots and the familiar nomenclature: Io-A, Io-B, Io-C, and Io-D "sources". Excellent descriptions of the Voyager Planetary Radio Instrument (PRA) observations can 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 occurrence of emission for ranges of Io orbital phase centered near ~250° 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; *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 co-rotational flow of plasma around Jupiter. More recently *Clarke et al.* [1998] have published UV observations of surface features at high Jovian latitudes, which they identify with the magnetic field line footprint of the Io flux tube. These observations lend credence to the hypothesis of *Gurnett and Goertz* [1981]. In fact, *Clarke et al.* [1998] also point out other UV features which they identify as probable signatures of the footprints of magnetic flux tubes passing near or through both Ganymede and Europa. Unfortunately, Callisto's orbit lies at such distances that the magnetic field through the moon maps to higher magnetic latitudes, within an almost omnipresent main aurora emission.

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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, and the Voyager and Ulysses flyby missions also did not show any clear satellite control of radio emission other than Io. Because of the continuous sampling of the radio emission data, 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. *Menietti et al.* [1998a] reported a small but significant portion of low frequency Jovian decametric radio emission correlated with the orbital phase of Ganymede. Such studies indicate that the interaction of Ganymede's own magnetosphere with that of Jupiter is dynamic and not fully understood. For a review of Galileo radio emissions influenced by the Jovian satellites to date, see *Kurth et al.* [2000]. Recently *Higgins et al.* [2000] reported possible satellite-dependent emission from Ganymede and Callisto observed by the planetary radio astronomy instrument on board Voyager.

The discovery of Ganymede-dependent radio emission is consistent with the observations of the footprint of the magnetic flux tube associated with Ganymede noted above [*Clarke et al.*, 1998], as well as a number of other observations indicating the unique nature of the Ganymede plasma environment. *Kivelson et al.* [1996; 1997] reported the possible discovery of an intrinsic magnetic field at Ganymede. *Gurnett et al.* [1996a] reported a magnetosphere with a relatively high-density ionosphere. *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. *Frank et al.* [1997] reported strong hydrogen outflows from the polar region of Ganymede. *Kurth et al.* [1997b] and *Menietti et al.* [1998b] 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. More 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 interaction.

The fields and particles observations near Callisto, however, have been much less dynamic or revealing. *Khurana et al.* [1997] have reported an absence of internal magnetic field at Callisto. *Khurana* et al. [1998] reported eddy currents and induced magnetic fields associated with this conducting body. *Kivelson et al.* [1999] have more recently revisited the question of internal fields at Callisto, and show that there are important induction fields at the satellite. *Neubauer* [1998; 1999] has discussed the expected Alfvén wings associated with Callisto and his results are consistent with the observations. The purpose of this paper is to report the discovery of statistically significant control of a portion of the DAM radio emission by Callisto.

II. Instrumentation

The Galileo plasma wave instrument provides excellent spectral frequency resolution over a range extending from a few hertz to almost 6 MHz (electric) and ~160 kHz (magnetic). Since Galileo is an orbiter, in contrast to past flyby missions, it provides unique local time information and continuous mapping of the equatorial mag-

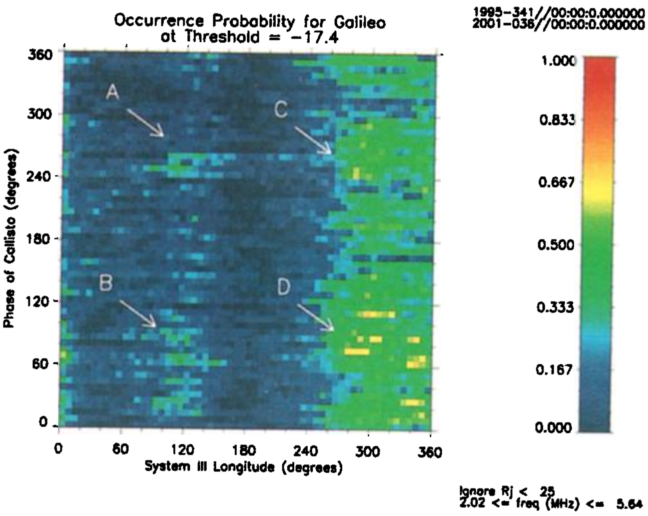

Plate 1. Orbital phase of Callisto versus system III longitude showing the expected regions of Callisto-dependent and Callisto-independent emission. The percent occurrence of the emission is color coded according to the color bar at the right. Enhanced emission occurrence is apparent centered near orbital phases of 80° and 245°. This is most noticeable in the range of system III longitudes $90° < \lambda_{III} < 160°$ and $260° < \lambda_{III} < 360°$.

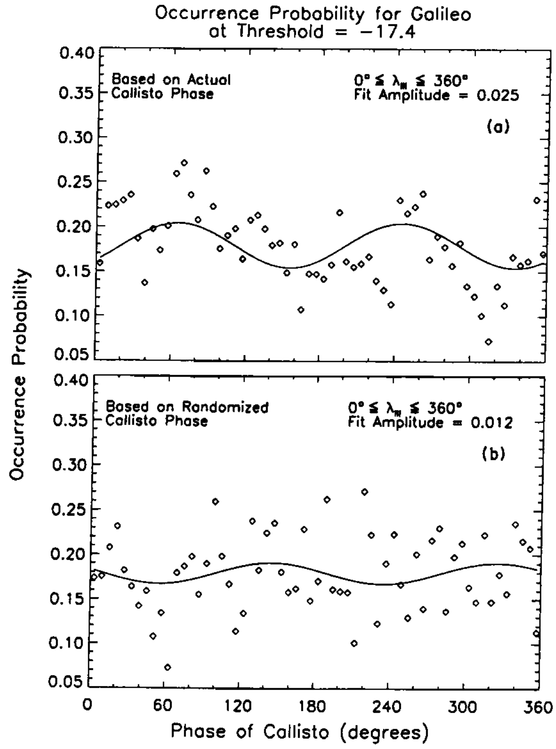

Figure 1. (a) A plot of percent occurrence versus orbital phase of Callisto showing two broad peaks above the more general background emission. This plot was constructed by calculating the average power above a threshold for a window of system III longitudes in the range $0° < \lambda_{III} < 360°$. Also superimposed on the data is a least-squares fit to the data points. (b) The results for the data displayed in Plate 2 with randomly generated orbital phases, and also for $0° < \lambda_{III} < 360°$. The superimposed least-squares fit has a small amplitude, because the data show no strong peaks.

netosphere in the radial distance range from ~9 R_J to over 140 R_J. The magnetic latitude of Galileo varies between -13° and +10° for the duration of the mission, i.e., the Jovicentric latitude is near 0.

The plasma wave receiver on board Galileo consists of four different swept-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. We will concentrate in this study on the electric fields obtained by the high-frequency receiver, 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 s with a frequency resolution of ~10% [cf. *Gurnett et al.*, 1992].

III. Observations and Analysis

We have conducted a survey of the Galileo data set in the frequency range 2.0 MHz $< f <$ 5.6 MHz for the time interval day 341, 1995, to day 36 of 2001. 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 versus system III longitude, λ_{III}. 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 ($10^{-17.4}$ W/m^2-Hz) relative to the total number of occurrences within each bin [cf. Menietti et al., 1998a]. 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 maximum frequency of the plasma wave instrument is 5.6 MHz, in the lower frequency range of DAM, a range that was not well resolved by the Voyager PRA.

In Plate 1 we show the results of sorting the relative occurrence in the frequency range (2.0 MHz $< f <$ 5.6 MHz) in a typical format of satellite orbital phase versus central meridian system III longitude. In this figure we see the possibility of four "sources" labeled A, B, C, and D, which indicate approximate areas of increased emission probability. Enhanced occurrence probability is seen for orbital phases, γ, near 80° and 245°. This is evident in the range of system III longitudes $90° < \lambda_{III} < 160°$ and in the range $260° < \lambda_{III} < 360°$. The number of occurrences N of emission in each bin was typically in the range of $200 < N < 650$. In addition, we have elimi-

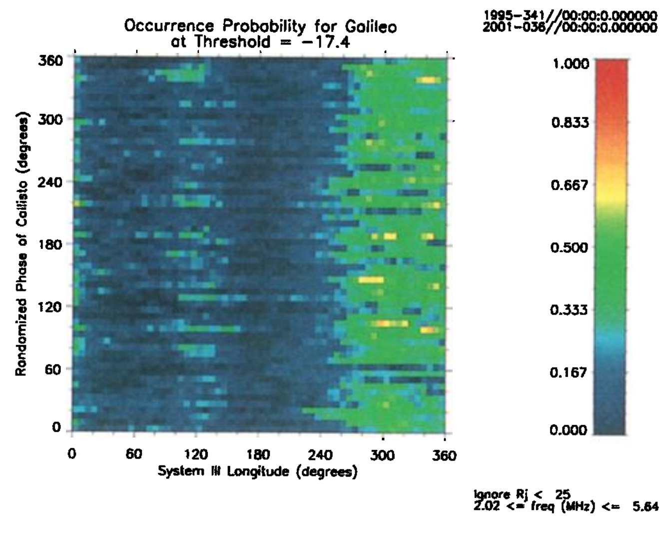

Plate 2. Orbital phase of Callisto versus system III longitude in the same format as Plate 1, but now with a randomly generated orbital phase as described in the text.

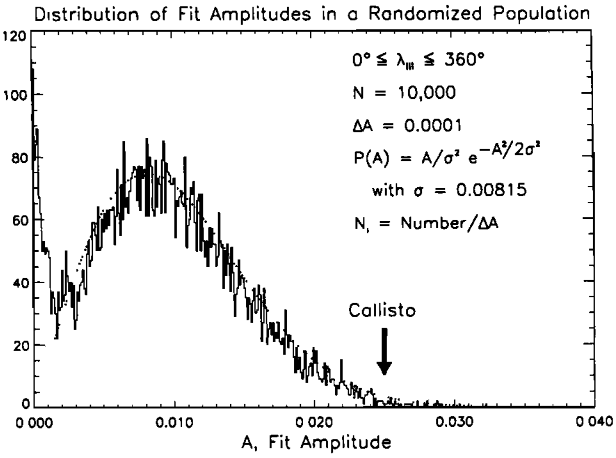

Figure 2. For randomly generated orbital phases we plot the number of times an amplitude (obtained from a least-squares fit) was obtained versus the value of that amplitude A. The probability distribution has the form $P = (A/\sigma^2)\, e^{-A^2/2\sigma^2}$ (with fit parameters given on the plot), and is shown as the dotted line. The arrow indicates the value of the amplitude obtained for the data of Figure 1a (actual orbital phases of Callisto).

nated data when the orbital phase of Io lay within the range $85° < \gamma_{Io} < 100°$ or $235° < \gamma_{Io} < 260°$, and when the orbital phase of Ganymede lay within the range $70° < \gamma_{Gan} < 90°$ or $240° < \gamma_{Gan} < 255°$. The latter range of Ganymede phases is based on the results of Menietti et al. [1998a]. We note that the orbital phase of Callisto has no resonances with the other Galilean satellites [*Peek*, 1981].

In Figure 1a we show a plot of the occurrence probability versus orbital phase of Callisto. The data have been integrated over the range of system III longitude $0° < \lambda_{III} < 360°$. The plot shows maxima near Callisto orbital phases of 80° and 260°. Superimposed on the data is a least-squares fit to the function $Y = \alpha + \beta \sin(2\,\theta + \varphi)$, where θ is the orbital phase of Callisto, φ is the phase shift and α and β are constants. This fit of the 60 data points yields peaks at phases of 65.3° and 245.3° and the amplitude of the sinusoidal fit is 0.025.

We have also performed this analysis for integrations over limited ranges of system III longitude, but due to limited space we only report the results without showing the fits. For the range $72° < \lambda_{III} < 162°$ the least-squares fit yields peaks at Callisto orbital phases of 58.1° and 238.1° and the amplitude of the fit is 0.034. For the range $258° < \lambda_{III} < 360°$ the fit yields peaks at phases of 72.9° and 252.9° and the amplitude of the curve is 0.039. In analogy to Io-dependent and Ganymede-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 Callisto (carrying the Alfvén current).

In order to investigate the significance of these results we have conducted a statistical analysis of the data as follows. In place of the actual orbital phase of Callisto we have introduced a random phase for each bin of data in Figure 1a (data integrated over the range of $0° < \lambda_{III} < 360°$). In Plate 2 we display a spectrogram in the same format as Plate 1, but the orbital phase is the randomly generated phase as follows. We bin the data of Plate 1 into a set of rows (6° in orbital phase by 360° in λ_{III}). We then assign a unique random phase to each row to produce Plate 2. On this plot there are no visibly dominant orbital phases. In Figure 1b we use the results of Plate 2 to plot occurrence probability versus orbital phase (now randomly generated) and again integrated over the range $0° < \lambda_{III} < 360°$. The data show only a small spread of values and the superimposed sinusoidal fit has a small amplitude of occurrence probability (0.012). We have repeated this analysis 10,000 times, each time calculating the amplitude of the fit to the data with a new set of random orbital phases. In Figure 2 we display a plot of the number of times a given fit amplitude A was obtained as a function of that amplitude (the amplitude bin size was 0.0001). The form of the parent distribution of this data is a Gaussian, but because the amplitude of the occurrence probability has two degrees of freedom, the probability distribution has the form $A/\sigma^2\ e^{-A^2/2\sigma}$ where σ is the standard deviation. The dotted curve of Figure 2 is a fit to the data with the fit parameters displayed on the plot. The most probable value of amplitude for data with randomly selected orbital phases is ~ 8.15×10^{-3}. The amplitude of the fit of the actual data displayed in Figure 1a is relatively much larger (note the arrow in Figure 2), and the relative probability of obtaining this amplitude from a completely random distribution of orbital phases is very small, 9.05×10^{-3}. The relative probability of obtaining the amplitude of Figure 1b, a typical amplitude for the examples of random orbital phase, is 0.511. We conclude that the fit shown in Figure 1a is statistically significant. In order to establish that Callisto is the unique source of the correlation of radio emission with orbital phase, instead of perhaps relatively short intervals of Ganymede or Io control, we have repeated the entire analysis for each of two equal spans of the data set. The results produce plots of occurrence probability versus Callisto orbital phase that are very similar to Figure 1a.

We have estimated the relative power of the satellite-dependent emission by assuming a common source region limited in volume along the magnetic field line and near the local cyclotron frequency. The results are summarized in Table 1 for Io, Ganymede, and Callisto. Average power levels integrated over time and normalized to a distance of 100 R_J were used. The frequency range of the calculations is the same for each satellite, 2.8 to 5.6 MHz. We assume the source emits isotropically in all directions. The power level of Ganymede and Callisto-dependent emission is a significant fraction of the power level of Io-dependent emission, even though the occurrence probability for Ganymede and Callisto-dependent emission is much lower than that of Io-dependent emission.

IV. Summary and Conclusions

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, 1995, until day 36, 2001, thus covering over 29 full orbits and all local times. 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 and Ganymede, but also by Callisto.

In light of past studies of the Io-dependent emission mechanisms [cf. *Gurnett and Goertz*, 1981], and Ganymede-dependent emission mechanisms [*Menietti et al.*, 1998a], we suggest that field-aligned currents in the form of Alfvén waves are responsible for particle precipitation at and near the instantaneous Callisto magnetic flux tube. *Gurnett et al.* [2000] have reported that Callisto is probably surrounded by a dense ionospheric-like plasma. The density peak in the near wake of Callisto (~400 cm^{-3}) is comparable to values obtained near Ganymede [*Gurnett et al.*, 1996a] and Europa [*Gurnett et al.*, 1998], but much lower than the large densities (4×10^4 cm^{-3}) observed in the wake of Io [*Gurnett et al.*, 1996b].

Table 1. Estimated Average Power of Satellite-dependent Emission

		(Power in Watts)
Io	Ganymede	Callisto
5.6×10^7	3.8×10^7	4.1×10^7

Clarke et al. [1998] have reported footprints in the UV emission associated with Io, Europa, and Ganymede. This may indicate active particle precipitation along the magnetic field line that is near or passes through the moons. Such plasma precipitation could be a free energy source of radio emission. No footprint has been observed for Callisto, but such a footprint would not be easily observable at its expected location within the main auroral emission at high Jovian magnetic latitudes. We look forward to further studies of additional planetary data.

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