CONTROL OF JOVIAN RADIO EMISSIONS BY THE GALILEAN MOONS AS OBSERVED BY CASSINI AND GALILEO

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Abstract

Previous ground–based and spacecraft studies have shown that the Galilean moon Io can control a portion of the Jovian radio emission. More recent studies using the Galileo and Voyager spacecraft have also shown that the orbital phase of Ganymede and Callisto plays a role in some of the low–frequency Jovian decametric radio (DAM) emission. The Cassini gravity–assist flyby of Jupiter on December 30, 2000, provides another opportunity to investigate the role of the Galilean moons on the Jovian radio emissions. The Cassini Radio and Plasma Wave Science (RPWS) investigation is the most advanced radio and plasma wave instrument to visit the Jovian system, and can detect electric fields over a range from 1 Hz to 16 MHz with high spectral and temporal resolution. This study will review the recent Galileo results, and examine the correlation of the Jovian radio emissions observed by Cassini with the orbital phase of the various Galilean moons. The same method will be used at Saturn to investigate the possible control of Saturnian radio emissions by the moons of Saturn.

1 Introduction

The discovery of low–frequency radio emissions from Jupiter by Burke and Franklin [1955] started a long period of study of the Jovian radio spectrum (both ground and space–based) that continues today. The additional discovery of the correlation between the Galilean moon Io and the Jovian decameter (∼3 to 40 MHz) radio emission (DAM) [Bigg, 1964] showed that Jupiter and Io had a complicated electrodynamic relationship that is still not completely understood today [Smith, 1976; Gurnett and Goertz, 1981a; Leblanc, 1981; Goldstein and Goertz, 1983; Crary and Bagenal, 1997; Queinnec and Zarka, 1998;

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Zarka, 1998, and references therein]. The observations of the DAM emission led to the development of the Jovian longitude–Io phase plots and the nomenclature of Io–A, Io–B, Io–C, Io–D, non–Io–A, non–Io–B, and non–Io–C "sources" (see Carr et al. [1983] for a review of the spectral phenomenology of the Jovian radio emissions). The flybys of Jupiter by the Voyager 1 and 2 spacecraft provided further details on the characteristics of the DAM emissions, including the discovery that nested families of arcs, or parts of arcs, comprise much of the DAM emission [Warwick et al., 1979a; Alexander et al., 1981; Boischot et al., 1981; Carr et al., 1983]. Figure 1 shows an example of the complicated

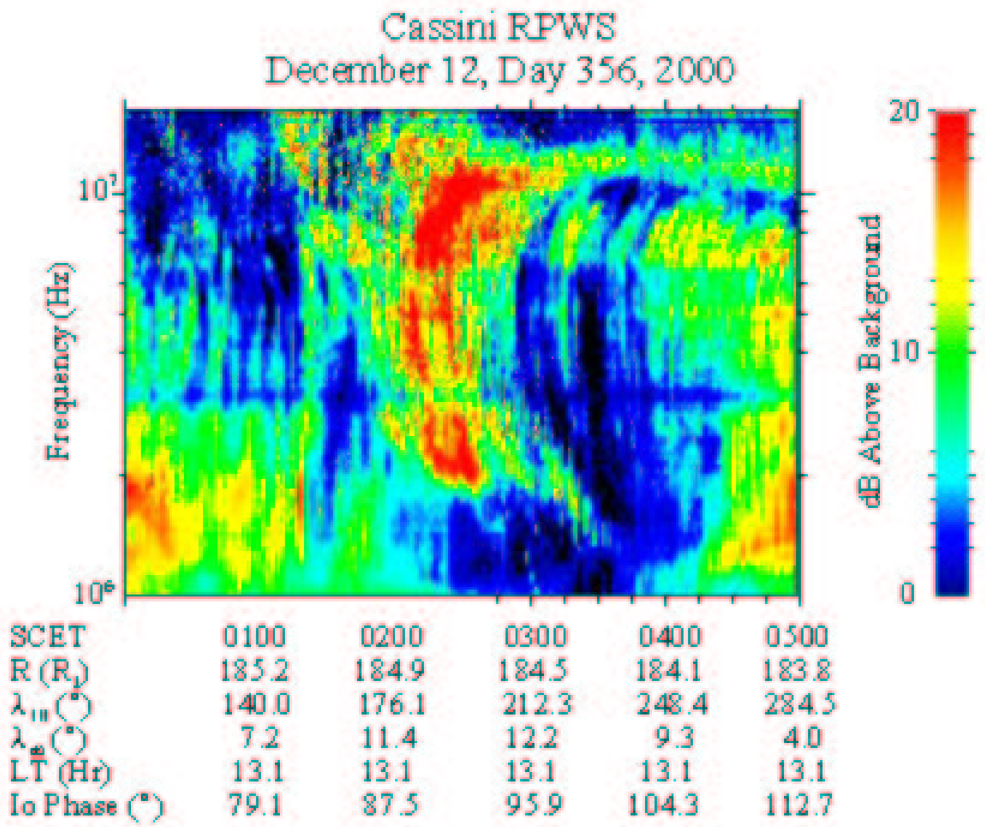

Figure 1: A time–frequency spectrogram showing the complicated arc structure associated with the DAM emission as observed by the Cassini spacecraft. The Io dependent enhancement of the emission from about 02:00 to 03:00 SCET (∼87° to ∼96° Io phase) is on the order of 20 dB more intense than the non–Io DAM emissions observed during this period.

arc structure associated with the DAM emission as observed by the Cassini spacecraft. The further discovery of the Io volcanoes and the torus added a source of plasma that must be factored into the development of a theory for the Io–DAM relationship. Although many of the exact details are still under debate, the basic source of the DAM emission is believed to be a cyclotron resonant emission at large wave normal angles in a hollow emission cone [Goldstein and Goertz, 1983; Green, 1984; Menietti et al., 1987; Wilkinson, 1989].

2 Instrument description

The Cassini Radio and Plasma Wave System (RPWS) consists of five receivers: a Langmuir Probe, three electric antennas, and a triaxial search coil magnetometer (see Gurnett et al. [2001b] for a detailed description of the instrument). The five receivers cover a frequency range from ∼1 Hz to 16 MHz for electric fields, and ∼1 Hz to 12 kHz for magnetic fields. This study uses the high–frequency receiver (HFR) that covers a frequency range of 3.5 kHz to 16 MHz. Although a variety of instrument modes were used during the flyby, the primary mode of operation for the RPWS instrument obtained a complete frequency sweep from 3.5 kHz to 16 MHz every 25.25 seconds, with a 25-kHz measurement band stepped in 50-kHz increments from 325 kHz to 4025 kHz, and a 25-kHz measurement band stepped in 200-kHz increments from 4.025 MHz to 16.025 MHz. The HFR connects to the electric antenna, either a dipole with a tip–to–tip length of 18.52 m, or a monopole antenna with a length of 10 m. The RPWS instrument obtained the data examined in this study from September 4, 2000 to July 20, 2001, and ranged from about 1535 R_J (September 4, 2000) to a closest approach distance of about 137 R_J (December 30, 2000) to an outbound distance of about 2618 R_J (July 20, 2001). The magnetic latitude of Cassini ranged from about -8° to about +13° before closest approach, and from about -13° to about +6° after closest approach.

The Galileo Plasma Wave System (PWS) consists of three sweep frequency receivers, a wideband receiver, an electric dipole antenna, and two search coil magnetometers. The three sweep frequency receivers cover a range from a few Hertz to 5.6 MHz. For this study, the high–frequency sweep frequency receiver was used, which covers a range from 100.8 to 5.6 kHz in 42 logarithmically spaced channels. The receiver is attached to the electric dipole antenna with an effective length of 3.5 meters (defined as the difference between the ‘center of mass’ of the two elements). The electric antenna is mounted perpendicular to the spacecraft spin axis. The receiver takes 18.67 seconds to complete a sweep of the electric field measurements, and has a frequency resolution of ∼10% [Gurnett et al., 1992]. Galileo has orbited Jupiter since December 1995, and provides a very good survey of the equatorial magnetosphere from ∼9 to ∼140 R_J. The magnetic latitude of Galileo ranged from about -13° to +10° during the duration of this study.

3 Method of analysis

For the frequency range of interest, the data from each spacecraft is sorted into 6° × 6° bins of Jovian satellite orbital phase versus system III longitude, λ_{III}. The intensity of the emissions are normalized to 100 R_J. Emission intensity and occurrence probability are then determined for each bin, with occurrence probability defined as the total number of occurrences of emission above a certain threshold value relative to the total number of occurrences in that bin [Menietti et al., 1998a; 2001]. The orbital phase is defined in a counter clockwise sense from superior conjunction, and the threshold value is determined by examining the noise level of each receiver for the period of the study. For Cassini, since the noise level of the instrument varies over the frequency range of interest (1 MHz to 16 MHz), a sliding threshold was used that varied with frequency. This method of analysis allows these plots to be compared to the similar Voyager plots [Alexander et al., 1981; Carr et al., 1983].

4 Galileo and Cassini results

The Galileo spacecraft entered orbit around Jupiter in December 1995. Since Galileo is an orbital mission, it has been able to collect a much larger set of radio data in close proximity to Jupiter than the flybys of Voyager and Ulysses were able to obtain, allowing better statistics for the investigation of the influence of other Galilean moons on the DAM emission. Using the Galileo radio data from 3.2 MHz to 5.6 MHz, Menietti et al., [1998a] showed that the expected correlation between Io and the DAM emission was observed in the Galileo data. Their study also found a relationship between the Galilean moon Ganymede and part of the DAM emission. More recently, Menietti et al., [2001] have found a relationship between the orbital phase of Callisto and the DAM emission. The Cassini gravity–assist flyby in December 2000, allowed another opportunity to examine the relationship between DAM emissions and the Galilean moons, and to develop the tools necessary to examine the possible relationship between the Saturnian moons and the radio emissions of Saturn.

5 Io

Previous ground–based and the Voyager results have shown that when the orbital phase of Io is near 90° or 240°, the DAM emission "turns on" and can increase the flux level over a hundred times the average intensity level value [Desch et al., 1975; Desch, 1980; Carr et al., 1983]. Menietti et al. [1998a] showed similar results for Io using the Galileo data from 3.2 MHz to 5.6 MHz, with the peak of occurrence for Galileo occurring at ∼90° and 245° (see their Plate 1). The Io dependent emissions are often easy to observe in the Cassini time–frequency spectrograms. For example, Figure 1 shows the Io dependent enhancement of the DAM emission at Io phase ∼90°. The emissions observed from about 02:00 to 03:00 SCET (∼87° to ∼96° Io phase) are on the order of 20 dB more intense than the non–Io DAM emissions observed during this period. Figure 2 shows a histogram of occurrence probability versus Io phase for four different frequency ranges as determined from the Cassini data for the period from November 25, 2000 to January 30, 2001 (66 days surrounding closest approach). The expected peaks centered at ∼90° and ∼240° are easy to see in the Cassini data. It is interesting that the peak at ∼240° is most easily observed at the higher frequencies, and may be due to the geometry of the flyby. Alexander et al. [1981] and Lecacheux et al. [1992] have shown the occurrence probability of some of the Jovian radio emission can be influenced by the jovigraphic latitude and the local time of the observing spacecraft. This influence on the Jovian emission changes with frequency [Alexander et al., 1981], and may explain the frequency dependence shown in Figure 2. During the flyby, Cassini went from about 3.7° (inbound) to about -3.7° (outbound) jovigraphic latitude, and ranged in local time from about 10.7 to 21.1 hr. Furthermore, the control of the Jovian emission by Io is known to disappear below 1 to 2 MHz [Carr et

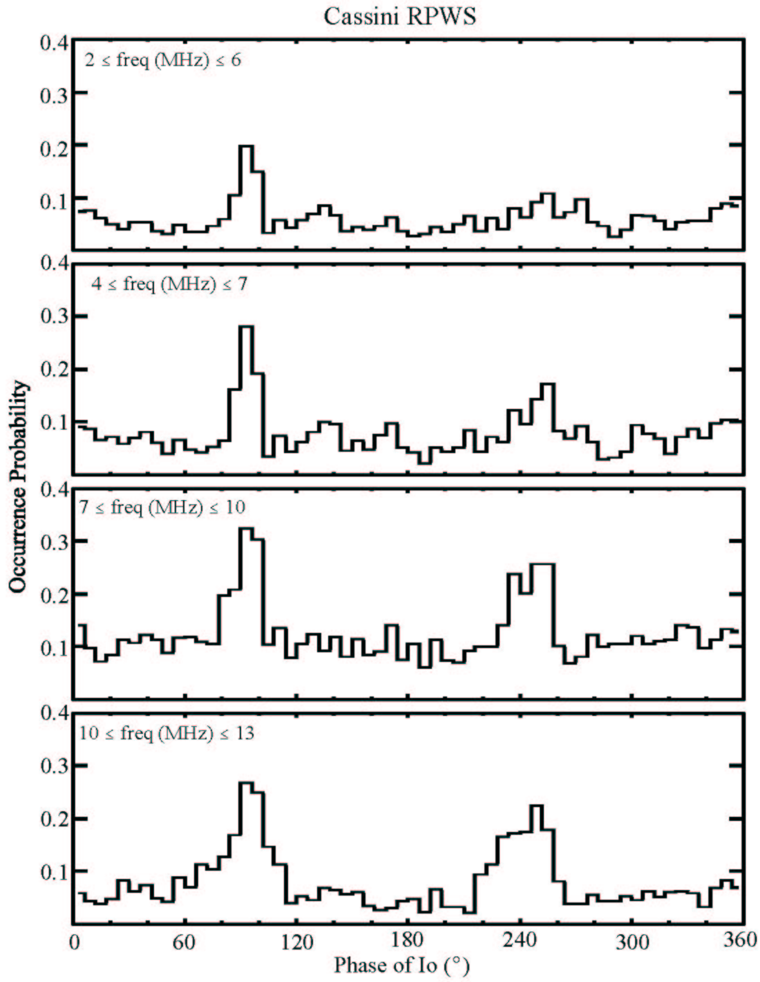

Figure 2: Plots of occurrence probability versus phase of Io as measured by Cassini. These plots were constructed by calculating the average power above a threshold (different for each frequency band) for a window of system III longitude in the range 0° to 360°, and cover the frequency ranges 2 MHz to 6 MHz, 4 MHz to 7 MHz, 7 MHz to 10 MHz, and 10 MHz to 13 MHz.

al., 1983; Zarka et al., 2001a]. This low–frequency cutoff is consistent with the occurrence probability being larger at the higher frequencies.

6 Ganymede

Although earlier ground–based studies [Kaiser and Alexander, 1973] and initial examination of the Voyager and Ulysses flyby data found that only the orbital phase of the Galilean moon Io appeared to be correlated with the DAM emissions, more recent results using data from the Galileo spacecraft [Menietti et al., 1998a], and a re–examination of the Voyager data [Higgins et al., 2000] have found a relationship between the low–frequency DAM and the Galilean moon Ganymede. The results found by Menietti et al. [1998a]

show an enhanced occurrence of the DAM emission at Ganymede orbital phase of ∼80° and ∼245°. Because of the resonance between the orbital periods of Io and Ganymede, the periods when Io and Ganymede are within 6° of each other, and when the orbital phase of Io lies within the range of 85° to 100° or 220° to 225° were not included in these studies. Figure 3 shows the occurrence probability (for $0° < \lambda_{III} < 360°$) versus

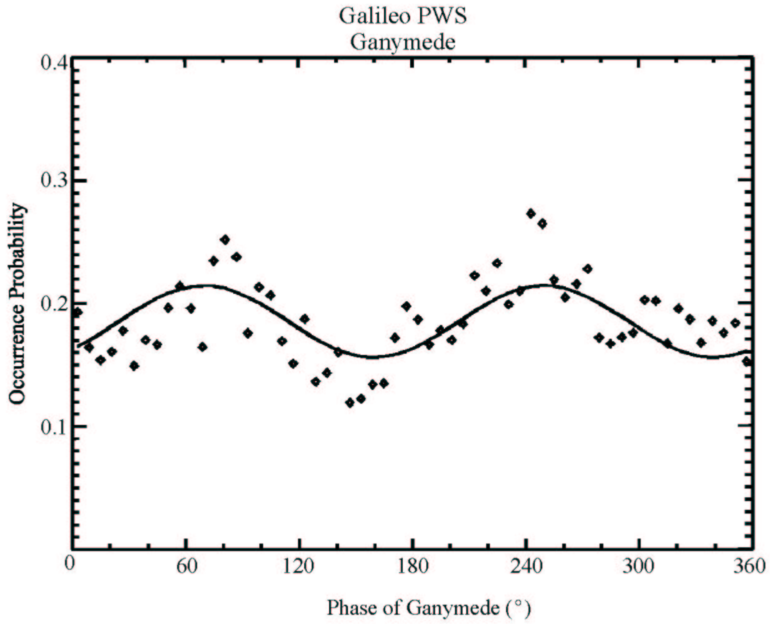

Figure 3: A plot of occurrence probability versus phase of Ganymede as observed by Galileo. The periods when Io phase was between 85° to 100° and 235° to 260° were not used in this analysis. The line is a least–squares fit to the data points.

the orbital phase of Ganymede as determined from the Galileo data in a frequency range of 2.02 MHz to 5.64 MHz. The two peaks centered at ∼80° and ∼245° are easy to see in this figure. To determine the statistical significance of these results, a least–squares fit to the sinusoidal function $Y = \alpha + \beta \sin(2\theta + \phi)$ where θ is the orbital phase of Ganymede, ϕ is the phase shift, and α and β are constants was calculated, and is plotted on Figure 3 as the solid line. The amplitude of the fit was found to be 0.029. Using an analysis technique recently developed for Callisto [Menietti et al., 2001], this fit is then compared to a fit of a randomization of the phase values from Figure 3. Each value of the occurrence probability from Figure 3 in a bin of width 6° in orbital phase and integrated over all system III longitude is assigned a random orbital phase, and the amplitude from the sinusoidal fit is calculated for this new data set. This randomizing and analysis was repeated 10,000 times. The probability distribution of this analysis has a form $A/\sigma^2 \exp(-A^2/2\sigma^2)$ where σ is the standard deviation (see Menietti et al. [2001] for a more detailed discussion of this statistical analysis). Figure 4 shows the distribution of the fit amplitudes of the randomized population. The standard deviation of this population was found to be $\sim 6.28 \times 10^{-3}$. The value obtained from the fit to the actual data shown in Figure 3 (0.029) is almost 5σ from the randomized probability. The probability of the

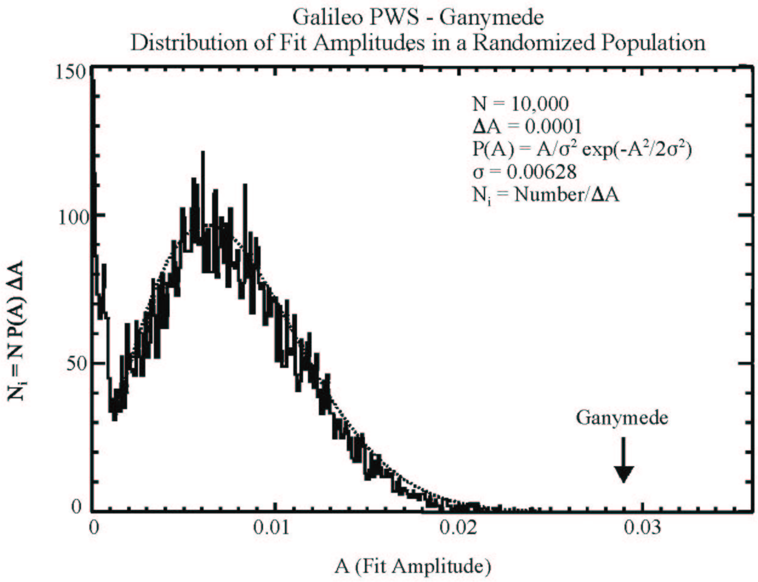

Figure 4: A plot of the distribution of fit amplitudes in the randomized orbital phases. The arrow indicates the value of the amplitude obtained from the Ganymede data in Figure 3 ($\sim 5\sigma$).

measured Ganymede amplitude being due to a random event is 2.3×10^{-5}, showing that the results for Ganymede are statistically quite significant. A similar analysis has been started with the Cassini data. However, at this time, no obvious correlation between Ganymede and the DAM emission has been detected. This lack of a correlation using the Cassini data will be discussed below.

The discovery of a relationship between Ganymede and part of the DAM emission is consistent with the discovery that Ganymede has both a magnetic field and a magnetosphere [Kivelson et al., 1996c, 1997; Gurnett et al., 1996; Frank et al., 1997; Kurth et al., 1997a; Menietti et al., 1998b]. Furthermore, Ganymede has been observed to be the source of non–thermal radio emissions [Kurth et al., 1997a], and direction finding measurements with Galileo [Kurth et al., 1997b; Menietti et al., 1998b] have suggested that the Ganymede flux tube may be a source of HOM/DAM emission (see Kurth et al. [2000] for a review of the radio emissions related to Ganymede). The observations of an auroral footprint of the magnetic flux tube associated with Ganymede [Clarke et al., 1998] supports the theory that Ganymede interacts with the auroral zone, and provides evidence that field aligned currents in the form of Alfvèn waves are responsible for particle precipitation at the Ganymede flux tube. Zarka et al. [2001b] has proposed a simple method to estimate the energy involved in a flow–obstacle interaction, and has applied it to the Ganymede–Jupiter case. The method predicts that the Ganymede–induced emission is about 10 times weaker than the Io–induced emission. This estimate is smaller than the estimate by Menietti et al. [2001] of the average power of the Ganymede–induced emission (about 68% of the average power of the Io–induced emission), but is consistent with the existence of a Ganymede source for part of the DAM emission.

7 Callisto

Recent results from Menietti et al. [2001] have also shown a relationship between the orbital phase of Callisto and part of the DAM emission using the Galileo PWS data from 2.02 MHz to 5.6 MHz. Like their earlier study for Ganymede, the intensity of the emissions was normalized to 100 R_J, and the data sorted in $6° \times 6°$ bins of Jovian satellite orbital phase versus system III longitude, λ_{III}. To remove the effects of Io and Ganymede, data was not used when the Io orbital phase was between 85° to 100° and 235° to 260°, and when the Ganymede orbital phase was between 70° to 90° and 240° to 255°. An increase in the occurrence probability of the emission was observed near the Callisto orbital phase of ∼80° and ∼245°. This enhancement was most easily seen in range of λ_{III} from 90° to 160° and 260° to 360° (see Plate 1 of Menietti et al. [2001]). Figure 5 shows the occurrence

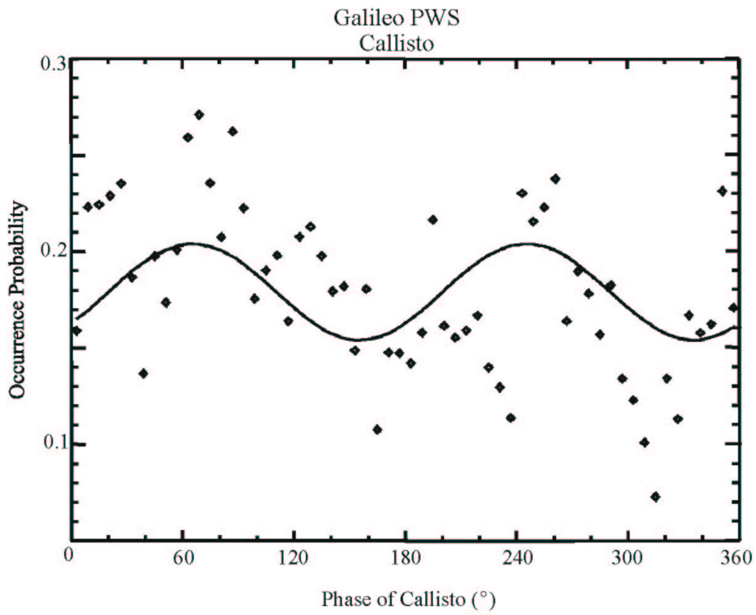

Figure 5: A plot of occurrence probability versus orbital phase of Callisto. The periods when the Io phase was between 85° to 100° and 235° to 260°, and Ganymede between phase 70° to 90° and 240° to 255° were not considered for this analysis. The line is a least–squares fit to the data points.

probability (for $0° < \lambda_{III} < 360°$) versus the orbital phase of Callisto as determined from the Galileo data in a frequency range of 2.02 MHz to 5.64 MHz. Although the peaks are not as well defined as the Ganymede case, there does appear to be an enhancement in the occurrence probability at ∼80° and ∼245° Callisto orbital phase.

As mentioned above, a statistical analysis of the Galileo Callisto data was performed by Menietti et al. [2001]. The least–squares fit of the 60 points (360/6° bins) from Figure 5 yielded peaks at phases 65.3° and 245.3° with an amplitude of 0.025. Fits for the specific λ_{III} ranges of 72° to 162° yielded peaks at orbital phases 58.1° and 238.1°, with an amplitude value of 0.034, and for λ_{III} ranging from 258° to 360°, peaks at phases 72.9°

and 252.9°, with an amplitude of 0.039. Again, the phase values were randomized 10000 times and the probability distribution is determined as discussed above. The resulting probability distribution is shown in Figure 6, and yields a $\sigma = 8.15 \times 10^{-3}$. The fit amplitude for the measured data was 0.025, which is about 3σ. The probability of obtaining

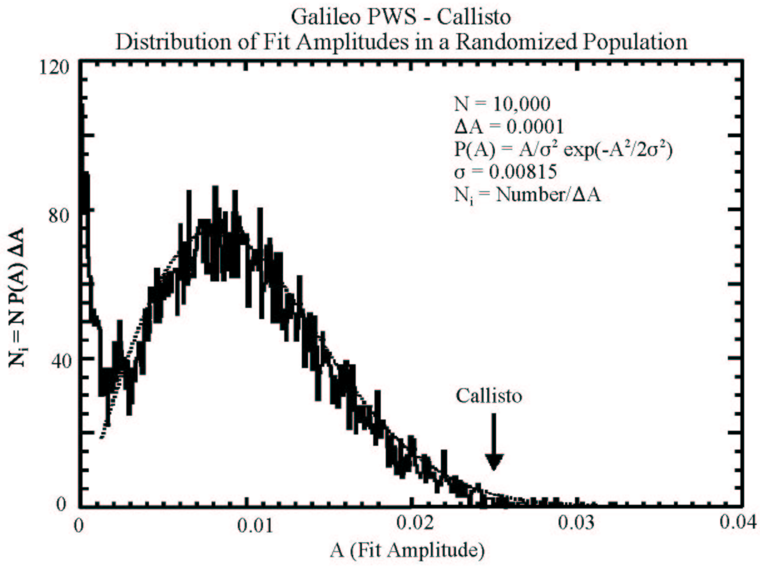

Figure 6: A plot of the distribution of fit amplitudes in the randomized orbital phases. The arrow indicates the value of the amplitude obtained from the Callisto data in Figure 5 (~3σ).

this measured value from a random population is 9.05 $\times 10^{-3}$. The fits for the smaller ranges of λ_{III} were 0.034 and 0.039 (both $\sim 4\sigma$). As a further test of the significance of these results, the data set was split in half, and the analysis repeated, resulting in very similar results for each half independently. Although these result for Callisto are not as strong as the Ganymede result, the Galileo evidence does support a relationship between Callisto and part of the DAM emission. Furthermore, recent analysis of the Voyager data by Higgins et al. [2001] has also found a relationship between Callisto and the DAM emission. However, the initial analysis of the Cassini data has not found any correlation between Callisto and the DAM emission.

The discovery of a Callisto dependence is somewhat more surprising than Ganymede, since Callisto does not appear to have an internal magnetic field [Khurana et al., 1997]. However, there is some evidence that Callisto has a conductive ocean and important induction fields have been detected [Khurana et al., 1998; Kivelson et al, 1999]. Gurnett et al. [2000] reported that Callisto is probably surrounded by a dense ionospheric–like plasma, with densities similar to densities observed near Ganymede. Menietti et al. [2001] suggested that field–aligned currents in the form of Alfvèn waves are responsible for particle precipitation at or near the instantaneous Callisto magnetic flux tube. Neubauer [1998, 1999] has discussed the expected Alfvèn wings associated with Callisto, and his results are consistent with the observations.

8 Summary

The relationship between the Galilean moons and the DAM emission is a complicated one. The recent results from Galileo and a reexamination of the Voyager data have shown that other moons besides Io can 'control' part of the DAM emissions. Preliminary results from the Cassini flyby show the expected correlation between Io and the DAM emissions, but no obvious relationship for the moons Ganymede, Europa, or Callisto has yet been discovered. This lack of a correlation for Ganymede and Callisto in the Cassini data may be due the difference between a flyby and an orbital mission. For the Galileo data set, the distance to Jupiter was always $< 140\ R_J$, and for the Cassini flyby, the spacecraft never was closer than $137\ R_J$. This results in much of the Cassini sampling period occurring at very large distances from Jupiter. This possibility is supported in the analysis of the Voyager data, where the initial analysis did not find a correlation for Ganymede or Callisto, but further, more detailed analysis has found possible relationships. Further analysis of the Cassini data is continuing, and improved tools, including some of the methods recently used with the Voyager data, are being developed. Similar studies will be undertaken during the Cassini mission at Saturn to explore the possible relationships between the Saturnian moons and the radio emissions from Saturn. Voyager results have suggested that the Saturnian moon Dione affects the low frequency radio emissions [Gurnett et al., 1981b; Kurth et al., 1981b; Desch and Kaiser, 1981; Warwick et al., 1982]. More recently, Zarka et al. [2001b], using the same method discussed above for Ganymede, has suggested that the apparent Dione control is either a spurious effect, or that Dione must have a magnetic field in order to influence the Saturnian emission. One of the goals of the Cassini RPWS instrument is to examine this possible relationship and resolve the issue.

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References

Alexander, J. K., T. D. Carr, J. R. Thieman, J. J. Schauble, and A. C. Riddle, Synoptic observations of Jupiter's radio emissions: Average statistical properties observed by Voyager, *J. Geophys. Res.*, **86**, 8529, 1981.

Bigg, E. K., Influence of the satellite Io on Jupiter's decametric emission, *Nature*, **203**, 1008, 1964.

Boischot, A., A. Lecacheux, M. L. Kaiser, M. D. Desch, and J. K. Alexander, Radio Jupiter after Voyager: An overview of the planetary radio astronomy observations, *J. Geophys. Res.*, **86**, 8213, 1981.

Burke, B. F., and K. L. Franklin, Observations of a variable radio source associated with the planet Jupiter, *J. Geophys. Res.*, **60**, 213, 1955.

Carr, T. D., M. D. Desch, and J. K. Alexander, Phenomenology of magnetospheric radio emissions, in *Physics of the Jovian Magnetosphere*, edited by A. J. Dessler, 226–284, Cambridge University Press, Cambridge, U. K., 1983.

Clarke, J. T., G. Ballester, J. Trauger, J. Ajello, W. Pryor, K. Tobiska, J. E. P. Connerney, G. R. Gladstone, J. H. Waite, Jr., L. B. Jaffel, and J.–C. Gérard, Hubble Space Telescope imaging of Jupiter's UV aurora during the Galileo orbital mission, *J. Geophys. Res.*, **103**, 20217, 1998.

Crary, F. J., and F. Bagenal, Coupling the plasma interaction at Io to Jupiter, *Geophys. Res. Lett.*, **24**, 2135, 1997.

Desch, M. D., T. D. Carr, and J. Levy, Observations of Jupiter at 26.3 MHz using a large array, *Icarus*, **25**, 12, 1975.

Desch, M. D., Io control of Jovian radio emission, *Nature*, **287**, 815, 1980.

Desch, M. D., and M. L. Kaiser, Saturnian kilometric radiation: Satellite modulation, *Nature*, **292**, 739, 1981.

Frank, L. A., W. R. Paterson, K. L. Ackerson, and S. J. Bolton, Outflow of hydrogen ions from Ganymede, *Geophys. Res. Lett.*, **24**, 2151, 1997.

Green, J. L., The Io decametric emission cone, *Radio Science*, **19**, 556, 1984.

Goldstein, M. L., and C. K. Goertz, Theories of radio emissions and plasma waves, in *Physics of the Jovian Magnetosphere*, edited by A. J. Dessler, 317–352, Cambridge University Press, Cambridge, U. K., 1983.

Gurnett, D. A., and C. K. Goertz, Multiple Alfvèn wave reflections excited by Io: Origin of the Jovian decametric arcs, *J. Geophys. Res.*, **86**, 717, 1981a.

Gurnett, D. A., W. S. Kurth, and F. L. Scarf, Plasma waves near Saturn: Initial results from Voyager 1, *Science*, **212**, 235, 1981b.

Gurnett, D. A., W. S. Kurth, R. R. Shaw, A. Roux, R. Gendrin, C. F. Kennel, F. L. Scarf, and S. D. Shawhan, The Galileo plasma wave science investigation, *Space Sci. Rev.*, **60**, 341, 1992.

Gurnett, D. A., W. S. Kurth, A. Roux, S. J. Bolton, and C. F. Kennel, Evidence for a magnetosphere at Ganymede from plasma–wave observations by the Galileo spacecraft, *Nature*, **384**, 535, 1996.

Gurnett, D. A., A. M. Persoon, W. S. Kurth, A. Roux, S. J Bolton, and C. F. Kennel, Plasma densities in the vicinity of Callisto from Galileo plasma wave observations, *Geophys. Res. Lett.*, **27**, 1867, 2000.

Gurnett, D. A., W. S. Kurth, D. L. Kirchner, G. B. Hospodarsky, T. F. Averkamp, P. Zarka, A. Lecacheux, R. Manning, A. Roux, P. Canu, N. Cornilleau–Wehrlin, P. Galopeau, A. Meyer, R. Boström, G. Gustafsson, J.–E. Wahlund, L. Aahlen, H. O. Rucker, H. P. Ladreiter, W. Macher, L. J. C. Woolliscroft, H. Alleyne, M. L. Kaiser, M. D. Desch, W. M. Farrell, C. C. Harvey, P. Louarn, P. J. Kellogg, K. Goetz, and

A. Pedersen, The Cassini radio and plasma wave science investigation, *Space Sci. Rev.*, in press, 2001b.

Higgins, C. A., J. D. Menietti, J. L. Green, and J. R. Thieman, Io, Ganymede, and Callisto orbital phase control of Jovian decametric emission, paper presented at the American Geophysical Union Fall Meeting, San Francisco, CA, December, 2000.

Higgins, C. A., J. D. Menietti, J. L. Green, and J. R. Thieman, Effects of Callisto on Jovian decametric emission, paper presented at the Jupiter: The Planet, Satellites and Magnetosphere Meeting, Boulder, CO, June, 2001.

Kaiser, M. L., and J. K. Alexander, Periodicities in the Jovian decametric emission, *Astrophys. Lett.*, **14**, 55, 1973.

Khurana, K. K., M. G. Kivelson, C. T. Russell, R. J. Walker, and D. J. Southwood, Absence of an internal magnetic field at Callisto, *Nature*, **387**, 262, 1997.

Khurana, K. K., M. G. Kivelson, D. J. Stevenson, G. Schubert, C. T. Russell, R. J. Walker, and C. Polanskey, Induced magnetic fields as evidence for subsurface oceans in Europa and Callisto, *Nature*, **395**, 777, 1998.

Kivelson, M. G., K. K. Khurana, C. T. Russell, R. J. Walker, J. Warnecke, F. V. Coroniti, C. Polanskey, D. J. Southwood, and G. Schubert, Discovery of Ganymede's magnetic field by the Galileo spacecraft, *Nature*, **384**, 537, 1996c.

Kivelson, M. G., K. K. Khurana, F. V. Coroniti, S. Joy, C. T. Russell, R. J. Walker, J. Warnecke, L. Bennett, and C. Polanskey, The magnetic field and magnetosphere of Ganymede, *Geophys. Res. Lett.*, **24**, 2155, 1997.

Kivelson, M. G., K. K. Khurana, D. J. Stevenson, L. Bennett, S. Joy, C. T. Russell, R. J. Walker, C. Zimmer, and C. Polanskey, Europa and Callisto: Induced or intrinsic fields in a periodically varying plasma environment, *J. Geophys. Res.*, **104**, 4609, 1999.

Kurth, W. S., D. A. Gurnett, and F. L. Scarf, The control of Saturn's kilometric radiation by Dione, *Nature*, **292**, 742, 1981b.

Kurth, W. S., D. A. Gurnett, A. Roux, and S. J. Bolton, Ganymede: A new radio source, *Geophys. Res. Lett.*, **24**, 2167, 1997a.

Kurth, W. S., S. J. Bolton, D. A. Gurnett, and S. Levin, A determination of the source of Jovian hectometric radiation via occultation by Ganymede, *Geophys. Res. Lett.*, **24**, 1171, 1997b.

Kurth, W. S., D. A. Gurnett, and J. D. Menietti, The influence of the Galilean satellites on radio emissions from the Jovian System, in *AGU Monograph 119, Radio Astronomy at Long Wavelengths*, 200, edited by R. A. Stone, 2000.

Leblanc, Y., On the arc structure of the DAM Jupiter emission, *J. Geophys. Res.*, **86**, 8546, 1981.

Lecacheux, A., B. M. Pedersen, P. Zarka, M. G. Aubier, M. D. Desch, W. M. Farrell, M. L. Kaiser, R. J. MacDowall, and R. G. Stone, In ecliptic observations of Jovian radio emissions by Ulysses: Comparison with Voyager results, *Geophys.. Res. Lett.*, **19**, 1307, 1992.

Menietti, J. D., J. L. Green, N. F. Six, and S. Gulkis, Ray tracing of Jovian decametric radiation from southern and northern hemisphere sources: Comparison with Voyager observations, *J. Geophys. Res.*, **92**, 27, 1987.

Menietti, J. D., D. A. Gurnett, W. S. Kurth, and J. B. Groene, Control of Jovian radio emission by Ganymede, *Geophys. Res. Lett.*, **25**, 4281, 1998a.

Menietti, J. D., D. A. Gurnett, W. S. Kurth, J. B. Groene, and L. J. Granroth, Galileo direction finding of Jovian radio emissions, *J. Geophys. Res.*, **103**, 20001, 1998b.

Menietti, J. D., D. A. Gurnett, and I. Christopher, Control of Jovian radio emission by Callisto, *Geophys. Res. Lett.*, **28**, 3047, 2001.

Neubauer, F. M., The sub–Alfvènic interaction of the Galilean satellites with the Jovian magnetosphere, *J. Geophys. Res.*, **103**, 19843, 1998.

Neubauer, F. M., Alfvèn wings and electromagnetic induction in the interiors: Europa and Callisto, *J. Geophys. Res.*, **104**, 28671, 1999.

Queinnec, J., and P. Zarka, Io–controlled decameter arcs and Io–Jupiter interaction, *J. Geophys. Res.*, **103**, 26649, 1998.

Smith, R. A., Models of Jovian decametric radiation, in *Jupiter*, edited by T. Gehrels, 1146, University of Arizona Press, Tucson, 1976.

Warwick, J. W, J. B. Pearce, A. C. Riddle, J. K. Alexander, M. D. Desch, M. L. Kaiser, J. R. Thieman, T. D. Carr, S. Gulkis, A. Boischot, C. C. Harvey, and B. M. Pedersen, Voyager 1 planetary radio astronomy observations near Jupiter, *Science*, **204**, 955, 1979a.

Warwick, J. W, D. R. Evans, J. H. Romig, J. K. Alexander, M. D. Desch, M. L. Kaiser, M. G. Aubier, Y. Leblanc, A. Lecacheux, and B. M. Pedersen, Planetary radio astronomy observations from Voyager 2 near Saturn, *Science*, **215**, 582, 1982.

Wilkinson, M. H., Io–related Jovian decametric arcs, *J. Geophys. Res.*, **94**, 11777, 1989.

Zarka, P., Auroral radio emissions at the outer planets: Observations and theories, *J. Geophys. Res.*, **103**, 20159–20194, 1998.

Zarka, P., J. Queinnec, and F. Crary, Low–frequency limit of Jovian radio emissions and implications on source locations and Io plasma wave, *Planet. Space Sci.*, **49**, 1137–1149, 2001a.

Zarka, P., R. A. Treumann, B. P. Ryabov, and V. B. Ryabov, Magnetically driven planetary radio emissions and applications to extrasolar planets, *Astrophys. Space Sci.*, **277**, 293–300, 2001b.