The Influence of the Galilean Satellites on Radio Emissions From the Jovian System

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The Galilean satellites influence radio emissions from the Jovian system in a variety of ways. The best and most familiar example of these is the Io control of decametric radiation discovered in 1964 by *Bigg*. Voyager observations of broadband kilometric radiation revealed a low-latitude shadow zone cast by the Io torus at frequencies between a few tens of kHz and about 1 MHz. Voyager also discovered narrowband kilometric radio emissions emanating from the outer edge of the torus. In this paper we will discuss expansions in the suite of satellite influences based on new observations by Galileo. These include the discovery of Ganymede's magnetosphere and evidence of radio emissions generated via mode conversion from upper hybrid waves in the frequency range of about 20 - 100 kHz. There is evidence that Ganymede may control some of the hectometric or low-frequency decametric radio emissions based on occultation measurements and statistical studies of radio emission occurrence as a function of Ganymede phase. Direction-finding measurements in the vicinity of Io suggest that a portion of the hectometric emissions may be generated near the Io L-shell. A rotationally modulated attenuation band in the hectometric emission appears to be the result of scattering at or near the Io L-shell where the waves propagate nearly parallel to the magnetic field. There is even a tantalizing hint of a Europa connection to the source of narrowband kilometric radiation.

1. INTRODUCTION

From early in the study of Jovian radio emissions, it was clear that Io had an important influence on the intensity of the observed decametric signal [*Bigg*, 1964]. In fact, it could be argued that a considerable amount of theoretical work which preceded any missions to Jupiter dwelt on the mechanism by which Io might control these radio emissions. These studies included dynamos, the generation of electric potentials, and current systems which could tie Io to Jupiter via Jupiter's magnetic field [cf. *Goldreich and Lynden-Bell*, 1969]. Voyager caused a revolution not only in the way radio astronomers and magnetospheric physicists viewed the Jovian system by the discovery of numerous new low-frequency radio emissions and their phenomenology [*Science*, Vol. *204*, 1 June 1979; *J. Geophys. Res.*, Vol. *86*, 30 Sept. 1981], but also by the discovery of the Io torus fueled at the rate of a ton per second of material originating in Io's volcanos [*Morabito et al.*, 1979; *Broadfoot et al.*, 1979]. The new radio emissions included a number of manifestations of Io control. For example, the newly-discovered broadband kilometric radiation exhibited an equatorial shadow zone in its occurrence which was attributed to the existence of the Io plasma torus [*Kurth et al.*, 1980]. And, the outer edge of the Io torus was

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determined to be the source of the narrowband kilometric radiation [*Kaiser and Desch*, 1980]. However, even after the Pioneer, Voyager, and Ulysses flybys, only Io seemed to have any credible influence on Jovian radio emissions.

The Galileo mission has provided two opportunities for further investigation of the influence of satellites on Jovian radio emissions. First, the nature of an orbiting mission is to provide a platform from which maps and statistical studies can be carried out at relatively close range to the planet, as opposed to a flyby mission. Second, Galileo's mission includes multiple flybys of each of the Galilean satellites at close range, allowing direct in situ observations of the interaction of each of those satellites with the Jovian magnetosphere. During its first nearly three years in orbit, Galileo has confirmed a number of the Io influences above and has identified new examples of satellite influences, some of which involve Ganymede.

This review will briefly summarize the satellite - magnetosphere interactions of the four Galilean satellites from the point of view of a wave receiver in Section 2, demonstrate the confirmation or extension by Galileo measurements of previously-known satellite influences in Section 3, and describe new satellite influences discovered by Galileo to date in Section 4. The observations used will be from the Galileo plasma wave investigation described fully by *Gurnett et al.* [1992]. This instrument covers electric fields in the frequency range of 5.6 Hz to 5.6 MHz using an electric dipole antenna with a tip-to-tip length of 6.6 m and magnetic fields in the range of 5.6 Hz to 160 kHz using a pair of magnetic search coil antennas tuned for low and high frequencies.

2. SUMMARY OF PLASMA WAVE OBSERVATIONS OF GALILEAN SATELLITE INTERACTIONS WITH THE JOVIAN MAGNETOSPHERE

Galileo has made a close flyby of Io and several close flybys of Europa, Ganymede, and Callisto since it arrived at Jupiter in December 1995. These encounters have provided our first look at the interactions between the satellites and the Jovian magnetosphere. Before we can discuss how these satellites may influence Jovian radio emissions, it is important to briefly describe these in situ observations. Table 1 summarizes some of the features of the satellite interactions including the peak electron density observed, types of wave emissions observed, and a very subjective classification of the importance or strength of the magnetospheric interaction based primarily on the wave observations thus far.

2.1. Io

Galileo used a flyby of Io to help slow the spacecraft so that it could be captured into orbit on 7 December 1995. Fields and particles observations were made for about a 3 hour interval spanning the radial distance range of about 7.6 to 5.4 R_J (Jovian radii) and culminating in a passage through Io's plasma wake at an altitude of about 900 km. Plate 1a shows electric and magnetic frequency-time spectrograms detailing the plasma wave observations during this interval [*Gurnett et al.*, 1996a]. The display indicates the amplitudes of waves as a function of frequency (ordinate) and time (abscissa) using color to indicate the relative intensity of the waves. Blue areas indicate the weakest amplitudes and red the most intense. The upper panel shows the electric component of the wave spectrum and the lower panel shows the magnetic component. The most prominent emissions at lower frequencies in these spectrograms are electromagnetic whistler-mode emissions. There are indications that kinetic Alfvén waves may also be present, at least in the intervals of enhanced wave intensities such as near 1710 spacecraft event time (SCET) [*A. Roux, personal communication,* 1996]. At the highest frequencies are the hectometric radio emissions. The narrowband emission at a few to several hundred kHz running over the entire duration of the interval is the upper hybrid resonance band that can be used to ascertain the electron density using

$$n_e = \frac{(f_{UH}^2 - f_{ce}^2)}{8980^2} \qquad (1)$$

Here n_e is in cm^{-3}, and f_{UH} and f_{ce} are the upper hybrid resonance frequency and electron cyclotron frequency, respectively, in Hz and $f_{UH}^2 = f_{pe}^2 + f_{ce}^2$ where f_{pe} is the electron plasma frequency. The electron cyclotron frequency can be determined from the measured magnetic field, however, it is of order 50 kHz and is negligible in Equation 1 over the time period in Plate 1a. As compared to the densities expected over the Galileo trajectory from the *Bagenal* [1994] Io torus density model based on Voyager measurements, the measured densities are about a factor of two greater [*Gurnett et al.*, 1996a; *Bagenal et al.*, 1997]. Perhaps the most extraordinary result, however, is the density peak of about 40,000 cm^{-3} observed at the closest approach to Io. Based on high plasma densities, low temperatures, and low flow velocities (relative to Io) *Frank et al.* [1996] suggest that Galileo actually passed through Io's ionosphere. Subsequent studies [*Warnecke et al.*, 1997; *Chust et al.*, 1999; *Frank and Paterson*, 1999] report the pickup of heavy ions and protons in the vicinity of Io.

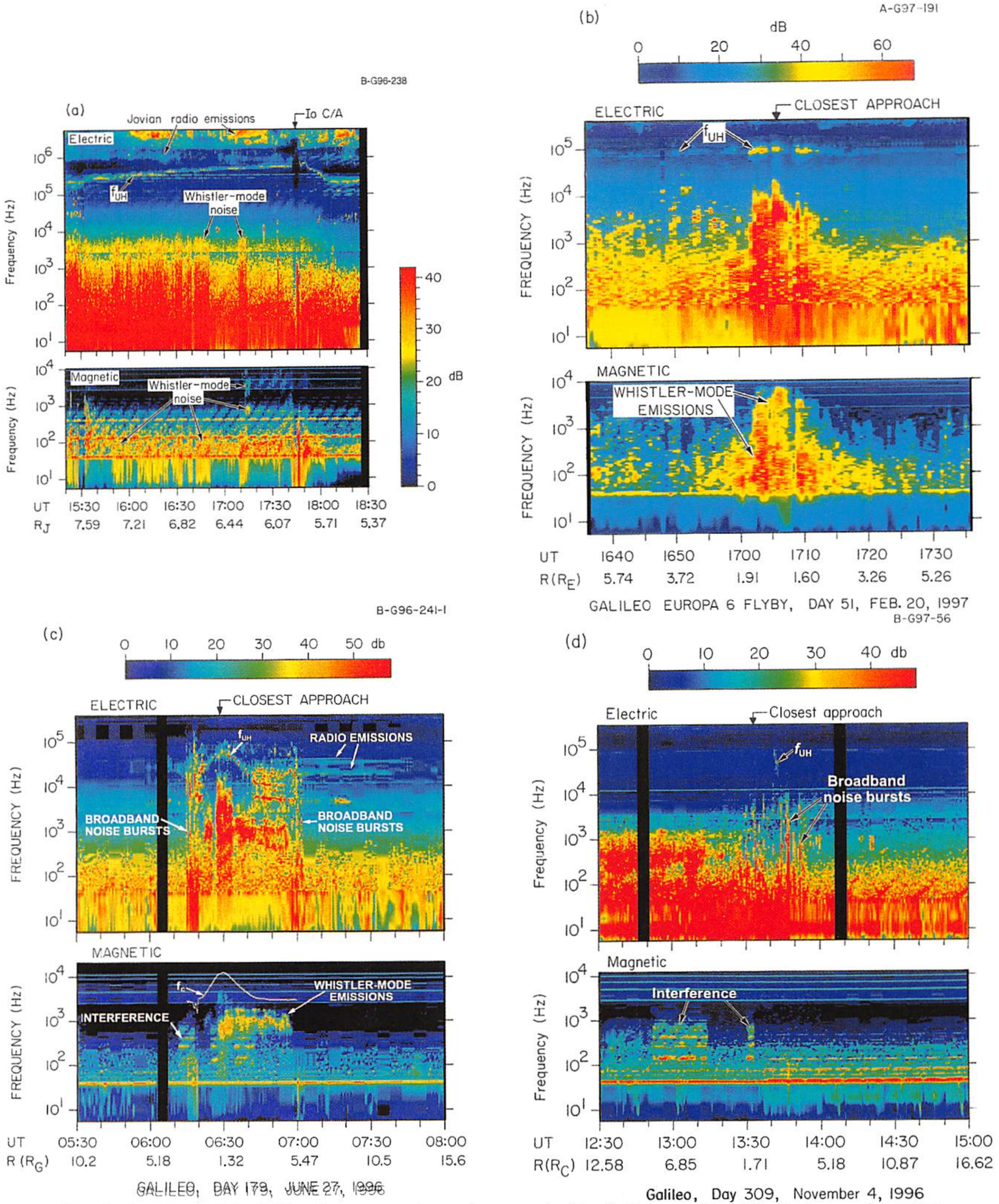

Plate 1. Overviews of the Galileo plasma wave observations at each of the Galilean satellites. The displays are frequency-time spectrograms showing the amplitude of waves as a function of frequency and time. The color bars show that the most intense waves are shown in red and the least intense waves in blue. (a) Io from *Gurnett et al.* [1996a]. [Reprinted with permission from *Science, 274*, 391, 1996; copyright 1996 American Association for the Advancement of Science]. (b) Europa from *Gurnett et al.* [1998a]. [Copyright by the American Geophysical Union]. (c) Ganymede from *Gurnett et al.* [1996b]. [Reprinted with permission from *Nature*, copyright 1996 Macmillan Magazines Limited]. (d) Callisto from *Gurnett et al.* [1997]. [Reprinted with permission from *Nature*, copyright 1997 Macmillan Magazines Limited].

Table 1. A Simple Comparison of the Galilean Satellite Interactions with the Jovian Magnetosphere

Satellite	Distance R_J	Peak n_e (cm^{-3})	Interaction Strength	Waves	Distant Effects
Io	6	41,000	Strongest	Ion cyclotron waves Whistler modes Kinetic Alfvén waves Upper hybrid band Radio emissions	Plasma torus Jovian aurora Radio control, propagation
Europa	9.5	180	Intermediate	Whistler modes Electron cyclotron harmonic bands Upper hybrid band Broadband electrostatic noise	Unknown
Ganymede	15	100	Intermediate	Whistler-mode hiss Chorus Electron cyclotron harmonic bands Upper hybrid band Broadband electrostatic noise Radio emissions	Wake or plume Radio control?
Callisto	26	100	Weakest	Kinetic Alfvén waves Upper hybrid band Broadband electrostatic noise	None known

2.2. *Europa*

Plate 1b shows the wave observations from the Europa flyby during the E6 orbit on 20 February 1997. The most clear signatures of Europa in this spectrogram are enhanced whistler-mode emissions near 1705 SCET accompanied by enhanced upper hybrid emissions near 100 kHz. During this flyby Galileo passed within 586 km of the surface on the upstream side of the moon. The upper hybrid signature yields density estimates of as high as about 180 cm^{-3} (during the E4 flyby). Given that the ambient density at the orbit of Europa is ~ 80 cm^{-3}, this represents an enhancement of up to about 100 cm^{-3} [*Gurnett et al.,* 1998a]. Plasma observations [*Paterson et al.,* 1999] suggest a source strength of about 2 kg/s generated by Europa's interaction with Jupiter's magnetosphere. The magnetometer observations show an enhanced magnetic field near the moon, but there is no clear evidence that this is due to an intrinsic field. In some sense, it is difficult to characterize the nature of Europa's interaction with Jupiter, probably because the moon is bathed in the outer reaches of the Io torus. This could mask what might be more significant interactions than those apparent in Plate 1b; it is also possible that the position of Europa relative to the plasma torus (elevation with respect to the centrifugal equator) at the time of a Galileo flyby strongly affects the signatures of the interaction *[Kivelson et al.,* 1999].

2.3. *Ganymede*

A surprise of the Galileo mission is the discovery of an intrinsic magnetic field at Ganymede and the existence of a Ganymede magnetosphere embedded within the Jovian magnetosphere [*Gurnett et al.,* 1996b; *Kivelson et al.,* 1996]. Plate 1c shows wave observations from the Ganymede flyby during the G1 orbit on 27 June 1996. This flyby had a closest approach altitude of 835 km downstream of the moon. Virtually all of the information needed to identify this magnetosphere and to ascertain the existence of an intrinsic field is provided by the data represented by Plate 1c. First, the search coil observations prove that the intense emissions below a few kHz centered near 0630 SCET are electromagnetic and, in particular, whistler-mode emissions. This mode exists only below both f_{pe} and f_{ce}, hence, *Gurnett et al.* [1996b] concluded that the magnetic field intensity was ~ 400 nT near closest approach as compared to the ambient field intensity at 15 R_J of about 100 nT. Second, there are very clear signatures of a magnetopause inbound at about 0615 and outbound near 0700 SCET as signified by broadband electrostatic emissions at these times. Third, the narrowband emission which peaks near 0630 is electrostatic and almost certainly the upper hybrid resonance (UHR) band indicating a relatively dense region at closest approach of about 45 cm^{-3} as compared to the ambient density of order 1 cm^{-3} in this region of the Jovian magnetosphere.

Furthermore, the upper spectrogram in Plate 1c shows evidence for banded electron cyclotron harmonic (ECH) emissions between harmonics of the electron cyclotron frequency. All of these emissions are typical of planetary magnetospheres. Finally, the weak banded emissions seen most prominently after Galileo has exited the magnetosphere (after 0700 SCET) appear to be radio emissions; these will be discussed in detail in Section 4 below. Of course, the Galileo magnetometer investigation [*Kivelson et al.*, 1996] and other instruments confirmed the conclusions listed above either directly or indirectly and the Ganymede magnetosphere has proven to exhibit a number of features common to planetary magnetospheres including evidence of reconnection (albeit with the Jovian magnetic field as opposed to the interplanetary field), a wealth of effects on thermal and energetic plasmas [*Frank et al.*, 1997a,b; *Williams and Mauk*, 1997; *Williams et al.*, 1998; *Paranicas et al.*, 1999], and even evidence for an extended plasma plume extending in the downstream direction [*Khurana et al.*, 1999].

2.4. Callisto

Observations from the Callisto flyby on the C3 orbit are shown in Plate 1d [*Gurnett et al.*, 1997]. This flyby occurred at a distance of 1129 km downstream of the moon on 4 November 1996. The signature of this interaction in the wave data is the least impressive of the four Galilean satellites. The broadband bursty signatures are possibly similar to broadband electrostatic noise signatures seen at various locations at Earth [*Gurnett and Frank*, 1977] and also at Jupiter [*Barbosa et al.*, 1981] but could also be the result of kinetic Alfvén waves. There is a brief burst of electrostatic emission near 90 kHz at about 1342 SCET, near closest approach. This emission is almost certainly an upper hybrid resonance emission and suggests a density of as much as 100 cm^{-3}. The ambient density at 26 R_J in the Jovian magnetosphere is < 1 cm^{-3}. The magnetometer observations do not suggest an intrinsic field at this moon [*Khurana et al.*, 1997].

3. PRE-GALILEO ASSESSMENT OF SATELLITE INFLUENCES ON JOVIAN RADIO EMISSIONS

It is not within the scope of this review to thoroughly cover the pre-Galileo state of understanding of Jovian radio emissions and the influences of the Galilean satellites on their generation and propagation. A number of papers already do this in great detail [c.f. *Boischot et al.*, 1981; *Alexander et al.*, 1981; *Ladreiter and Leblanc*, 1990; *Lecacheux et al.*, 1992]. However, it is fair to summarize that virtually all of the generally-accepted satellite influences are related to Io and the Io torus.

3.1. Io Control of Decametric Emissions

The oldest and most obvious of the Galilean satellite influences are the Io-related decametric radio emissions [*Bigg*, 1964; *Carr and Desch*, 1976]. Galileo's frequency range extends to only 5.6 MHz, just above the peak in the hectometric spectrum, however, *Menietti et al.* [1998c] have shown that even in the frequency range 3.2 to 5.6 MHz enhancements in the radio spectrum can be found when Io is near 90° and 240° in phase. This result raises further questions about the relationship between the decametric and hectometric emissions and whether the hectometric spectrum is just a lower frequency extension of the decametric emissions. The existence of an Io control of the lower-frequency emissions could either suggest the extension of the decametric emissions to lower frequencies, or a similar control of the hectometric emissions. Both classes of radio emissions are presumed to be generated by the cyclotron maser instability; the lower frequency of the hectometric emissions clearly indicates that they are generated at higher altitudes than the decametric radiation where the local electron cyclotron frequency is lower.

3.2. Broadband Kilometric Radiation Equatorial Shadow Zone Cast by the Io Torus

Kaiser and Desch [1980] differentiated the kilometric radiation into two clearly different types of radio emissions and suggested different source locations and mechanisms for them. *Kurth et al.* [1980] showed that there was a magnetic equatorial shadow zone with half-width about 10° within which the broadband kilometric radiation is usually not observed. They attributed this shadow zone to the blocking effect of the Io plasma torus on the relatively low frequency radio emissions. Galileo has confirmed the existence of this equatorial shadow zone [*Kurth et al.*, 1997a] and, in fact, Galileo seldom observed broadband kilometric radiation after the G2 Ganymede flyby. The G2 flyby was used to reduce the few-degree inclination of the initial Galileo orbit to nearly 0°. The 9.6° wobble of the magnetic field as Jupiter rotates is not sufficient to carry Galileo out of the shadow zone.

3.3. Narrowband Kilometric Radiation Source Region in the Outer Io Torus

The narrowband kilometric radiation was isolated from the broadband kilometric radiation by *Warwick et al.* [1979] and *Kaiser and Desch* [1980]. These emissions near 100 kHz are typically about 40 kHz in bandwidth and show an entirely different temporal character than the broadband kilometric radiation. *Kaiser and Desch* first deduced that the narrowband emissions were generated in the outer edge of the Io torus in the radial distance range of about 8 - 9 R_J. Furthermore, the narrowband emissions did not appear completely synchronized with Jupiter's rotation; instead the emissions appeared to slip with respect to the system III rotation period by 3 - 5% [*Kaiser and Desch,* 1980]. This further supported a source in the outer regions of the torus since mass loading will slow the plasma there to below the full corotation speed. Ulysses direction-finding results confirmed the Io torus source region for these emissions and also concluded that they were primarily generated in the extraordinary mode [*Reiner et al.,* 1993].

Galileo routinely observes the narrowband kilometric radiation [*Kurth et al.,* 1997a] appearing episodically in such a way as to suggest the birth of a new source region which lasts for several Jovian rotations before fading away. *Louarn et al.* [1998] have shown that the narrowband kilometric episodes appear to have onsets which coincide with brightening in the hectometric emissions and changes in the trapped continuum radiation spectrum. These onsets, in turn, correlate well with quasi-periodic changes in the energetic particle spectrum in the outer magnetosphere reported by *Krupp et al.* [*1998*] and *Woch et al.* [1998]. These reports suggest that these quasi-periodic changes are symptoms of magnetospheric dynamics of uncertain origin.

Galileo repeatedly passes through the equatorial magnetosphere into distances of 9 R_J and smaller, hence, there would appear to be ample opportunities to fly through a narrowband kilometric radiation source region. Based on prior studies, we would expect to find intense electrostatic upper hybrid bands at about 100 kHz in the region of 8 - 9 R_J which mode-couple into electromagnetic waves at the same frequency through either a linear mechanism [c.f. *Jones,* 1987] or a nonlinear mechanism [c.f. *Melrose,* 1981] or perhaps to up-converted waves [*Fung and Papadopoulous,* 1987]. While there are a few instances which may prove to be evidence of such source regions in the data acquired to date, none of them are particularly compelling. The quasi-periodicity of the onset of these emissions, however, would seem to reduce the probability of Galileo being at the right place at the right time to actually traverse a source region. Perhaps the most tantalizing aspect of the Galilean observations in this region of the magnetosphere is that Europa appears to be the site of enhanced upper hybrid emissions near 100 kHz [*Gurnett et al.,* 1998a]. It is conceivable that Europa plays a role in the generation of at least some of these emissions.

4. GALILEO CONTRIBUTIONS

Galileo has found evidence for several ways in which the Galilean satellites influence radio waves from the Jovian system which were not previously recognized. In this section we summarize these new Galileo findings.

4.1. Radio Emissions from Ganymede's Magnetosphere

By far the most exciting result from the Galileo mission from the point of view of planetary radio emissions is the discovery of Ganymede's magnetosphere and radio emissions generated at that magnetosphere [*Gurnett et al.,* 1996a; *Kivelson et al.,* 1996; *Kurth et al.,* 1997c]. Plates 1c and 2 show the first and second flybys of Ganymede via measurements from the Galileo plasma wave receiver up to a frequency of 5.6 MHz. The signatures of the familiar planetary plasma wave phenomena pointed out in section 2 and in Plate 1c are also evident in Plate 2. One of these common features is the existence of weak, narrowband emissions most evident following each of these encounters, that is, on the Jupiterward side of Ganymede. There is, however, evidence for these emissions just prior to both encounters as well, although these are not as extensive. These emissions are found between approximately 20 and 50 kHz, although there is some evidence for weaker emissions inside the magnetosphere near 100 kHz in the first encounter (Plate 1c). Wideband observations from the second encounter show that the integrated bandwidth of these emissions is of order 10 kHz and they extend no more than about 18 Ganymede radii from the moon, limited almost certainly by the sensitivity of the Galileo receiver.

Kurth et al. [1997c] argued that these radio emissions have their source in the upper hybrid emissions near the Ganymede magnetopause. The frequency-time character and frequency range of these emissions is unlike other known Jovian radio emissions and their presence only in the near vicinity of Ganymede is a strong indication of a source at Ganymede. The clearest evidence for a source associated with Ganymede's magnetosphere, however, is summarized in Figure 1. Here, the intensity of waves at 20.1 kHz is plotted as a function of the distance from Ganymede as Galileo left the magnetosphere of Ganymede. The larger intensity, bursty emissions early in this time interval are the electrostatic upper hybrid waves at and just inside the magnetopause. Later, the wave intensity decreases more smoothly as the spacecraft leaves the vicinity of the magnetopause, although the amplitude uncertainty arising from the use of a lossy compression algorithm is responsible for the peculiar patterns which appear in this region.

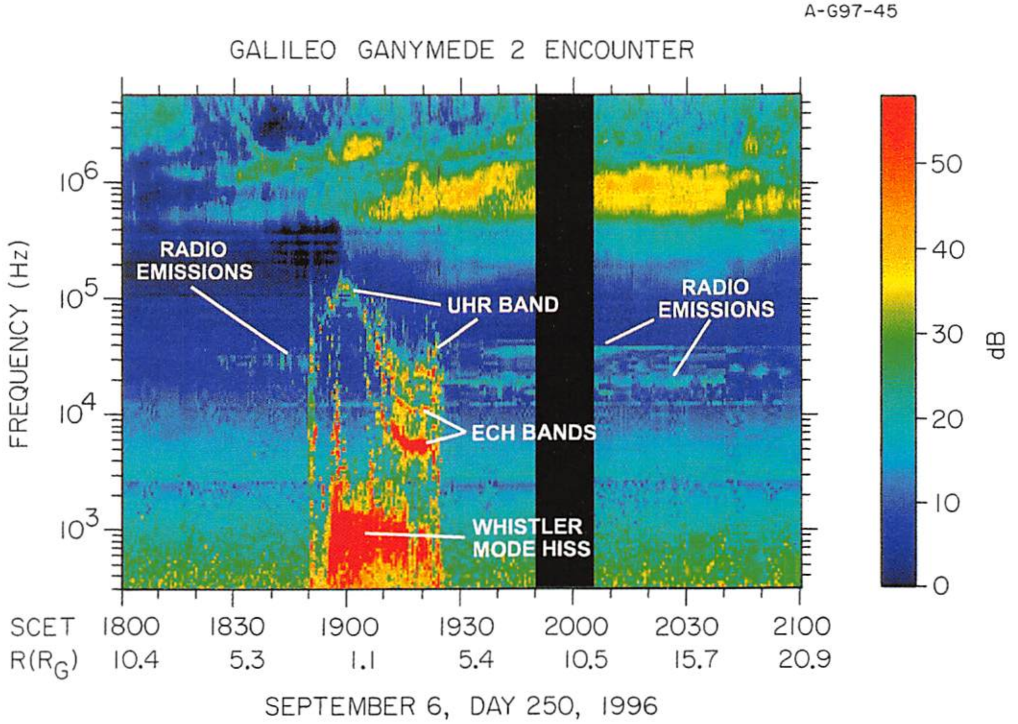

Plate 2. Radio emissions observed emanating from Ganymede's magnetosphere [*Kurth et al.*, 1997c]. [Copyright by the American Geophysical Union].

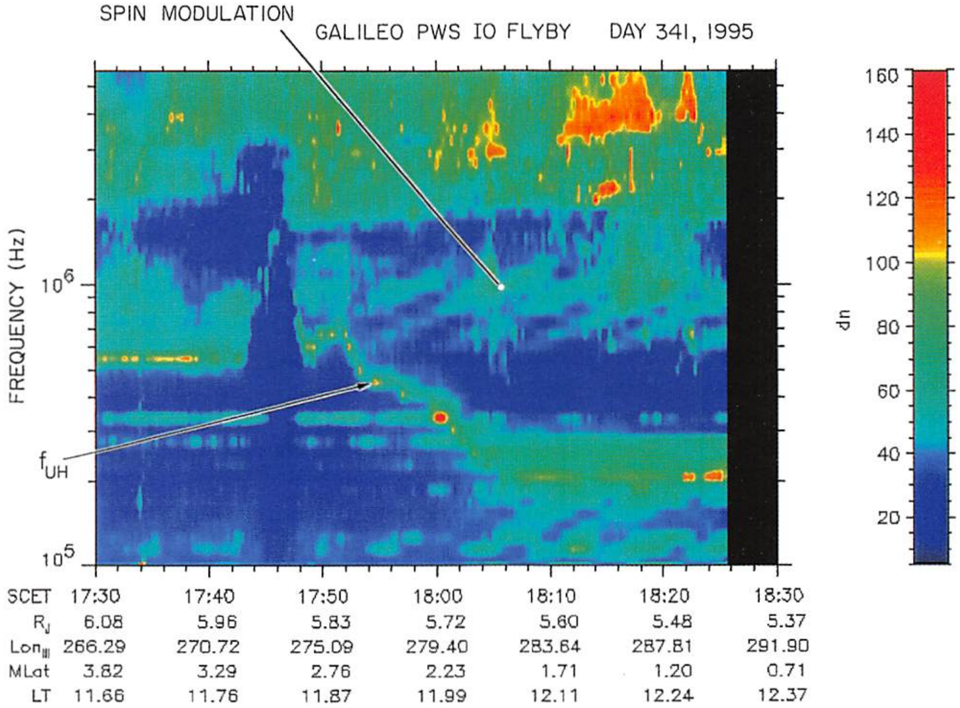

Plate 3. A spin-modulated radio emission feature found close to Io [*Menietti et al.*, 1998b]. [Copyright by the American Geophysical Union].

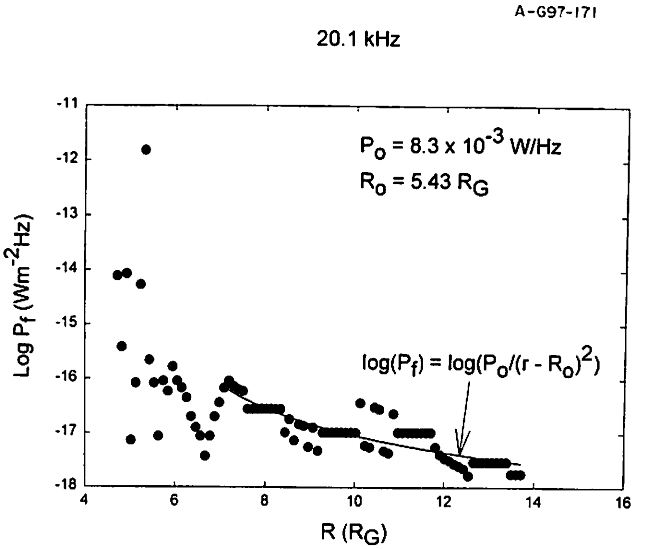

Figure 1. The intensity of waves as a function of distance from Ganymede showing the radio emissions decrease in intensity as r^{-2} from a source at or near the magnetopause [*Kurth et al.*, 1997c]. [Copyright by the American Geophysical Union].

Hypothesizing a source at the magnetopause between Galileo and Ganymede, *Kurth et al.* fit a curve with an r^{-2} dependence to the data showing that the source was near 5.4 R_G (Ganymede radii), consistent with a magnetopause source.

Kurth et al. [1997c] also suggested that the evidence in Plates 1c and 2 strongly supports generation by mode conversion from electrostatic upper hybrid waves, similar to the mechanism commonly accepted for the nonthermal continuum radiation at Earth, Jupiter, and the other outer planets. Particularly in Plate 2, an intense upper hybrid band is evident near the magnetopause at nearly the same frequency (~ 20 kHz) as one of the bands of radio waves. The conditions are just what one would expect for the mode conversion theory to apply: there is evidence of electrostatic upper hybrid resonance emissions at a sharp density gradient and the density gradient is more-or-less perpendicular to the magnetic field (based on the magnetic field configuration near the magnetopause [*Kivelson et al.*, 1996]). Furthermore, the second fit parameter P_0 given in Figure 1 allows one to calculate a total power of approximately 80 W from the source, assuming radiation into a large solid angle and using 10 kHz for the emission bandwidth. This is similar to the total power in the terrestrial continuum radiation [*Gurnett*, 1975].

The importance of the Ganymede radio emissions is not so much their intensity as the mere fact that we now have yet another "planetary" magnetosphere which is the source of one of the two nearly ubiquitous types of radio emissions (nonthermal continuum-like radio emissions and the stronger auroral cyclotron maser emissions). This is even more important given that Ganymede is now the smallest magnetosphere known to support radio emissions and also that this magnetosphere is embedded not in the solar wind but the Jovian magnetosphere. Of course, this begs the question of why there are no obvious cyclotron maser emissions from this magnetosphere. We believe the answer to this is that at least near Ganymede, the plasma frequency as determined by the upper hybrid resonance band seen in Plates 1c and 2 is always greater than f_{cc}. Hence, the usual cyclotron maser requirement that $f_{pc}/f_{cc} < 0.3$ is clearly not met.

4.2. An Io Source for Hectometric Radiation

Menietti et al. [1998a] have developed a direction-finding analysis methodology for the Galileo plasma wave receiver measurements based on the rotating dipole technique [*Fainberg et al.*, 1972; *Kurth et al.*, 1975]. *Menietti et al.* [1998b] have applied this technique to a specific interval just after the Io encounter on 7 December 1995 between ~ 600 kHz and ~ 1 MHz. Plate 3 is taken from the *Menietti et al.* [1998b] study and shows the strong spin modulation of the feature in the hectometric frequency range after the Io flyby.

The rotating dipole technique determines only the plane in which a radio source exists. This plane is defined by the spin axis of the spacecraft and the centroid of the direction of arrival of the radio waves (the direction to the source). Hence, it is not very specific. Additionally, the technique is most useful for sources near the plane perpendicular to the spacecraft spin axis.

During the Io encounter, Galileo was at a local time (with respect to Jupiter) of ~12 hours (local noon) and based on the geometry shown in Figure 2 [*Menietti et al.*, 1998b], it is clear that Jupiter was very close to Galileo's spin axis. This geometry, then, more or less excludes any of the normal hectometric sources at low altitudes in Jupiter's auroral zone since such sources would exhibit little or no spin modulation. Instead, *Menietti et al.* point out that the source direction is consistent with the approximate location of the Io L-shell and perhaps that associated with the high-density plume extending downstream of Io.

This is the first evidence for radio waves originating from the vicinity of Io (as opposed to the foot of Io's flux tube or L-shell near Jupiter) and represents a possible detection of radio emissions in the Io-magnetospheric interaction region. *Menietti et al.* [1998b] note that density gradients, electron beams, and upper-hybrid emissions are all present near Io. The upper hybrid emission may mode-convert into electromagnetic waves [e.g. *Jones*, 1986; *Melrose*, 1981] or

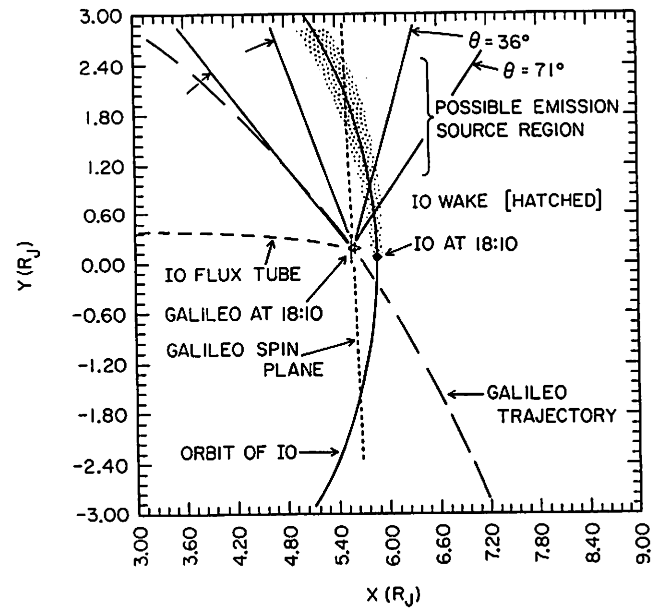

Figure 2. A schematic of the geometry of the direction-finding results of the feature shown in Plate 3 indicating that an extended plume from Io or L-shells associated with the plume are consistent with the source of the waves [*Menietti et al.*, 1998b]. [Copyright by the American Geophysical Union].

the temperature anisotropy beam instability could result in the waves [e.g. *Wong and Goldstein*, 1990]. An alternative to a source near Io, however, has been suggested by *Farrell et al.* [1999] who argue that the waves may simply be the usual auroral hectometric emissions refracted or reflected at the density gradients in the Io L-shell.

4.3. Ganymede Control of Low-Frequency Decametric or Hectometric Radiation

Given the strong interaction now known to exist between the magnetospheres of Ganymede and Jupiter, it is natural to suspect that currents flowing from Ganymede to Jupiter's ionosphere may result in the generation of radio emissions in a manner similar to the Io-related decametric emissions. The existence of such emission is consistent with occultation measurements of hectometric radiation [*Kurth et al.*, 1997b] which suggest that at least some hectometric emission may be generated on or near Ganymede's flux tube near Jupiter.

We have analyzed most of the prime mission radio observations for such a Ganymede influence using the familiar satellite phase vs. system III longitude displays used to highlight Io-related sources. Plate 4 is an example of such an analysis after *Menietti et al.* [1998c] using radio measurements between 3.2 and 5.6 MHz and showing the occurrence of emissions above a threshold of 4×10^{-18} W m^{-2} Hz^{-1} scaled to 100 R$_J$ as a function of Ganymede phase (superior conjunction relative to Jupiter as viewed by Galileo is 0° phase) and system III longitude λ_{III} (of Galileo). Peaks can be seen between 100 - 160° λ_{III} near 80° and 240° Ganymede phase. In this analysis, periods when the phase of Io is between 85° and 100° or 220° and 225° have been filtered out. While the effect shown is not strong, there is an apparent Ganymede emission, consistent with expectations and the occultation measurements of *Kurth et al.* [1997b]. It is almost certainly the case, though, that hectometric emissions are generated by magnetospheric sources situated over a wide range of λ_{III} and local time, hence, one would not expect a Ganymede source to necessarily dominate the hectometric spectrum.

Kaiser and MacDowall [1998] have reported a small number of observations by Ulysses of radio "bullseyes" in the frequency range of 20 to 50 kHz. The bullseye nomenclature arises from the appearance of these features in a frequency-time display. While *Kaiser and MacDowell* show a good correlation between these events and periods of enhanced solar wind ram pressure, they also note that sometimes there is 10.5-hour periodicity between successive events. Since this is the period between successive passages of a given system III longitude past Ganymede, these authors suggest that there may be some Ganymede influence on the radio emissions. To date, there have been no observations of these radio emissions identified in the Galileo data set.

4.4. The Hectometric Attenuation Band

Gurnett et al. [1998b] have reported an attenuation band observed repeatedly in the hectometric emission spectrum which they attribute to a propagation effect at or near the Io L-shell. Plate 5 shows a 24-hour interval of hectometric observations which display parabolic-shaped attenuation features with two features per rotation. These attenuation bands are related to the "lanes" observed by the Voyager spacecraft [*Lecacheux et al.*, 1980; *Higgins et al.*, 1995]. *Gurnett et al.* noted that there are clear indications that the attenuation bands are tied to the rotation of Jupiter. Each of the parabolic features is near a maximum excursion in magnetic latitude by the spacecraft, either north or south of the equator (near $\lambda_{III} = 50°$ or 185°) and the peak frequency of the feature varies as the radial distance of the spacecraft.

Gurnett et al. [1998b] modeled the frequency of maximum attenuation by assuming scattering or shallow-angle reflection for ray paths nearly parallel to an L-shell near Io. A schematic of the geometry and the model are given in Figure 3. Essentially, for any given geometry, one can locate a hectometric radio source on an auroral field line and at the

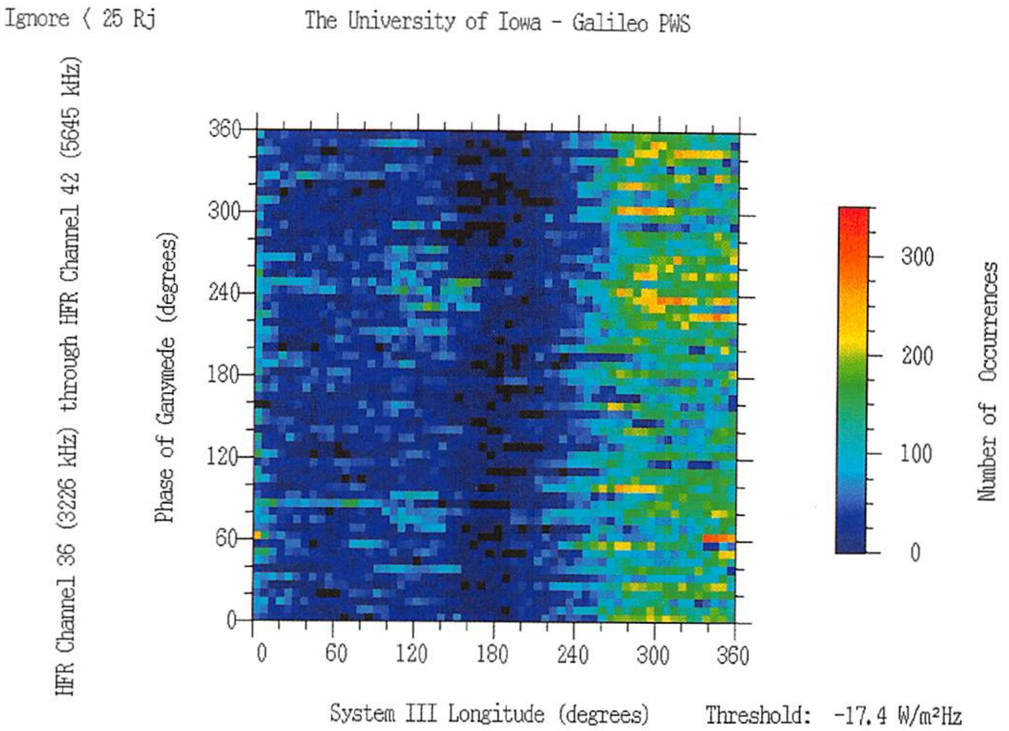

Plate 4. An analysis of the occurrence of hectometric radiation as a function of Galileo's system III longitude and the phase of Ganymede relative to Jupiter as viewed by Galileo. Weak peaks in the occurrence rate occur when Ganymede is near 90° and 270° phase [*Menietti et al.,* 1998c]. [Copyright by the American Geophysical Union].

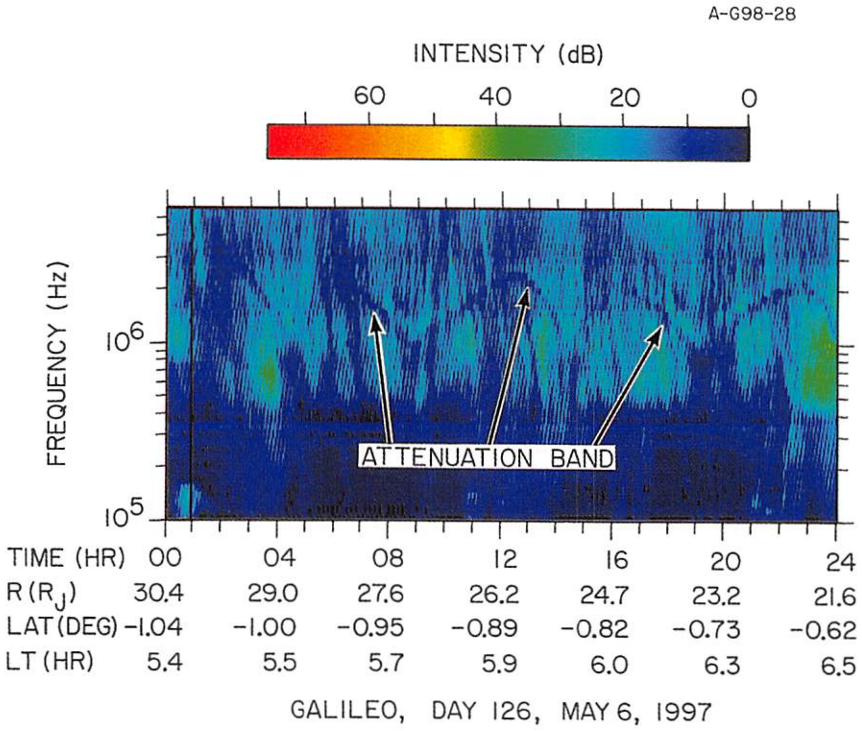

Plate 5. A frequency-time spectrogram showing an attenuation band in the hectometric radio spectrum which varies in frequency at twice the rotation rate of Jupiter [*Gurnett et al.*, 1998b]. [Copyright by the American Geophysical Union].

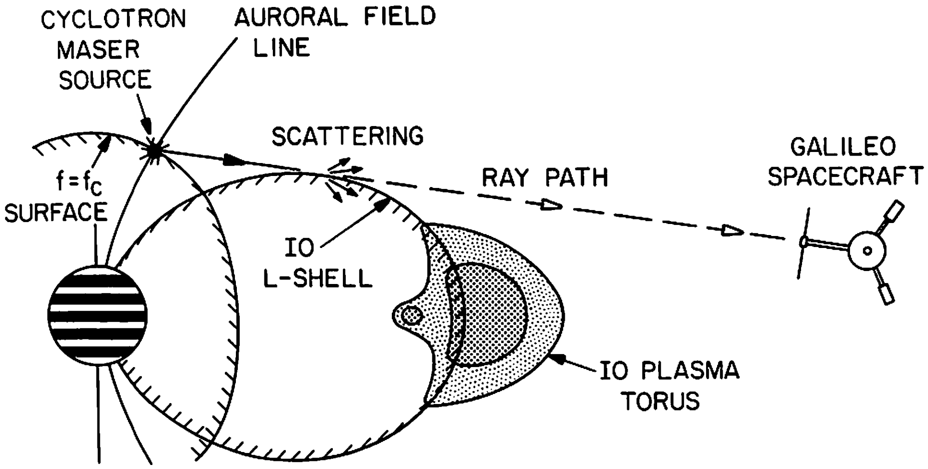

Figure 3. A model by *Gurnett et al.* [1998b] for the attenuation mechanism which accounts for most of the features observed in the spectrogram in Plate 5. Hectometric radio waves which propagate nearly parallel to an L-shell near Io suffer either scattering or shallow-angle reflection; observed wave amplitudes observed in this direction are decreased in amplitude from those at higher and lower frequencies. [Copyright by the American Geophysical Union].

source electron cyclotron frequency (assuming the cyclotron maser instability as a source mechanism) which must propagate nearly tangentially along an L-shell near that of Io. If one assumes scattering by density fluctuations along that L-shell or alternately, shallow-angle reflection at the surface of the L-shell due to field-aligned density variations (gradients perpendicular to the magnetic field), one can reproduce the attenuation pattern observed by Galileo quite accurately. *Higgins et al.* [1999] have carried out additional statistical studies of this feature and have clearly related the effect to the Voyager "lanes." *Menietti et al.* [1998d] have also shown evidence of two nested attenuation bands which provides the first clear evidence of second harmonic cyclotron maser emission in Jovian hectometric radiation. *Menietti et al.* [1999] conclude that shallow-angle reflection can account for the observations, but coherent scattering cannot be ruled out at present.

5. SUMMARY

The Galilean satellites interact with the magnetosphere of Jupiter in a variety of ways and across a spectrum of relative importance. Io certainly has the most important influence on the system, but Galileo has shown that Ganymede, with its intrinsic magnetic field, has a much more interesting interaction with Jupiter than previously thought. Callisto is evidently the least important of the Galilean satellites in terms of its interaction with the magnetosphere. Europa's interaction is largely masked by the Io torus, hence, it is difficult to understand the true nature of its interaction at this time.

The most dramatic contribution of Galileo to our understanding of the satellites' influence on Jovian radio emissions is the discovery of Ganymede's magnetic field. The existence of radio emissions from Ganymede enforces the hypothesis that remotely-sensed radio emissions are a reliable indication of a body with an intrinsic magnetic field, hence, magnetosphere.

Galileo has also provided evidence that Ganymede may control some of the Jovian radio emissions in a manner similar to, but to a lesser extent than, Io.

Galileo observations have provided new insight into effects of the Io torus on the propagation of hectometric radiation in the form of rotationally-modulated attenuation bands. There is also some evidence for radio emissions in the kilometric/hectometric radiation range having a source on the Io L-shell, but in the vicinity of the moon as opposed to the high latitude, low altitude location of most of the Jovian hectometric and kilometric emissions.

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