Ganymede: A new radio source

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Abstract. Observations by the Galileo plasma wave receiver during the first two flybys of Ganymede revealed that this Jovian moon is the source of narrowband electromagnetic radio waves, making it the only satellite in the solar system known to generate non-thermal radio emissions. The emissions are the result of mode-coupling from electrostatic electron cyclotron emissions near the upper hybrid resonance frequency, similar to non-thermal continuum radiation found at the known magnetized planets.

Introduction

Of the planets with known intrinsic magnetic fields (Mercury, Earth, Jupiter, Saturn, Uranus, and Neptune), all except Mercury are sources of nonthermal radio emissions [c.f. Kaiser, 1989]. Mercury is likewise a source, but no radio astronomy investigation has ever visited this planet and there are no Earth-based observations of Hermean radio emissions. Heretofore, no satellite of any of the planets has been found to be a source of radio emissions, although the strong influence of Io in the production of decametric radiation at Jupiter [Bigg, 1964] is well known. Now, however, with the discovery of a magnetosphere associated with Ganymede [Gurnett et al., 1996; Kivelson et al., 1996] clear evidence for radio emissions emanating directly from this magnetosphere has been found.

Radio emissions from planetary magnetospheres are currently classified in three categories by the generation mechanism thought to be responsible for the various emissions. The most intense emission at each of the planets is thought to be generated by the cyclotron maser instability [Wu and Lee, 1979] near the electron cyclotron frequency in the high magnetic latitude region. Auroral kilometric radiation at the Earth [Gurnett, 1974], Jovian decametric radiation, and Saturnian and Uranian kilometric radiation are all examples of this type of emission [Kaiser, 1989]. Neptune's higher frequency smooth and bursty emissions are also of this type [Zarka et al., 1995]. Generally speaking, there is either a demonstrable or suspected relationship between the cyclotron maser instability emissions and auroral processes in each of the planetary magnetospheres. The second type of emission is much less intense but just as ubiquitous. It has generally been termed nonthermal continuum radiation [Gurnett, 1975], myriametric radiation [Jones, 1988], or narrowband electromagnetic radiation [Gurnett et al., 1983] and is the result of the conversion of electrostatic waves at the upper hybrid resonance frequency into electromagnetic radio waves via either a linear [c.f. Jones, 1988] and/or a nonlinear mechanism [c.f. Rönnmark, 1992]. These emissions are typically generated at greater distances from the planet than the cyclotron maser emissions (e.g. at the plasmapause, plasmasheet, or magnetopause) and, hence, are typically at lower frequencies. Especially at Earth and Jupiter a significant portion of the continuum spectrum is generated at frequencies below the surrounding solar wind plasma frequency and is therefore trapped within the magnetospheric cavity. Higher frequency components can escape the magnetosphere. The third known type of planetary radio emission is often called 2f, emission from the planetary bow shock [Gurnett, 1975] and is the result of nonlinear interactions of Langmuir waves in the electron foreshocks of planetary magnetospheres which produce weak electromagnetic emissions at twice the electron plasma frequency in the foreshock [c.f. Cairns, 1988].

The radio emissions discussed here are of the second category. We will show using wave observations from the first two Galileo flybys of Ganymede that these emissions are clearly generated in the magnetosphere of Ganymede, that their source is associated with intense upper hybrid resonance bands in the magnetosphere, and that they are very similar to the terrestrial escaping nonthermal continuum (myriametric) radiation and the narrowband electromagnetic radiation at Jupiter and Saturn.

The Galileo plasma wave instrument utilizes an electric dipole antenna mounted on the end of the 10.6-m magnetometer boom with a length of approximately 6.6 m tip-to-tip. Search coil magnetometers covering the frequency range up to 160 kHz are also used, mounted on the high gain antenna feed. The plasma wave receiver consists of a 4-channel spectrum analyzer covering the range from 5.62 Hz to 31.1 Hz, a medium frequency receiver covering the range from 40 Hz to 160 kHz with 112 channels, and a high frequency receiver covering 100 kHz - 5.6 MHz with 42 channels. In essence, these 158 channels can be thought of as a single sweep frequency receiver which accumulates a complete spectrum every 18.67 seconds. For a more detailed description of the instrument, see Gurnett et al. [1992].

Observations

Figures 1 and 2 show frequency-time spectrograms summarizing the radio and plasma wave observations from the first and second Galileo flybys of Ganymede on June 27 and September 6, 1996. In these spectrograms we have plotted the intensity of the electric field component of the wave spectrum as a function of time (abscissa) and frequency (ordinate) using the color bar at the right to indicate intensity. Red areas represent the most intense wave features and blue the weakest. Spectrograms from the two flybys are remarkably similar and show the wealth of wave phenomena associated with the interaction between Ganymede's environment and the Jovian magnetosphere which led Gurnett et al. [1996] to conclude that the region was identical to a miniature planetary magnetosphere in numerous ways based solely on the plasma and radio waves observed.
The upper hybrid resonance band is a special case of the ECH wave activity just inside the inbound magnetopause in both encounter data sets.

High spectral resolution wideband data were obtained for both flybys with a bandwidth of 80 kHz. Fortunately, the wideband data from the second flyby extended to beyond both the inbound and outbound magnetopause crossings and reveal the radio emissions just outside Ganymede’s magnetosphere. The electric field data are shown in Figure 3. The periodic gaps are time periods when the wideband receiver was connected to the magnetic antenna and configured with a 10-kHz bandwidth. The spectrogram is created through a series of Fourier transforms, hence, the frequency scale is linear instead of logarithmic as are those in Figures 1 and 2. The first ECH harmonic, commonly referred to as the $3f_c/2$ band, is easily observed both inbound around 1851 spacecraft event time (SCET) and also outbound from about 1908 SCET to the magnetopause at 1923 SCET. The highest frequency band is denoted as the upper hybrid band. This band is quite bursty and extends well above the 80-kHz bandpass of the receiver near closest approach. At some times, such as near 1905 SCET the UHR band actually appears in two successive cyclotron harmonic bands. This can occur when the upper hybrid frequency lies very close to a cyclotron harmonic. Notice that two rather intense bands occur just prior to the outbound magnetopause crossing which are at nearly the same frequencies as the two radio emissions which appear just prior to the end of the spectrogram. Radio emissions which appear prior to the entry into the magnetosphere are more sporadic and variable in bandwidth. The bright (red), but very brief burst of UHR emission centered near 30 kHz at 1850 SCET may be related to these inbound radio emissions.
The radio emissions extend to a distance of some 15-20 Ganymede radii \( R_0 \) \( (R_0 = 2634 \text{ km}) \) in the direction of the outbound Galileo trajectory in both flybys (towards Jupiter) as shown in Figure 4. Here, we plot the trajectories of Galileo for the two flybys on a coordinate system centered at Ganymede and having \( x \) in the nominal plasma corotation direction and \( y \) in the direction towards Jupiter. The trajectory is represented by a thick line during times when the radio emissions are seen beyond the Ganymede magnetopause as identified by Gurnett et al. [1996]. The weak emissions above 50 kHz very close to Ganymede are not included here.

The emissions appear in two or three bands in the range of about 15 to 50 kHz. The bandwidths of each of the bands span from one to a few of the Galileo sweep frequency receiver's channels, or of the order of 10 percent of the frequency. In Figure 5 we show the power flux of radio emissions at 20.1 kHz as a function of radial distance taken from the first encounter's outbound observations. The alternating series of constant or sloping amplitudes is due to the amplitude inaccuracy introduced by the lossy integer cosine transform used to compress these data in response to the failure of the Galileo high gain antenna. As can be seen in Figure 5, this results in errors of the order of ~ 5 dB. The rather sporadic, bursty behavior of the signals nearest Ganymede is likely due to electrostatic emissions in the magnetosphere of Ganymede. We attribute the local minimum in the signal at about 6.7 \( R_0 \) to the spacecraft being both outside of the magnetosphere and temporarily shadowed from a radio emission beam. Just beyond 7 \( R_0 \) however, the spacecraft is in a radio emission beam which decreases in intensity with distance (but subject to the data compression effects noted above). We initially assume that the source is between Ganymede and the spacecraft and fit to a curve for power flux \( P_f \) in W/m²Hz of the form \( \log(P_f) = \log(P_0/(|X-x|)^2 + (|Y-y|)^2 + (|Z-z|)^2)) \) where we use Cartesian coordinates with respect to Ganymede as the position of the source and Galileo. The curve derived for this fit is virtually identical to that shown in Figure 5, however, the parameters have extremely large (100 to 1000 times the parameter value) uncertainties due to strong dependencies between them. The position for the source obtained from this fit, ambiguous as it is, is at about 5.4 \( R_0 \) from Ganymede and close to the Galileo trajectory. We take this as additional evidence that our assumption for nearly radial motion from the source for the fit in Figure 5 is not unwarranted and that the \( R_0 \) derived from the simpler fit is consistent. This result is consistent with other arguments presented below that the 20-kHz source is likely near the magnetopause.

The determination of \( P_0 = 8.32 \times 10^{-3} \text{ W/Hz} \) gives a total power emitted of about 83 Watts (using an integrated bandwidth of about 10 kHz). Using the observed power flux of 6.2 \times 10^{-17} \text{ W/m²Hz} at 7.2 \( R_0 \), we find that the power flux at a standard distance of 1 astronomical unit (AU) is approximately 6 \times 10^{-24} \text{ W/m²Hz}. This can be compared to other planetary radio emissions and, according to Kaiser [1989], is ~ 10^6 less intense than the median power flux of Jovian narrowband kilometric radiation at 1 AU which is likely generated via a similar mechanism to these Ganymede emissions. Given the much smaller source size, one would expect such a minuscule value for Ganymede.

**Generation Mechanism**

The most obvious source of the Ganymede radio emissions are the upper hybrid resonance emissions in the Ganymede magnetosphere shown clearly in Figures 1 - 3. These are known to be the source of narrowband continuum radiation at Earth [Kurth et al. 1981] and narrowband electromagnetic bands at Jupiter [Gurnett et al., 1983]. Figure 6 shows a spectrum of the emissions observed at 0649:46 SCET just inside the outbound magnetopause during the first Ganymede flyby. The most intense peak here is near 300 \( \mu \text{V/m} \), similar to the intensity of the emissions at Earth. It is likely that even more intense bursts occur, perhaps into the mV/m range.

**Figure 4.** Schematic of the first two Ganymede flybys showing by the use of thick lines the regions in which Ganymede's radio emissions were observed.

**Figure 5.** Power flux at 20.1 kHz versus distance from Ganymede showing that the radio emissions decrease in intensity as the inverse square of the distance from the source.
hectometric radiation at Jupiter. Given the large plasma magnetosphere is the source of nonthermal radio emissions is kilometric radiation at Earth or the decametric and present. This is the cyclotron maser emission such as auroral to find such emissions. It is interesting, though, that the other, more intense magnetospheric emission is apparently not the most dramatic of the Galileo mission to date. That this hybrid bands near the magnetopause are most likely to be upper hybrid band near closest approach implies the upper radiation at the known magnetized planets, it is not surprising magnetospheres. Given the ubiquity of the continuum densities measured near Ganymede in the vicinity of its magnetic pole, the reason for the lack of the cyclotron maser instability is most likely due to the lack of an auroral cavity, or regime where \( f_p / f_m \leq 0.3 \) which is the criterion for X mode radiation at the Earth by this mechanism.

Acknowledgments. The research at The University of Iowa is supported by NASA through Contract 958779 through the Jet Propulsion Laboratory. The authors are grateful for the especially valuable comments from one of the referees.

References


\[ f_p / f_m \leq 0.3 \]

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(Received: February 28, 1997; revised: July 30, 1997; accepted: August 5, 1997.)