JOVIAN RADIO EMISSIONS: AN EARLY OVERVIEW OF GALILEO OBSERVATIONS

W. S. Kurth*, D. A. Gurnett*,
S. J. Bolton†, A. Roux‡, and S. M. Levin†

Abstract

This paper summarizes the very early results from the Galileo investigation of Jovian radio emissions. While some of the Galileo results are already quite interesting and novel, this report serves primarily to introduce the Galileo observations and place them into context with previous studies. We briefly discuss the decametric, hectometric, kilometric, and continuum radiations, as well as the Jovian type III radio bursts, also known as quasi-periodic noise bursts.

1 Introduction

The Galileo mission has suffered numerous difficulties on its way to Jupiter, but these have been overcome, for the most part, and observations have now begun. In this paper we present an early overview of the observations of Jovian radio emissions obtained by the plasma wave receiver on the Galileo orbiter. The instrument consists of a set of receivers that act together as a sweep frequency receiver covering the frequency range of 5.6 Hz to 5.6 MHz with 152 logarithmically spaced channels. (The receiver actually has 158 channels, but six overlapping channels have been dropped in the software which edits and compresses the data to utilize the low-gain antenna link as a result of the high gain antenna failure.) Sensors include a 6.6-m dipole antenna mounted at the end of the 10.6-m magnetometer boom and a search coil magnetic sensor assembly mounted in the high gain antenna feed tower. The electric field measurements span the entire frequency range to 5.6 MHz while the magnetic measurements extend to 100 kHz. Since the electric dipole antenna is most efficient for freely-propagating radio waves, we will only use the electric field measurements in this paper. A thorough discussion of the Galileo plasma wave instrumentation is given by Gurnett et al. [1992].

---

*The University of Iowa, Department of Physics and Astronomy, Iowa City, IA 52242, USA
†Jet Propulsion Laboratory, California Inst. of Technology, Pasadena, CA 91109, USA
‡Centre d'Étude des Environnements Terrestre et Planétaire, F-78140 Vélizy, FRANCE

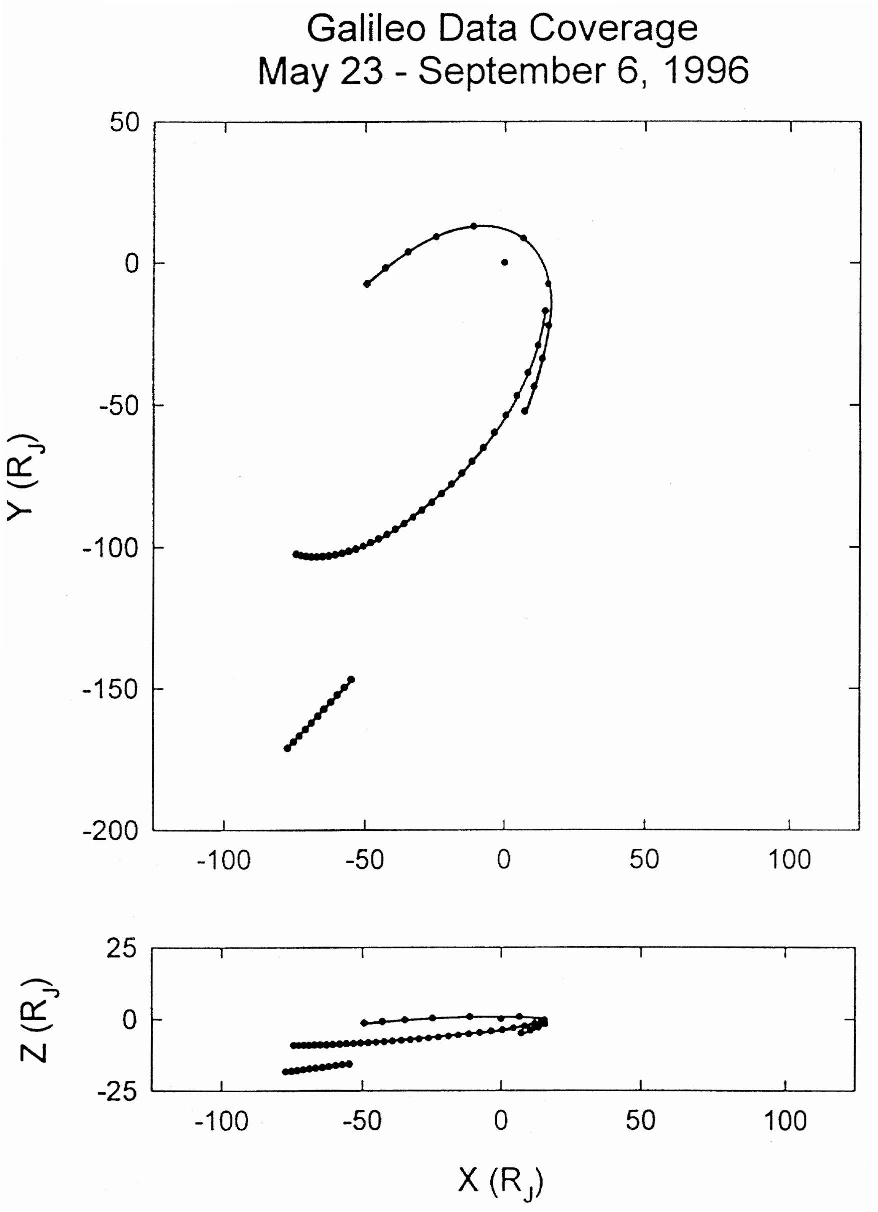

Figure 1: The geometry of the three intervals of time utilized in compiling this overview. Shown are the orbital segments projected into the Jovian equatorial plane (upper panel) and in the noon-midnight meridian (lower panel).

The measurements included in this paper are from four distinct phases in the mission: 1) several hours of the Io torus pass taken on the Jupiter arrival passage on December 7-8 1995, 2) an approximately 10-day interval following the initial load of the new flight software enabling data compression several weeks prior to the first Ganymede encounter period, 3) an approximately 10-day interval covering the trajectory inside of about 50 R_J around the first Ganymede flyby, and 4) an approximately 25-day interval from apoapsis of the Ganymede 1 orbit inbound toward the second Ganymede encounter interval. The latter three intervals are displayed in Figure 1. It is important to notice that for the more distant periods the orbit inclination is about 5 degrees with the apojove in the southern hemisphere and is, therefore, significantly different than the two Voyager trajectories that ranged from about 3 degrees to 7 degrees north of the Jovian equator. This will have a strong bearing on the System III longitude at which the hectometric radiation (HOM) and broadband kilometric radiation (bKOM) are observed.

2 A Brief Introduction to Jovian Radio Emissions as Observed by Galileo

Figures 2 and 3 provide examples of most of the known Jovian radio emissions below 5.6 MHz. Both of these Figures are in the form of frequency-time spectrograms covering the frequency range of 300 Hz to 5.6 MHz over 24-hour time intervals in which the intensity of the emissions are coded according to the color bars. Blue represents the least intense waves or instrument background and red the most intense.

At the very top of Figure 2 is an example of the lower frequency extension of the decametric radiation (DAM) spectrum near 1130 spacecraft event time (SCET). This is clearly an extension of a vertex-late arc [Leblanc, 1981] and likely an Io-C emission. In cases where the DAM extends into the HOM emissions, it is difficult to differentiate between the two phenomena and we use a working definition for DAM of arc-like structures extending upward out of the Galileo frequency range that are not likely to be confused with HOM event. Given a fair amount of ground-based observations of the DAM emissions [c.f., Boischot et al., 1980b] as well as the capability of observing DAM from the Wind spacecraft in Earth orbit [Bougeret et al., 1995] we hope to be able to incorporate the Galileo lower frequency observations with these other data sets.

Proceeding lower in frequency, three complex sets of HOM emissions are seen at frequencies from a few hundred kHz to as high as 5.6 MHz but peaking in intensity at around 600 kHz; it is uncertain whether the higher frequencies are properly HOM or DAM. These three sets are centered at about 0400, 1400, and 2300 SCET. These events are characterized by some arc-like structures with very rapid variation in frequency with time and also somewhat ill-defined banded structures at more constant frequency but with some tendency to decrease, then increase in frequency with time. These HOM events, like most observed by Galileo to date, are centered near 180 degrees in System III longitude.

The occurrence of HOM primarily centered around 180 degrees longitude seems at first to be in contradiction to Voyager Planetary Radio Astronomy (PRA) results [Alexander et al., 1981] where the peak in the HOM occurrence probability was near 0 degrees. In fact, the 0-degree emissions are often referred to as the “main” beam because of the longitude most commonly observed by Voyager for this phenomenon [c.f. Ladreiter and Leblanc, 1991]. Indeed, the 180-degree events are referred to as the “weak” beam [Reiner et al., 1993c]. However, if one considers the HOM beaming characteristics determined by Voyager [c.f. Alexander et al., 1981] and the latitude coverage of Galileo, it is simple to understand why Galileo observes the “weak” beam as opposed to the main beam. To illustrate this, we take a sketch of the HOM latitudinal beaming model by Ladreiter and Leblanc [1991] in Figure 4 and superimpose Galileo’s magnetic latitude for an interval in which Galileo is approaching perijove during the Ganymede 1 orbit, it is clear that Galileo is near the equatorial beam only at its highest magnetic latitude excursion. This is because the inclination of Galileo's orbit at this time is about 5 degrees and the excursions in latitude due to the rocking dipole only bring Galileo near the equator around 200 degrees when the north magnetic pole is tilted toward Galileo. In Figure 3 the HOM is seen virtually all the time. By use of Figure 4 it can be seen that the near-equatorial location of the Galileo trajectory in the inner magnetosphere places it in the HOM beam most of the time. There is some evidence for the shadow zone in Ladreiter and Leblanc's [1991] model beaming pattern centered around 1000 and 2200 SCET on June 27. Incidently, the arc-like structures are even more prevalent in these examples than in the HOM shown in Figure 2. The two Voyagers both had predominantly positive inclinations during their flyby trajectories, hence, would be in the equatorial region at opposite longitudes (near 0). Alexander et al. [1981] and Lecacheux et al. [1992] demonstrate the importance of the observer's Jovigraphic latitude in the longitudinal occurrence probability. Details of the Galileo-derived occurrence probability are the subject of a future paper.

At frequencies generally below the HOM in Figure 2 one finds the broadband kilometric radiation (bKOM). Two full episodes are shown here centered on about 0930 and 1930 SCET between about 30 and 300 kHz, but extending as high as 700 kHz at the peak. Partial episodes are seen at the beginning and end of the plotted interval as well. The lower frequency extents of these examples of bKOM are masked by the escaping continuum radiation extending over the entire day between about 20 and 35 kHz. The frequency-time envelopes of the bKOM episodes are broad at low frequencies and narrow at the highest frequencies. Each of the episodes clearly consists of narrow, mostly rising tones with very rapid drift rates, although there is some evidence for tones with negative drifts.

The bKOM events shown in Figure 2 are centered near 0 degrees System III longitude and, hence, correspond to the southern hemisphere portion of the bKOM emission [Kurth et al., 1979; Kaiser and Desch, 1980; Desch and Kaiser, 1980]. The Voyager analyses of the occurrence of these emissions showed an equatorial shadow zone of approximately 10 degrees half-width in which bKOM is not usually observed. Since the 5 degree inclination

Figure 2: (plate, next page) A frequency-time spectrogram showing examples of several types of Jovian radio emissions observed by Galileo during the early part of its mission at Jupiter. The spectrogram displays the intensity of waves as a function of time (abscissa) and frequency (ordinate) with color representing amplitudes. Blue represents weak wave emissions or instrument background and red the most intense waves. DAM is decametric radiation which is predominately at higher frequencies than the 5.6-MHz upper limit of the Galileo wave receiver. HOM is hectometric radiation. Broadband kilometric radiation is identified as bKOM.

Figure 3: (plate, following page) Here, several instances of narrowband kilometric radiation nKOM are shown. The frequency of these radio emissions approaches that of the highest frequency band of the electron cyclotron harmonic (ECH) bands also known as the upper hybrid resonance band. It is the upper hybrid bands which are thought to be the source of the nKOM in the outer Io torus near 8 - 9 R_J. The brief encounter with Ganymede's magnetosphere appears near 0630 SCET on this day. An expanded view of this time period is provided in Figure 5.

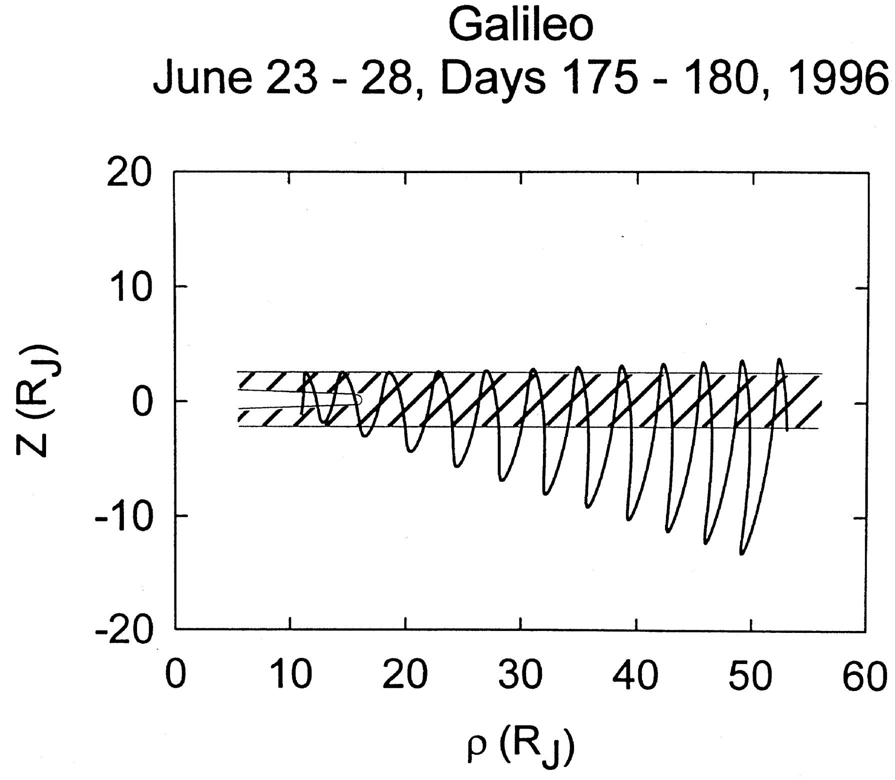

Figure 4: The trajectory of Galileo inbound on the Ganymede 1 orbit in magnetic cylindrical coordinates superimposed on a sketch of the hectometric radiation beam near the magnetic equator from Ladreiter and Leblanc [1991]. This demonstrates that for the early Galileo orbit which had a southerly inclination, hectometric radiation would only be expected to be observed near System III longitudes near 200 degrees when the north dipole is tipped toward the spacecraft, because this is the only time when Galileo would be in the emission beam. Closer to the planet, this model suggests that Galileo would observe hectometric radiation more continuously, as is the case.

of Galileo's current orbit does not allow excursions anywhere near +10 degrees magnetic latitude but as far south as −13.5 degrees magnetic latitude, it is clear why Galileo should see the emissions around 0 degrees System III longitude and not the (Voyager) primary population of events near 180 degrees [see the bKOM occurrence probability curves given by Lecacheux et al., 1992]. Again, it is appropriate to extend the statistical studies of the occurrence of bKOM, but that is beyond the scope of this overview. We point out, however, that the second Ganymede encounter on 6 September 1996 changed Galileo's inclination to nearly 0 degrees, and it is likely that Galileo will not be well situated to observe bKOM regularly for the rest of the mission.

The band of escaping continuum radiation shown around 30 kHz in Figure 2 extended over the entire day. Continuum radiation was first reported by Scarf et al. [1979] and further described by Gurnett et al. [1980] and Kaiser et al. [1992]. This type of radiation is found in all known planetary magnetospheres (except for Mercury, but no wave investigation has explored Mercury's magnetosphere for such emissions) and is thought to be generated by the conversion of electrostatic waves at the upper hybrid resonance frequency into electromagnetic waves, primarily in the ordinary mode [Kurth, 1992]. The escaping component is so-called because it is generated at a frequency above the solar wind plasma frequency and propagates freely out of the magnetosphere. The band of emission in Figure 2 is rather featureless in both frequency and time although Voyager studies indicated the likelihood of banded intensifications. Recently Kaiser [1997] has suggested that escaping continuum radiation may be a misnomer. Instead, he suggests that this band may be due to the coalescence of numerous Jovian type III bursts, or quasi-periodic noise bursts.

The trapped component of the continuum radiation lies below the solar wind plasma frequency and extends down to the local plasma frequency in the magnetosphere. In Figure 2, this covers the range from about 10 kHz down to as low as 500 Hz. Because the frequency of these waves is less than that of the surrounding solar wind plasma, the waves cannot escape the magnetospheric cavity, hence the term trapped continuum. In fact, it is likely the waves propagate down the magnetotail in the anti-solar direction as far as 5 or more astronomical units (AU) where the solar wind plasma frequency is low enough to allow the emissions to escape. This emission is more likely to have a continuous spectrum than the escaping component because multiple sources and Fermi scattering off the moving magnetopause tend to smooth the spectrum [Barbosa, 1981]. Nevertheless, some banded structures may be found even in the trapped component. The abrupt change in frequency at about 2.4 kHz in Figure 2 is due to a band edge in the receiver and will not appear in an appropriately calibrated spectrum. Gurnett et al. [1980] showed that the trapped continuum spectrum fell off as f^{-4}. Because of the very rarified cavities in the Jovian magnetospheric lobes and the fact that the waves cannot easily escape means that this emission can be among the most intense of all Jovian emissions.

Perhaps the most interesting and useful aspect of the trapped continuum radiation is the lower frequency cutoff. Since the continuum radiation is thought to be generated primarily in the ordinary mode and is known at the Earth to be a combination of both ordinary and extraordinary modes [Gurnett and Shaw, 1973], the sharp low-frequency cutoff can be used as an accurate measure of the electron plasma frequency in the Jovian magnetosphere [Gurnett et al., 1980, Ansher et al., 1992]. In the example given in Figure 2, several abrupt, significant variations in the plasma frequency can be seen, especially between about 0600 and 2000 SCET. Perraut et al. [1997] have confirmed the identification of this cutoff as the plasma frequency and have further identified other characteristic frequencies of the plasma under certain circumstances.

At frequencies of about 100 kHz in Figure 3 are several examples of narrowband kilometric radiation (nKOM). These emissions have approximately the same average frequency as the bKOM, but cover a much smaller frequency range and generally show little temporal variation, although these examples show significant structure. The nKOM emissions were shown to slip with respect to the System III rotation rate by Kurth et al. [1980b], Kaiser and Desch [1980], and others. Culminating with unambiguous direction-finding analyses with Ulysses [Reiner et al., 1993b], the source of these emissions was found to be on the outer edge of the Io torus. We believe the sources of these emissions are electrostatic upper hybrid waves found near the magnetic equator also on the outer edge of the torus. In fact, examples of these are seen in Figure 3. Brief bursts of banded emissions are seen near

0440, 1000, 1500, and 2130 SCET which are identified as electrostatic electron cyclotron harmonic emissions [Kurth et al., 1980a]. The most intense of these bands are the lowest frequency components seen in Figure 3 near 2 kHz at 0440 SCET and about 7 kHz for the 2130 SCET event. This component is the so-called $3f_{\rm ce}/2$ band, occurring just above the electron cyclotron frequency. Emissions at higher odd half-harmonics are also seen. Well above these emissions is an emission which is called the upper hybrid resonance band which is the odd half-harmonic electron cyclotron band at the upper hybrid resonance frequency $f_{\rm UHR} = (f_{\rm pe}^2 + f_{\rm ce}^2)^{1/2}$. For example, the $f_{\rm UHR}$ emission is just below 40 kHz at 1000 SCET, at 50 kHz at 1500 SCET and at 60 kHz near 2100 SCET. It is clear that the frequency of the upper hybrid band will increase as the torus density, hence $f_{\rm pe}$, and the magnetic field, hence $f_{\rm ce}$, increase planetward. It is reasonable that such emissions occur in the same frequency range as the observed nKOM emissions just inward of the closest approach of this orbit, consistent with the $\sim$9 $\rm R_J$ determination using Voyager and Ulysses observations.

3 Some Special Observations

3.1 Occultation of the Hectrometric Radiation Source by Ganymede

A serendipitous occultation of the HOM source by Ganymede during Galileo's first flyby of the moon [Kurth et al., 1997a] has provided one of the earlier advances in Jovian radio astronomy to come from the Galileo mission. This flyby was targeted to provide a crossing of Ganymede's wake, remote sensing of the moon's sunlit hemisphere at high phase angles, and also to place Galileo on a trajectory which would bring it back to Ganymede for the second Ganymede flyby in the following orbit. It wasn't until the observations in Figure 5 were available that the occultation of the HOM radio source was recognized. As can be seen in Figure 3, HOM is present continuously during 27 June 1996 except for several minutes just prior to the Ganymede closest approach highlighted by the intense emissions seen to above 100 kHz centered around 0630 SCET. Figure 5 shows an expanded view of the period around the Ganymede encounter. Of course, the extensive interaction of Ganymede with the Jovian magnetosphere and the inference of a magnetosphere-like structure is perhaps the most profound discovery of Galileo so far in its mission, but a discussion of this interaction is given by Gurnett et al. [1996b] and will not be repeated here. However, the signature of the occultation is clearly visible in the HOM emissions at 700 kHz and above between about 0552 and 0623 SCET.

Using a technique very similar to that employed by Kaiser and Alexander [1976] to determine the 2-dimensional source location of auroral kilometric radiation at the Earth using lunar occultations as viewed by RAE-2, Kurth et al. [1997a] have used the occultation to determine the direction to the HOM source from 700 kHz to 5.6 MHz. Figure 6 shows the essence of the technique as well as the results. Centered in the Figure is Jupiter with four different views of the limb of Ganymede as seen by Galileo at the times at the beginning and end of the occultation ingress and the beginning and end of the egress at 1 MHz determined from Figure 5. The smaller pair of these represent the limb of Ganymede at 0559:30 and 0602:40 during which time the 1.0-MHz emission was occulted. The larger pair of circles represent the limb of Ganymede at 0620:20 and 0621:00 SCET when the 1.0-MHz emission reappeared. The source of the radio emissions must be at one or the other of the regions of intersection of these four limbs.

Also shown in Figure 6 are two other sets of solutions for the occultations at 4.8 and 3.6 MHz. These are nearly aligned in a linear fashion with the highest frequencies closest to Jupiter. Such a result is to be expected. HOM is generally believed to be generated in the polar auroral region over Jupiter near the electron cyclotron frequency by the cyclotron maser instability [Wu and Lee, 1979]. The electron cyclotron frequency decreases with the magnetic field strength as the radial distance increases. Kurth et al. [1997a] point out that it is highly unlikely that the occultation coincidently occults two sources simultaneously and that only one of the sets of regions in Figure 6 represents the actual source. They argue the northern set are more consistent with emission along a single or restricted set of magnetic field lines than the southern set, hence, the northern set of solutions is likely the actual source.

Perhaps the most striking aspect of the occultation results are that the occultation is so sharp and so complete. The sharp cutoffs are consistent with a very small source and the complete nature of the occultation implies that there are no other sources in view at the same time. As prolific as HOM seems to be on this day (see Figure 3), it is surprising that the source is both small and singular. Kurth et al. [1997a] also demonstrate that the northern set of sources align reasonably well with the field line which threads Galileo at the time of the occultation, Ganymede's field line, and also Europa's, all of which fall with a longitude range of only about 7 degrees near 160° in System III. They point out that the presence of a magnetosphere at Ganymede is likely to generate currents along the Ganymede flux tube, hence, present a possible driver for radio emissions near the foot of the flux tube. A similar effect could be operative near Europa, although the Europa environment has not yet been studied. Finally, Kurth et al. suggest that the emission could simply be beamed into the central meridian, although this would not seem to be easy to do over such a wide range of frequencies.

The small source size and the lack of other sources at this time would seem to argue for 160 degrees being special for some reason. One obvious suggestion is that the Ganymede flux tube, connected to its newly discovered magnetosphere, might carry currents much the same way as Io and produce radio emissions similar to DAM. However, this observation is equally consistent with radio emission confined to the magnetic meridian plane.

Figure 5: (plate, next page) An overview of the Ganymede magnetospheric plasma and radio emissions (see Gurnett et al., [1996b]). Both the inbound and outbound magnetopause crossings are clearly defined as broadband noise bursts. Extending outwards from the magnetopause, primarily after the Ganymede encounter are relatively weak banded radio emissions. The high frequency band of emission which peaks near closest approach is the upper hybrid band. Electron cyclotron harmonic bands are seen near both the inbound and outbound magnetopause. The intense emissions at lower frequencies peaking near closest approach are whistler mode hiss emissions with evidence for some chorus. Notice the complete occultation of the hectometric radio emissions just prior to the Ganymede encounter.

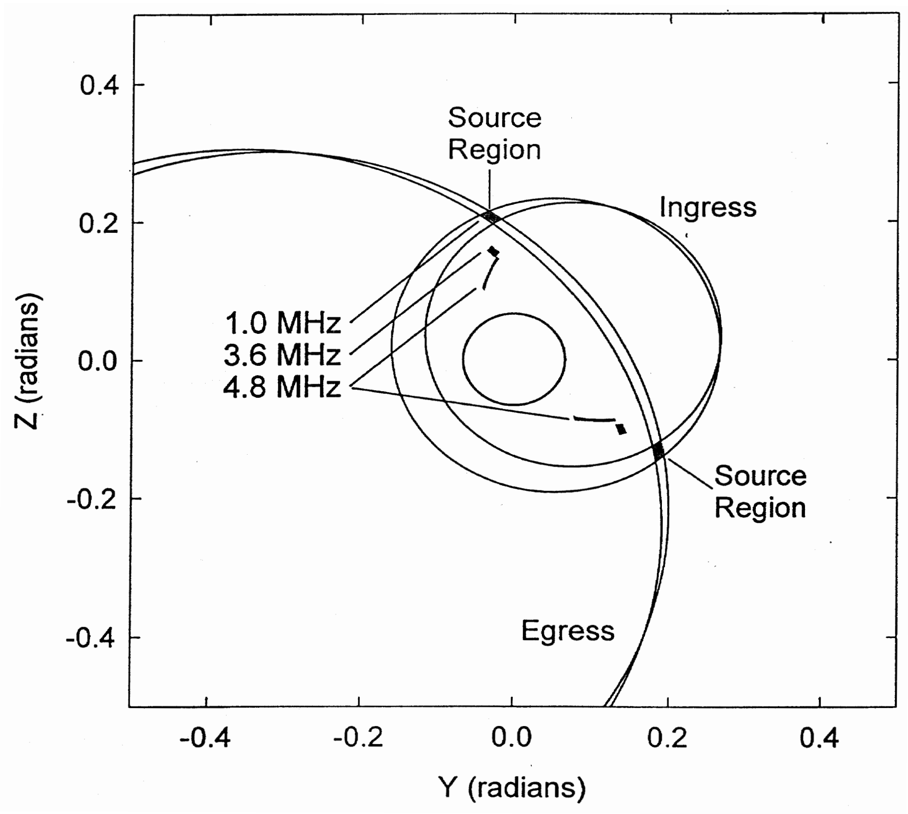

Figure 6: A summary of results from the occultation of the hectometric radio source by Ganymede during the first Ganymede encounter [Kurth et al., 1997a]. The four large circles represent the limb of Ganymede at various times during the ingress and egress phase of the occultation of 1-MHz radio emissions. The intersections of these limbs define two sets of possible source regions. Results for 3.6 and 4.8 MHz are also shown.

Additional occultations during the upcoming satellite flybys are likely and that of the first Ganymede flyby is only one result. The possibility for coincidental alignments cannot be ruled out, hence, further observations will hopefully further clarify these results.

3.2 Ganymede Radio Emissions

Another feature of the Ganymede flyby shown in Figure 5 is appropriate for this overview. As described by Gurnett et al. [1996b] and also Kurth et al. [1997b], Ganymede is also a radio source. The narrowband emissions between 15 and 50 kHz seen at the end of the Ganymede interaction (magnetopause) and extending to about 0745 SCET are almost certainly radio waves generated in the Ganymede magnetosphere in a manner similar to the escaping continuum radiation described above. That is, the upper hybrid resonance bands, which are the highest frequency of the electron cyclotron harmonic emissions, are likely the source of these emissions. Kurth et al. estimate the total power in these radio emissions to be of the order of 100 W. The generation mechanism is mode conversion from the electrostatic waves to electromagnetic radiation as suggested by Jones [1988] and references therein or by Rönnmark [1992]. The difference between these two theories is whether the conversion is linear (as in the Jones model) or non-linear, involving a three wave process such as coalescence or decay.

The existence of radio waves generated in Ganymede's magnetosphere make Ganymede the first known satellite to generate non-thermal emissions (ignoring Io since Io-related emissions are evidently located in Jupiter's auroral zone). Nevertheless, the ubiquitous nature of radio emissions at planetary magnetospheres, and specifically the so-called escaping continuum radiation that Ganymede's emissions appear to resemble would lead one to expect such emissions at any magnetosphere. In fact this is one of the arguments by Gurnett et al. [1996b] that the Ganymede observations should be interpreted as a magnetosphere.

3.3 Broadband Kilometric Radiation Inside the Io Torus

There has been considerable work done on determining the source location of bKOM (see the review by Kaiser, [1989] and Ladreiter et al., [1994]). There remains some question, however, as to whether the source lies on auroral field lines near Jupiter or on the inner edge of the Io torus. During the initial pass by Jupiter on 7 - 8 December 1995 a two-hour interval of data was recorded from just after the end of the Probe relay activities to just after the main engine burn which placed Galileo into its initial orbit. These data are shown in Figure 7. For the most part, the data in Figure 7 are heavily polluted by thruster activity for the turn to the injection burn attitude between 2347 on 7 December and 0013 SCET on 8 December and the injection burn itself between 0028 and 0117 SCET on 8 December. The thrusters are pulsed for each of these maneuvers and the herringbone patterns in the spectrogram are the result of beating between the thruster pulse rate and the receiver sweep rate.

However, there are some usable observations during the interval plotted in Figure 7. The signals of interest here are those between about 20 and 300 kHz prior to about 0040 on 8 December. Both the upper and lower frequency cutoffs of this band are extremely stable; so much so that there was concern that this could be a new band of interference. However, wideband measurements covering the range from 50 Hz to 80 kHz showed that the lower cutoff did, indeed, vary somewhat with time and very close inspection of Figure 7 shows that the cutoff actually occurs in three successively lower frequency channels during the interval from 2330 SCET on 7 December to just before the onset of the injection burn. Given that the band is not likely to be interference, then, we can interpret this band as radio emissions quasi-trapped between the high density Io torus at larger radial distances

Figure 7: (plate, next page) A spectrogram showing observations obtained just prior to and during the Jupiter orbit insertion maneuver (appearing as the intense herringbone pattern emissions identified as thruster activity). The broadband emission between about 20 and 300 kHz is thought to be a natural phenomenon not related to the thruster activity and most likely hectometric radio emissions which are partly trapped between the high density Io torus at larger distances (beginning at about 0040 SCET) and Jupiter itself.

and the presumably high density plasma closer to Jupiter, or the Jovian ionosphere. The 20-kHz low-frequency cutoff is not inconsistent with the plasma frequency in the cool Io torus based on either the Bagenal [1994] or Devine and Garrett [1983] models for this region of the inner magnetosphere. We note that it is possible that this cutoff is possibly due to a relatively high density region between the source and Galileo or perhaps a generation cutoff; the emission is simply not emitted at lower frequencies. In either case, 20 kHz is an upper limit to the local plasma frequency. At about 0040 SCET this radio emission is evidently cutoff at sharply higher frequencies as the spacecraft re-enters the high-density portion of the torus on its outbound leg. Eventually, the cutoff frequency rises almost to the upper frequency limit of the radio emission band at nearly 300 kHz. Bagenal et al. [1997] have used these observations to compare torus densities to those measured by Voyager in 1979 and report significant differences in the overall torus density, which is approximately twice as dense as during the Voyager epoch (see also Gurnett et al., [1996a]) and a missing ribbon feature. The obvious interpretation, then, is that there exists a source of radio waves in the frequency range of 20 - 300 kHz which has access to the region planetward of the high-density torus and the waves are multiply reflected within this region up to the ∼300-kHz limit of the torus plasma frequency. Since there are no strong intensifications on the density gradient at 0040 which might be interpreted as intense upper hybrid bands, we do not believe the source occurs at this particular location. However, that waves in the bKOM frequency range have access to this region of the magnetosphere may argue in favor of a source on the inner edge of the torus.

3.4 Jovian Type III or Quasi-Periodic Emissions

A relatively new type of Jovian radio emission was first reported by Kurth et al. [1989] and labeled Jovian type III bursts because they qualitatively resembled the frequency-time structure of solar type III bursts. These emissions were found in the frequency range of about 10 to above 12 kHz, to be impulsive, and exhibited dispersion. Furthermore, Kurth et al. demonstrated a primary periodicity of about 15 minutes with some bursts showing "echos" at a period of two or three minutes. Ulysses provided additional measurements of these emissions during its northern inbound pass [Kaiser et al., 1992] and additionally found similar bursty emissions in the southern outbound pass but with primarily 40-minute periodicities [MacDowall et al., 1993]. MacDowall et al. differentiated between the two classes of bursts with the terms QP15 and QP40 for quasi-periodic bursts with 15 or 40 minute periodicities, respectively. Galileo has seen some evidence for both the 15-minute and 40-minute bursts, however, examples of the two periodicities seem to be observable more or less equally, with no as-yet-discernable latitudinal pattern. Galileo occasionally observes the 40-minute periodicities extend down in frequency to appear as intensifications of the trapped continuum radiation. For example, Figure 8 shows an interval of continuum radiation in the frequency range from 0 to 10 kHz on 14 August 1996 which shows brief, broadband intensifications with an approximately 40-minute period. During the observed periodic events, Galileo varied over nearly its entire magnetic latitude range and was near 4 hours local time, hence, in an entirely different region of the magnetosphere from where Ulysses observed the 40-minute bursts. While we have drawn no new conclusions from the limited Galileo observations of these to date, it seems clear that it will be useful to combine them with the earlier Voyager and Ulysses observations in an attempt to identify the source of these emissions.

3.5 Evidence of Solar Wind Control of Broadband Kilometric and Hectometric Radiation

Numerous studies have shown that Jovian radio emissions exhibit varying degrees of solar wind control, even though the sources are evidently imbedded deep in the magnetosphere and possibly even driven by the physics of the Io torus [Barrow et al., 1988; Desch and Barrow, 1984; Kaiser, 1993]. Most of these studies were undertaken by Voyager and Ulysses when they were situated well outside the magnetosphere and had in situ solar wind monitoring on board to compare with the remote sensing of radio emissions. Since Galileo will likely spend virtually all of its orbital tour inside the Jovian magnetosphere, it would seem unlikely that Galileo will be able to contribute significantly to such studies. However, there is already evidence of solar wind control of the HOM and bKOM in the Galileo data. Figure 9 demonstrates this. The spectrogram in Figure 9 shows some four weeks of radio observations including HOM, bKOM, and continuum radiation. While precise identification of each type is not possible in such a compressed display, the emissions above a few hundred kHz are mostly HOM, those between about 20 kHz and 300 kHz are bKOM and the continuum radiation lies below. We use the results of Kaiser et al. [1992] to determine that the solar wind density evidently increased around days 223, 229, and 245 of 1996 (see times marked A, B, and C in Figure 9). Specifically, the frequency of the escaping continuum radiation peaks around these days and Kaiser et al. observed a strong correlation between such increases in escaping continuum radiation frequencies and the passage of a high density compression region over the magnetosphere. Further, there are two abrupt increases in the lower frequency cutoff of the trapped continuum radiation at about the same time (events A and B). Particularly in the latter event (on day 229) such an increase is indicative of a compression of the magnetopause in to and closer than the position of Galileo at this time (approximately 114 R_J), leaving the spacecraft in the magnetosheath temporarily. While we do not know for sure the exact nature of the solar

Figure 8: (plate, next page) Examples of quasi-periodic noise bursts with a period of about 40 minutes extending from several kHz down to the trapped continuum between about 1 and 2 kHz.

Figure 9: (plate, following page) A long-period spectrogram showing gross features of the continuum radiation as well as the broadband kilometric and hectometric radiation. The three times marked A, B, and C at the top show increased intensities of both the HOM and bKOM emissions followed immediately by lower intensities. At each of these times the escaping continuum radiation increases in frequency and for event B, the abrupt rise in the lower frequency cutoff of the trapped continuum suggests the spacecraft was briefly in the magnetosheath. Based on previous work, we suggest these three events are related to the arrival of a solar wind compression region.

wind perturbation, it is clear that the solar wind pressure increased so as to compress the magnetosphere.

At the same time as the three compression events in Figure 9, enhancements in the intensity of both the HOM and bKOM emissions can be seen followed immediately by a significant reduction in intensity for both components. It is difficult to conclude anything other than that the increased solar wind pressure and the response of the magnetosphere intensified both emissions and the subsequent relaxation of the magnetosphere reduced the emission intensity. Without reasonable close solar wind observations, it will not be possible to carry out additional solar wind-radio emission correlations like those of Voyager and Ulysses referenced above. However, we should definitely be able to use the variations in radio emission intensity as a crude proxy for solar wind measurements as the Galileo team begins to examine the dynamics of the outer Jovian magnetosphere.

4 Summary

In this very general survey, we have attempted to introduce the nature of the Galileo observations of the Jovian radio spectrum below 6 MHz. It is clear that Galileo will contribute significant new observations of the HOM including additional statistics on the beaming characteristics as well as direction-finding via satellite occultations and via the rotating dipole technique (not discussed here). It is possible that the bKOM observations to date may be the best of the mission due to the change in orbit inclinations to near-equatorial, but even with the observations gained so far, considerable information about the spectral and temporal evolution of bKOM, its beaming characteristics, and source location are likely. On later orbits which take Galileo in to as close as 9 R_J it is possible that direct passages through the nKOM source region will be possible. Continuous observations of nKOM bursts from one orbit to the next will enable the continuation of studies of the non-rigid corotation of the nKOM source, found to lag System III by about 3% from Voyager studies. In situ studies of the nKOM source may shed light on where and how the mass-loading and field line slippage occur causing the period of these emissions to lag the Jovian rotation rate. The continuum radiation dominates the outer magnetosphere and will enable studies of the dynamical aspects of the outer magnetosphere, accurate density maps of the outer magnetosphere, and clarification of various regions in the magnetosphere such as the structure noted from similar Voyager studies [Barbosa et al., 1979; Gurnett et al., 1980; 1981]. The repetitive orbits of Galileo should enable a more complete survey of the quasi-periodic bursts and help to understand the two basic periodicities of 15 and 40 minutes. Finally, we even hope to perform studies of the DAM radiation, however, these studies will almost certainly rely on ground-based and Wind observations at higher frequencies in order to tie into the primary frequency range of these emissions.

Acknowledgments: The research at The University of Iowa is supported by the National Aeronautics and Space Administration through Contract 958779 with the Jet Propulsion Laboratory.