JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 109, A09S08, doi:10.1029/2003JA010233, 2004

New observations from Cassini and Ulysses of Jovian VLF radio emissions

M. L. Kaiser and W. M. Farrell
NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

W. S. Kurth, G. B. Hospodarsky, and D. A. Gurnett
Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa, USA

Received 11 September 2003; revised 19 December 2003; accepted 9 February 2004; published 29 June 2004.

[1] Simultaneous observations of Jupiter's so-called reradiated VLF radio emission by the Cassini and Ulysses spacecraft confirm that the emission is radiated into all directions in a pulse or strobe light-like fashion. These observations rule out a source that corotates with the planet. Observations of the same VLF emission component during the Cassini distant flyby of Jupiter in early 2001 strongly suggest that the emission, which originates fairly close to the planet, is modified by the magnetosheath so that the magnetosheath acts as a leaky wave guide of VLF radiation. *INDEX TERMS:* 6220 Planetology: Solar System Objects: Jupiter; 6954 Radio Science: Radio astronomy; 5737 Planetology: Fluid Planets: Magnetospheres (2756); 2728 Magnetospheric Physics: Magnetosheath; *KEYWORDS:* Jupiter, radio, VLF

Citation: Kaiser, M. L., W. M. Farrell, W. S. Kurth, G. B. Hospodarsky, and D. A. Gurnett (2004), New observations from Cassini and Ulysses of Jovian VLF radio emissions, *J. Geophys. Res.*, *109*, A09S08, doi:10.1029/2003JA010233.

1. Introduction

[2] During the several-month period surrounding the Ulysses spacecraft's encounter with Jupiter (closest approach in February 1992), the radio and plasma waves instrument Unified Radio and Plasma Wave (URAP) [*Stone et al.*, 1992] observed very low frequency (VLF <20 kHz) emissions of Jovian origin from distances of more than 2 AU [*Kaiser et al.*, 1992]. They showed that these emissions had a sharply defined low-frequency limit that matched twice the solar wind plasma frequency projected to Jupiter's distance and that the overall band of emission varied in frequency with the projected solar wind density. They concluded that the emission was likely associated with the Jovian magnetosheath, since the maximum plasma frequency inside the sheath should equal twice the solar wind plasma frequency. This emission was assumed to be the escaping continuum described by *Scarf et al.*, [1979, 1981] and attributed to conversion of upper hybrid resonance emission to escaping emission at Jupiter's magnetopause.

[3] Later, *Kaiser* [1998] noted that the spectrum of this VLF component was distinctly steeper than that reported for Jovian continuum and the peak intensity was essentially at the Jovian bow shock and not at the magnetopause. He also further examined the apparent connection between the low-frequency portion of Jovian "quasi-periodic (QP)" or "type III" bursts [*MacDowall et al.*, 1993] and the VLF emission, first pointed out by *Kaiser et al.* [1992], and concluded that the main source of the VLF emission was probably not the escaping continuum but instead was the magnetosheath itself which acts as a "reradiator" (somewhat of a misnomer compared with the usual case of reradiation of optical emission) of low-frequency emissions generated inside the Jovian magnetosphere. When these low-frequency signals transit the magnetosheath, their group velocity tends toward zero as their frequency approaches the magnetosheath plasma frequency; thus the bursts become highly dispersed at low frequencies. In the case of the QP bursts, the low-frequency portion of one burst has not completely propagated through the magnetosheath before another burst arrives. The observed VLF emission is then an amalgamation of all the highly dispersed low-frequency emissions generated closer to Jupiter including the QP bursts, the "true" continuum emission and the low-frequency extent of other bursts like broadband kilometric radiation (bKOM) [*Warwick et al.*, 1979]. The observed 10-hour periodicity of the reradiated emission simply reflects the 10-hour periodicity in these original radio sources.

[4] In the scenario presented by *Kaiser* [1998], when a high ram pressure solar wind structure impinges on the magnetosphere, the magnetosheath gets compressed and its characteristic plasma frequencies increase, thus raising the frequency of the dispersed low-frequency emissions. More planetary radio emission is typically generated during these compression events [*Reiner et al.*, 2000]; thus the reradiated VLF emission becomes more intense as well as at somewhat higher frequency than before the compression. As the high ram pressure structure continues to flow past Jupiter, the magnetosheath relaxes to its precompression configuration and the characteristic frequencies decline along with the intensities. This pattern is repeated roughly with every solar sector structure passage past Jupiter [*Kaiser et al.*, 1992; *Kaiser*, 1998], creating a 12.5 or 25-day periodicity. Thus the magnetosheath acts as a semicontinuous processor of low-frequency signals generated elsewhere.

0148-0227/04/2003JA010233$09.00

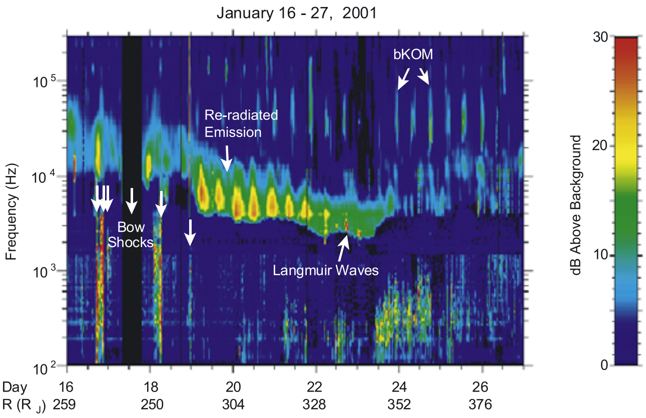

Figure 1. An 11-day frequency-time spectrogram acquired while Cassini was on the duskside flank of the Jovian magnetosphere. The reradiated emission has a sharp low-frequency cutoff at the plasma frequency in the magnetosheath. Note the Langmuir waves near the low-frequency cutoff on days 22 and 23. Most prominent in this illustration is the ~10-hour modulation of the intensity of the reradiated emission.

[5] Here we describe new observations of this VLF reradiated emission obtained by the Cassini spacecraft which passed close to Jupiter in late 2000 en route to Saturn. During this same period, simultaneous measurements of the VLF emission were also obtained with the quite distant Ulysses/URAP instrument. We believe these combined observations strengthen the scenario described above.

2. Observations

[6] The Cassini spacecraft, launched in 1997, is destined for Saturn, where it will arrive in 2004. During its complicated trajectory, it flew relatively close to Jupiter in late 2000 for a gravity assist. During that flyby period and for many months on either side, Jovian radio emissions were easily detected by the Radio and Plasma Wave Science (RPWS) instrument [*Gurnett et al.*, 2004]. RPWS consists of a suite of radio and plasma wave receivers connect to a set of three 10-m antennas. Of interest here is the upper frequency range of RPWS which consists of two sets of four analog receivers with a digital processing unit. These receivers sweep the frequency range from 3.6 kHz to 16.1 MHz approximately every minute or less, depending on instrument mode.

[7] The Ulysses spacecraft is in a solar orbit highly inclined to the ecliptic with an aphelion near Jupiter's orbit and a perihelion of about 1 AU. The URAP instrument [*Stone et al.*, 1992] is also a suite of plasma and radio receivers connected to a 72-m long dipole antenna. Of interest here is the low-frequency radio receiver sweeping the frequency range from 1.25 kHz to 48 kHz in 64 steps every 2 min.

[8] Figure 1 shows an 11-day interval from the Cassini RPWS instrument in early 2001 shortly after the 30 December 2000 closest approach (CA) to Jupiter when Cassini was moving down, but generally just outside of, the dusk flank of the magnetosphere. Clearly observed are many episodes of reradiated emission below around 10 kHz between days 17 and 22. Many of these episodes exhibit a 10-hour periodicity, consistent with prior Ulysses observations [*Kaiser et al.*, 1993]. Figure 1 indicates a series of encounters with the Jovian bow shock as determined collectively by the fields and particles investigations on Cassini. The last shock indicated, at 2350 on 18 January, was identified as an inbound shock crossing, although the ion bulk speed initially increased (M. F. Thomsen, personal communication, 2003) before decreasing. As seen in the subsequent 5 days in Figure 1, however, the plasma density at the spacecraft as determined by the low-frequency cutoff of the reradiated emissions is very low, suggesting that the solar wind pressure is low and hence the magnetosheath would be expanded. Furthermore, Langmuir waves at frequencies approximately at the same frequency, perhaps a bit higher, than the low-frequency cutoff are seen on 22 January. This suggests that the density local to the spacecraft is similar to that in the magnetosheath, which sets the low-frequency cutoff of the reradiated emissions. If the spacecraft were in the solar wind, the Langmuir waves would be at frequencies below the reradiated low-frequency cutoff. Hence we conclude that from the shock late on 18 January onward throughout the remaining plotted interval, the spacecraft was in Jupiter's magnetosheath and that the magnetosheath determines the low-frequency extent of the reradiated emission.

[9] Figure 2 shows "simultaneous" data from the Ulysses/URAP instrument (top) and the Cassini/RPWS instrument (bottom) for 20 April 2003. At this time, Ulysses was about 2.4 AU from Jupiter and at Jovicentric latitude +53° and local time of 8.8 hours. Cassini was about 5.6 AU from Jupiter at −4° latitude and 18.6 hours local time. The total angle between the two spacecraft as seen from Jupiter was about 124° and the light travel time difference from Jupiter was 26.7 min.

[10] Clearly observed by Ulysses/URAP (Figure 2) were the Jovian bKOM bursts and the reradiated emission with QP bursts characteristically "feeding" into it [*Kaiser*, 1998]. Cassini/RPWS barely detected the bKOM and only a hint of the QP bursts but observed the reradiated emission quite easily. For this and similar events studied, Ulysses observed the reradiated emission at frequencies both above and below 10 kHz near the beginning of the events, whereas Cassini only observed the events below 10 kHz. Ulysses also observed the emission to slightly lower frequencies than Cassini, but this could be due to Ulysses' enhanced sensitivity in this frequency range afforded by the much longer antenna. Frequency-by-frequency inspection of Figure 2 and at least 25 other similar events show that the emission is roughly simultaneous (±1 hour) below 10 kHz. If the emission source corotated with Jupiter (quite contrary to the reradiated hypothesis), the observed offset in time would have been about 4 hours (with Ulysses observing first, followed by Cassini). Also, most of the simultaneous observations are similar in the fact that Ulysses observed the reradiated emission at higher frequencies early in each event.

[11] The Cassini encounter with the Jovian magnetosheath in early 2001 provided some semidirect evidence for the magnetosheath emission trapping and containment

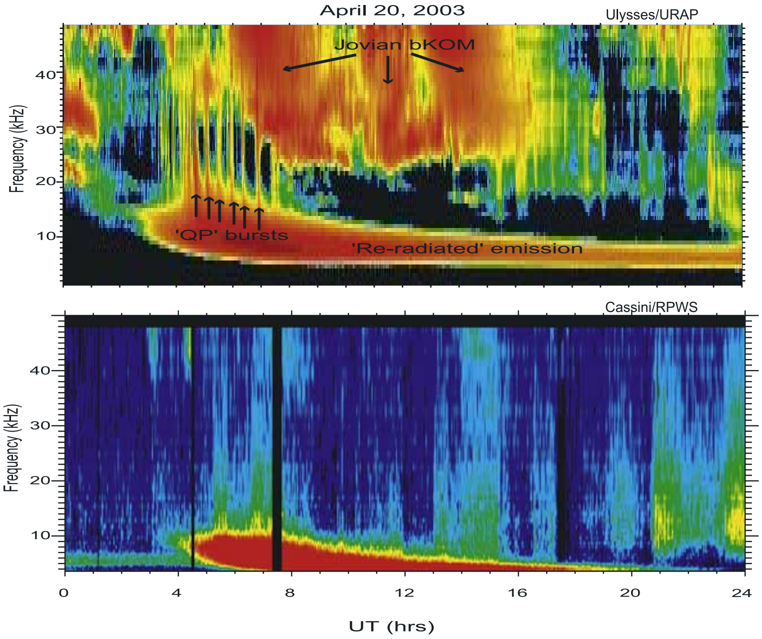

Figure 2. Near simultaneous dynamic spectra measured by Ulysses Unified Radio and Plasma Wave (URAP) (top) and Cassini Radio and Plasma Wave Science (RPWS) (bottom). At this time, Ulysses was some 2.4 AU from Jupiter and at +53° jovicentric latitude and 8.8 hours local time. Cassini was 5.6 AU from Jupiter at −4° latitude and 18.6 hours local time. The reradiated emission is clearly detected by both instruments, although URAP observes the emission at somewhat higher frequencies near the start of the episode. At frequencies where both instruments detect the emission, it occurs simultaneously to within ±1 hour.

scenario described by *Kaiser* [1998]. Specifically, Figure 3 shows a 2.5-day spectrogram covering the interval from 10 through 13 January 2001, several days after the Cassini CA to Jupiter (30 December 2000) and a few days prior to Figure 1. Like in Figure 1, Cassini was following a trajectory down the dusk flank of the Jovian magnetosphere and slightly outside of it. However, during the interval shown in Figure 3, the solar wind pressure dramatically decreased in association with a solar wind pressure pulse [*Kurth et al.*, 2002] causing the magnetosphere to balloon outward to envelope the dusk-flanking Cassini at 200 R_J and 19.3 hours local time. Of particular interest is the abrupt magnetopause boundary indicated in the figure as MP. The magnetosphere is defined by the continuum emission, with the low-frequency emission cutoff indicating the local plasma frequency (i.e., indicative of local magnetospheric density). As this panel suggests, the continuum low-frequency cutoff abruptly rose from 300 Hz to 3 kHz in <15 min as the spacecraft moved from the low-density magnetospheric plasma into the high-density sheath plasma. When Cassini was in the magnetosheath, reradiated emission extending from 7 to 50 kHz was detected.

[12] There are two interesting features with this magnetopause transition: First, the higher-frequency reradiated emission present in the magnetosheath appears to cease abruptly at the magnetopause. In essence, the reradiated emission is confined to the magnetosheath region. The emission cessation suggests a reflection at the magnetopause in association with the steep change in index of refraction resulting from density drop-off into the magnetosphere. Second, there is not an obvious magnetospheric component associated with this reradiated emission. *Kaiser et al.* [1992] demonstrated that reradiated emission could be easily observed in association with the impulsive QP bursts [*MacDowall et al.*, 1993] that subsequently interact with the high-density sheath plasma. The original impulsive magnetospheric emission becomes temporally dispersed and scattered in the sheath resulting in a second trailing amorphous reradiated component at low QP burst frequencies (e.g., see Figure 2). These original cases had both the impulsive magnetospheric event and the subsequent reradiated component. In the cases shown in Figure 3, only the amorphous reradiated component is present. When Cassini was in the magnetosphere, there was basically no emission detected between 5 and 30 kHz. There is no obvious magnetospheric source for the emission observed at these same frequencies in the adjacent magnetosheath regions. This suggests that either the magnetosheath itself generated the emission or the emission was generated elsewhere and was propagation-limited to the magnetosheath.

3. Discussion

[13] The near simultaneity of the Ulysses/URAP and Cassini/RPWS detections of the reradiated emission convincingly but not unexpectedly demonstrates that the emission source does not corotate with Jupiter but is emitted into all directions simultaneously. This fact allows us to estimate the total radiated power and it is in the range of 10^8 to 10^9 W, quite comparable with many of the better studied Jovian radio components [*Carr et al.*, 1983] and a clearly dominant solar system radio source in this frequency range.

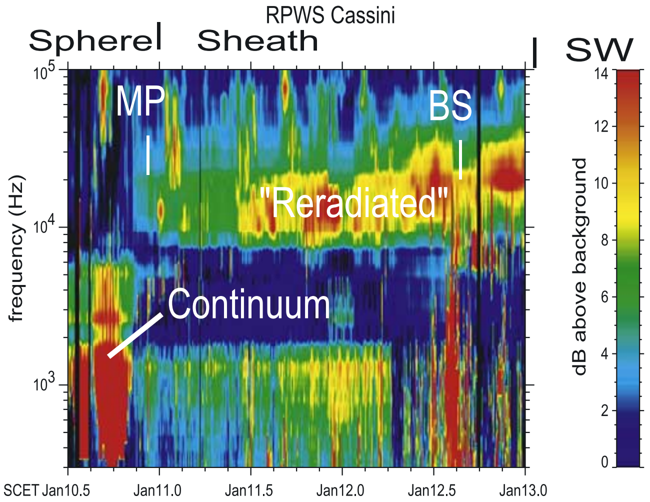

Figure 3. An RPWS spectrogram showing a Cassini magnetosheath crossing in the deep dusk flank of the magnetosphere. The magnetosphere is identified by the intense continuum emission at frequencies below about 3 kHz. Upon crossing the magnetopause (MP), Cassini detected reradiated emission between 8 and 40 kHz. Note the emission displays an abrupt intensity decrease upon crossing the bow shock (BS).

[14] We believe the observed frequency difference in the Ulysses and Cassini measurements can be attributed to the typical Jovian magnetosheath density structure and the viewing geometry. Figure 4 is a combination of ideas first shown by *Desch and Farrell* [2000] and later by *Steinberg et al.* [2004]. Low-frequency emissions generated deep in Jupiter's magnetosphere can escape into interplanetary space in all directions provided their frequency is at least about 2 f_{psw}, which is the maximum frequency at the nose of the magnetosheath. Thus these frequencies receive little or no "processing" as they traverse the magnetosheath and would likely be somewhat weaker relative to "processed" signals. At the opposite extreme, planetary emission near f_{psw} must travel far down the magnetotail before the magnetosheath plasma frequency becomes low enough to allow escape and can receive a great deal of processing. For planetary emissions between 2 f_{psw} and f_{psw}, the emission must escape progressively further tailward with decreasing frequency, as shown in the figure. Ulysses consistently observed the reradiated emission to somewhat higher frequencies than Cassini which we believe can be attributed to Ulysses greater sensitivity which allowed it to observe the weaker "unprocessed" emissions above f_{psw}. Cassini, on the other hand, had (Figure 2, bottom panel) a view of the flank of the magnetosheath where highly processed lower frequency emissions could escape. At the very lowest frequency portion of the reradiated emission, again Ulysses' greater sensitivity comes into play.

[15] Figure 4 (inset) shows an interpretation of the reradiated magnetosheath emission propagation. Because of the high frequencies of the emission, it is assumed to be generated in the magnetosphere close to the planet. The emission is incident at the magnetopause region close to the planet and rays passing into the high-density sheath are then bent to propagate obliquely relative to the magnetopause normal. These oblique rays propagate down the tailward directed magnetosheath, reflecting from bow shock and magnetopause boundaries and remaining contained in the magnetosheath. These magnetosheath observations strongly complement a recent model presented by *Steinberg et al.* [2004] who conceived of similar ray paths for the analogous terrestrial LF bursts.

[16] Another important concept depicted in Figure 4, as described by *Steinberg et al.* [2004], is that the same escape position as a function of frequency described above also temporally broadens planetary low-frequency emissions simply because the lower the frequency compared to 2 f_{psw}, the farther it must travel before it can reach the observer, independent of the observer's position.

[17] There is observational evidence for this magnetosheath channeling process. Specifically, for the reradiated emission to be reflected at the magnetopause density drop-off (like in Figure 3), the angle of incidence of the emission has to be very oblique relative to the local magnetopause boundary normal. Figure 5 displays the transmission coefficient for a boundary with emission of frequency f = 10 kHz, propagating in a magnetosheath with plasma frequency f_{p1} = 3 kHz, entering into a second medium, the magnetosphere, with plasma frequency f_{p2} = 300 Hz. The associated indices of

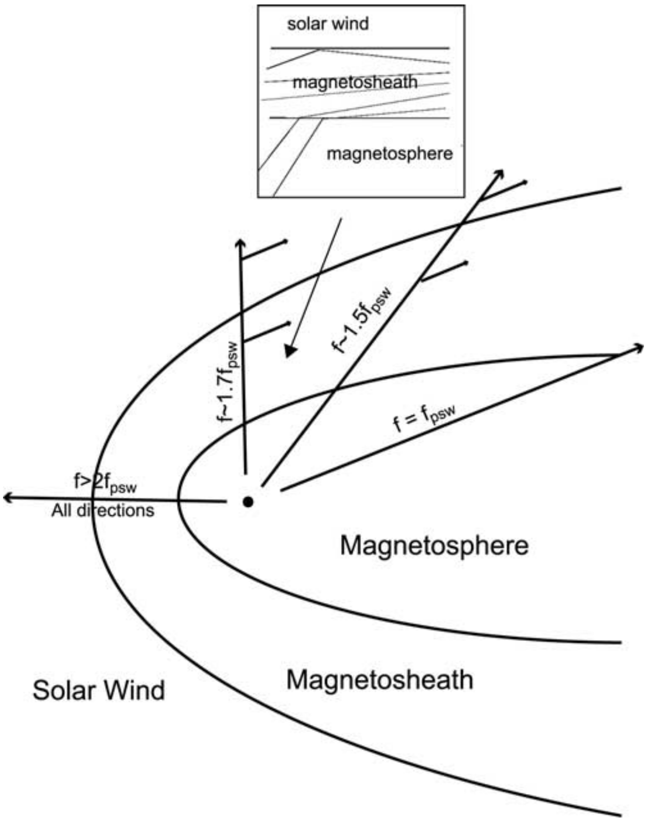

Figure 4. Emission generated near the planet at frequencies between $2f_{psw}$ and f_{psw} can only escape through the planet's magnetosheath into the solar wind at points down the magnetotail where the sheath density has dropped low enough to permit propogation. (inset) Many of the waves transiting through the magnetopause and into the magnetosheath are refracted so that they propagate parallel to the tail and reflect off both the magnetopause and bow shock.

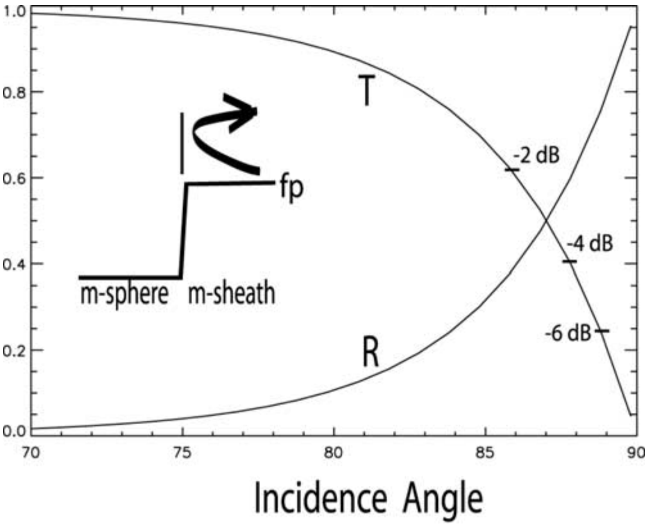

Figure 5. A plot of the transmission and reflection coefficients for an o-mode wave at 10 kHz crossing from a sheath region ($f_p \sim 3000$ kHz) into the low-density magnetosphere ($f_p \sim 300$ Hz). The incidence angle is defined as the wave k-vector orientation relative to the magnetopause normal. Note that for highly oblique propagation, 10 kHz emission is reflected from this boundary, and the magnetopause can be considered a waveguide for the emission, channeling rays down the tail.

refraction are then $n_1 = (1 - f_{p1}^2/f^2)^{1/2}$, $n_2 = (1 - f_{p2}^2/f^2)^{1/2}$, and $\theta_2 = \arcsin(n_1 \sin \theta_1/n_2)$. The transmission coefficient calculated is the case given in geometric optics assuming equal s and p polarization contributions [*Hecht and Zajak*, 1979, equations 4.63 and 4.64]. As suggested by the figure, as the angle of incidence into the magnetopause increases (becomes more "glancing"), the emission reflectivity increases thereby reducing the transmission through the boundary. This transmission loss due to reflection is plotted in the figure.

[18] Figure 3 suggests that the reradiated sheath emission between 10 and 20 kHz near the magnetopause is 6–14 dB above the noise floor but abruptly drops to the noise floor in the magnetosphere. Thus there is at least 6 dB of transmission loss due to reflection across the boundary. Figure 5 indicates that this emission loss is consistent with emission propagation angles >88° relative to the local magnetopause normal. The reflectance at these angles is >0.75, indicative of a fairly reflective magnetopause surface at these glancing-like angles. This exercise suggests these rays are directed nearly perpendicular to the local magnetopause normal.

[19] From this analysis of the Cassini observations, we conclude the magnetopause is acting like a "half-silvered mirror," reflecting obliquely propagating VLF emission at the boundary and confining the emission to the sheath. We note that a similar effect is observed at the bow shock (outer sheath boundary), where a density drop-off occurs from the high-density sheath to low-density solar wind. The reradiated emission has a consistent 4 dB reduction in signal strength on 12 January, the closest bow shock associated with these events. The associated reflectance for this case is ~0.6. Thus at both the magnetopause and bow shock, incident emissions are reflected back toward the magnetosheath due to the index of refraction change at their respective density drop-offs; these density variations effectively behaving as a mirrored surface. In this regard we can think of the magnetosheath as a waveguide, channeling obliquely propagating emission along the tail.

[20] We cannot rule out a local sheath generation mechanism for the "reradiated" emission. However, the tightly beamed oblique wave k-vectors relative to the magnetopause normal suggests a bulk propagation effect rather than source phenomena. For example, the magnetosheath is many tens of R_J in width. It seems unlikely that a local wave/particle instability or wave/wave conversion process operating in the middle magnetosheath would serendipitously beam itself into a tight, oblique direction relative to a distant magnetopause or bow shock normal. How would a local plasma wave process know the magnetopause orientation for the ideal alignment? It would require all the local magnetosheath sources to be beamed at approximately the same angle, and each source would require some information about the local magnetopause and bow shock orientation for proper k-vector orientation. It is far easier to conceive of Figure 4 (inset), where all the rays, generated elsewhere from a more distant location (and hence plane-wave like waves), undergo a large-scale geometric optical change along the extended magnetopause boundary.

[21] The interpretive analyses of Figures 2 and 3 have a common theme: that the magnetosheath not only temporally distorts the emission but spatially distorts the emission as well by transferring energy along the sheath. As indicated in Figure 2, even a localized emission (like QP bursts) "feeds" the sheath, which in turn appears to reradiate in bulk as a quasi-global continuous emission pattern. The process by which energy is transferred along the sheath, to account for this extended brightening/angular broadening, is observed in Figure 3 and illustrated in Figure 4 as the streaming of quasi-trapped energy along the tail to its escape point along the sheath. We conclude that the Jovian sheath acts as a VLF wave reservoir taking in various discrete emissions (discrete in time, frequency, or spatial extent) and reradiating them as a quasi-continuous "glow" from the confining, trapping container.

[22] **Acknowledgments.** The research at the University of Iowa is supported by the National Aeronautics and Space Administration through contracts 961152 and 958779 with the Jet Propulsion Laboratory.

[23] Arthur Richmond thanks Thomas D. Carr and Alain Roux for their assistance in evaluating this paper.

References

Carr, T. D., M. D. Desch, and J. K. Alexander (1983), Phenomenology of magnetospheric radio emissions, in *Physics of the Jovian Magnetosphere*, edited by A. J. Dessler, pp. 226, Cambridge Univ. Press, New York.

Desch, M. D., and W. M. Farrell (2000), Terrestrial LF bursts: Escape paths and wave intensification, in *Radio Astronomy at Long Wavelengths*, *Geophys. Monogr. Ser.*, vol. 119, edited by R. G. Stone et al., pp. 205–211, AGU, Washington, D. C.

Gurnett, D. A., et al. (2004), The Cassini radio and plasma wave investigation, *Space Sci. Rev.*, in press.

Hecht, E., and A. Zajak (1979), *Optics*, Addison-Wesley, Reading, Mass.

Kaiser, M. L. (1998), Jovian and terrestrial low-frequency radio bursts: Possible cause of anomalous continuum, *J. Geophys. Res.*, *103*, 19,993–19,999.

Kaiser, M. L., M. D. Desch, W. M. Farrell, R. J. MacDowall, and R. G. Stone (1992), Ulysses observations of escaping VLF emissions from Jupiter, *Geophys. Res. Lett.*, *17*, 649–652.

Kaiser, M. L., M. D. Desch, and W. M. Farrell (1993), Clock-like behavior of Jovian continuum radiation, *Planet. Space Sci.*, *41*, 1073.

Kurth, W. S., et al. (2002), The dusk flank of Jupiter's magnetosphere, *Nature*, *415*, 991–994.

MacDowall, R. J., M. L. Kaiser, M. D. Desch, W. M. Farrell, R. A. Hess, and R. G. Stone (1993), Quasi-periodic Jovian radio bursts: Observations from the Ulysses radio and plasma wave experiment, *Planet. Space Sci.*, *41*, 1059–1072.

Reiner, M. J., M. L. Kaiser, and M. D. Desch (2000), Long-term behavior of Jovian bKOM and nKOM radio emissions observed during the Ulysses-Jupiter encounter, *Geophys. Res. Lett.*, *27*, 297.

Scarf, F. L., D. A. Gurnett, and W. S. Kurth (1979), Jupiter plasma wave observations: An initial Voyager 1 overview, *Science*, *204*, 991–995.

Scarf, F. L., W. S. Kurth, D. A. Gurnett, H. S. Bridge, and J. D. Sullivan (1981), Jupiter tail phenomena upstream from Saturn, *Nature*, *292*, 585–586.

Steinberg, J.-L., C. Lacombe, P. Zarka, S. Hoang, and C. Perche (2004), Terrestrial low frequency bursts: Escape paths of radio waves through the bow shock, *Planet. Space Sci.*, *52*, 643–660.

Stone, R. G., J.-L. Bougeret, J. Caldwell, P. Canu, Y. DeConchy, and N. Cornilleau-Wehrlin (1992), The Ulysses URAP instrument: Description and first results, *Astron. Astrophys. Suppl.*, *92*, 291.

Warwick, J. W., et al. (1979), Voyager 1 planetary radio astronomy observations near Jupiter, *Science*, *204*, 995.

W. M. Farrell and M. L. Kaiser, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA. (farrell@faltraz.gsfc.nasa.gov; michael.kaiser@nasa.gov)

D. A. Gurnett, G. B. Hospodarsky, and W. S. Kurth, Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242, USA. (donald-gurnett@uiowa.edu; gbh@space.physics.uiowa.edu; william-kurth@uiowa.edu)