JOVIAN BURSTY HIGH-LATITUDE EMISSIONS REVISITED: THE ULYSSES-JUPITER DISTANT ENCOUNTER

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Abstract

New observations of Jovian bursty high-latitude (BHL) emissions, in the frequency range from 150 kHz to 1 MHz, were made with the URAP experiment during the Ulysses' Distant Encounter with Jupiter in 2003–4. Four well-defined Jovian BHL events, observed when Ulysses was at northern Jovigraphic latitudes between 26° and 44°, were triggered by distinct solar wind density pulses, associated with corotating interaction regions at Jupiter. In this article, we analyze the second of these BHL episodes that occurred on February 26, 2004, following a solar wind density pulse observed at Ulysses on February 25. In addition to exhibiting the unique radiation characteristics of BHL, this BHL episode was followed by a period of particularly intense Jovian nKOM activity that persisted for some 16 Jovian rotations.

1 Introduction

During the Ulysses flyby of Jupiter in February of 1992 [Stone et al., 1992], Ulysses climbed briefly to northern Jovigraphic latitudes as high as 40° (magnetic latitude, 47°), where it detected several new components of Jovian radiation [Kaiser et al. 1993; Reiner et al., 1994]. One of these new components, called bursty high-latitude (BHL) emission, was found to be elliptically polarized—the only elliptically polarized radiation from a Jovian radio source ever observed below 1 MHz [Reiner et al., 1995, hereafter Paper I].

Since the period of the out-of-ecliptic orbit of Ulysses is 6.2 years and the sidereal orbital period of Jupiter is 11.9 years, it follows that as Ulysses neared its second aphelion, after two traversals of its high-solar-latitude orbit, it would once again be relatively close ($\sim$ 1 AU) to Jupiter. Moreover, the orbit geometry was such that as Ulysses approached aphelion it would maintain high Jovigraphic latitudes for an extended period of time. Figure 1a is a plot of the Jovigraphic latitude of Ulysses versus the Jovian local time,

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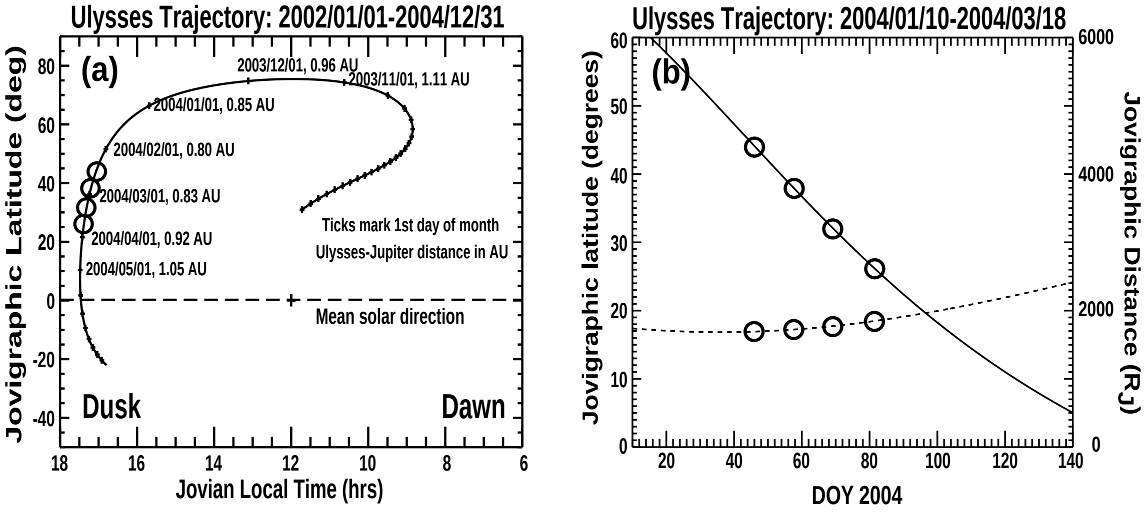

Figure 1: (a) Ulysses trajectory plotted as a function of Jovigraphic latitude and Jovian local time. (b) Jovigraph latitude (solid curve – left scale) and distance (dashed curve – right scale) of Ulysses during a portion of the Ulysses-Jupiter Distant Encounter from January 10 to May 18, 2004. The circles represent the locations of Ulysses at the times of the observed BHL emissions.

from January 1, 2002 to December 31, 2004. The distances of Ulysses to Jupiter are also provided, expressed in units of AU. Ulysses was at Jovigraphic latitudes in excess of 60° from July of 2003, with Ulysses at 1.8 AU (3740 R_J) from Jupiter, through January of 2004, with Ulysses at 0.82 AU (1720 R_J) from Jupiter. From this vantage point the Unified Radio and Plasma Wave (URAP) experiment on Ulysses detected numerous well-established components of Jovian radio emissions. It was anticipated that during this Ulysses-Jupiter Distant Encounter, Jovian BHL emissions would likely be observed once again.

Indeed, when Ulysses reached its minimum distance of 0.8 AU (1684 R_J) from Jupiter and a Jovigraphic latitude of $\sim$ 44°, Ulysses/URAP detected radio components with characteristics similar to those of the BHL emissions that were previously observed during its high-latitude flyby of Jupiter in February of 1992. These emissions, extending below the Ulysses/URAP highest frequency of 1 MHz, were found to be highly time-variable and elliptically polarized — the characteristic signatures of BHL [Reiner et al., 2005, hereafter Paper II]. During this distant encounter, these Jovian radio emissions were observed from high latitudes over an extended time period. Figure 1b shows the Jovigraphic latitude and distance of Ulysses from January 10, 2004 to March 18, 2004. During this time period, four distinct, but brief, episodes of BHL emissions, indicated by the circles on Figure 1, were observed when Ulysses was at Jovigraphic latitudes ranging from 26° to 44°.

Since Ulysses was well outside the Jovian magnetosphere and near the ecliptic plane, it could simultaneously monitor the remote Jovian radio emissions and the solar wind structures in the vicinity of Jupiter. Consequently, new information concerning the long-term behavior of the BHL emission component was revealed; the four brief BHL episodes were apparently triggered by corotating interaction regions (CIRs) passing Jupiter [Paper II]. Details of the first episode of BHL emission were provided in Paper II. We focus here on the recurrence of the BHL emission on February 26, 2004 (DOY = 57) that was triggered by a solar wind density pulse observed at Ulysses on February 25, 2004.

2 Analysis of the February 26, 2004 BHL Event

Figure 2a is a dynamic spectral plot of the radio intensity as a function of frequency (vertical axis) and of time (horizontal axis); red represents the most intense radio emissions. The frequency range shown is from 25 to 940 kHz and the time extends from 12:00 UT on Feburary 26 to 24:00 UT on February 27, 2004. On this dynamic spectrum a single BHL event is evident between 16:00 and 20:00 UT on February 26, extending from the highest Ulysses/URAP frequency of 940 kHz to about 150 kHz. These BHL emissions were preceded by emissions drifting from about 200 kHz, beginning at 13:00 UT, to below 50 kHz by 19:00 UT. Although these latter emissions have characteristics similar to that of the BHL emission, they are believed to be Jovian bKOM emission, observed here from high Jovigraphic latitudes. This identification is based primarily on the fact that similar emissions were observed in this same frequency range 10 hours earlier, starting at about 03:00 UT on February 26. This 10-hour periodicity is one of the distinguishing characteristics of Jovian bKOM emissions, which are believed to originate, in this frequency range, in Jupiter's auroral region [Desch and Kaiser, 1980; Ladreiter et al., 1994]. The single BHL episode, which ceased after 20 UT, was followed four hours later by an extended series of Jovian nKOM events in the frequency range from below ~ 50 to 200 kHz. Jovian nKOM emissions are known to originate in the Io plasma torus [Kaiser and Desch, 1980; Reiner et al., 1993].

The intensity characteristics of these various Jovian radio emission components are more distinctly revealed in the intensity-time plots (in units of log of $W\ m^{-2}\ Hz^{-1}$), at ten fixed frequencies, shown below the dynamic spectrum in Figure 2b. These single-frequency, intensity-time profiles, ranging from 52 to 940 kHz (numbers to the right on Figure 2b), reveal that the BHL event had a well-defined onset and termination, which was essentially the same at each frequency, suggesting a broad overall bandwidth of the emission, while the corresponding spectrum (Figure 2a) suggests narrower bandwidth substructures. The intensity profiles of the BHL emissions are highly variable on short time scales. (Note that the logarithmic scale tends to conceal the magnitude of this variability). As discussed in Paper I, burstiness, implying more power on short time scales, is one of the distinguishing characteristics of Jovian BHL emissions. The bKOM intensity profiles in Figure 2b appear to exhibit less time variability, but this may be partly due to the sampling rate at the lower frequencies being significantly less than at the higher frequencies. The burstiness of the bKOM emissions may in fact be similar to that of the BHL emission. By contrast to the BHL and bKOM emissions, the frequency profiles in Figure 2b indicate that the nKOM emissions exhibit a relatively smooth temporal behavior.

The demodulation analysis of the Ulysses/URAP signal permits a determination of the direction of arrival and the complete polarization state (four Stokes parameters) of the incoming radiation [Manning and Fainberg, 1980]. To better reveal the radiation characteristics of this BHL event, results of the direction-finding/polarization analysis at 540 kHz are provided in Figure 3 for the BHL event in Figure 2.

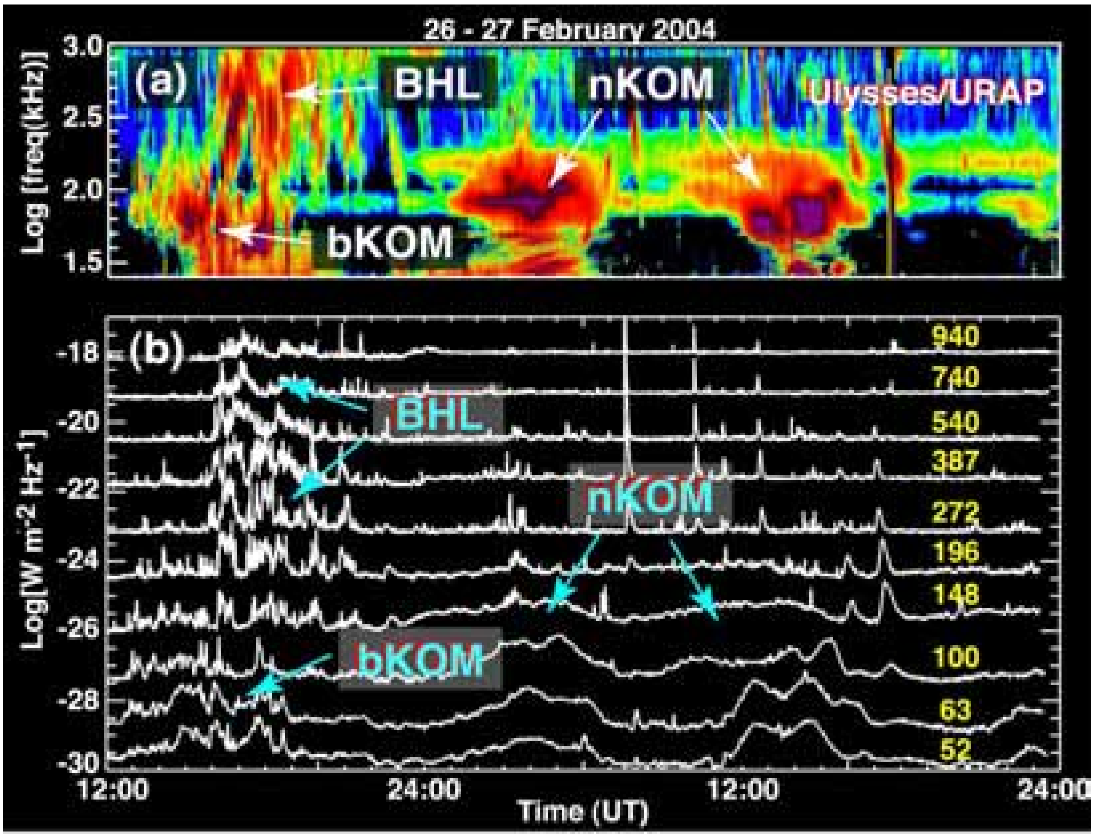

Figure 2: (a) Dynamic spectrum of the Ulysses/URAP radio observations from 12 UT on February 26 to 24 UT on February 27, 2004. (b) Intensity-time plots of the radio data at selected frequencies for the same time period. The scale on the left refers to the flux density at 940 kHz. The single-frequency plots at the other frequencies were (arbitrarily) downshifted, while maintaining the same intensity scale, to reveal the intensity-time profiles at consecutively lower frequencies.

The lower panel, Figure 3a, shows the (despun) intensity of the incident radiation from 15:00 to 21:00 UT on February 26. The BHL emission begins just before 16:00 UT, reaches maximum intensity at about 17:00 UT, and ceases after about 20:00 UT. The next two panels, Figures 3b and c, show the derived azimuthal and colatitudinal angles that define the direction of arrival of the radiation. These angles are expressed in a right-handed orthogonal coordinate system, fixed to the spacecraft, with x-axis passing through the center of Jupiter and with z-axis in the plane containing the northern ecliptic pole. In this system, the azimuth and colatitude of Jupiter are always 0° and 90°, respectively. At these distances from Jupiter, the angular resolution provided by the despun analysis is not sufficiently accurate to provide any detailed information about the source location and evolution relative to Jupiter. Nevertheless, the average direction indicated by these angles confirms a radiation source originating from Jupiter, some 0.82 AU distant from Ulysses.

The derived parameters that define the polarization characteristics of the radiation are shown in the four upper panels in Figure 3. Figure 3g displays the (normalized) Stokes parameter V that indicates the degree of circular polarization. A value $V = +1$ corre-

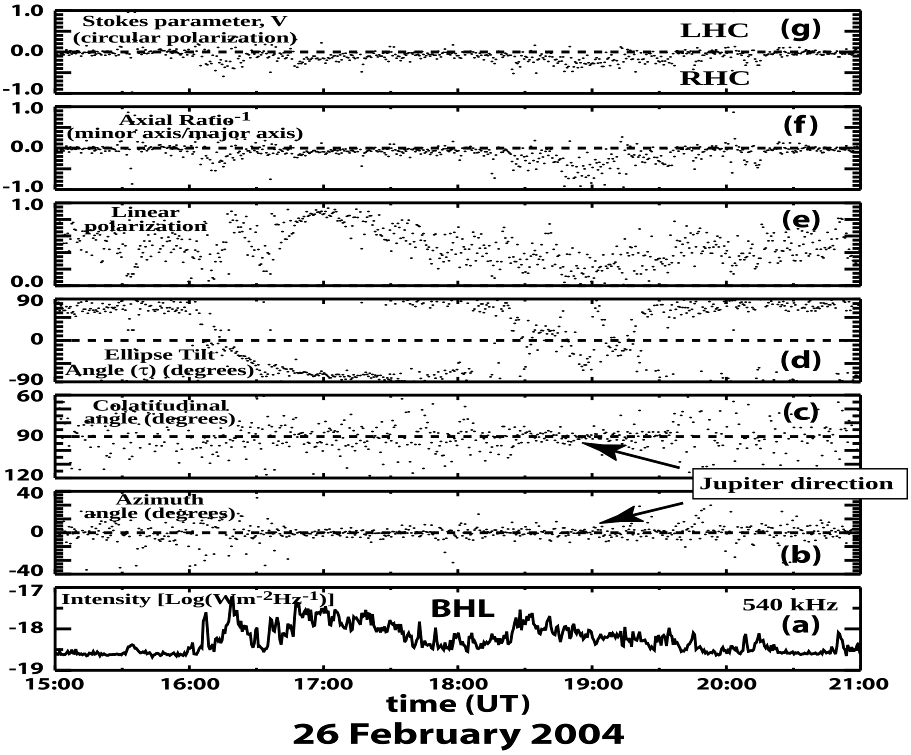

Figure 3: Derived source parameters, at 540 kHz, on February 26, 2004 (a) Radio source intensity (Log[W m^{-2} Hz^{-1}]) as a function of time. (b) Source azimuth as viewed from the Ulysses, relative to the azimuth of Jupiter (0°). (c) Source colatitude, relative to the colatitude of Jupiter (90°). (d) Tilt angle of the polarization ellipse. (e) Degree of linear polarization. (f) Inverse of the axial ratio. (g) Stokes parameter V.

sponds to 100% left-hand circular (LHC) polarization; V = –1 to 100% right-hand circular (RHC) polarization (Institute of Radio Engineers (IRE) convention). This BHL source, viewed from high northern Jovigraphic latitudes, exhibits a small amount (10 to 25%) of circular polarization in the right-hand sense, significantly less than the approximately 100% circular polarization that is typically observed for Jovian radio sources in this frequency range [Ortega-Molina and Lecacheux, 1991]. This degree of circular polarization is similar to that measured for the BHL emissions observed by Ulysses in 1992 [Paper I].

Figure 3f plots the inverse of the axial ratio (AR), which is the ratio of the semimajor to semiminor axis of the polarization ellipse. AR is ±1 for 100% circular polarization. For the BHL emissions, the values for AR are relatively large (AR^{-1} is near 0), indicating a significant linearly polarized radiation component. This is confirmed by the degree of linear polarization, defined as $(Q^2 + U^2)^{1/2}$, where Q and U are the (normalized) Stokes parameters, plotted in Figure 3e. The degree of linear polarization is significantly different from zero between ~17:00 and 20:00 UT. (When there is no significant signal above the galactic background, this value lies near +0.5, but this is just an artifact of the direction-finding analysis).

Finally, Figure 3d plots the derived tilt angle of the polarization ellipse, defined as $\tau = 0.5 \tan^{-1}(U/Q)$. (Note that there is an 180° ambiguity in the orientation angle of this ellipse — so that tilt angles $< -90°$ are equivalent to those $> 90°$). Although there are large fluctuations due to the rapid time variability of these emissions, the values of τ indicate a well-defined spatial orientation of the polarization ellipse during the period of the observed BHL emissions. More significantly, there is a systematic variation in the orientation of the polarization ellipse from about 90° to about -180° over this approximately 4-hour time period. As argued in Paper I, such a systematic variation in τ provides compelling evidence that the radiation is elliptically polarized. The derived polarization parameters shown in the four upper panels in Figure 3 therefore indicate that the BHL emissions are elliptically polarized in the RH sense, consistent with the results in Paper I for the BHL emissions observed from northern Jovigraphic latitudes. Hence the observations presented here represent a new example of Jovian BHL emission.

The elliptical polarization of the BHL emission suggests a possible relationship to Jovian DAM emisssion observed at higher frequencies, which are known to be elliptically polarized in the RH sense when observed from northern latitudes. Indeed, we have noted that at the time of this episode of BHL emission observed by Ulysses, the WAVES experiment on the Wind spacecraft, located near Earth, detected clear arc structures in the frequency range from 1 to 14 MHz that correspond to Jovian DAM emissions [Paper II]. We have therefore speculated that the BHL emissions, observed below 1 MHz by Ulysses/URAP, may in fact represent a low-frequency extension of the Jovian DAM emissions.

3 Global Characteristics of the Radiation Associated with the February 26, 2004 BHL event

An overview dynamic spectrum of this BHL episode is provided in Figure 4. The frequency range is from 1.25 to 940 kHz and the time period is 10 days, from February 24 to March 4, 2004 (DOY = 55 – 65). The February 26 (DOY = 57) BHL event, extending from 940 to nearly 100 kHz from 16:00 UT to 20:00 UT, is clearly visible. No further BHL episodes were observed during this time period. (Subsequent activity seen at high frequencies on February 28 (DOY = 59) and March 3 and 4 (DOY = 63 – 64) are radio emissions of solar origin.)

Just prior to this BHL event, in the frequency range from 30 to a few hundred kHz, there were clear episodes of the more common bKOM emission, with its characteristic 10-hour periodicity. Direction-finding/polarization analyses of these bKOM emissions indicated that they were circularly polarized in the RH sense. This suggests that the BHL and bKOM emissions were both generated by radio sources in the northern auroral region of Jupiter.

For 4 days prior to the BHL event there was no Jovian nKOM activity. However, beginning about 4 hours after the end of the BHL event, the spectrum is dominated by a sequence of intense nKOM events that extended over 15.5 Jovian rotations (6.5 Earth days). The first two of these nKOM events (see Figure 2) were very intense and extended over a wide CML range ($\sim$ 30° to 280°) and over an unusually wide frequency range ($\sim$50 to 200 kHz). These nKOM sources, which represent distinct radio sources in the Io plasma torus, exhibited the typical corotational lag of $\sim$5% of the Jovian rotation period (9.925 hours).

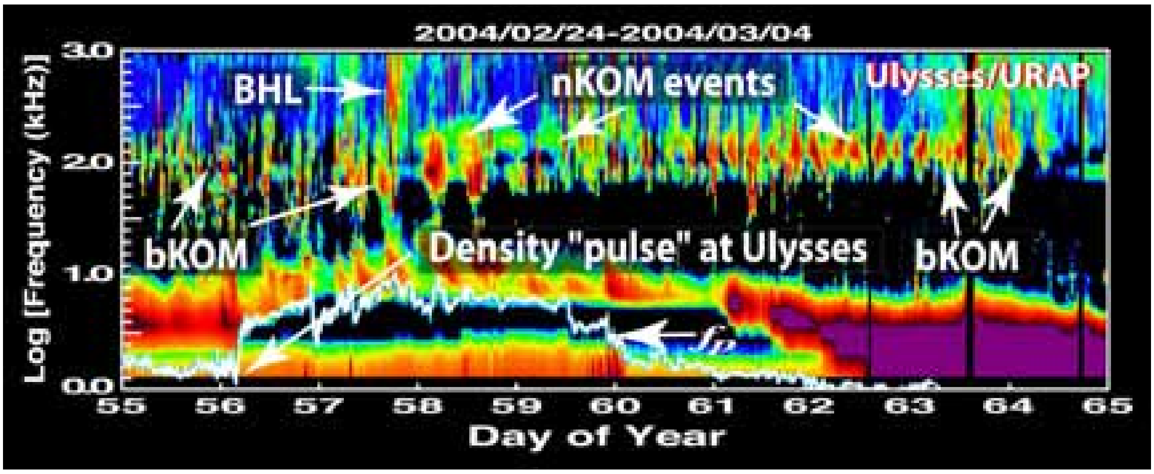

Figure 4: Dynamic spectrum from February 24 to March 4, 2004 showing an overview of the Jovian radio emissions as they respond to a density pulse at Jupiter. The white-blue curve is the local plasma frequency calculated from the measured in-situ density at Ulysses.

These emissions appeared in the same CML range as the nKOM emissions observed from northern Jovigraphic latitudes during the 1992 flyby [Reiner et al., 1993].

Subsequently, the nKOM emissions weakened significantly, while maintaining their ~5% corotational lag. Then, on March 1 (DOY = 61) the nKOM sources again intensified, without a new BHL event, and an additional intense nKOM source appeared between the ~10-hour nKOM recurrences, so that now there were two distinct, intense nKOM sources per Jovian rotation, with approximately the same corotational lag of about 5%. During this time period the nKOM emissions were confined to their more usual frequency range, between ~100 and 200 kHz. These intense nKOM sources were observed until the middle of March 4 (DOY = 64), when all the nKOM activity ceased. The reason for the sudden intensification in the nKOM activity and for the abrupt end of the intense nKOM activity is not known.

The direction-finding/polarization analysis of the nKOM emissions observed at this time indicates that all of the nKOM radio sources were LHC polarized, i.e., opposite to the polarization sense of the elliptically polarized BHL emissions and to the circularly polarized bKOM emissions. This agrees with previous observations that found nKOM, viewed from northern latitudes, to be predominantly LHC polarized [Daigne and Leblanc, 1986; Reiner et al., 1993]. This is also consistent with the fact that nKOM has a completely different origin (Io plasma torus) and most probably is generated by a different emission mechanism.

It was previously shown that the onset of sequences of nKOM events, such as those observed in Figure 4, were triggered by density pulses at Jupiter, related to the solar wind sector structure [Reiner et al., 2000]. The blue and white curve superposed on the dynamic spectrum in Figure 4 represents the local plasma frequency at Ulysses. It was calculated from the plasma density, measured in-situ by the SWOOPS experiment on Ulysses. The plasma density (frequency) shows a clear discontinuity at ~4 UT on February 25 (DOY = 56), due to an interplanetary shock associated with a CIR. Assuming an ideal Parker spiral corresponding to a nominal solar wind speed of 400km s^{-1}, it is expected that this CIR arrived at Jupiter at about 19 UT on February 25, about 21 hours before the observed onset of the BHL emissions. Recurrences of this CIR produced similar sequences of nKOM activity starting on February 16 and on March 8 and 21 [Paper II]. What is new here is that in each case the onset of the nKOM activity was itself preceded by a distinct BHL event.

The observations presented here indicate that in spite of their very different origins and presumably different emission mechanisms, both BHL and nKOM are strongly influenced by the large-scale response of the Jovian magnetosphere to solar wind structures. However, it is difficult to ascertain whether the same physical phenomenon responsible for initiating the BHL event also triggered the subsequent nKOM activity or whether the BHL event and the nKOM activity were each generated by distinct physical phenomena related to the encounter of the solar wind density pulse with the Jovian magnetosphere. Since the BHL emissions are likely generated in the auroral region while the nKOM emissions are generated in the Io plasma torus, it seems unlikely that the same physical phenomenon that led to the onset of the BHL emissions also directly triggered the nKOM activity; it is more likely that both the BHL and nKOM activity represent independent responses to the large-scale behavior of the Jovian magnetospheric due to its encounter with the solar wind density pulse related to the CIR and associated sector structure [Louarn et al., 1998; Reiner et al., 2000; Gurnett et al., 2002].

3.1 Conclusions

Four episodes of Jovian BHL emissions were detected by the URAP experiment on the Ulysses spacecraft from high Jovigraphic latitudes during the Ulysses-Jupiter Distant Encounter that occurred in the latter half of 2003 and first half of 2004. Each of these four BHL episodes, which were followed by extended periods of nKOM activity, appeared to have been triggered by the response of the Jovian magnetosphere to distinct solar wind density pulses associated with a CIR. The BHL episode that occurred on February 26, 2004 was found to exhibit the classic BHL signatures of highly time-variable radiation and elliptical polarization in the RH sense. This episode was apparently triggered by the arrival of a CIR at Jupiter's magnetosphere, which was observed at Ulysses on February 25, 2004. This BHL event was preceded by 10-hour episodes of Jovian bKOM emissions. On the other hand, while there was no evidence of Jovian nKOM emissions prior to the BHL event, it was followed, four hours later, by an extended period of intense nKOM activity that lasted for about 16 Jovian rotational periods. These results indicate that the density pulse at Jupiter, associated with the CIR, had a very significant effect on all three of these Jovian radio emission components, observed from high Jovigraphic latitudes.

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