ULYSSES OBSERVATIONS OF JOVIAN RADIO EMISSIONS OVER A WIDE RANGE OF JOVICENTRIC LATITUDES

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Abstract

In 2003 and early 2004, the Ulysses spacecraft descended from higher heliographic latitudes toward aphelion, bringing it to within 0.8 AU of Jupiter. The geometry of this distant flyby caused Ulysses to spend more than 11 months above a jovicentric latitude of 50° at a distance from Jupiter of less than 3 AU, while the spacecraft traversed a considerable range of Jovian local time from 9 hours to 17 hours. During much of this time interval, Jupiter was intercepted each solar rotation by a two sector heliospheric magnetic field (HMF) and two corotating interaction regions (CIRs). From this Ulysses perspective, which is unique for observations of Jupiter, the radio response of the magnetosphere to a given corotating structure was the intensification of either Jovian broad-band kilometric (bKOM) emission or of a combination of emissions, including bKOM and Jovian narrow-band kilometric (nKOM) emission. Such enhancements have been studied previously with Voyager, Ulysses, Galileo, and Cassini radio data, but not from such high jovicentric latitudes. Here, we briefly review Ulysses radio observations of Jupiter and examine variations in solar wind and magnetic field parameters (measured by Ulysses) that appear to trigger intense radio emissions in the Jovian magnetosphere.

1 Introduction

The Ulysses spacecraft is an ESA/NASA mission to study the high latitude regions of the heliosphere, which it accomplishes with a highly-elliptical orbit of inclination ∼80° relative to the ecliptic plane and a period of 6.2 years. This orbit was achieved using a close flyby of Jupiter in 1992; consequently, Ulysses returned to the vicinity of Jupiter in 2004,

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at which time the closest approach was 0.8 AU. The geometry and relative velocities of Jupiter and Ulysses caused the spacecraft to remain at high jovicentric latitudes for many months (Figure 1). During that time interval, the Ulysses radio astronomy receiver (RAR) observed Jovian radio emissions on an almost continous basis. Furthermore, the Ulysses magnetic field and solar wind plasma instruments measured the upstream environment of Jupiter, helping to elucidate the causes of variability of the radio emissions.

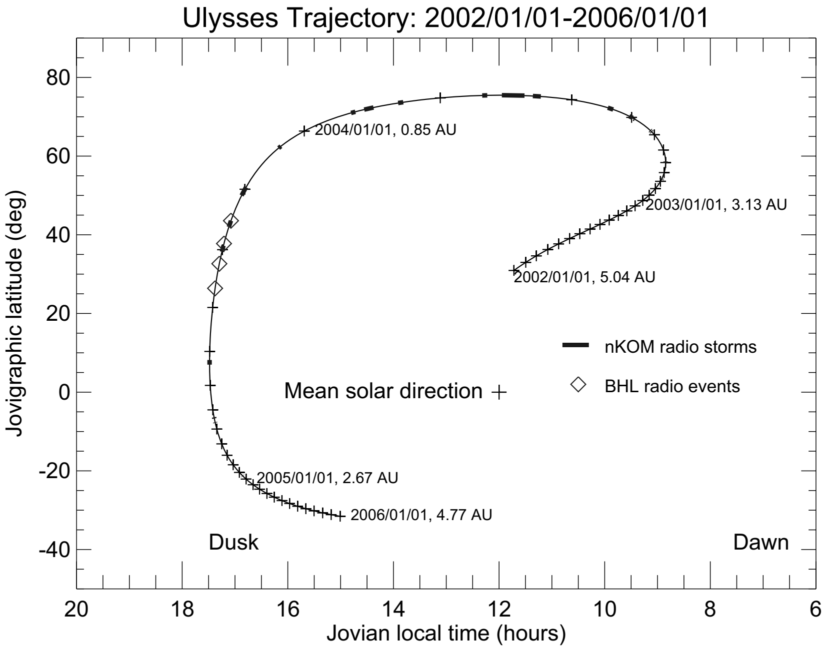

Figure 1: Ulysses' trajectory from 2002 through 2005, as a function of jovicentric latitude and Jovian local time of the spacecraft. Tick marks on the trajectory indicate one month intervals. Distance of Ulysses from Jupiter is shown at the start of each year. Occurrences of nKOM storm and BHL radio events (discussed in text; also, see Reiner et al. [2006]) are shown. Note that from 2003/01/01 to 2005/01/01, Ulysses covered the heliographic latitude range of 24.0° to -15.6°, i.e., Ulysses was always in relatively low latitude solar wind.

2 Overview of Jovian Radio Emissions

Jupiter is a prodigious and powerful source of radio emissions. The sensitivity of the RAR permits it to detect these emissions from distances of more than 5 AU [Stone et al., 1992]. In the frequency range observed by the RAR (1 – 940 kHz), there are at least six emission components, most of which are seen in Figure 2. At the bottom of the dynamic spectrum during the first day, so-called continuum emission is observed; it disappears beginning on day 31 when a CIR-related density increase blocks propagation of the < 10 kHz emissions to the spacecraft. At frequencies above the escaping continuum, the broad band, bursty activity typically observed from high jovicentric latitudes is seen to occur up to ∼300 kHz. The interaction of the corotating structures with the Jovian magnetosphere transforms this emission to a more intense, more continuous emission, whose morphology resembles the broad-band kilometric emission (bKOM) routinely observed when a spacecraft is at

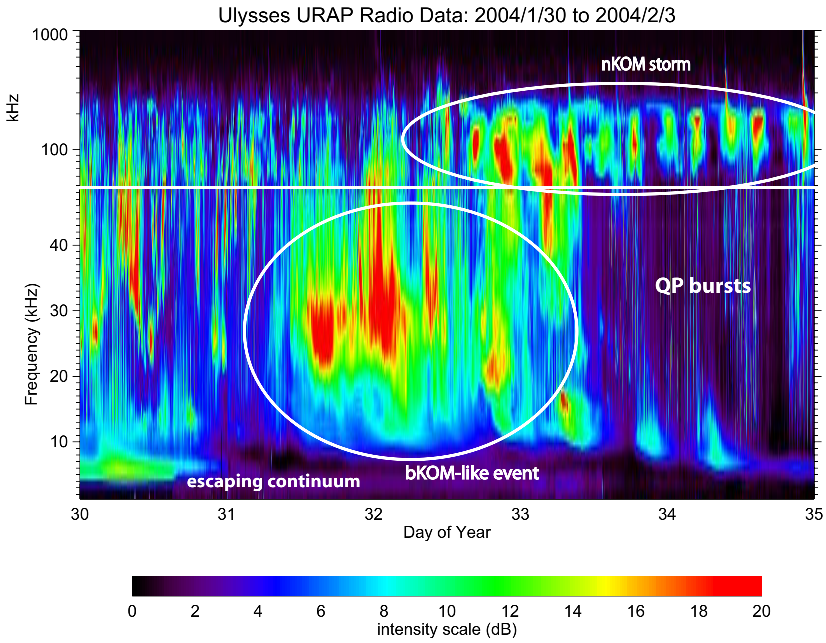

Figure 2: Plot of 5 days of Ulysses RAR data, showing a variety of Jovian radio emission components (described in the text). The rainbow color scale indicates the intensity of the emission with red being most intense.

low jovicentric latitude. (Note that typically, Ulysses does not observe bKOM when at higher (> 50°) jovicentric latitudes.) Approximately one day later, a narrow-band kilometric (nKOM) storm commences, similar to occurrences reported by Louarn et al. [1998]. Soon after the onset of the nKOM storm, the bKOM-like activity ceases and is replaced by numerous quasi-periodic (QP) bursts [MacDowall et al., 1993], also known as Jovian type III bursts [Kurth et al., 1989; Hospodarsky et al., 2004]. Missing from this figure are bursty high-latitude (BHL) emissions [Reiner et al., 1995; Reiner et al., this issue]. Also, hectometric (HOM) emission is not observed at these high jovicentric latitudes; it is only seen when Ulysses moves into the HOM beam at jovimagnetic latitudes of less than 10°. The emission observed by the RAR at high jovicentric latitudes during levels of low solar wind activity is predominantly either bursty activity, like that on the first day of Figure 2 (day 30), or QP burst activity like day 34. As shown in Figure 3, using 30 kHz as the reference, these short duration emissions are occasionally replaced by less bursty emissions (like that marked bKOM-like in Figure 2); however, burstiness is generally more pronounced at high latitudes, compared to in-ecliptic observations.

Many studies of Voyager, Ulysses, Galileo and other data show that the giant planet's radio emissions respond to solar wind variability. Figure 4 shows the radio response to a dense, fast transient in the solar wind, produced by coronal mass ejections (CMEs) during the October and November 2003 solar activity [de Koning et al., 2005]. Corotating structures have also been demonstrated to increase radio intensity of various emissions, like the bKOM-like and nKOM bursts shown in Figure 2 [see also Reiner et al., 2000].

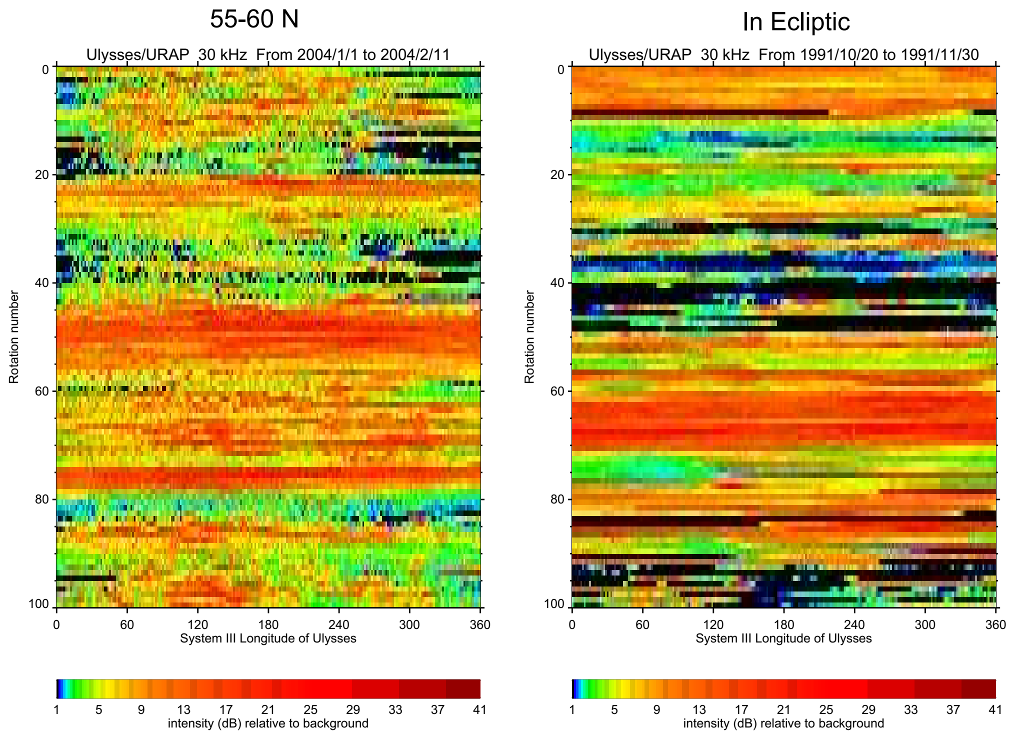

Figure 3: (Left) Stacked plot of 30 kHz RAR data for 100 Jovian rotations, for the interval 2004 Jan 1 to 2004 Feb 11, when Ulysses was at jovicentric latitudes of 55° to 60° N. As is typical at high latitudes, the 30 kHz data are bursty at all System III longitudes, with occasional intervals of less bursty, more intense bKOM-like emissions. (Right) In-ecliptic 30 kHz RAR data acquired when Ulysses was approaching Jupiter from 1991 Oct 20 to 1991 Nov 30, at similar distances from Jupiter as in Jan-Feb 2004. Relatively smoothly varying bKOM emission occurs for many Jovian rotations, interspersed with intervals of little activity. There is almost no bursty emission.

3 Recurrent Jovian radio events in 2003 and 2004

Recurrent solar wind variability due to CIRs and/or sector boundary (SB) crossings produces characteristic radio responses from Jupiter. For Ulysses observations in 1991 and 1992, the typical scenario was brightening in the Jovian bKOM emission, followed by a sudden cessation of the bKOM emission and an onset of an nKOM event that lasted for ∼10 Jovian rotations [Reiner et al., 2000]. The recent Ulysses observations, shown in Figures 5 and 6, present an interesting complication. As seen in Figure 5, the first intensification of bKOM-like emission (on the left) in two of the 3 panels is less intense than the second, while the nKOM storm tends to be more intense for the first of each pair of events. This pattern was observed by the RAR for at least 5 solar rotations.

The in situ variations in the solar wind and HMF, measured at Ulysses, are compared to the Jovian radio emission variations for a single 26-day interval (2004 Jan 28 to 2004 Feb 22) in Figure 6. The top (bottom) 3 panels show magnetic field (solar wind) data. The two CIRs per solar rotation and the 2-sector HMF are readily apparent. The more intense, longer lasting nKOM storms appear when Jupiter is in the sector with $B_{phi} > 0$; however, we have determined that neither $B_{phi} > 0$ nor crossing the SB is a sufficient conditions for

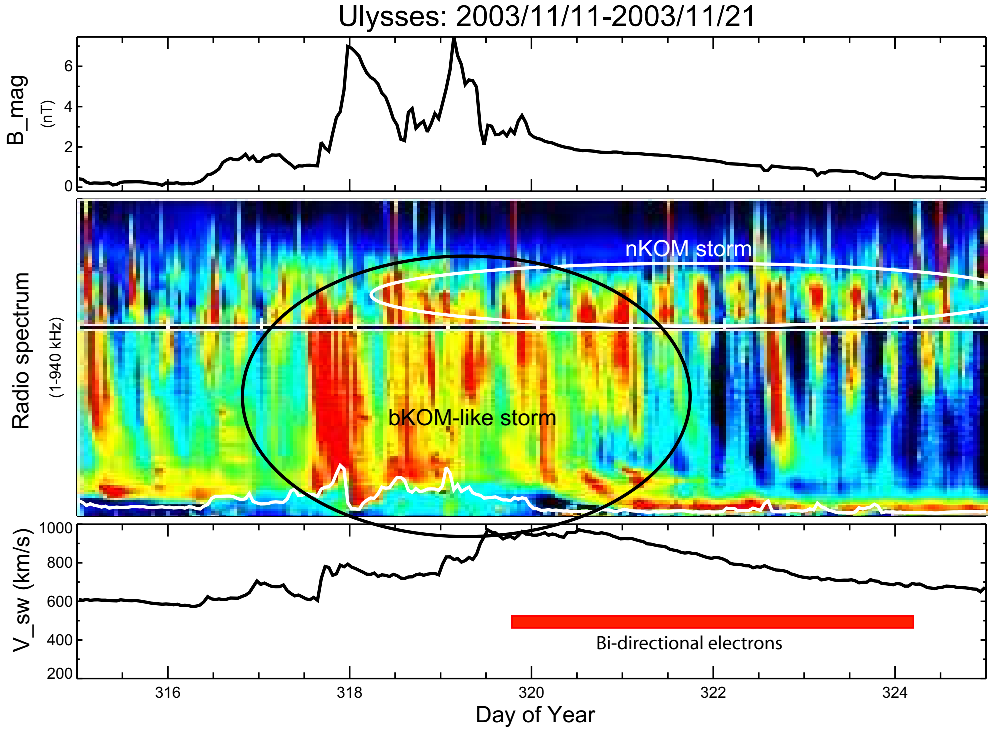

Figure 4: Ten days of Ulysses data. (Top) Magnetic field amplitude at Ulysses, showing merged solar transients of 2003 October-November. (Middle) RAR radio data, indicative of Jovian magnetospheric response to solar transient; the jovian bKOM-like event is followed by an nKOM storm. The white line indicates the electron plasma frequency $\sim \sqrt{density}$*. (Bottom) Ulysses solar wind velocity increases associated with the solar transients; the red bar indicates an interval of bi-directional electrons, proxies for an interplanetary CME. Note that Ulysses in situ data in this figure (and also in Figure 6) are not time shifted to Jupiter.*

an nKOM storm onset. Some trigger such as the density pulse that initiates bKOM also seems to be required. There may also be a minimum V_{sw} constraint for intense nKOM events. Clearly, the role of $B_{phi} > 0$ is intriguing, but the occurrence of SB crossings in the CIRs complicates a simple determination of the nKOM storm trigger. More detailed analysis of the Jovian radio components during this interval of corotating heliospheric structure could yield an improved understanding of the radio emissions and, potentially, of the solar wind-magnetospheric interaction.

4 Other Applications and Conclusion

The long interval of continuous Jovian observations, supported by Ulysses in situ data, also permits other, interesting studies. For example, Figure 7 shows measured angular sizes of Jovian nKOM events as observed by Ulysses. The geometric size of the source (in the Io torus) viewed from Ulysses would be a fraction of a degree, so the measured size must be due to scattering from electron density fluctuations in the interplanetary medium (IPM). The solid line is a theoretical prediction of the scattering angle along the Ulysses trajectory for a simple model of the electron density in the IPM [Hess and MacDowall, 2003]. Since

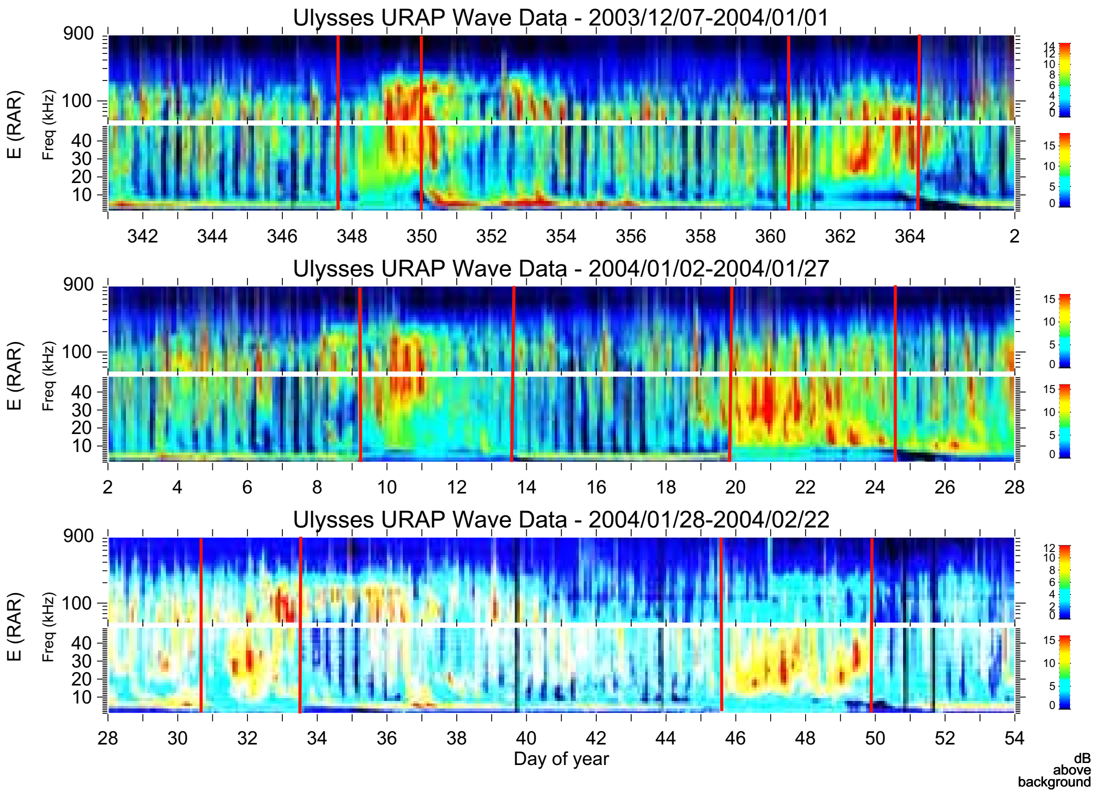

Figure 5: Three 26-day intervals of Ulysses data, covering 7 Dec 2003 to 22 Feb 2004. In correspondence with the passage of the corotating structures (delineated by pairs of red lines), significant intensifications of the radio emissions occur (as indicated by the intense (red) areas in the dynamic spectra). During this time interval, Ulysses is approximately 1 AU from Jupiter (see Fig. 1), so that Jovian radio emission comprises a significant fraction of all observed radio events. Note: Rotation of the planet (period ∼9.9 hours) causes long-duration radio sources that are fixed in Jovian longitude to reappear repeatedly, producing the ∼10-hour background variation as a function of time.

the actual level of electron density fluctuations is not known, the theoretical scattering angle has been linearly scaled to best fit the measured points. The measured points show scatter because the measured source size is very sensitive to the level of background emissions received, which can be difficult to determine accurately, and because the level of density fluctuations along the path of the radio waves from Jupiter to Ulysses could vary significantly for different events due to solar wind variability. Consequently, we hope to demonstrate tracking of overdense regions between the source and the spacecraft.

In summary, the Jovian radio emissions represent a wealth of data relating to magnetospheric and solar wind activity. It is our challenge to fully decipher the information provided by these diverse Jovian radio emissions.

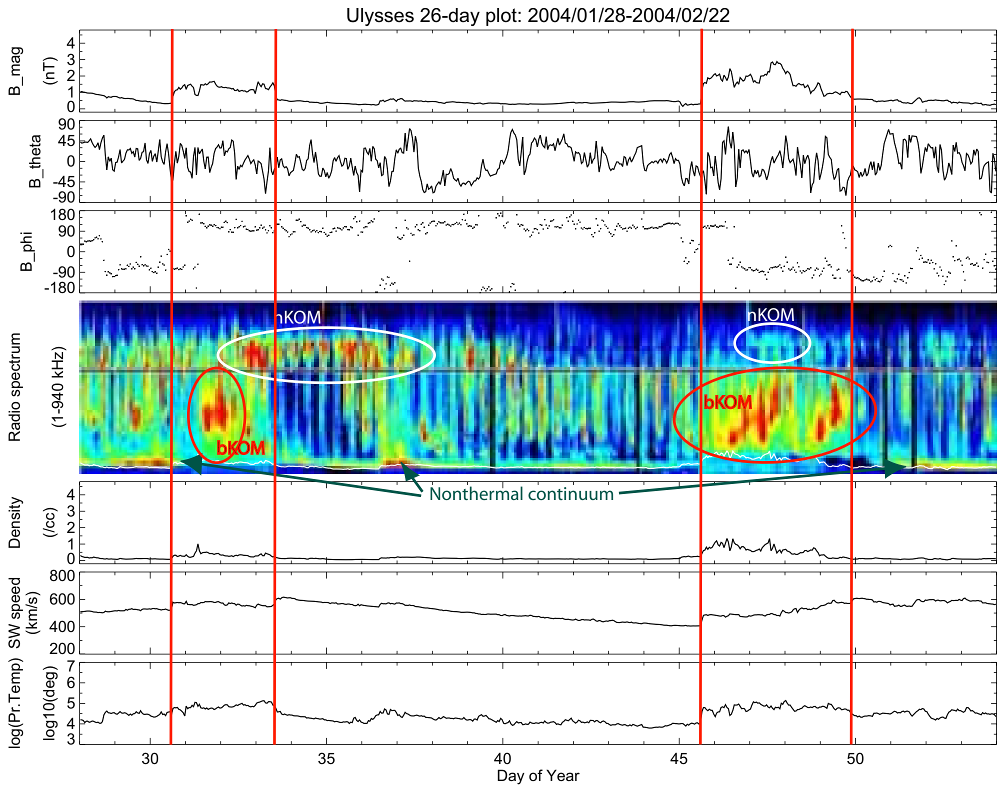

Figure 6: Twenty-six-day interval of Ulysses data, covering 28 Jan 2004 to 22 Feb 2004. From top to bottom: the top 3 panels are Ulysses magnetic field data (magnitude and components in elevation (theta) and azimuth (phi)), the middle panel is a dynamic spectrum from the RAR, and the bottom 3 panels are solar wind proton density, solar wind speed, and proton temperature. The magnetic field data show the passage of a 2-sector solar wind at the spacecraft. CIRs (within pairs of red lines) occur in approximate time coincidence with sector boundary crossings.

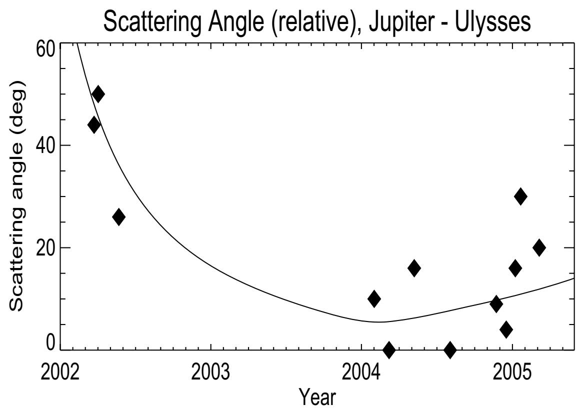

Figure 7: Angular size (half-angle in degrees) of selected Jovian nKOM events observed by Ulysses from 2002 to 2005. Points marked with diamonds are measured angular size, due to interplanetary scattering, at 52 kHz. The solid line is a theoretical calculation of the expected scattering angle, linearly scaled to best fit the measured data.

References

De Koning, C. A., J. T. Steinberg, J. T. Gosling, D. B. Reisenfeld, R. M. Skoug, O. C. St. Cyr, M. L. Malayeri, A. Balogh, A. Rees, D. J. McComas, An unusually fast interplanetary coronal mass ejection observed by Ulysses at 5 AU on 15 November 2003, *J. Geophys. Res.*, **110 (A1)**, Art. No. A01102, doi:10.1029/2004JA010645, 2005.

Hess, R. H., and R. J. MacDowall, Scattering of interplanetary radio waves at kilometric wavelengths, *J. Geophys. Res.*, **108 (A8)**, Art. No. 1313, doi: 10.1029/2002JA009783, 2003.

Hospodarsky, G. B., W. S. Kurth, B. Cecconi, D. A. Gurnett, M. L. Kaiser, M. D. Desch, and P. Zarka, Simultaneous observations of Jovian quasi-periodic radio emissions by the Galileo and Cassini spacecraft, *J. Geophys. Res.*, **109 (A9)**, Art. No. A09S07, doi:10.1029/2003JA010263, 2004.

Kurth, W. S., D. A. Gurnett, and F. L. Scarf, Jovian type-III radio bursts, *J. Geophys. Res.*, **94 (A6)**, 6917–6924, 1989.

Louarn, P., A. Roux, S. Perraut, W. Kurth, and D. Gurnett, A study of the large-scale dynamics of the Jovian magnetosphere using the Galileo plasma wave experiment, *Geophys. Res. Lett.*, **25**, 2905–2908, 1998.

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

Reiner, M. J., M. D. Desch, M. L. Kaiser, R. Manning, J. Fainberg, and R. G. Stone, Elliptically polarized bursty radio emissions from Jupiter, *Geophys. Res. Let.*, **22**, 345–348, 1995.

Reiner, M. J., M. L. Kaiser, and M. D. Desch, Long-term behavior of Jovian bKOM and nKOM radio emissions observed during the Ulysses-Jupiter encounter, *Geophys. Res. Let.*, **27**, 297-3030, 2000.

Reiner, M. J., M. L. Kaiser, M. D. Desch, and R. J. MacDowall, Jovian bursty high latitude emissions revisited: The Ulysses-Jupiter distant encounter, in *Planetary Radio Emissions VI*, H. O. Rucker, W. S. Kurth, and G. Mann (eds.), Austrian Academy of Sciences Press, Vienna, 2006, *this issue*.

Stone, R. G., J. L. Bougeret, J. Caldwell, P. Canu, Y. de Conchy, N. Cornilleau-Wehrlin, M. D. Desch, J. Fainberg, K. Goetz, M. L. Goldstein, The unified radio and plasma wave investigation, *Astron. Astrophys. Supp. Ser.*, **92**, 291-316, 1992.