GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L05106, doi:10.1029/2010GL042488, 2010

New periodicity in Jovian decametric radio emission

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Received 14 January 2010; revised 4 February 2010; accepted 16 February 2010; published 12 March 2010.

[1] We report on the finding of a new periodicity in the Jovian decametric radio emission (DAM). Periodic bursts of non-Io component of DAM which recur with a period 1.5% longer than the Jupiter rotation (System III) have been found in the dynamic radio spectra acquired by STEREO/WAVES, Wind/WAVES and Cassini/RPWS during the years 2002–2008. Typically, the bursts appear very periodically over several Jovian days with a decreasing intensity and they display a negative frequency drift. All the bursts were detected within the same sector of Jovian Central Meridian Longitude (III), between 300° and 60° (via 360°) of CML (III), close to the region of the non-Io-C source. No correlation has been found with the position of Io. Considering the simultaneous stereoscopic observations onboard STEREO-A and STEREO-B, as well as Wind and Cassini we can conclude that the sources of the periodic bursts most probably sub-corotate with Jupiter. **Citation:** Panchenko, M., H. O. Rucker, M. L. Kaiser, O. C. St. Cyr, J.-L. Bougeret, K. Goetz, and S. D. Bale (2010), New periodicity in Jovian decametric radio emission, *Geophys. Res. Lett.*, *37*, L05106, doi:10.1029/2010GL042488.

1. Introduction

[2] Jupiter emits an intense non-thermal radiation in the decametric (DAM) frequency range. The DAM emission is generated via the cyclotron maser mechanism in sources located along Jovian magnetic field lines [*Zarka*, 1998]. As a result of non-axisymmetric magnetic field, non-isotropic emitting directivity and interaction with the satellite Io the DAM exhibits strong periodicities related to the rotation of the Jupiter's magnetosphere (9.9249 h, System III), Io orbital period (42.46 h) as well as the beat period between System III and Io orbital period, 12.95 h [*Carr et al.*, 1983; *Kaiser*, 1993; *Queinnec and Zarka*, 1998]. The non-Io component of the DAM, which is the subject of our study, appears in a form of arcs in time-frequency coordinates and is generally modulated by the Jovian 9.9249 h rotation period.

[3] The other components of Jovian radiation also exhibit several strong periodicities. *Kaiser and Desch* [1980] reported that the occurrence of a narrow-band Jovian kilometric radiation (nKOM) is modulated with a period slower by 3%–5% than System III. Taking into consideration the previously reported periodical variation of the optical features in the Io plasma torus as well as the fact that nKOM emission originates in the outermost regions of the Io plasma torus (7–13 R_J) *Sandel and Dessler* [1988] proposed the existence of an additional independent Jovian rotation period, called System IV, which closely relates to the Io plasma torus and has a period 10.224 h, 3% slower than System III. *Kaiser et al.* [1996] have shown that the intensity of the hectometric Jovian radiation (HOM) is also modulated with the period of System IV. The authors suggested the existence of a high density region in the Io plasma torus which rotates with a System IV period and can periodically block the HOM emission.

[4] In the present paper we report the new periodicity in non-Io DAM emission. Analyzing the data recorded by the radio instruments onboard STEREO, Wind and Cassini spacecraft we have found several episodes when the bursts of the non-Io DAM periodically recurred with an average rate of 10.07 ± 0.09 h which is 1.5% longer than the rotation of the Jovian magnetosphere (9.9249 h, System III).

2. Observations and Data Analysis

[5] In our study we have analyzed dynamic radio spectra of Jovian decametric radiation acquired by STEREO/WAVES, Wind/WAVES and Cassini/RPWS instruments [*Bougeret et al.*, 1995, 2008; *Gurnett et al.*, 2004] in the years 2002–2008. Being mainly dedicated for measurements of solar radio bursts (STEREO/WAVES, Wind/WAVES), Earth's (Wind/WAVES) and Saturn's (Cassini/RPWS) radio emissions the experiments also provided a large amount of observations of the Jovian decametric (DAM) radiation. In the present study we use only the highest part of the frequency range of each instrument (from about 2 MHz to about 14–16 MHz, depending on the instrument) to avoid observations of the terrestrial Auroral Kilometric Radiation (AKR) as well as Jovian HOM emission which are not subject of our study. The time resolutions of the STEREO/WAVES, Cassini/RPWS and WIND/Waves depend on working modes of each instrument and can vary from 16 s to about 39 s.

[6] The main part of this study is based on the STEREO/WAVES data recorded stereoscopically by the two STEREO spacecraft. The stereoscopic measurements facilitate unambiguous discrimination of the Jovian DAM emission in the observed dynamic spectra as well as identification of its components. The DAM emission is identified by means of the time delay between sequential detection of the radio burst from the same radio source by two spacecraft separated in space. In case of Jovian radio emission this time delay consists of two parts $dt = dt_0 + dt_1$. The first part, dt_0, is equal to the difference in light travel time from the radio

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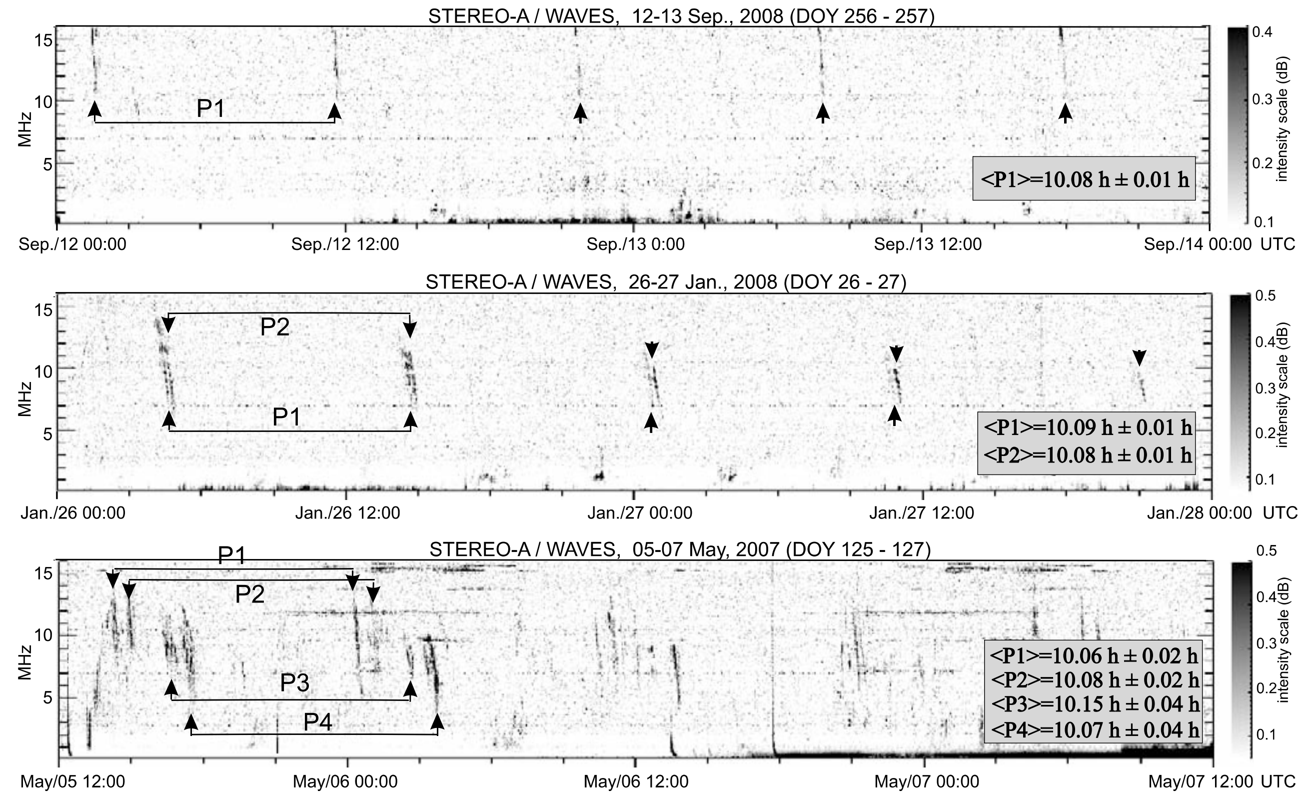

Figure 1. Examples of the periodic burst observed by STEREO/WAVES on (top) 12–13 Sep., 2008 (group of single bursts), (middle) 26–27 Jan., 2008 (group of double bursts) and (bottom) 5–6 May, 2007 (several groups of single or double bursts). P1, P2, P3 and P4 and arrows mark different groups of the periodic burst during one episode. The average period of the burst repetition in each group is given.

source to each of the spacecraft. If the same radio burst is detected simultaneously by two STEREO spacecraft (dt_0 is less than time resolution of the STEREO/WAVES) then this emission usually has its origin at the Sun, since the STEREO spacecraft differ about 0.1 AU in radial distance from the Sun. Otherwise the radiation is from Jupiter.

[7] The second term of the time delay dt_1 can be used for unambiguous identification of the DAM component. Since the Jovian DAM is emitted in thin hollow cones attached to the Jovian magnetic field or to the Io flux tube, the Jovian decametric bursts are detected sequentially by each of STEREO with a delay dt_1 which is equal to the time necessary to rotate the emission cone by the angle α - the angular separation between the spacecraft as seen from Jupiter. If this delay is equal to the time for Io to move through the angle α along its orbit then this strongly suggests that the observed radiation is Io-related DAM. Otherwise, the radiation is assumed to be a non-Io component of the DAM.

3. Periodic Bursts of Jovian Decametric Radiation Observed by STEREO/WAVES

[8] Analyzing the measurements of the Jovian DAM we have found periodic radio bursts (see examples in Figure 1) which have an intensity comparable to non-Io-DAM emission and recurred during several Jupiter's days with a few percent different period than the planetary rotation. These bursts occurred as tilted lines in the dynamic spectra within a frequency range from about 5 MHz to about 12 MHz or in some cases more than 16 MHz - the higher frequency limit of the STEREO/WAVES instrument. In most cases the bursts displayed negative drift in time-frequency coordinates and the intensity of each successive burst was lower than the previous one. In some cases these features were very similar to vertex late arcs of non-Io DAM [*Queinnec and Zarka*, 1998]. Typical duration of each burst at the same frequency was several minutes. The time delay (after correction on light travel time from Jupiter to each of the spacecraft) between sequential detection of the same bursts onboard STEREO-A and STEREO-B corresponds to the time for Jupiter to rotate through the angular spacecraft separation, and, therefore, these periodic bursts have been identified as non-Io DAM. In total, 15 episodes of periodic bursts have been recorded by STEREO/WAVES during two years (2007–2008) of observations (one episode means continuous repetition of the periodic structures in the dynamic spectra).

[9] The fact that the periodic bursts were observed sequentially by STEREO-A and STEREO-B during several Jovian rotations may suggest that a source of this emission sub-corotates with Jupiter and it is operating during longer periods of time. Taking also into consideration the similarity of the periodic bursts and non-Io DAM where the sources are suggested to be located on the magnetic field lines of Jupiter, it is naturally to expect that the periodicity of the observed bursts must correspond to the rotation of the Jovian magnetosphere (9.9249 h, System III). Nevertheless, it has

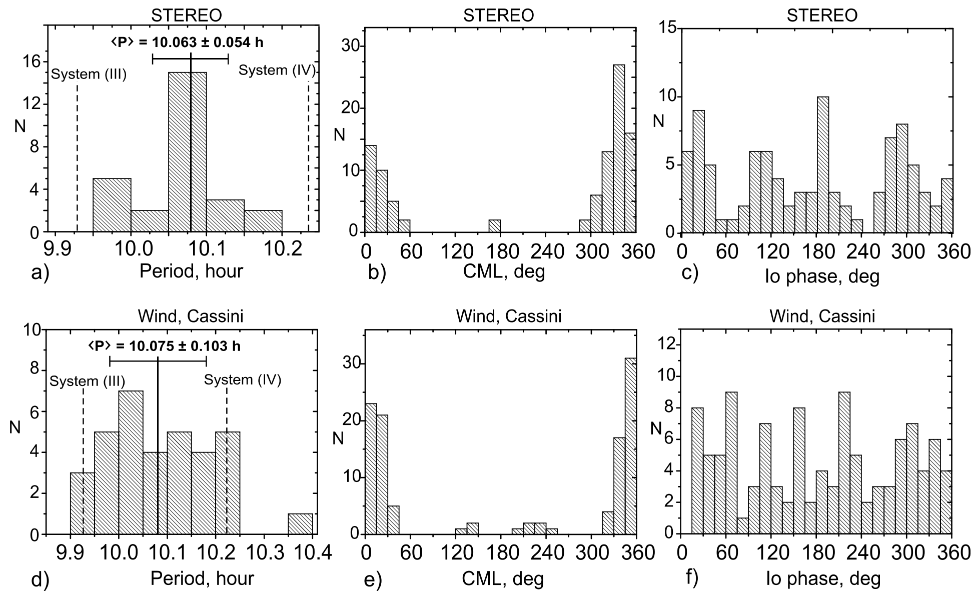

Figure 2. Statistical results of observations acquired by (top) STEREO/WAVES (97 bursts in 27 groups) and (bottom) Wind/WAVES-Cassini/RPWS (110 bursts in 34 groups). (a and d) Histograms of the distribution of the determined periods of the burst repetition. The horizontal lines centered about 10.063 h and 10.075 h denote one sigma error of the mean values. Distribution of the (b and e) Central Meridian Longitudes (III) and (c and f) Io phases of the spacecraft at times of detection of the burst.

been found that all observed bursts recurred a few minutes longer than System III.

[10] In order to examine our data for periodicities, we have measured the time interval between individual bursts of each group (P1–P4) for each episode (see Figure 1) on different frequencies. Then, the averaged period has been calculated for each group of the bursts. Moreover, we have defined a STEREO's (only for STEREO-A) Jovian Central Meridian Longitude (CML) and Io-phase at the time when each particular burst was observed. Generally, to determine the period of the burst repetition it is necessary to account for Doppler shifting of the period caused by the motion of STEREO along its orbit around the Sun relative to the rotating Jupiter. Nevertheless, a very simple calculation shows that such effect leads to an error in the period determination <8 sec, which is less than the time resolution of the STEREO/Waves instrument (light travel time difference has been accounted for).

[11] Figure 2a shows a histogram of the distribution of the determined periods. It is clearly seen that all bursts recurred with periods longer than System III but shorter than System IV (10.224). Out of the observations the averaged period is 10.065 ± 0.054 hours (10 h 3 m 54 s ± 194 s), which is 1.4% longer than System III but 1.6% shorter than System IV. Figure 2b and 2c show a histogram of a CML(III) position and Io phase of the STEREO-A at times of detection of each burst. We note the strong correlation between the CML position of STEREO and the occurrence of the periodic bursts (Figure 2b). The histogram shows that all periodic bursts were detected in the same sector of Jovian CML(III), between 300°–60° (via 360°). This CML range corresponds to source locations of the non-Io-C DAM [see, e.g., *Carr et al.*, 1983]. Only one group of two weak bursts observed on 1–2 January 2008 was detected at 180° of CML. This case is discussed in the section 5. From the Io phase histogram (Figure 2c), we can conclude the absence of any correlation between the position of Io and occurrence of the periodic bursts.

4. Periodic Bursts Observed by Cassini and Wind Spacecraft

[12] We have also analyzed the radio observations in the decametric frequency range acquired by Cassini/RPWS over the period 2002–2003 when the spacecraft was between Jupiter and Saturn orbit, and by Wind/WAVES instrument during the years 2004–2006, when the satellite was orbiting the L1 point. Although it is impossible to unambiguously determine from Cassini and Wind data if the observed radiation arrived from Jupiter or from the Sun we have found 30 episodes with clear periodic bursts similar to those observed in the STEREO's dynamic radio spectra.

[13] The same statistical approach which was used for STEREO data, gives similar results. In particular, the determined periods are distributed between System III and System IV (Figure 2d), and the averaged period of the burst repetition is 10.075 ± 0.103 h (10 h 4 m 30 s ± 371 s). The periodic bursts occurred mainly when Wind or Cassini were located between 320° and 40° of CML(III) (Figure 2e), except for two groups of bursts detected between 120° and 240° of CML. We suppose that there may be several active longitudes where periodic bursts may occur but the sources at longitudes between 300° and 60° are significantly stronger. No correlation with Io position has been found (Figure 2f).

[14] We also found several episodes when the same periodic bursts were detected stereoscopically onboard Wind and Cassini spacecraft. Figure 3 shows an example of such an observation. The averaged period of bursts repetition for the presented episode 21–22 March, 2004 was about 9 h 58 m, and the radio emission was detected when Wind and Cassini were at about 340° of CML(III). The time delay between sequential burst observation onboard both space-

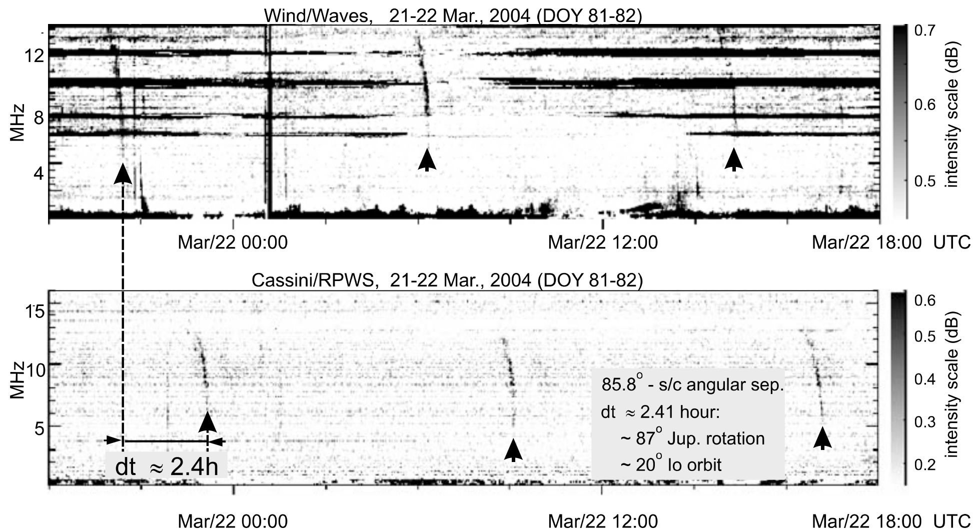

Figure 3. Example of the stereoscopic observations of the periodic bursts by Wind/WAVES and Cassini/RPWS. The intense horizontal striations are man-made radio transmissions.

craft was 2.42 h (after correction on light time travel difference), which corresponds to the time for Jupiter to rotate through the angle of spacecraft separation, which was α = 87.4°. These stereoscopic observations performed by Wind and Cassini strongly supports the hypothesis that the source of the periodic bursts sub-corotates with Jupiter with a period few minutes longer than System III.

5. Discussion

[15] The weighted average reoccurrence rate of the periodic bursts observed by STEREO/WAVES, Wind/WAVES and Cassini/RPWS is 10.07 ± 0.09 h (≈10 h 4 m ± 5 m). As was mentioned in the introduction, the non-thermal Jovian radio emission exhibits several strong modulation periods, related with the rotation of the magnetosphere and Io orbital period. The presence of a new periodicity in non-Io DAM emission at 10.07 h, which does not correspond to neither System III nor System IV, is very surprising. Additionally, since the periodic bursts, reported in this paper, were observed consecutively by two spacecraft (STEREO-A and STEREO-B or Wind and Cassini) most probably we are dealing with a rotating emission beam rather than with a clock-like (stroboscopic) emission. The source of the period bursts should corotate around Jupiter and the observed periodicity is not due to the beating between other periods or modulation of a received signal.

[16] The non-Io-DAM is significantly influenced by the fluctuation of the solar wind [*Barrow et al.*, 1986; *Zarka*, 1998]. Therefore it is widely believed that sources of this emission are located in high-latitude auroral regions of the Jupiter's magnetosphere not connected with the Io torus. However there are several studies which indicate also the existence of a low-latitude ($L < 6$) component of the non-Io emission, possibly related to the Io torus. *Arkhypov and Rucker* [2009] have shown that the periodicity of the non-Io storms coincide with the fundamental eigenmode of the Io torus oscillation and therefore part of the non-Io emission can be directly related to the plasma torus.

[17] In general a generation of non-thermal radio emission via a mechanism of cyclotron maser requires energetic electrons accelerated along magnetic field lines. In case of Io-controlled DAM the source of the hot electrons is believed to be the Io ionosphere. One possible source candidate for the energetic particles which may produce the periodic burst of DAM is the Io torus.

[18] The existence of the periodic variation in ultraviolet, infrared and optical observations of the Io torus with 10.224-hour period of System IV (3% longer than System III) have been reported in several publications [*Sandel and Dessler*, 1988; *Brown*, 1995; *Woodward et al.*, 1997; *Nozawa et al.*, 2004]. Moreover, *Kaiser et al.* [1996] suggested the existence of a long-living dense plasma spot in the Io torus which corotates around Jupiter with period of System IV and can produce the modulation of the HOM.

[19] However the periodic non-Io bursts, reported in this paper, have the intermediate period (10.07 ± 0.09 h), 1.5% shorter than canonical torus periodicity (System IV). Nevertheless [*Steffl et al.*, 2006] have reported the new finding of ≈ 10.07 h variation of ion azimuthal composition in the Io plasma torus observed by Cassini/UVIS. The defined period was 1.5% longer than System III but faster than System IV. *Steffl et al.* [2006] suggested that this period is a result of the neutral source event which occurred several weeks before the analyzed Cassini/UVIS observations. Additionally, *Steffl et al.* [2008] have developed a model which can reproduce the Cassini/UVIS observations. Their model is based on the postulated assumption about the existence of two azimuthal variations of superthermal electrons: one variation remains fixed in System III and the other one subcorotates with a period of 10.07 hour.

[20] Finally, it is interesting to note another important feature visible in the spectra of the periodic burst. Having in mind that the non-Io DAM emits in a hollow cone attached to magnetic field lines we would expect to observe the periodic burst twice per rotation period of Jupiter similar to vertex-early and vertex-late arcs of Io-DAM. Nevertheless, generally we have observed only one burst per Jupiter rotation (as seen in Figure 1). Only once the two pairs of bursts were detected by STEREO/WAVES on 1–2 January 2008. In this episode two weak bursts with small positive frequency drift (like non-Io vertex-early) were observed at

180° of CML together with the main group of periodic burst (vertex-late) at 320° of CML. Additionally, in some cases of Cassini observation during the year 2002, when the spacecraft was relatively close to Jupiter, a few very weak vertex-early bursts were detected in a pair with main burst. The absence of the second burst per rotation period as well as detecting of the burst at CML shifted by 180° may be linked to an anisotropy of the emission hollow cone pattern, when the intensity of the radiation depends on an angle with respect to a symmetry axis. The examples of such an anisotropy of the beaming patterns have been found for terrestrial AKR. *Mutel et al.* [2008] have shown that individual bursts of AKR radiate not in cones but rather in a narrow plane tangent to the source's magnetic latitude and containing the local magnetic field vector. Nevertheless the "tangent plane" model requires that the radio source should be situated in the plasma density cavity, analogous to the AKR, which was not yet detected directly in the Jovian magnetosphere.

6. Conclusions

[21] The main finding of the study reported here is the detection of a new periodicity in Jovian decametric radio emission. The results of the observation are as follows:

[22] 1. Periodic bursts have been detected in decametric wavelengths between 5 and 12–16 MHz.

[23] 2. The bursts were observed sequentially by STEREO-A and STEREO-B, as well as by Wind and Cassini during several Jovian rotations with proper time delay which was close to the Jupiter time rotation through angular separation of the spacecraft. This suggests that the source of the periodic bursts sub-corotates with Jupiter and it may be active during longer periods of time.

[24] 3. The periodic bursts mainly display negative frequency drift in the frequency-time domain similar to vertex late arcs.

[25] 4. The averaged period of the burst recurrence is $\approx 10.07 \pm 0.09$ h –1.5% longer than System III (9.9249 h) but shorter than System IV (i.e. System III +3%, 10.224 h).

[26] 5. The probability of observing the periodic bursts was found to be significantly greater between 300° and 60° (via 360°) of CML (III). No correlation with the Io position has been found.

[27] **Acknowledgments.** The authors are pleased to acknowledge the Plasma Physics Data Center (CDPP) team for providing the STEREO data and Wind/WAVES and Cassini/RPWS teams for access to Wind and Cassini data. This work was financed by the Austrian Fonds zur Förderung der wissenschaftlichen Forschung (project P20680-N16).

References

Arkhypov, O. V., and H. O. Rucker (2009), Sub-hour modulation of non-Io Jovian decametric emission, *Astron. Astrophys.*, *497*, 551, doi:10.1051/0004-6361/200811038.

Barrow, C. H., F. Genova, and M. D. Desch (1986), Solar wind control of Jupiter's decametric radio emission, *Astron. Astrophys.*, *165*, 244.

Bougeret, J.-L., et al. (1995), Waves: The Radio and Plasma Wave Investigation on the Wind spacecraft, *Space Sci. Rev.*, *71*, 231.

Bougeret, J.-L., et al. (2008), S/WAVES: The Radio and Plasma Wave Investigation on the STEREO mission, *Space Sci. Rev.*, *136*, 487, doi:10.1007/s11214-007-9298-8.

Brown, M. E. (1995), Periodicities in the Io plasma torus, *J. Geophys. Res.*, *100*, 21,683, doi:10.1029/95JA01988.

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, p. 226, Cambridge Univ. Press, New York.

Gurnett, D. A., et al. (2004), The Cassini Radio and Plasma Wave Investigation, *Space Sci. Rev.*, *114*, 395, doi:10.1007/s11214-004-1434-0.

Kaiser, M. L. (1993), Time-variable magnetospheric radio emissions from Jupiter, *J. Geophys. Res.*, *98*, 18,757, doi:10.1029/93JE01279.

Kaiser, M. L., and M. D. Desch (1980), Narrow-band Jovian kilometric radiation: A new radio component, *Geophys. Res. Lett.*, *7*(5), 389–392, doi:10.1029/GL007i005p00389.

Kaiser, M. L., M. D. Desch, and M. E. Brown (1996), Evidence for an Io plasma torus influence on high-latitude Jovian radio emission, *J. Geophys. Res.*, *101*, 13, doi:10.1029/95JA02389.

Mutel, R. L., I. W. Christopher, and J. S. Pickett (2008), Cluster multispacecraft determination of AKR angular beaming, *Geophys. Res. Lett.*, *35*, L07104, doi:10.1029/2008GL033377.

Nozawa, H., H. Misawa, S. Takahashi, A. Morioka, S. Okano, and R. Sood (2004), Long-term variability of [SII] emissions from the Io plasma torus between 1997 and 2000, *J. Geophys. Res.*, *109*, A07209, doi:10.1029/2003JA010241.

Queinnec, J., and P. Zarka (1998), Io-controlled decameter arcs and Io-Jupiter interaction, *J. Geophys. Res.*, *103*, 26,649, doi:10.1029/98JA02435.

Sandel, B. R., and A. J. Dessler (1988), Dual periodicity of the Jovian magnetosphere, *J. Geophys. Res.*, *93*, 5487, doi:10.1029/JA093iA06p05487.

Steffl, A. J., P. A. Delamere, and F. Bagenal (2006), Cassini UVIS observations of the Io plasma torus. III. Observations of temporal and azimuthal variability, *Icarus*, *180*, 124, doi:10.1016/j.icarus.2005.07.013.

Steffl, A. J., P. A. Delamere, and F. Bagenal (2008), Cassini UVIS observations of the Io plasma torus. IV. Modeling temporal and azimuthal variability, *Icarus*, *194*, 153, doi:10.1016/j.icarus.2007.09.019.

Woodward, R. C. J., F. Scherb, and F. L. Roesler (1997), Variations in optical S^+ emission from the Io plasma torus: Evidence for quasi periodicity, *Astrophys. J.*, *479*, 984, doi:10.1086/303925.

Zarka, P. (1998), Auroral radio emissions at the outer planets: Observations and theories, *J. Geophys. Res.*, *103*, 20,159, doi:10.1029/98JE01323.

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