Planetary and Space Science 77 (2013) 3–11

Contents lists available at SciVerse ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Periodic bursts of Jovian non-Io decametric radio emission

M. Panchenko [a,]*, H.O. Rucker [a], W.M. Farrell [b]

[a] Space Research Institute AAS, Graz, Austria
[b] NASA Goddard Space Flight Center, Greenbelt, MD, USA

ARTICLE INFO

Article history:
Received 30 November 2011
Received in revised form
26 July 2012
Accepted 10 August 2012
Available online 23 August 2012

Keywords:
Jovian radio emission
Jovian decametric radio emission
Periodic radio bursts
Jovian radio arcs
Jupiter–Io interaction
DAM

ABSTRACT

During the years 2000–2011 the radio instruments onboard Cassini, Wind and STEREO spacecraft have recorded a large amount of the Jovian decametric radio emission (DAM). In this paper we report on the analysis of the new type of Jovian periodic radio bursts recently revealed in the decametric frequency range. These bursts, which are non-Io component of DAM, are characterized by a strong periodic reoccurrence over several Jovian days with a period $\approx 1.5\%$ longer than the rotation rate of the planet's magnetosphere (System III). The bursts are typically observed between 4 and 12 MHz and their occurrence probability has been found to be significantly higher in the sector of Jovian Central Meridian Longitude between 300° and 60° (via 360°). The stereoscopic multispacecraft observations have shown that the radio sources of the periodic bursts radiate in a non-axisymmetric hollow cone-like pattern and sub-corotate with Jupiter remaining active during several planet's rotations. The occurrence of the periodic non-Io DAM bursts is strongly correlated with pulses of the solar wind ram pressure at Jupiter. Moreover the periodic bursts exhibit a tendency to occur in groups every ~ 25 days. The polarization measurements have shown that the periodic bursts are right hand polarized radio emission associated with the Northern magnetic hemisphere of Jupiter. We suggest that periodic non-Io DAM bursts may be connected with the interchange instability in Io plasma torus triggered by the solar wind.

1. Introduction

Jupiter has the largest planetary magnetosphere in the solar system and emits radio emission in a wide frequency range. The non-thermal auroral radiation is a product of complex interaction between the dynamic Jovian magnetosphere and energetic particles originated mainly from the internal plasma sources. As such, the auroral radio emission is a valuable tool to survey the energy dissipation in the auroral zones as well as to monitor the global magnetospheric activity.

Decametric radio emission (DAM), the strongest component of Jovian auroral radiation, was discovered more than 50 years ago by Burke and Franklin (1955). DAM is observed in a form of arc shaped radio bursts (in time–frequency domain on timescale of minutes) in a frequency range from few MHz up to 40 MHz (Carr et al., 1983; Zarka, 1998). This emission is thought to be generated by the accelerated electrons characterized by an unstable distribution function via the electron cyclotron maser instability (Wu and Lee, 1979). The hectometric component of Jovian radio emission (HOM) observed below a few MHz can be also interpreted as a low-frequency extension of the DAM (e.g. Lecacheux et al., 1980). Two types of DAM are distinguished: (1) Io controlled component of DAM (Io-DAM), which occurrence is well organized into longitudinal systems related with the Io orbital position (period 42.46 h), is a product of electrodynamic interaction between Jupiter and its moon Io (Crary and Bagenal, 1997; Saur et al., 2004), and (2) Io independent DAM (non-Io DAM) driven by the precipitating electrons accelerated by field-aligned currents caused, most probably, due to the breakdown of rigid corotation of the magnetosphere (Cowley et al., 2003) or reconnection in the magnetotail and the magnetopause. The last component, i.e. non-Io DAM, is the subject of our study.

As a magnetospheric phenomenon, most of the Jovian radio emissions are strongly modulated by the rotation of the non-axisymmetric Jovian magnetic field (System III period, 9.9249 h), as well as by the Io plasma torus (System IV period, ~ 10.224) or controlled by the Io orbital position with respect to the active longitudes of the Jovian magnetic field (Kaiser, 1993). Generally, non-Io DAM is a highly variable and sporadic radio emission which appears in a form of arcs in time–frequency coordinates and modulated by the rotation of the Jovian magnetosphere. Recently, Panchenko et al. (2010) and Panchenko and Rucker (2011) have reported findings of the new type of Io independent radio bursts of DAM—periodic non-Io DAM burst. This emission is observed in the decametric frequency range (typically 5–12 MHz) in the form of arc-like radio bursts. These new non-Io bursts are

---

* Corresponding author. Tel.: +43 31 64 120622.
E-mail address: mykhaylo.panchenko@oeaw.ac.at (M. Panchenko).

0032-0633/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.pss.2012.08.015

distinguished from other non-Io DAM by the following: (1) have a very regular periodicity that is a few percent longer than the Jovian System III rotation rate and (2) are found to occur in episodes that last only a few days in association with times of enhanced solar wind pressure.

This paper is a summary of all our findings regarding the new type of periodic non-Io DAM radio burst. On the basis of more than 10 years of observation performed by STEREO/WAVES, Wind/WAVES and Cassini/RPWS radio instruments we have investigated the main properties of these radio bursts, such as the periodicity, the dependence on the active Jovian magnetic longitudes, characteristics of the radio sources and their radiation pattern as well as solar wind control. Moreover, we discuss the interchange instability in the Io plasma torus as a possible mechanism of generation of the periodic bursts. It is important to note, that the quasi periodic QP bursts named also "Jovian Type III bursts" (see e.g. Kurth et al., 1989) are not subject of this study.

2. Observations

Several spacecraft are able to detect Jovian decametric radio emission. Our data set consists of observations acquired by the Cassini, Wind and STEREO spacecraft in the frequency range from below 1 MHz to ~ 16 MHz. In particular, we have used the data recorded by the WAVES experiment onboard Wind spacecraft—a mission which was launched on November 1, 1994 as part of the International Solar-Terrestrial Physics (ISTP) program (Bougeret et al., 1995). From 2001 to 2011 Wind was positioned mainly in a sunward location near the Lagrangian point L1 of Earth. Wind/WAVES instruments covers the frequency range from a few Hz up to ~ 14 MHz.

Our analysis also uses the data from the Radio and Plasma Wave Science (RPWS) instrument (Gurnett et al., 2004) operated in a frequency range up to 16 MHz onboard the Cassini/Huygens mission, launched on October 15, 1997. We have analyzed the observations recorded in the years 2000–2003, when Cassini flew by Jupiter (the closest approach was on December 30, 2000) and was able to detect relatively weaker radio bursts of the DAM which are inaccessible for observation by the Earth orbiting spacecraft.

The other source of the radio data which have been examined in our study is the WAVES experiment onboard two STEREO spacecraft (Bougeret et al., 2008). STEREO (Solar TErrestrial RElations Observatory) consists of two nearly identical 3-axis-stabilized spacecraft (STEREO-A and STEREO-B), launched on October 25, 2006 into heliocentric orbits with one spacecraft ahead and another behind the Earth in its orbit. The STEREO/WAVES covers the frequency range up to 16 MHz. The special interest represents simultaneously stereoscopic observation of the Jovian DAM by the two STEREO spacecraft located at different Jovicentric longitudes. In contrast to the observations from a single point, the stereoscopic measurements facilitate unambiguous recognition of the Jovian decametric radio emission in the observed dynamic spectra as well as identification of its components. Using the fact that Jovian radio emission is emitted in a hollow cone attached to the Jovian magnetic field or to the Io flux tube and the known rotation rate of Jovian magnetosphere (9.925 h) or Io's orbital period (42.46 h) as well as distances between Jupiter and each of the spacecraft the DAM emission can be identified by means of the time difference between sequential detection of the radio emission from the same radio source by the two spacecraft separated in space. In particular, this time delay consists of the light travel time difference between a radio source and an observer and the time interval which is necessary to rotate the radio beam by the angular separation (as seen from Jupiter) between the two spacecraft (see Panchenko et al., 2010). Therefore, the stereoscopic observations allow to (1) separate Jovian arc-like radio emission from the solar radio bursts and (2) unambiguously distinguish between Io and non-Io controlled component of DAM.

In addition to the above radio instruments we have also used the Ulysses/URAP and Ulysses/SWOOPS instruments onboard Ulysses spacecraft launched in October 1990. Ulysses/URAP (Ulysses Unified Radio and Plasma Wave Experiment) is a radio receiver which operates in a frequency range from 1.25 to 940 kHz (Stone et al., 1992). Solar Wind Observations Over the Poles of the Sun experiment, Ulysses/SWOOPS, investigates the solar wind plasma (Bame et al., 1992). In our study we examined Ulysses/URAP and Ulysses/SWOOPS observations acquired during the Ulysses second flyby at Jupiter (in the year 2004).

3. Observations and properties of DAM periodic bursts

As was mentioned in the previous section, we have examined the data recorded in the decametric frequency range by the Cassini/RPWS, Wind/Waves and STEREO/WAVES. By means of the visual inspection of the dynamic radio spectra we have found intense radio bursts in the decametric frequency range from $\sim 4-5$ MHz up to 12–16 MHz (16 MHz is the higher frequency limit of the Cassini/RPWS and STEREO/WAVES). These bursts recurred very periodically during several Jupiter rotations (the examples are shown in Fig. 1). The duration of each periodic burst at the same frequency was several minutes.

In total, 107 episodes of periodic bursts (or 492 individual bursts) have been detected between October 2000 and August 2011. One episode means continuous repetition of the periodic structures in the dynamic spectra. In particular, the Cassini/RPWS observed 36 episodes (185 bursts) during the period of time between October 2000 and December 2003, Wind/WAVES detected 24 episodes (95 bursts) during January 2004 to December 2006, and 47 episodes (212 individual bursts) have been found in STEREO/WAVES radio spectra during January 2007 to August 2011.

Out of the stereoscopic observations performed by the pair of STEREO/WAVES spacecraft the detected periodic decametric radio bursts have been classified as the non-Io controlled component of DAM. In particular the measured time difference (after correction on signal travel time difference) between sequentially detection of the same radio bursts onboard STEREO-A and STEREO-B spacecraft corresponds to the time required for the Jupiter magnetosphere to rotate through the angular spacecraft separation.

Almost all detected periodic bursts have very similar spectral features: 'burst-like' structures with small negative frequency drift in the time–frequency coordinates, similar to the vertex late arcs of non-Io DAM (Queinnec and Zarka, 1998). Such type of bursts has been observed in 96 episodes out of all 107 episodes with periodic bursts. In this study we have analyzed only this most observed group of the bursts—i.e. periodic radio bursts with negative frequency drift. As seen in Fig. 1, the periodic radio features were observed as single bursts (Fig. 1c, e, f), multiple bursts (Fig. 1a, d), or more complex periodic structures consisting of the single and multiple bursts (Fig. 1b). On average, each episode consists of 4–5 bursts.

Besides that, we have also found 11 episodes with periodic radio bursts with positive frequency drift as well as broad non-arcs periodic radio features. These more rare observations are discussed in Section 3.5.

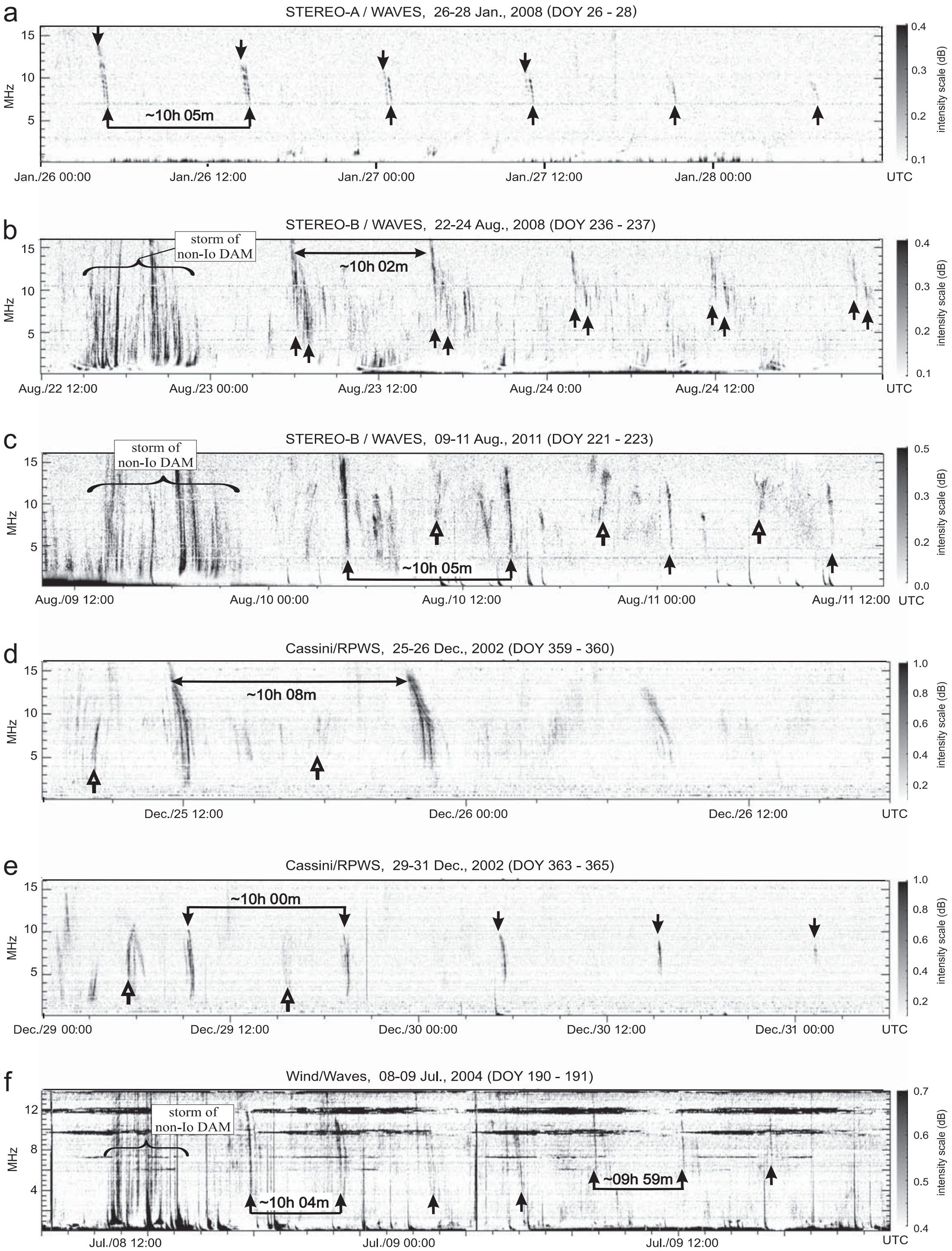

Fig. 1. Examples of the periodic bursts observed by STEREO/WAVES, Cassini/RPWS and Wind/WAVES. The periodic bursts are marked by arrows. The open arrows indicate the weaker vertex-early like bursts accompanied by the more stronger vertex-late bursts (discussed in Section 3.2). The average period of the burst repetition in each group is given. Curly brackets in panels b, c, d and g indicate the intensive storms of the non-Io DAM radio bursts.

3.1. *Periodicity and active longitudes*

Measuring the temporal distances between pairs of consecutive bursts, for each episode we have calculated the average period of the bursts repetition. It should be noted, that determining the period of the burst repetition we have neglected possible Doppler shifting of the period caused by the motion of spacecraft along its orbit relative to the rotating Jupiter. As was mentioned in Panchenko et al. (2010) such effect may lead to an error in the period determination which is below the time resolution of the used radio instruments. Statistical distribution of determined periods, presented in Fig. 2a, clearly shows that all observed periodic non-Io DAM bursts (with negative frequency drift) repeated with the periods which are slightly longer than the rotational rate of Jovian magnetosphere (System III, 9.925 h). In particular, the averaged period of the DAM bursts reoccurrence is

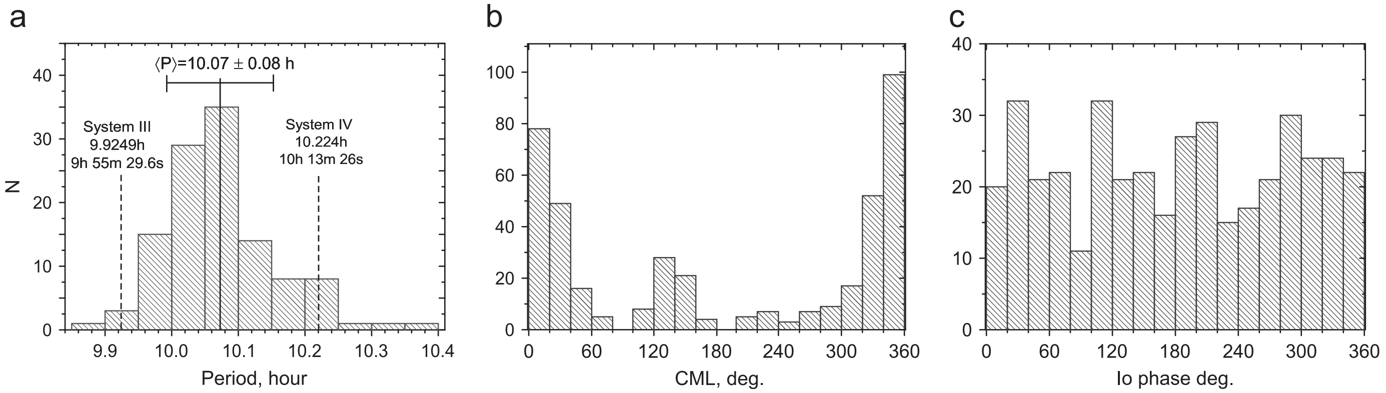

Fig. 2. Statistical results of observations acquired by Cassini/RPWS (185 bursts in 36 episodes), Wind/WAVES (95 bursts in 24 episodes) and STEREO/WAVES (212 bursts in 47 episodes). Panel (a) shows histograms of the distribution of the determined periods of the burst repetition. The averaged period is 10.07 h. One error sigma 0.08 of the mean period is marked by the horizontal line centered at 10.07. Panels (b) and (c) show the distribution of the CML (III) and Io phases of the spacecraft at times of detection of each radio burst.

10.07 ± 0.08 h (10 h 4 m ± 5 m). This rate is 1.5% longer than the System III period.

Moreover, we have also identified the Jovian Meridian Longitude (CML III) and Io-phase of the spacecraft in the times when each particular burst has been detected. The corresponding distributions are depicted in Fig. 2b and c. The results show that the periodic bursts are mainly observed when the Jovian magnetic field has a particular spin phase angle with respect to the observer. This fact suggests that the periodic burst can be excited only on the preferable CML where the generation mechanism is more efficient. This is similar to the existence of Io's active longitudes where the Io-DAM arcs are observed (Carr et al., 1983; Galopeau et al., 2004). In particular, the histogram Fig. 2b shows that most of the periodic bursts were detected when the spacecraft were between 300° and 60° (via 360°) of CML (III). This CML range corresponds to source locations of the non-Io-C DAM (see e.g. Carr et al., 1983). Almost all bursts detected in the sector 120°–180° of CML are the weaker 'vertex-early' bursts which sometimes are observed together with main 'vertex-late' like bursts. These 'vertex-early' bursts are related with the non-axisymmetric hollow emission cone rotating with the Jovian magnetosphere, as discussed in Section 3.2. The above discussed CML dependence may be also related to the visibility effects due to the possible specific radiation patterns of the periodic radio bursts. The last suggestion requires further study which will include the detailed modeling the visibility of the periodic DAM bursts.

From the distribution shown in Fig. 2c we conclude the absence of any relation between the position of Io and occurrence of the periodic bursts. Therefore, this result supports the findings, that the observed periodic bursts are Io independent component of the DAM (non-Io DAM). Moreover, we have also not found any correlations between the occurrence of the periodic non-Io DAM burst and orbital positions of other Galilean moons.

3.2. *Corotating radio sources and radio beaming pattern*

The recurrent appearance of the periodic non-Io DAM bursts during several Jovian rotations may suggest that a source of this emission nearly sub-corotates with the Jovian magnetosphere. The stereoscopical observations have supported this suggestion. In particular, we found several episodes when the same group of periodic non-Io DAM bursts were detected stereoscopically by Wind and Cassini spacecraft which were located at large angular distances, i.e. about 90°. The examples of such observations are presented in Panchenko et al. (2010, Fig. 3). For this episode the time delay between sequential burst observation onboard both spacecraft were ~2.4 h (after correction on light time travel difference). This corresponds to the time for Jupiter to rotate through the angle of spacecraft separation, which was $\alpha = 85^\circ$. Therefore, such stereoscopic observations with large angular separation allow us to draw the conclusion that we are dealing with a sub-corotating radio source.

Considering that the radiation of such sub-corotating sources of periodic non-Io DAM bursts are confined within thin-walled hollow cone attached to an instant magnetic field line, similar to Io DAM, we would expect to observe the radio burst twice per rotation period of Jupiter just as vertex-early and vertex-late arcs of Io-DAM (Carr et al., 1983). Nevertheless, the observations have shown that generally only one burst per Jupiter rotation is detected, as seen in Fig. 1. We have found a small number of episodes when two bursts were observed per planet rotation. As seen in Fig. 1 these bursts (marked by open arrows), were significantly weaker (Fig. 1c), or quickly faded after one Jovian rotation (Fig. 1d and 1e). Moreover, as was mentioned in Section 3.1 these secondary bursts were observed at CML's shifted by 120°–170° with respect to the sector where most of the periodic bursts are observed.

The absence or weakness of the second burst per planet's rotation indicates a strong anisotropy of the emission cone pattern of the periodic non-Io DAM. Most probably the intensity of the radiation depends on an angle with respect to a symmetry axis of the emission cone. Recently Galopeau and Boudjada (2011), analyzing the occurrence probability of the Io controlled sources of DAM depending on the local magnetic field coordinates, have proposed that the Io-DAM is radiated in a flattened non-axisymmetrical hollow cone. The other example of the emission pattern anisotropy is terrestrial Auroral Kilometric radiation (AKR). Mutel et al. (2008), studying the angular beaming patterns of individual AKR bursts observed by four Cluster spacecraft, concluded that the AKR is confined not within a cone but rather within a narrow plane tangent to the source's magnetic latitude and containing the local magnetic field vector. In general, such anisotropy beaming patterns may suggest the strong non-axisymmetrical amplification of the emission inside the source or the existence of a specific plasma environment in the source region, e.g. plasma density cavity. Therefore, further investigation of the strong anisotropy of beaming pattern of the periodic non-Io DAM bursts may give an information about plasma conditions inside the Jovian DAM sources.

3.3. Solar wind control

Upon initial inspection of the measured radio spectra we have noted some close relationships between “storms” of the non-Io DAM (sequences of the strong non-Io DAM bursts) and occurrence of the periodic non-Io DAM bursts. We have selected the episodes in which the periodic bursts appeared during the following 10 h after “storms” of the non-Io DAM (e.g. Fig. 1b, c, f). The results have shown that in $\sim 70\%$ of episodes observed in years 2001–2011 the periodic bursts were detected after strong intensification of the sporadic non-Io DAM. This correlation shows the close relation between the periodic bursts and ”storms” of non-Io DAM emission. In the same time, it is well known since the Voyager observations that non-Io DAM is significantly affected by the solar wind (Barrow and Desch, 1989; Genova et al., 1987; Echer et al., 2010), although the mechanism of this impact is still unknown. Furthermore Gurnett et al. (2002) have shown, that part of the non-Io DAM emission became enhanced after passing the shocks of the solar wind.

In order to study the occurrence of periodic non-Io DAM as a response to the solar wind pulses we have used the observations performed by Ulysses/SWOOPS in 2004 during its second encounter with Jupiter. In 2004 Ulysses measured the solar wind parameters close to the ecliptic plane from a distance less than 1 AU from Jupiter. The measured ram pressure of the solar wind (ρV^2) has been ballistically propagated to the position of Jupiter (Fig. 3). The vertical dashed lines in Fig. 3 indicate the time when the radio instrument Wind/WAVES detected the episodes of periodic non-Io DAM bursts. It is well seen that 9 out of 13 episodes are well correlated with the pulses of the solar wind ram pressure.

Additionally, we have also studied the possible long lasting periodicities in temporal occurrence of the episodes when the non-Io DAM periodic bursts have been observed. The time series of the occurrence of the episodes (onset time of each episode) recorded by STEREO/WAVES during 2008–2011 have been analyzed using the Lomb–Scargle algorithm. The periodogram, shown in Fig. 4, has a clear peak at 0.4724 micro Hz or 24.5 days. This periodicity is very close to the well known 25 days variations of the solar wind ram pressure at Jupiter, related with the Sun rotation. This result shows that episodes of the periodic bursts have a tendency to occur with the periodicity of ≈ 25 days and, therefore, supports our findings that the solar wind plays an important role in triggering or controlling the periodic non-Io DAM burst. We also note that, for the other periods of observations, e.g. in the years 2001–2007 the 25 days periodicity in the periodogram is not very clear, most probably due to rare detection of the periodic bursts by Wind/Waves (2003–2007).

3.4. Polarization

Polarization is one of the major properties of the planetary radio emission which characterize the generation mechanism as well as wave propagation. Since the early observations it is known that the Jovian DAM is highly polarized (e.g. Lecacheux, 1976) which is a signature of non-thermal radiation produced by electron–cyclotron maser instability. At least on one of the spacecraft, Cassini/RPWS has the capability to determine the polarization state of the emission in the decametric frequency range. An algorithm described in Cecconi and Zarka (2005) has been applied for the Cassini/RPWS measurements, in order to define the polarization state of the periodic bursts. Fig. 5 shows that periodic bursts (marked by vertical arrows) are right-hand polarized radio emission. Moreover, we have found that in all 32 episodes detected by Cassini in 2000–2002 the periodic bursts were observed as right hand (RH) circular polarized emission. Assuming, that the periodic non-Io DAM bursts propagate mainly in the right hand extraordinary R–X mode (similar to Io-DAM) we can conclude, that all periodic bursts observed by Cassini/RPWS propagate from the Northern magnetic hemisphere of Jupiter (extraordinary X waves originated from a Jovian Northern magnetic hemisphere is right hand polarization while the emission from the South magnetic hemisphere is left hand polarization).

3.5. Other periodic features observed in Jovian decametric radio spectra

As was mentioned in the beginning of Section 3 in 96 cases out of 107 observed episodes of periodic non-Io DAM the burst has small negative frequency drift in the time–frequency coordinates similar to vertex-late arcs of the Io-DAM. In some episodes this type of the periodic bursts were observed together with weaker accompanying vertex-early or arcs with positive frequency drift, as discussed in Section 3.2. Besides this main group, we have also found two other groups of the periodic features rarely observed in the radio spectra—(1) “vertex-early” periodic non-Io DAM bursts

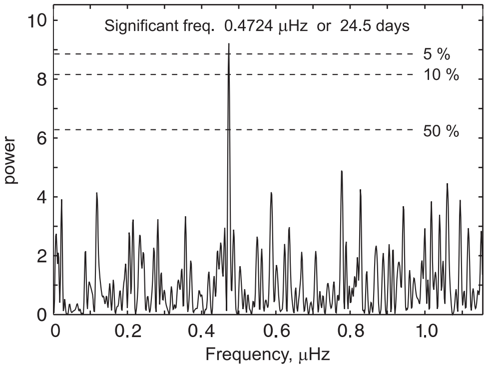

Fig. 4. Lomb Scargle periodogram of the occurrence of the periodic non-Io DAM bursts observed by STEREO/WAVES during 2008–2011. The horizontal dashed lines denote the false alarm probability levels, 50%, 10% and 5%. The significant frequency is at 0.4724 micro Hz corresponds to 24.5 days.

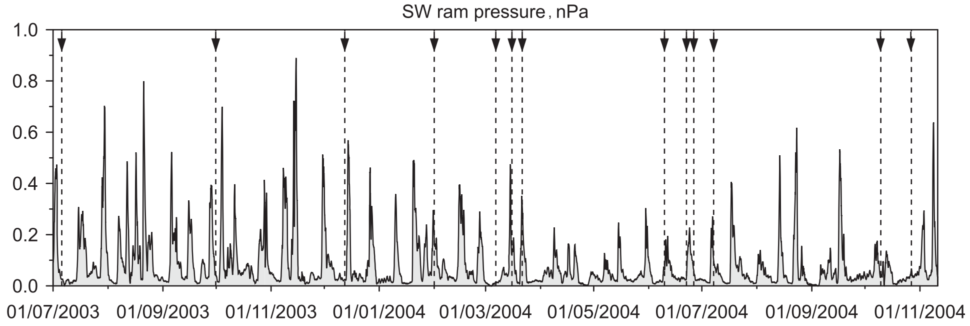

Fig. 3. Solar wind ram pressure measured by Ulysses/SWOOPS and ballistically propagated to Jupiter orbit. The vertical dashed lines with arrows indicate the beginning of the episodes of periodic non-Io bursts detected by Wind/WAVES.

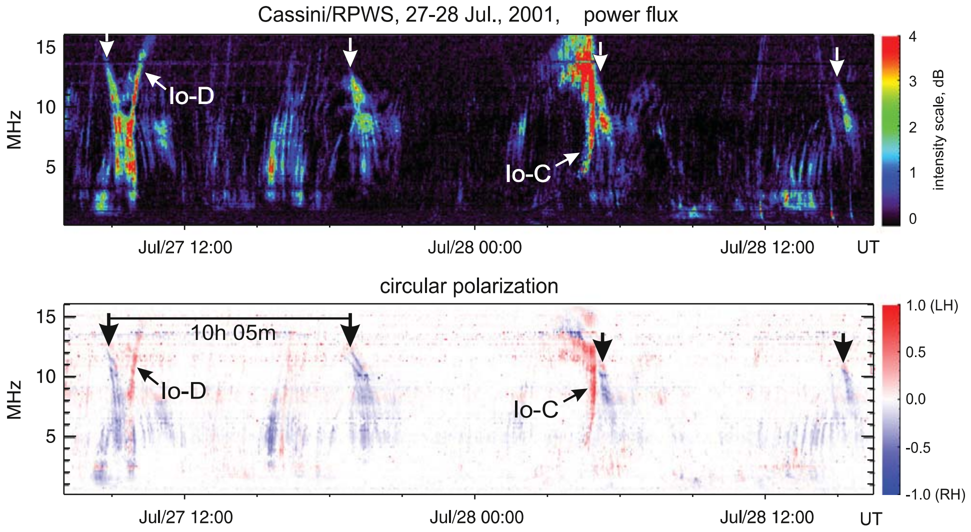

Fig. 5. Dynamic spectrum of the total power (top panel) and degree of the circular polarization (bottom panel) observed by Cassini/RPWS. The periodic non-Io DAM bursts, marked by vertical arrows, are right hand polarized and therefore originated from the Northern magnetic hemisphere of Jupiter. At the same time Io controlled DAM associated with the southern Io-C and Io-D sources are left hand polarized.

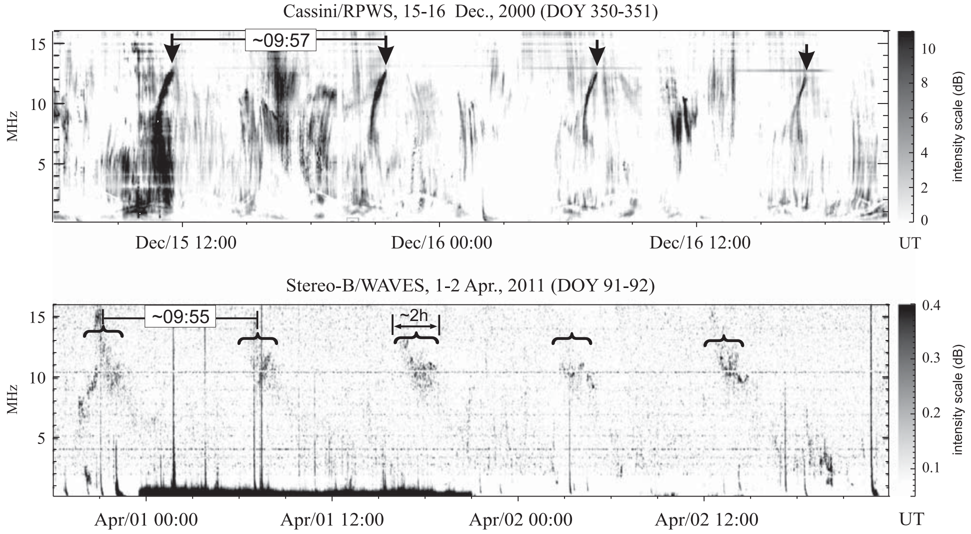

Fig. 6. Examples of “vertex-early” periodic bursts (top panel) and periodic non-arc Jovian radio emission.

and (2) non-arc periodic features. Despite the small number of such episodes we may suggest the existence of more complex periodic spectral features in Jovian radio emission which may have different origins and are attributed to other particle dissipation processes in the Jovian magnetosphere.

Cassini/RWPS in the course of its Jupiter flyby recorded 9 episodes in which all periodic bursts had positive frequency drift, similar to the vertex-early bursts on Io-DAM. As seen in Fig. 6 (top panel) these bursts were very similar to those presented in Fig. 1, except of its inverted shape. These bursts have lower intensity and few were observed by STEREO or Wind due to larger distance from the source. The main features which differentiate “vertex-early” periodic bursts is the fact that their period of reoccurrence is very close to the Jupiter rotation—the averaged period is 9.96 ± 0.06 h. At the same time, these bursts were also observed in the same sector of the Jovian magnetosphere, i.e. between 300° and 60° (via 360°) of CML (III). The other interesting features of the “vertex-early” bursts is the significant longer duration of the episode. In contrast to the periodic “vertex-late” bursts with typical 4–5 bursts in one episode, “vertex-early” periodic bursts repeated on average during 7–9 Jupiter rotations. The most long lasting episode, observed by Cassini/RPWS on November 27 to December 5, 2000, consisted of 22 individual “vertex-early” bursts in a row.

The other rare group of the periodic non-arc radio features which are observed in a form of broad beamed radio emission in the decametric range is shown in Fig. 6 (bottom panel). The period of repetition of the non-arc radio emission is close to the System III period, though such type of radiation lacked clear discrete features to define the exact periodicity.

4. Discussion

Taking into account the number of observed episodes the existence of a new type of periodic non-Io DAM radio burst appears to be very likely. The morphological similarities between periodic bursts and other arc-like Io and non-Io controlled DAM may suggest the same microscopic generation mechanism—cyclotron maser instability (CMI). This mechanism requires energetic electrons accelerated along magnetic field lines. In the case of Io controlled DAM it is believed that the Io ionosphere supplies the hot plasma to the auroral regions of the Jovian magnetosphere.

The theory which may explain the generation of the periodic non-Io DAM bursts in Jovian system should involve the explanation of the origin of the energetic particles. This source of hot plasma should (1) sub-corotate with Jupiter (with 1.5% lag with regard to System III), (2) continuously supply the CMI during longer period of time (sometimes more than 10 bursts in a row were observed) and (3) be strongly affected by the solar wind. The observations suggests that the sources of the periodic bursts, most probably, are deeply connected with the complex interaction between the Jovian magnetosphere and sub-corotating highly structured plasma environment. One of the possible candidates to be a source of the energized particles which may produce the periodic non-Io DAM bursts is the "middle" magnetosphere linked with the co-rotating "main aurora oval". This oval is thought to be connected with the magnetosphere–ionosphere coupling current system associated with the breakdown of rigid co-rotation in the middle magnetosphere (Cowley et al., 2003).

Nevertheless, taking into account 1.5% difference in reoccurrence of the periodic bursts and rotational period of Jovian magnetosphere, the Io plasma torus seems to be a stronger candidate for the hot plasma source location. This highly structured plasma region exhibits the lack of corotation with respect to Jupiter. Several observations, including in the ultraviolet, infrared and optical frequency range, have clearly shown that the Io torus plasma corotates with Jupiter in the centrifugal equatorial plane with averaged ≈ 10.224 h period (System IV, $\sim 3\%$ longer than System III) (Sandel and Dessler, 1988; Brown, 1995; Woodward et al., 1997; Nozawa et al., 2004). At the same time, Steffl et al. (2006) have reported that the azimuthal composition in the Io plasma torus, observed by Cassini/UVIS, vary with ~ 10.07 h (1.5% longer than System III) period. This rate is equal to the 10.07 ± 0.08 h averaged period of the periodic non-Io DAM bursts repetitions (see Section 3.1). Moreover, the radio emission, related (or suggested to be related) with the Io plasma torus also exhibits strong modulation with respect to the Io torus rotation. Several studies have shown that the occurrence of a narrow-band Jovian kilometric radiation (nKOM) as well as the intensity of the hectometric Jovian radiation (HOM) is modulated with a period slower by 3% to 5% than System III (Kaiser et al., 1996). Reiner et al. (2000) have found that nKOM events were detected by Ulysses/URAP after a few rotations of Jupiter following strong solar wind ram pressure pulses, and that there was a clear 26 days cadence of nKOM observations. Farrell et al. (2004) have interpreted a Jovian broadband kilometric radiation (bKOM) as an Electron–Cyclotron Harmonic radiation originating from a plasma density depletion or plasma bubble at the outer edge of the Io torus.

Furthermore, Kaiser and MacDowall (1998) have reported the findings of so-called "bullseyes" emission in Ulysses/URAP spectra. This emission is observed in a form of U-shaped narrowband (1–2 kHz) tones in the low frequency band, 20–50 kHz. Thus, Kaiser and MacDowall (1998) have shown that "bullseyes" emission have a tendency to occur after the passage of a solar wind pressure pulse, which crosses the Jovian magnetosphere every 13 or 26 days and the temporal spacing between the centers of the individual "bullseyes" was $\sim 6\%$ longer than the Jupiter rotation. Farrell et al. (2004) have proposed that "bullseyes" emission can be explained (non-uniquely) as typically nKOM emissions from the radially extended plasma fingers developed in the course of the strong interchange instability which may operate along the outer Io torus edge (Yang et al., 1992, 1994). This instability, which in general can be considered as a competition between cold and energetic plasma components, can be triggered by the strong solar wind impulses. In particular, Farrell et al. (2004) proposed, that the solar wind ram pressure pulses cause the compression of the frontside of the Jovian magnetosphere and, as a consequence, lead to an increase of the inward pressure on the outer Io torus. Then, after the pressure pulse passes by Jupiter, the magnetosphere expands releasing quickly the pressure in Io plasma torus which becomes unstable to the interchange instability. The MHD simulations performed by Yang et al. (1994) demonstrate that the Io torus undergoing the strong interchange instability breaks up into long fingers extending out to more than $L > 10$.

During Ulysses second approach to Jupiter (in 2004) the Ulysses/URAP experiment was able to detect the Jovian radio emission. We have analyzed the data recorded by URAP low frequency receiver (1.25–48.5 kHz) in 2003–2004 and found five episodes of "bullseyes" emission observed simultaneously with periodic non-Io DAM bursts. Two most interesting episodes are shown in Fig. 7. The other three examples are presented in Supplementary Materials. The panels (a) and (b) are the dynamic spectra observed by Wind/Waves and Ulysses/URAP on March 15–16, 2004. The time axis of the Wind spectrum has been shifted by 1.76 h with respect to Ulysses observation in order to account for the light time difference between Jupiter and both of the spacecraft as well as angular separation between Jupiter and each of the spacecraft. Thus, the two spectra were co-aligned to the same Jovian CML coordinates. The five strong periodic bursts of non-Io DAM, marked by arrows, are well seen in the top panel of Fig. 7. The spacing between each of the bursts was ~ 10 h 5 min. At the same time, Ulysses/URAP observed five groups of the "bullseyes" emission—series of narrowband U-shaped fine structures in a frequency range $\sim 25-50$ kHz. The distance between centers of the "bullseyes" was also ~ 10 h 5 min. The periodic non-Io bursts and "bullseyes" appear to be temporal nearly co-aligned. The time difference between non-Io DAM and center of "bulleyes" is ~ 2.5 h or 90° rotation phase of Jupiter. We suggest that this is due to the different radiation pattern of the non-Io DAM burst and "bullseyes" radio emission. Note also that the intensities of the periodic bursts and "bullseyes" emission decrease in the same manner.

The next two panels (c) and (d) in Fig. 7 show the Cassini/RPWS observations of the periodic non-Io DAM bursts on January 1–2, 2003 and corresponding Ulysses/URAP radio spectra. The Cassini/RPWS spectra was shifted by 5.7 h. As seen in Fig. 7c Cassini/RPWS recorded three periodic bursts marked by arrows. The spacing between the bursts was ~ 10 h 17 min. At the same time, Ulyses/URAP observed three "bullseyes" emission.

Out of these observations we can conclude the close relation between low frequency "bullseyes" emission and periodic non-Io DAM bursts. As a consequence we may assume that the sources of the non-Io DAM periodic bursts which are most probably located in the auroral regions of the Jovian magnetosphere may be connected with the ends of the interchange fingers in the Io torus. These latitudinal extended fingers, nearly sub-corotating with Jupiter, may be a plasma source which supply the cyclotron maser in the auroral region. It is worth to note, that DeJong et al. (2010) have shown that low-energy electrons beams in Saturn's inner magnetosphere can be associated with interchange injections. Therefore, we suggest that the interchange instability in the Io torus, triggered by the solar wind pulses, may be a possible mechanism which can explain the origin and the main properties of the periodic non-Io DAM bursts, such as strong correlation with the solar wind, and reoccurrence rate which is 1.5% longer than the Jupiter System III rotation. The detailed mechanism of the periodic bursts generation via interchange instability require further justifications and is subject for further study.

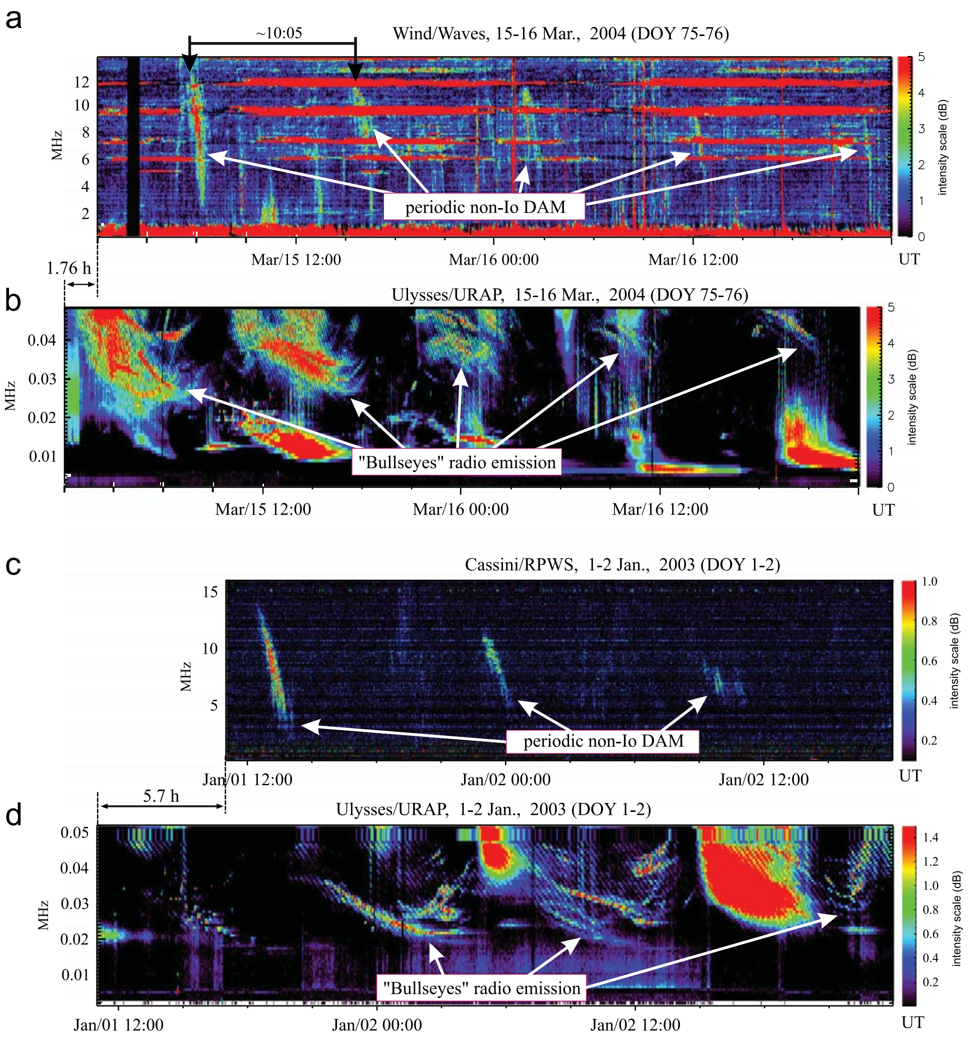

Fig. 7. Periodic bursts of non-Io DAM observed by Wind/Waves (panel a) and Cassini/RPWS (panel c) simultaneously with “bullseyes” radio emission recorded by Ulysses/URAP (panels b and d) at low frequencies. The Wind and Cassini spectrum are shifted in time with respect to Ulysses measurements due to the light time difference as well as angular separation between Jupiter and each of the spacecraft.

5. Conclusion

The main findings of the study reported here is the detection of the new periodic bursts on the non-Io DAM. The results of the observation are as follows:

1. Periodic bursts have been detected in decametric wavelengths between 5 and 12–16 MHz. The averaged period of the burst recurrence is slightly longer, by $\sim 1.5\%$, than System III (9.925 h).
2. Periodic bursts favor only a preferable sector of Jovian CML (III) between 300° and 60° (via 360°), where the probability of observing the periodic bursts was found to be significant. No correlation with the Io position as well as other satellites has been found.
3. The periodic bursts are a non-Io component of DAM and its sources sub-corotate with Jupiter and it may be active during longer periods of time.
4. The radiation beam pattern of the periodic bursts exhibits strong anisotropy.
5. Occurrence of periodic bursts of non-Io DAM is correlated with enhancement of the solar wind ram pressure around Jupiter. Additionally, the periodic bursts show a tendency to occur in groups every ~ 24.5 days.
6. The Cassini/RPWS polarization measurements have shown that the periodic bursts (at least in a 32 episodes observed by Cassini in 2000–2002) are right hand polarized radio emission and therefore the sources of these bursts are originated in Northern magnetic hemisphere of Jupiter.
7. Based on the facts, that periodic bursts are strongly controlled by the solar wind and that their sources exhibit a slight lack of co-rotation with respect to Jupiter similar to other known radio emission related with Io plasma torus, we hypothesize that periodic non-Io DAM bursts may be originated at the end of the interchange fingers developed in Io plasma torus undergoing strong interchange instability triggered by the solar wind pulses.

Acknowledgments

The authors are pleased to acknowledge the Plasma Physics Data Center (CDPP), ESA data Archive, STEREO/WAVES, Wind/WAVES, Cassini/RPWS, Ulysses/URAP and Ulysses/SWOOPS teams for access to data. This work was financed by the Austrian Science Fund (FWF projects P23762-N16 and P20680-N16). The authors are grateful to the referees for their helpful comments that improved this paper.

Appendix A. Supplementary material

Supplementary data associated with this paper can be found in the online version, at http://dx.doi.org.10.1016/j.pss.2012.08.015

References

Bame, S.J., McComas, D.J., Barraclough, B.L., Phillips, J.L., Sofaly, K.J., Chavez, J.C., Goldstein, B.E., Sakurai, R.K., 1992. The ULYSSES solar wind plasma experiment. Astronomy and Astrophysics Supplement Series 92, 237–265.

Barrow, C.H., Desch, M.D., 1989. Solar wind control of Jupiter's hectometric radio emission. Astronomy & Astrophysics 213, 495–501.

Bougeret, J.L., Goetz, K., Kaiser, M.L., Bale, S.D., Kellogg, P.J., Maksimovic, M., Monge, N., Monson, S.J., Astier, P.L., Davy, S., Dekkali, M., Hinze, J.J., Manning, R.E., Aguilar-Rodriguez, E., Bonnin, X., Briand, C., Cairns, I.H., Cattell, C.A., Cecconi, B., Eastwood, J., Ergun, R.E., Fainberg, J., Hoang, S., Huttunen, K.E.J., Krucker, S., Lecacheux, A., MacDowall, R.J., Macher, W., Mangeney, A., Meetre, C.A., Moussas, X., Nguyen, Q.N., Oswald, T.H., Pulupa, M., Reiner, M.J., Robinson, P.A., Rucker, H., Salem, C., Santolik, O., Silvis, J.M., Ullrich, R., Zarka, P., Zouganelis, I., 2008. S/WAVES: the radio and plasma wave investigation on the STEREO Mission. Space Science Reviews 136, 487–528.

Bougeret, J.-L., Kaiser, M.L., Kellogg, P.J., Manning, R., Goetz, K., Monson, S.J., Monge, N., Friel, L., Meetre, C.A., Perche, C., Sitruk, L., Hoang, S., 1995. Waves: the radio and plasma wave investigation on the wind spacecraft. Space Science Reviews 71, 231–263.

Brown, M.E., 1995. Periodicities in the Io plasma torus. Journal of Geophysical Research 100, 21683–21696.

Burke, B.F., Franklin, K.L., 1955. Observations of a variable radio source associated with the planet Jupiter. Journal of Geophysical Research 60, 213–217.

Carr, T.D., Desch, M.D., Alexander, J.K., 1983. Phenomenology of magnetospheric radio emissions. In: Dessler, A.J. (Ed.), Physics of the Jovian Magnetosphere. Cambridge University Press, New York, pp. 226–284.

Cecconi, B., Zarka, P., 2005. Direction finding and antenna calibration through analytical inversion of radio measurements performed using a system of two or three electric dipole antennas on a three-axis stabilized spacecraft. Radio Science 40, 3003.

Cowley, S.W.H., Bunce, E.J., Nichols, J.D., 2003. Origins of Jupiter's main oval auroral emissions. Journal of Geophysical Research 108, 8002.

Crary, F.J., Bagenal, F., 1997. Coupling the plasma interaction at Io to Jupiter. Geophysical Research Letters 24, 2135.

DeJong, A.D., Burch, J.L., Goldstein, J., Coates, A.J., Young, D.T., 2010. Low-energy electrons in Saturn's inner magnetosphere and their role in interchange injections. Journal of Geophysical Research 115, 10229.

Echer, E., Zarka, P., Gonzalez, W.D., Morioka, A., Denis, L., 2010. Solar wind effects on Jupiter non-Io DAM emissions during Ulysses distant encounter (2003–2004). Astronomy & Astrophysics 519, A84.

Farrell, W.M., Kaiser, M.L., Kurth, W.S., Desch, M.D., Gurnett, D.A., Hospodarsky, G.B., MacDowall, R.J., 2004. Remote sensing of possible plasma density bubbles in the inner Jovian dayside magnetosphere. Journal of Geophysical Research 109, 9.

Galopeau, P., Boudjada, M., 2011. Beaming cone of Io-controlled Jovian decameter radio emission and existence of localized active longitude. In: Rucker, H.O., Kurth, W.S., Louarn, P., Fischer, G. (Eds.), Planetary Radio Emissions VII. Austrian Academy of Sciences Press, Vienna, pp. 197–204.

Galopeau, P.H.M., Boudjada, M.Y., Rucker, H.O., 2004. Evidence of Jovian active longitude: 1. Efficiency of cyclotron maser instability. Journal of Geophysical Research 109, A12217.

Genova, F., Zarka, P., Barrow, C.H., 1987. Voyager and Nancay observations of the Jovian radio-emission at different frequencies—solar wind effect and source extent. Astronomy & Astrophysics 182, 159–162.

Gurnett, D.A., Kurth, W.S., Hospodarsky, G.B., Persoon, A.M., Zarka, P., Lecacheux, A., Bolton, S.J., Desch, M.D., Farrell, W.M., Kaiser, M.L., Ladreiter, H., Rucker, H.O., Galopeau, P., Louarn, P., Young, D.T., Pryor, W.R., Dougherty, M.K., 2002. Control of Jupiter's radio emission and aurorae by the solar wind. Nature 415, 985–987.

Gurnett, D.A., Kurth, W.S., Kirchner, D.L., Hospodarsky, G.B., Averkamp, T.F., Zarka, P., Lecacheux, A., Manning, R., Roux, A., Canu, P., Cornilleau-Wehrlin, N., Galopeau, P., Meyer, A., Boström, R., Gustafsson, G., Wahlund, J.-E., Åhlen, L., Rucker, H.O., Ladreiter, H.P., Macher, W., Woolliscroft, L.J.C., Alleyne, H., Kaiser, M.L., Desch, M.D., Farrell, W.M., Harvey, C.C., Louarn, P., Kellogg, P.J., Goetz, K., Pedersen, A., 2004. The Cassini radio and plasma wave investigation. Space Science Reviews 114, 395–463.

Kaiser, M.L., 1993. Time-variable magnetospheric radio emissions from Jupiter. Journal of Geophysical Research 98 (October), 18757–18765.

Kaiser, M.L., Desch, M.D., Brown, M.E., 1996. Evidence for an Io plasma torus influence on high-latitude Jovian radio emission. Journal of Geophysical Research 101, 13–18.

Kaiser, M.L., MacDowall, R.J., 1998. Jovian radio ''bullseyes'' observed by Ulysses. Geophysical Research Letters 25, 3113–3116.

Kurth, W.S., Gurnett, D.A., Scarf, F.L., 1989. Jovian type III radio bursts. Journal of Geophysical Research 94 (June), 6917–6924.

Lecacheux, A., 1976. Spectral study of the polarization of the Jovian decametric radiobursts. Astronomy & Astrophysics 49, 197–204.

Lecacheux, A., Moller-Pedersen, B., Riddle, A.C., Pearce, J.B., Boischot, A., Warwick, J.W., 1980. Some spectral characteristics of the hectometric Jovian emission. Journal of Geophysical Research 85, 6877–6882.

Mutel, R.L., Christopher, I.W., Pickett, J.S., 2008. Cluster multispacecraft determination of AKR angular beaming. Geophysical Research Letters 35, 7104.

Nozawa, H., Misawa, H., Takahashi, S., Morioka, A., Okano, S., Sood, R., 2004. Long-term variability of [SII] emissions from the Io plasma torus between 1997 and 2000. Journal of Geophysical Research 109, 7209.

Panchenko, M., Rucker, H.O., 2011. New type of periodic bursts of non-Io Jovian decametric radio emission. In: Rucker, H.O., Kurth, W.S., Louarn, P., Fischer, G. (Eds.), Planetary Radio Emissions VII. Austrian Academy of Sciences Press, Vienna, pp. 157–166.

Panchenko, M., Rucker, H.O., Kaiser, M.L., St. Cyr, O.C., Bougeret, J., Goetz, K., Bale, S.D., 2010. New periodicity in Jovian decametric radio emission. Geophysical Research Letters 37 (March), 5106.

Queinnec, J., Zarka, P., 1998. Io-controlled decameter arcs and Io–Jupiter interaction. Journal of Geophysical Research 103, 26649–26666.

Reiner, M.J., Kaiser, M.L., Desch, M.D., 2000. Long-term behavior of Jovian bKOM and nKOM radio emissions observed during the Ulysses–Jupiter encounter. Geophysical Research Letters 27, 297–300.

Sandel, B.R., Dessler, A.J., 1988. Dual periodicity of the Jovian magnetosphere. Journal of Geophysical Research 93, 5487–5504.

Saur, J., Neubauer, F.M., Connerney, J.E.P., Zarka, P., Kivelson, M.G., 2004. Plasma interaction of Io with its plasma torus. In: Bagenal, F., Dowling, T.E., McKinnon, W.B. (Eds.), Jupiter. The Planet, Satellites and Magnetosphere. Cambridge University Press, pp. 537–560.

Steffl, A.J., Delamere, P.A., Bagenal, F., 2006. Cassini UVIS observations of the Io plasma torus. III. Observations of temporal and azimuthal variability. Icarus 180, 124–140.

Stone, R.G., Bougeret, J.L., Caldwell, J., Canu, P., de Conchy, Y., Cornilleau-Wehrlin, N., Desch, M.D., Fainberg, J., Goetz, K., Goldstein, M.L., 1992. The unified radio and plasma wave investigation. Astronomy and Astrophysics Supplement Series 92, 291–316.

Woodward, R.C.J., Scherb, F., Roesler, F.L., 1997. Variations in optical S+ emission from the Io plasma torus: evidence for quasi periodicity. Astrophysical Journal 479, 984–991.

Wu, C.S., Lee, L.C., 1979. A theory of the terrestrial kilometric radiation. Astrophysical Journal 230, 621–626.

Yang, Y.S., Wolf, R.A., Spiro, R.W., Dessler, A.J., 1992. Numerical simulation of plasma transport driven by the Io torus. Geophysical Research Letters 19, 957–960.

Yang, Y.S., Wolf, R.A., Spiro, R.W., Hill, T.W., Dessler, A.J., 1994. Numerical simulation of torus-driven plasma transport in the Jovian magnetosphere. Journal of Geophysical Research 99, 8755–8770.

Zarka, P., 1998. Auroral radio emissions at the outer planets: observations and theories. Journal of Geophysical Research 103, 20159–20194.