Periodic bursts of Jovian non-Io decametric radio emission

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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 (Cravat 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
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. Our 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 ~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 latitude arcs of non-Io DAM (Quinn 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.
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
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 longitude 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 x = 85°. 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 beam ing 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 ~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 ($V^2/2$) 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.

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...
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 suggest 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 $\approx 10.224$ h period (System IV, $\approx 3\%$ longer than System III) (Sandel and Dessler, 1988; Brown, 1995; Woodward et al., 1997; Nozawa et al., 2004). At the same time, Steff et al. (2006) have reported that the azimuthal composition in the Io plasma torus, observed by Cassini/UVIS, vary with $\approx 10.07$ 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 longer than the Jupiter rotation. Several studies have shown that this is due to the different radiation pattern of the non-Io bursts and “bullseyes” appear to be temporal nearly co-aligned. The time difference between centers of the “bullseyes” was also $\approx 10$ 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 “bullseyes” is $\approx 2.5$ 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 $\approx 10$ h 17 min. At the same time, Ulysses/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.
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 ~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.
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.

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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

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