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Sub-hour modulation of non-Io Jovian decametric emission

O. V. Arkhypov[1,2] and H. O. Rucker[3]

[1] Institute of Radio Astronomy, National Academy of Sciences of Ukraine, Chervonopraporna 4, 61002 Kharkiv, Ukraine
e-mail: alexeyarkhipov@rambler.ru
[2] Department of Space Radio Physics, Kharkiv V. N. Karazin National University, Svoboda Square 4, 61077 Kharkiv, Ukraine
[3] Space Research Institute, Austrian Academy of Sciences, Schmiedlstrasse 6, 8042 Graz, Austria
e-mail: rucker@oeaw.ac.at

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ABSTRACT

The variability of Jovian decametric emission (DAM), which is not controlled by the Io satellite (non-Io), was studied of timescales of between 1 min and 1 h with DAM records of 1991–2007 from the archive of Nançay Radio Observatory. We found that the internal structure of the non-Io radio storms has the dominating periodicity on of average 21 ± 2 min . This estimate is in close agreement with the periodicity of Io-related emission and with fundamental eigenoscillations of transversal magnetic pulsations in the Io's plasma torus. The average duration of an arc in non-Io DAM dynamic spectra was estimated to be 7.0 ± 0.3 min, although the most probable value was 5.3 ± 0.7 min, which corresponds to Io-related arcs and 3rd and 4th harmonics of torus proper-oscillations. Our results could be interpreted in terms of electron acceleration in parallel electric fields of standing Alfvén waves generated by Io and trapped in the Io torus. This interpretation agrees with previous arguments that the location of some sources of non-Io emission are in the magnetic shell of the Io plasma torus. However, the aurora component of non-Io DAM is not excluded, since the suggested DAM modulation by the fundamental mode of eigenoscillations inherent in aurora magnetic-lines is undetectable in our analysis because of the short duration of non-Io radio storms.

Key words. planets and satellites: individual: Jupiter – radio continuum: solar system – magnetohydrodynamics (MHD) – waves – radiation mechanisms: non-thermal

1. Introduction

Jovian decametric emission (DAM) appears mainly in the form of long (L) bursts on timescales of ~1 s. This modulation is produced by emission scattered in the interplanetary medium (Genova & Leblanc 1981) and inner magnetosphere of Jupiter (Arkhypov & Rucker 2007). The terrestrial ionosphere is responsible for DAM flux variability with quasi-periods of between 10 and 70 s (Genova et al. 1981). DAM flux variations on timescales of between 1 and 10 h are the product of Jupiter rotation (Galopeau et al. 2004) and Io orbital motion (Bigg 1964). All of these modulations have been studied in detail. However, the phenomenology and origin of DAM variations on intermediate scales (1 to 60 min) are poorly understood.

In a previous paper (Arkhypov & Rucker 2008), we studied the sub-hour modulation of L-bursts, which are correlated with the orbital position of the Jovian satellite Io. We found that the internal structure of the Io-related radio storms has the dominating periodicity of 23 min on average. This estimate agrees with the fundamental eigenoscillations of transversal, magnetic pulsations in the Io plasma torus. This result implies that electron acceleration is present in field-aligned electric-fields of standing Alfvén waves trapped in the Io torus. There is an analogous modulation of auroral kilometric radiation from the Earth by magnetic pulsations at field-line resonances in the terrestrial magnetosphere (Hanasz et al. 2006).

We consider whether field-line resonances modulate the yet uninvestigated DAM component (non-Io L-bursts), which is uncorrelated with the Io satellite position. This problem is important because of the localization uncertainty of non-Io radio sources. For example, the correlation between the non-Io DAM and solar wind implies that high-latitude radio sources are connected with the auroral zones, magnetospheric cusps, or magnetotail (Terasawa et al. 1978; Barrow et al. 1986; Zarka 1998). However, results derived from various methods support the existence of low-latitude sources, connected instead with the Io plasma torus (Goldstein et al. 1979; Calvert 1983; Imai et al. 1997; Arkhipov 2003). Hence, non-Io-emission could be generated in different magnetic shells for different field-line resonances and corresponding timescales of DAM flux variations. Figure 1 in Glassmeier et al. (1989) showed that the eigenperiod of the aurora magnetic field-line with the McIlwain parameter of $L \approx 20$ to 30 (Pallier & Prange 2001) is about a factor of ten higher than the period of the Io torus field line ($L \approx 6$).

This is the background to our intention to analyze the sub-hour modulations of non-Io DAM and compare them with the timescales of the Io-related DAM modulations.

These sub-hour modulations of the non-Io DAM component are described as arcs of emission in DAM dynamic spectra (Leblanc 1981). Arcs are usually repeated quasi-periodically (Fig. 1), and an arc covers about 6 min. Successive arcs are usually observed to have a well-defined time delay of 5–10 min. Non-Io emissions are divided into vertex early arcs and vertex late arcs. Both arc families correlate with the observation geometry. The greater and lesser arcs with similar signs of polarization are described by both of these families (Leblanc 1981). This division implies that, at least, two types of non-Io radio sources exist. However, their timescale was studied only visually with Voyager-1, 2 data (Leblanc 1981; Staelin et al. 1988). In these studies, the main approach was a statistical analysis of the time intervals between DAM arcs. Unfortunately, these interval

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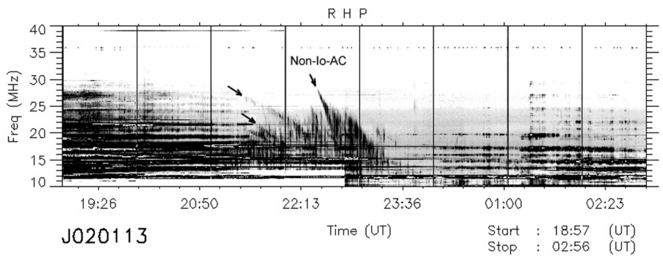

Fig. 1. An example of DAM dynamic spectra with clear arcs (arrowed) is recorded 2002 January 13 at the Nançay Radio Observatory.

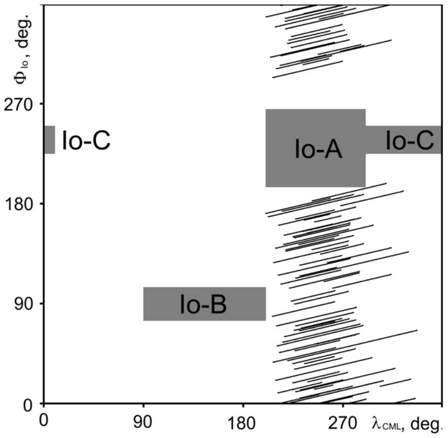

Fig. 2. The studied non-Io radio storms (black lines) avoid the Io-related DAM (grey boxes according to Flagg 2000) on the plot "central meridian longitude ($\lambda_{\rm CML}$) – Io's orbital longitude ($\Phi_{\rm Io}$)".

methods are inadequate for any study of arc groups that are divided into short inter-arc intervals.

We study the DAM modulations with objective, efficient spectral and correlation methods using the archive of 17-yr broadband DAM observations at the Nançay Radio Observatory. Our purpose is to reveal sub-hour modulations of non-Io DAM and compare them with the timescales of Io-related DAM.

The methods and experimental material are described in Sect. 2. Section 3 describes our analysis of the DAM spectra. Our interpretations are presented in Sect. 4. Section 5 summarizes the results.

2. Experimental material and methods

We used the collection of DAM spectra from the site of the Nançay Radio Observatory (`http://www.obs-nancay.fr/dam/`). Data for every observational session are displayed separately as a pair of dynamic spectra for right-hand (RH) and left-hand (LH) polarization. The time coverage (8 h) and resolution (generally 40 s per pixel) of the spectra are sufficient for studying DAM variations with periods from 2 h to minutes. Only 89 non-Io-AC storms of 1990–2005 with right-hand polarization are selected for our analysis because of their high radio flux and frequencies, relatively low interference level, and long duration. They avoid the regions of Io-related DAM in the plot "central meridian longitude – Io's orbital longitude" (Fig. 2).

Since the calibration of individual spectra has not yet been published, only relative intensity could be analyzed. The intensity is color coded in the spectrum. In RGB coding, the red (R) channel data exhibits powerful interference, while the blue one (B) depicts mainly antennae/amplifier noise. The most informative data is the green (G) channel, which shows DAM storms in detail, why, for our analysis, we usually used spectra from the G-channel as grey images in 256 gradations (Fig. 1).

The purpose of this paper is the estimate of the main timescale of the interior structure inside a non-Io DAM storm. This is practically the only way of studying the physical DAM variability with minimal masking by geometrical effects. We cannot study the DAM flux variations on timescales longer than the intersection time of the radiation beam (i.e., the radio-storm duration of 2 h). To avoid interference and modulation of DAM from the Jovian rotation, we selected data corresponding only to the radio storm of the dynamic spectrum. This spectral fragment is rectangular in shape and covers the entire region affected by non-Io radio emission at minimal interference.

We calculated the squared harmonics of Fourier transform from the time variations of spectral intensity:

$$C_m^2 = A_m^2 + B_m^2, \tag{1}$$

$$A_m = \frac{1}{N}\sum_{i=1}^{N} F_i \cos\frac{2\pi m i}{N}, \tag{2}$$

$$B_m = \frac{1}{N}\sum_{i=1}^{N} F_i \sin\frac{2\pi m i}{N}, \tag{3}$$

where m is the harmonic number, N is the number of all intensity readings (F_i) in the spectrum, and i is the intensity reading number. These power estimates C_m^2 are obtained in every radio-frequency channel of the spectral fragment and averaged into $\langle C_m^2\rangle$ with the standard error σ. Since the number of radio frequency channels is between 14 and 87 (the frequency range is 2.1 MHz to 12.9 MHz), parameter σ describes the Gaussian statistic of $\langle C_m^2\rangle$ reasonably well. The key parameter in the next step of our analysis is the period P of the spectral peak with maximal $\langle C_m^2\rangle$ and of significant ($>3\sigma$) amplitude relative to the adjacent minima. This period P describes the timescale of the interior structure (arcs and groups of arcs) inside a DAM storm.

Unfortunately, any well-known arc-structure of DAM storms does not dominate in the described power spectra. Therefore, the Fourier transform must be supplied with the correlation approach. This is the calculation of the average autocorrelation function of spectral intensity $F_{i,k}$

$$r_{\rm a}(\Delta k) = \frac{1}{n}\sum_{i=1}^{n}\sum_{k=1}^{m}\frac{[F_{i,k}-\langle F\rangle_i][F_{i,k+\Delta k}-\langle F\rangle_i]}{M\sigma_i^2}, \tag{4}$$

where i and k are the pixel numbers in the frequency and time scales, m and n are the width and height of the analyzed dynamic spectrum, Δk is a time shift in pixels, $\langle F\rangle_i$ is the average spectral intensity along the spectral line at constant i or radio frequency, and σ_i is the dispersion in the spectral intensity of the line, M is the number of terms in the right sum in accordance with the m and Δk.

Examples of the main types of experimental autocorrelation function are shown in Fig. 3, where the time shift in seconds is displaced instead of Δk. The narrow peak at near-zero shift reflects the short-duration details in the DAM dynamic spectrum. Hence, the peak width (Δt) is controlled by the arc duration in time at fixed frequency. The arc groups appear as a bell-like "pedestal" under the peak of their autocorrelation function (Figs. 3b,c). The autocorrelation minimum or the inflection point between the peak and the pedestal are used as formal borders to estimate Δt (Fig. 3d). The inflection point is found with the condition of $d^2r_{\rm a}/d\tau^2 = 0$, where $r_{\rm a}$ is the autocorrelation function at the τ time shift in seconds.

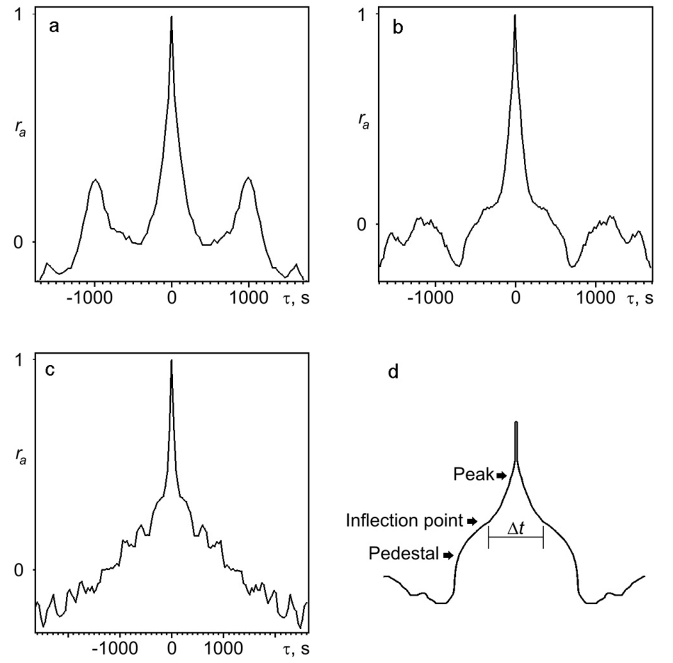

Fig. 3. The main types of the autocorrelation function of spectral intensity in non-Io-AC radio storms: **a)** the pair of arcs (2000 October 25); **b)** the periodic groups of arcs (2000 March 28); **c)** irregularly spaced arcs (2000 October 13); **d)** the idealized scheme of measurements for the timescale of arcs (Δt) on the central details of the function.

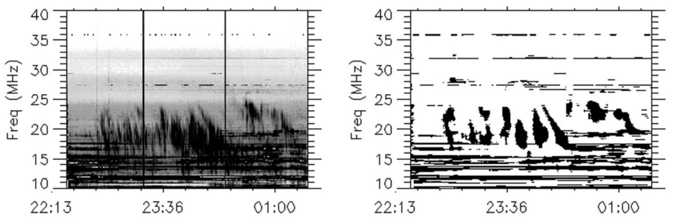

Fig. 4. Example of Non-Io-AC dynamic spectrum exhibiting the structures of deca-minute time scale. *Left*: the original spectra (2000 December 2, Nançay Radio Observatory archive; right-hand polarization). *Right*: the visualization of deca-minute pattern.

3. Analysis

Our survey of DAM dynamic spectra from the Nançay Jovian archive has revealed the existence of specific modulation (arc groups) on timescales of deca-minutes (Fig. 4).

To identify the dominating timescale in DAM storms, we applied Fourier transforms (see details in Sect. 2). For each radio storm, the power spectrum of DAM fluctuations with time was calculated, and the significant peak with maximal power identified. The period P of the corresponding spectral harmonic was an individual measurement of the dominating scale. These estimates are clustered just in the range of deca-minutes (Fig. 5). The average period is $\langle P \rangle = 1254 \pm 96$ s or 21 ± 2 min.

This estimate is about the average period of Io-related emission: $\langle P \rangle = 1403 \pm 102$ s or 23 ± 2 min (Arkhypov & Rucker 2008). For toroidal (transverse) magnetic oscillations in the Io torus, Glassmeier et al. (1989) found theoretically the fundamental period of 1296 s (marked as F0 in Fig. 5), which is in good agreement with the data histogram. Transverse Alfvén waves have field-aligned electric fields to accelerate electrons and modulate related DAM. These proper magnetic oscillations of period

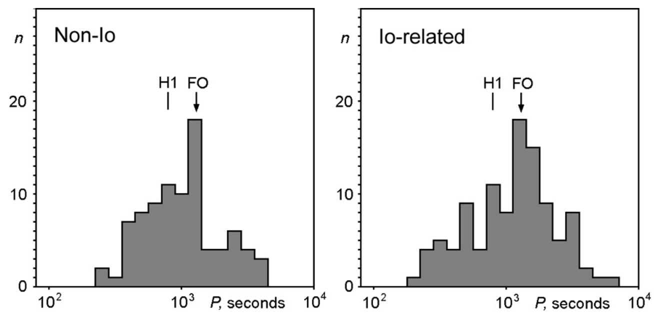

Fig. 5. Histograms of the dominating timescale of radio-storm interior structure in a dynamic spectrum of non-Io DAM. The vertical parameter n is the number of lg P estimates (i.e. processed spectra) in one bin of the histogram. For comparison, we indicate the fundamental period of transverse magnetic oscillations in the Io torus (FO) and the first harmonic (H1) according to Glassmeier et al. (1989). The histogram for Io-related DAM is adopted from Arkhypov & Rucker (2008) but recalculated with the other bin set.

1200 s (20 min) are confirmed with Voyager-1 in situ magnetometer measurements (Glassmeier et al. 1989).

To estimate the scale of the DAM arc pattern, we used the histogram of the width Δt of the autocorrelation main peak (Fig. 3d). As a result, the summary histogram of Δt estimates for non-Io-AC DAM spectra is shown in Fig. 6. Seventy percent of the estimates are concentrated in the interval $4.6 < \Delta t < 8.6$ min, having an average value $\langle \Delta t \rangle = 418 \pm 17$ s or 7.0 ± 0.3 min. This result correlates with the old visual estimate for non-Io emission (5–10 min; Leblanc 1981). However, the most probable value is 5.3 ± 0.7 min for non-Io DAM as well as for Io-related emission.

4. Discussion

The correlation of the non-Io DAM with the solar wind has been interpreted as evidence of high-latitude radio sources, connected with auroral zones (Terasawa et al. 1978; Barrow et al. 1986; Zarka et al. 1998). However, the aurora magnetic-field lines with the McIlwain parameter of $L \approx 20$ to 30 (Pallier & Prange 2001) have the fundamental eigenperiod of ~230 min to ~760 min (Fig. 1 in Glassmeier et al. 1989). This is longer than the typical duration of a DAM storm. Hence, the DAM modulation due to the Jupiter rotation (595 min) obscures long-periodic eigenperiods, if they do in fact occur.

However, we identified far shorter timescales of non-Io DAM variations (≈20 min and ≈5 min). These results and histograms (Fig. 5 and 6) for non-Io emission are approximate to the modulation of Io-related DAM (Arkhypov & Rucker 2008). The simplest interpretation of these agreements is the identity of the modulator.

We argued in a previous paper (Arkhypov & Rucker 2008) that the Io-related L-burst emission is modulated by the proper oscillations of the Io plasma torus. Such oscillations in the form of a quasi-axisymmetric azimuthal twisting of magnetic-field lines are found in situ (Fig. 7, Glassmeier et al. 1989). In this geometry, the phase of the torus oscillation depends negligibly on the longitude. Alfvénic disturbances from the Io motion (Kivelson et al. 2004) and the spontaneous, volcanic mass-loading with subsequent co-rotation braking (Glassmeier et al. 1989) can excite the Io torus as a resonator. The standing Alfvén waves, in the torus, accelerate electrons, which modulate part of the non-Io DAM in the connected polar regions of the Jovian magnetosphere. These Alfvén waves, trapped in the Io torus, can

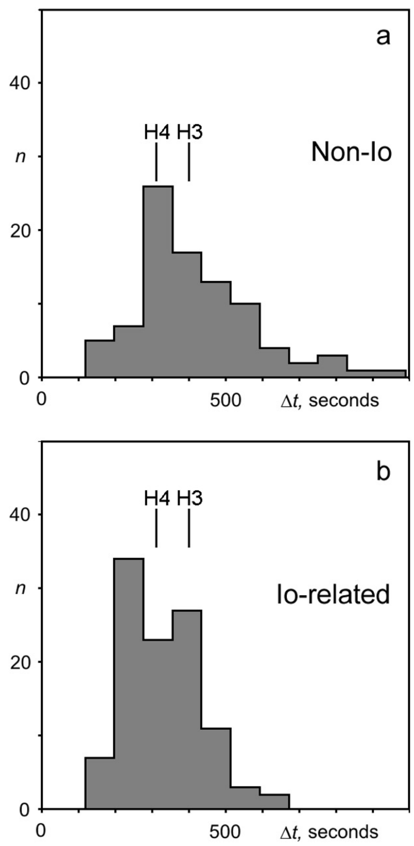

Fig. 6. The histogram of the Δt estimates shows the timescale of the arc pattern at fixed frequencies from 12 MHz to 30 MHz. The histogram for Io-related DAM is adopted from Arkhypov & Rucker (2008) but recalculated with the other bin set. H3 and H4 markers are the 3rd and 4th harmonics of transversal Alfvénic oscillations in the Io torus (Smith & Wright 1989).

apparently modulate the DAM at various longitudes without direct connection with the Io position.

The connection between non-Io radio sources and the Io torus was found independently with the modulation lane method. Most modulation lanes in dynamic spectra of DAM are formed by radiation scattering on field-aligned inhomogeneities in the Io plasma torus (Arkhypov & Rucker 2007). Since the lane drift is controlled by the DAM source position, the search for the source's magnetic shell is possible by calculating the minimal frequency drift rate of the lanes. The comparison between the experimental estimates of lane drifts and the calculations for different L-shells supports the existence of non-Io radio sources (at least some of them) in the Io torus shell ($L \approx 6$, Imai et al. 1997; Arkhipov 2003).

The fundamental period for Alfvén waves, trapped in the Io torus, is found experimentally to be about 20 min (Glassmeier et al. 1989), which is practically equal to our timescale (P) estimate for arc groups of non-Io DAM. The arc duration (7.0 or 4.6 min) could be considered as a 3rd harmonic with a period of about 6.64 min or as a 4th harmonic with a period of about 5.19 min according to the numerical calculations (Smith & Wright 1989). The effective excitation of the 3rd harmonic could be explained by the proximity of its standing-wave maximum to Io's altitude above the centrifugal equator of the torus during Io-A radio storms (Arkhypov & Rucker 2008). However, the 4th harmonic could be excited during Io-C storms. The most probable mechanism for producing this excitation is the

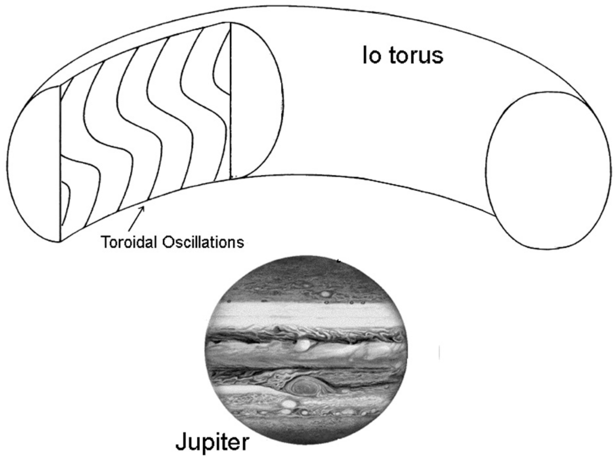

Fig. 7. Example of axisymmetric azimuthal-twisting of magnetic-field lines (toroidal oscillations; not to scale) found in the Io plasma torus (Glassmeier et al. 1989). In this geometry, the phase of the torus oscillation depends negligibly on the longitude. Hence, these standing Alfvén waves, trapped in the torus, can accelerate synchronously electrons and modulate non-Io DAM at different longitudes independently of the Io position.

spontaneous volcanic mass-loading and subsequent co-rotation braking as argued by Glassmeier et al. (1989).

5. Conclusions

We have processed observational material, covering 17 years, and derived the following results.

1) It is found that the internal structure (arcs and groups of arcs) of the non-Io radio storms has the dominating periodicity of 21 ± 2 min on average. This estimate coincides with the fundamental mode of the Io torus eigenoscillations.
2) This result could be interpreted in terms of electron acceleration in parallel electric fields of standing Alfvén waves trapped in the Io torus, where the torus acts as a resonator.
3) The histogram of timescales of non-Io DAM variations practically coincides with the histogram for Io-related DAM. This similarity suggests that the same eigenoscillations in close magnetic shells are present for both types DAM. The significant part of non-Io DAM appears to be connected with the Io torus. This conclusion strengthens the localization of non-Io radio sources (at least a part of them) by the modulation lane method.
4) The partial connection between non-Io DAM and aurora zones is however not excluded. The fundamental mode of eigenoscillations inherent in aurora magnetic-lines is undetectable in our analysis because of the short duration of non-Io radio storms.

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