ZEBRA–LIKE FINE SPECTRAL STRUCTURES IN JOVIAN DECAMETRIC RADIO EMISSION

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Abstract

We report the first systematic analysis of zebra–like fine spectral structures in the decametric frequency range of Jovian radio emission (DAM). These zebra patterns are observed in the frequency range from 12 to 30 MHz as a quasi-harmonically related bands (from 3 to 9) of enhanced brightness. The features have been observed by the ground-based radio telescope URAN-2 (Poltava, Ukraine). In total, 55 zebra pattern events have been detected during the period from September 2012 to March 2016. The minimum duration of one single zebra pattern was 20 s, and the maximum one was 4 min 50 s. The intensity of the zebra stripes is 1–2 magnitudes lower than the intensity of Io–controlled DAM. The numbers of stripes in one event may vary in time. The frequency interval between neighboring stripes is from 0.26 to 1.5 MHz. The zebra patterns are strongly polarized and have been observed as right-handed and left-handed polarized radio emission. The zebra patterns are mainly detected in two active sectors of Jovian CMLs: 100° to 160° for northern sources (right-handed polarized) and between 275° and 60° (via 360°) for the southern sources (left-handed). No correlation with the position of Io has been detected. We conclude that the observed zebra patterns are a new type of narrow band spectral structures in the Jovian decametric radio emission.

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1 Introduction

Jupiter with the largest planetary magnetosphere in the solar system is the complex source of a powerful non-thermal radio emission in a wide frequency band extending from several kHz up to hundreds of MHz. Jovian decametric radio emission (DAM) is the strongest component of the radio emissions of Jupiter observed in the frequency range from a few MHz up to 40 MHz. Depending on time scales, the Jovian DAM exhibits different complex spectral structures. The "long" L-burst emission or wide-band noise radio storms vary at a time scale of minutes, whereas very short impulsive S-bursts are characterized by micro–milliseconds duration [Carr et al., 1983; Zarka, 1998; Ryabov et al., 2014].

Different modulations effects are observed in the Jovian L- and S- bursts. As a result of the non-axisymmetric magnetic field and the non-isotropic emission pattern DAM exhibits strong periodicities related to the rotation of Jupiter's magnetosphere (9.92492 h, System III) and Io orbital period (42.46 hours) [Carr et al., 1983; Kaiser, 1993]. Panchenko et al. [2013] reported on the finding of new types of intense non-Io DAM bursts which recurred very periodically during several Jupiter's rotations with an averaged period of $\sim$ 10.07 hours, which is $\sim$ 1.5% longer than the period of System III.

The modulation effects in S-bursts have been discussed in a large number of works [Riihimaa, 1970; Genova et al., 1981; Litvinenko et al., 2009; Ryabov et al., 2014]. Recently, Litvinenko et al. [2016] reported a new fine structure of non-Io-DAM in form of quasi harmonic parallel stripes of enhanced brightness drifting synchronously in time similar to the zebra patterns observed in solar radiation. Similar structures were also observed in the Jovian broad-band kilometric radiation by the RPWS (Radio and Plasma Wave Science) instrument onboard Cassini mission during its Jupiter flyby [Kurth et al., 2001].

In this paper we report the first analysis of 55 zebra pattern events recorded in the decametric frequency range (10–30 MHz) of Jovian DAM. The data have been obtained during four observation campaigns in 2012–2016 by the URAN-2 (Poltava, Ukraine) ground-based radio telescope.

2 Observations

URAN is a decametric VLBI (Very Long Baseline Interferometry) network which includes the five telescopes UTR-2, URAN-1, URAN-2, URAN-3, and URAN-4 [Konovalenko et al., 2016]. In our study we have used the data from the URAN-2 (Poltava, Ukraine) telescope, which is operated in the frequency range 8–32 MHz. The antenna array of URAN-2 consists of 512 pairs of linearly polarized crossed dipoles (dual–polarization antennas) with an effective area of 28,000 m^2 and a beam pattern size of $3.5° \times 7°$ (at 25 MHz). URAN-2 is able to measure the linear and circular polarization of radio signals. Since September 2012 URAN-2 performs regular monitoring of Jovian radio emission.

In our study we have analyzed the data obtained during four observation campaigns: 18 September 2012 – 23 May 2013, 21 August 2013 – 31 March 2014, 25 November 2014 – 31 May 2015, 03 November 2015 – 15 March 2016, and 3 November 2015 – 15 March 2016.

These campaigns included long–term continuous observation of Jovian radio emission (during periods of Jupiter's visibility) in the frequency range from 8 MHz to 32 MHz, with a time and frequency resolution of 0.1 s and 4 kHz, respectively. The telescope was operated in polarization mode when four values were measured simultaneously at each frequency: auto-correlation of each of the two crossed dipole antennas and the real and imaginary part of cross-correlation between pairs of the antennas. In total 696 observation sessions have been performed during these four campaigns. Each of these sessions lasted from about 3 to 9 hours, depending on Jupiter's position over the horizon.

3 Zebra patterns in decametric radio emission

In the course of the analysis of dynamic spectra we have found a new type of fine structures in the DAM, i.e. "zebra" stripe–like spectral structures which were first reported in Litvinenko et al. [2016]. The zebra patterns were observed as quasi-harmonically related bands (stripes) of enhanced brightness. Zebra stripes were wavy and almost parallel with only a small drift in time. The minimum duration of one single zebra pattern event was 20 s, and the maximum one was 4 min 50 s. The mean duration averaged over all zebra events was 120 s. Zebra patterns were observed in an overall frequency range from 12.5 MHz to almost 30 MHz. It is worth noting that the zebra patterns were recorded almost in the full observing frequency range of the URAN-2 telescope (8–32 MHz). This may suggest that some zebra patterns could be observed also at lower or higher frequencies.

The examples of dynamic spectra with zebra patterns are shown in Figure 1. In total 55 clear individual events have been detected. These 55 zebra patterns events have been observed in only 46 out of all 696 observation sessions (or in 6.6% of the observed session), thus the zebra pattern is a rather rare phenomenon in Jovian radio emission.

In this section we provide the statistics of the main properties of the zebra patterns. The results of the statistical analysis should provide the basis for the theoretical framework of this phenomenon.

Each zebra event was characterized by duration, frequency range, number of stripes, frequency splitting between stripes, degree of circular polarization as well as the Central Meridian Longitude (CML) and the Io phase of URAN-2 at the moment of the event observation.

Figure 1a shows a striped spectral structure recorded on 10 November 2012 in the time interval 23:46:15–23:49:30 UT in the frequency range between 20 and 26.5 MHz. It is clearly seen that the number of stripes and its observational frequencies vary with time. Up to five individual emission stripes were recorded simultaneously between 23:46:20–23:47:00 UT and 23:47:30–23:48:00 UT. The duration of the event was 3.5 minutes.

Figure 1b shows the observation on 11 November 2012. The most prominent four stripes were observed in the time interval 21:07:40 –21:08:10 UT in the frequency range 12.5–13.5 MHz. The striped structures were detected during a 30 seconds period of time which is significantly shorter than for the event in Figure 1a.

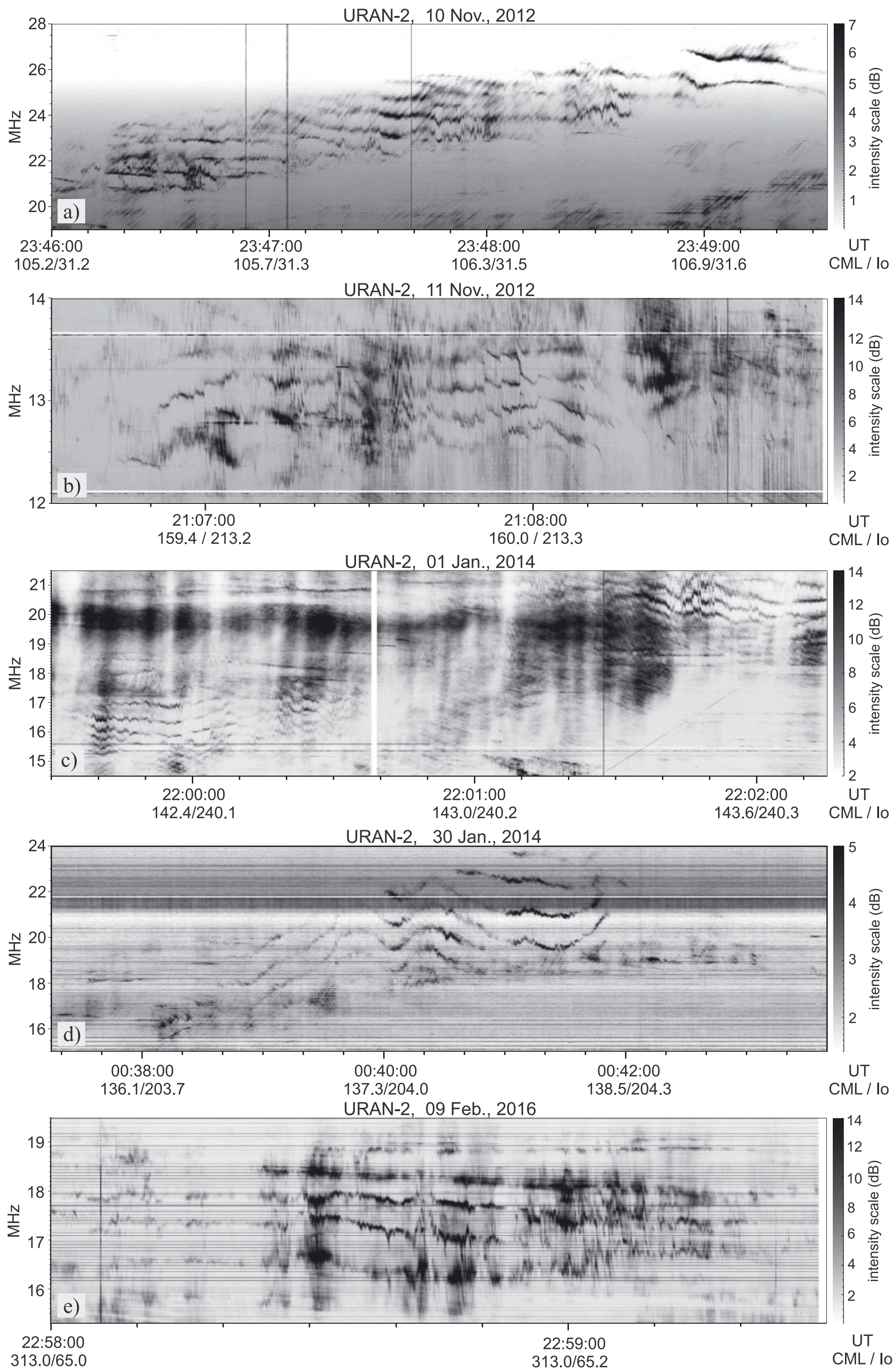

Figure 1: Examples of zebra patterns observed by the URAN-2 radio telescope. The dynamic spectra show the intensity (I) of radio emissions in dB above the background level. The intensity $I = I_A + I_B$ is the sum of intensities measured by pairs of two orthogonal antenna dipoles.

Two groups of zebra patterns were observed on 1 January 2014 (Figure 1c). The first group with up to five stripes was detected on 21:59:35–22:00:35 UT in the frequency range 15–17.5 MHz. The second group was detected at higher frequencies of 19.5–21.5 MHz during the time interval 22:01:30–22:02:15 UT.

Figure 1d shows the example of the weaker zebra patterns observed on 30 January 2014, 00:38:40–00:42:00 UT in the frequency range 16–23 MHz. A maximum of four stripes have been detected simultaneously. The intensity of the zebra patterns was about 10 dB lower than in Figures 1b and 1d.

Finally, Figure 1e is the dynamic spectrum observed by URAN-2 on 9 February 2016. During the time interval between 22:58:05 and 22:59:25 UT from three to five stripes were observed between 16.0 and 19.0 MHz.

The intensities of the zebra stripes shown in Figure 1 have been estimated to be $\sim 10^4 - 10^5$ Jy (Jansky) at 12–27 MHz, which is 1–2 orders of magnitude lower than the rotation–averaged flux densities of Io–controlled DAM [e.g. Zarka, 1998]. The flux densities of zebra patterns vary in time and frequency.

The presented dynamic spectra give indications that some zebra patterns show substructures which are not fully resolved due to insufficient temporal resolution. Observations with a better spectral resolution will be needed to observe these fine structures.

3.1 Polarization

Using the polarization measurement capability of the URAN-2 telescope polarization properties of the zebra patterns have been investigated. Figure 2 shows the dynamic spectra of Stokes parameters of the zebra pattern observed on 17 October 2012 and 14 December 2013. The spectra show that the events are highly polarized radio emissions with a degree of polarization above 90%. The zebra patterns recorded on 17 October 2012 (left panels in Figure 2) are right-hand polarized, and the zebra patterns observed on 14 December 2013 are left-hand polarized radio emission.

URAN-2 is able to measure the full polarization state, i.e. all Stokes parameters of incident radio waves. Nevertheless, in order to have reliable polarization measurements a very precise calibration of antenna receiving properties should be performed, and this work is currently in progress and it is not finished yet. Therefore, in our study we used the parameter of circular polarization V only for a qualitative determination of the polarization sense, i.e. right-hand or left-hand. Nevertheless, we have found clear Faraday fringes due to Faraday rotation (change in orientation of the polarization ellipse of a radio wave measured by linear polarized antennas). These Faraday fringes occur on the dynamic spectra when the highly elliptically polarized radio emission is observed by linearly polarized antennas. The fringes are well visible as bright horizontal stripes in the dynamic spectra in Figure 2. Therefore we can conclude that the zebra patterns are elliptically polarized radio emission, similar to the Jovian DAM [e.g. Shaposhnikov et al., 1997].

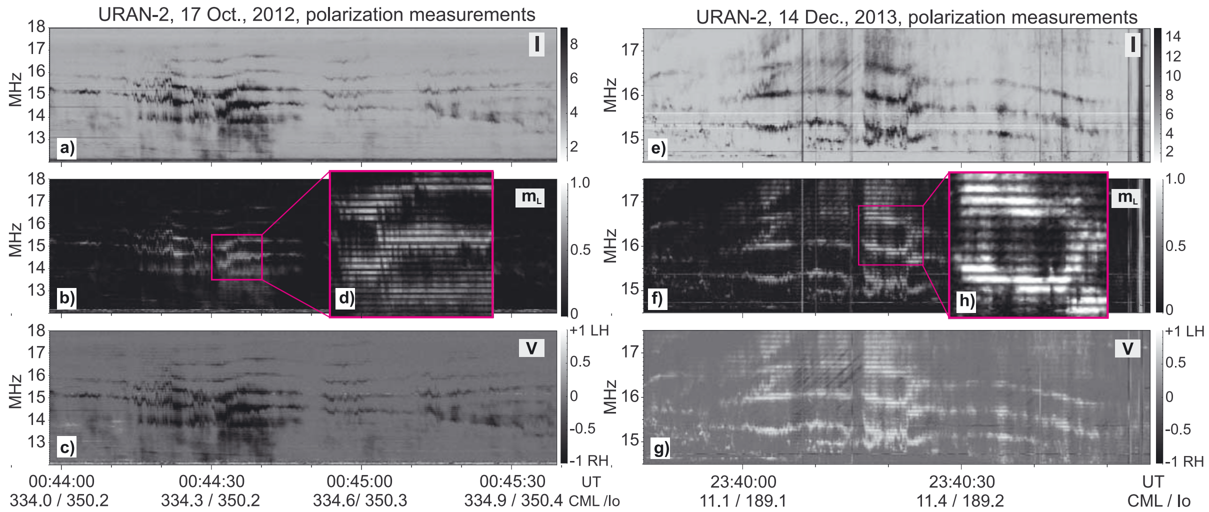

Figure 2: URAN-2 polarization measurements of the zebra pattern in the Jovian DAM. Dynamic radio spectra in panels a) and e) show the intensity of the radio emission in dB. The panels b) and f) are the degree of normalized linear polarization ($m_L = \sqrt{(Q^2 + U^2)}/I$), and panels c) and f) are the normalized degree of circular polarization (Q, U, and V are the Stokes parameter). The dark color in panels c) and g) defines the right-hand polarization (RH), and the bright color means the left-hand polarization (LH). Horizontal fringes being alternately bright and dark in the spectra are due to Faraday rotation. Panels d) and f) show zoomed regions of the linear polarization spectra with well visible Faraday rotation fringes.

Assuming, that the zebra patterns propagate as the right hand extraordinary R-X mode (similar to DAM) the sign of the circular polarization V can be used for subsequent separation between the emission radiated by the northern or the southern magnetic hemisphere of Jupiter. The R-X waves from northern sources are observed as right-handed while the emissions from the southern sources are observed as left-handed polarized radio emission.

The polarization measurements of the zebra patterns reveal a rather even distribution of left-hand and right-hand polarized events, i.e. 30 events (54% of observed events) have been observed as RH emission and 25 (46%) events as LH polarization. The polarization of the events is not related with certain periods of time. The measurements have shown that the zebra patterns can be observed as right- and left-hand polarized radio emission and can be associated with both magnetic hemispheres of Jupiter. The RH polarized events consist of a somewhat larger number of stripes within the zebra pattern, i.e. from 3 to 9 individual stripes in each event, while LH events comprise from 3 to 7 individual stripes.

3.2 Distribution of the observed zebra pattern in CML (III) and Io phase coordinates

The occurrence probability of Jovian radio emission depends on Jovian CML (III) and Io–phase coordinates of an observer. Figure 3 shows the CML and Io phase at the central time of each particular zebra event. We note the strong correlation between CML position of the observer and the occurrence of the zebra patterns. In particular, RH polarized or

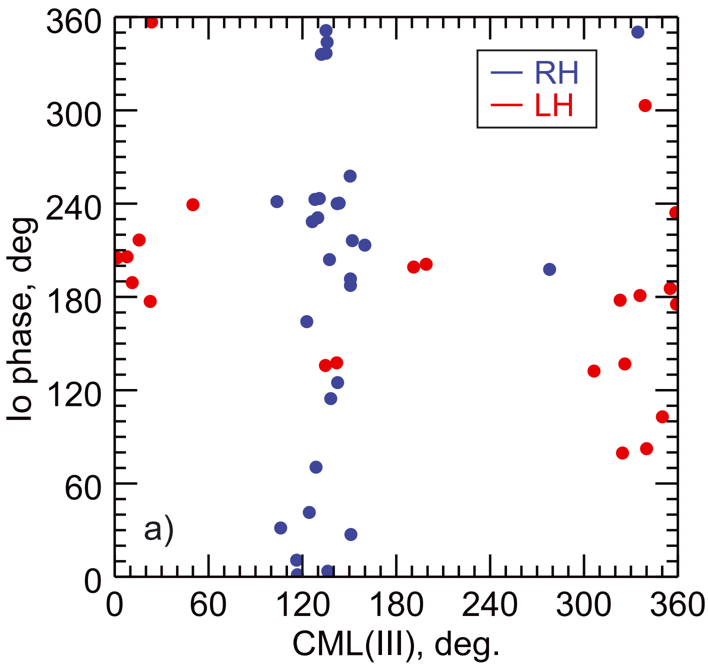

Figure 3: Distribution of the occurrence of the zebra patterns in CML–Io phase coordinates. Blue color indicates the right-handed polarized events (northern sources), and the left-handed polarized events (southern sources) are marked by red color.

northern zebra patterns, except of two outlier events which will be discussed below, were observed in sector of CMLs from 100° to 160°. Most of the southern events were recorded between 275° and 60° (via 360°) of CML with a maximum around 330° − 360°. In the same time no evident correlation between the zebra pattern's occurrence and the position of the moon Io is shown. Thus we can conclude that the zebra events are non-Io controlled radio emission.

As was shown in Figure 3 most of the events are observed in the two separate CML regions, except of several outlier events. In particular, two RH zebra patterns (17 and 26 October, 2012) were observed outside of the main distribution at 270° and 330° of CML and four LH zebra patterns (two events on 15 October 2012 and two events on 23 December 2013) were detected at 130° and 180° of CML. We have found that one of the "outlier" RH event (26 October 2012) has been observed together with a strong Io-A burst of the DAM (Io-A source of the DAM). The emission from the Io-A source is right-handed polarized and corresponds to the sources in the northern hemisphere when CML ranges around 200° − 270° and Io has a phase around 205° − 260° [Carr et al., 1983]. The other two outlier LH events, 15 October 2012, 23:24 UT, and 15 October 2012, 23:36 UT have been observed in the latter part of a strong Io-D arc of DAM which is a left-handed polarized emission from the southern hemisphere observed in CMLs between around 90° − 200° and an Io phase around 95° − 130°. Thus we can suggest that these three outlier events may be part of the Io–controlled DAM while Figure 3 shows that most of the observed zebra patterns are non-Io DAM. Nevertheless, additional observations will be needed to verify whether or not the zebra patterns can be associated also with the Io–controlled DAM. The other two outlier events (17 October 2012 and 23 December 2013) are non-Io DAM.

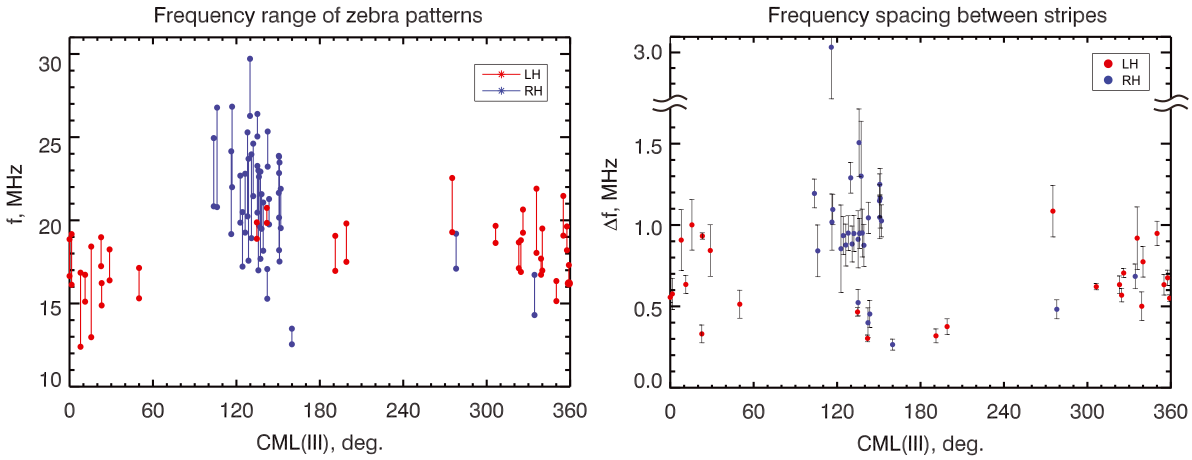

Figure 4: Frequency range (left panel) and frequency intervals Δf between stripes (right panel) as a function of CML. Red color indicates the left-handed polarized (LH) zebra patterns, and blue color denotes the right-handed (RH) polarized events. The lower markers on the bars, which denote the events in the left panel, represent the minimum frequency, and the upper markers indicate the highest recorded frequency of each zebra event.

3.3 Frequency range, bandwidth and frequency splitting between the stripes

Figure 4a shows the frequency ranges of all 55 zebra events as a function of CML. One bar denotes one event. The lower marker on the bar represents the minimum frequency in the lowest stripe, the upper marker indicates the highest recorded frequency in the highest stripe of the event. Moreover, the events are marked by color in accordance to the sense of the polarization. The RH zebra patterns are spread over a wider frequency range compared to the LH events. The northern zebra patterns have been observed in the frequency range from 12.3 up to 29.7 MHz, while the southern ones have been recorded in frequency range from 15.1 MHz to 22.5 MHz. This is also consistent with the distribution of the surface (1-bar pressure level) magnetic field of Jupiter and, therefore, with the maximum electron cyclotron frequency. As was shown by Genova and Aubier [1985] and Hess et al. [2011] the maximum radio frequency for the northern Io-DAM (Io-A and Io-B sources) is $\approx$ 38 MHz, while the southern Io-DAM sources (Io-C and Io-D) are mainly observed at lower frequencies < 25 MHz.

Another important parameter is the frequency interval Δf between neighboring stripes which may shed light on the generation mechanism of zebra patterns. For instance, the mechanism of excitation of harmonically–related plasma waves such as Bernstein modes predicts frequency–equidistant stripes. At the same time the non-equidistant stripes can be explained by inhomogeneous models such as the Double Plasma Resonance (DPR) in which the sources of each zebra stripe are spread out along the magnetic field line.

For each event we defined the frequency splitting Δf as a frequency interval between intensity maxima of the neighboring stripes in the frequency profile. Figure 4 (right panel) shows the averaged (for each zebra pattern event) Δf between the stripes vs CML of the observer. The defined Δf for 54 out of all 55 events ranges from 0.26 to 1.5 MHz. Only in one case (1 February 2014) the averaged frequency splitting was significantly higher $\Delta f = 3$ MHz. Figure 4 also shows that Δf for RH polarized zebra patterns are generally larger than for LH events. The mean value of frequency splitting for RH events (except of 1 February 2014) is $\overline{\Delta f} = 0.9 \pm 0.3$ MHz and for LH zebra patterns $\overline{\Delta f} = 0.7 \pm 0.2$ MHz. It is important to note that the frequency splitting between the stripes varies in time during one single event while Figure 4 (right panel) shows only the averaged value for each of the events.

In fact, the stripes in the zebra patterns are not exactly equidistant. Analysis have shown that in most cases the frequency splitting slightly increase with the emission frequency. This was observed in 47 events. Nevertheless, in 6 events the frequency splitting between stripes decreases with increasing of the emission frequency. This is not usual for the zebra patterns observed in a solar radio emission, where the frequency intervals between stripes always increase with the frequency of an emission. It is interesting, that all these 6 events with decreasing frequency splitting were observed as LH emission, i.e. from the southern hemisphere. Moreover we have also found 2 events in which the frequency intervals decrease with the emission frequency in the earlier part of the considered events and then Δf becomes wider in the latter half of the zebra pattern spectrum.

The instantaneous bandwidth *df* of one stripe, defined as full width at half maximum of the frequency profile, varies from 0.1 MHz to 0.2 MHz; that is less than the frequency spacing Δf between the stripes.

4 Discussion

The fine structure known as zebra structures were first observed against the continuum background of solar type IV radio bursts at meter and decimeter wavelengths as a system of quasi-parallel drifting stripes of enhanced brightness. The theories of generation of the zebra patterns in the solar radio spectra are reviewed in Chernov [2010]. The most accepted theory of generation of the solar zebra patterns is based on a double plasma resonance (DPR) mechanism [e.g. Zheleznyakov and Zlotnik, 1975]. In the DPR the fast electron beams with an unstable distribution (e.g. loss–cone) excite plasma waves in an inhomogeneous plasma at the upper hybrid frequencies. The increased generation of plasma waves occurs in regions where the local upper hybrid frequency (f_{UH}) is close to the harmonics of the electron cyclotron frequency (f_{ce}). These plasma waves couple with low-frequency oscillations or are scattered by ions. These processes result in an appearance of electromagnetic radiation with a spectrum which has the form of quasi-harmonic emission stripes. The DPR is possible only in weakly anisotropic plasma when $f_{pe} >> f_{ce}$ and then $f_{UH} = \sqrt{f_{ce}^2 + f_{pe}^2} \approx f_{pe}$, where f_{pe} and f_{ce} are plasma and cyclotron frequencies of electrons. Thus the resonance condition is $f_{pe} = s f_{ce}$, where $s = 2, 3, 4...$ are the harmonic numbers of the electron gyrofrequency.

The zebra patterns observed in solar and Jovian radio emission demonstrate some similar spectral properties. Comparative morphological analysis for the parameters of the zebra structures in the solar and the Jovian decametric radio emissions was first presented in Litvinenko et al. [2016]. The analogy between the zebra patterns in the solar and the Jovian radiation allows us first to assume that the DPR mechanism is also responsible for the generation of Jupiter's decametric zebras. Moreover, the RPWS instrument onboard the Cassini mission registered similar complex striped spectral structures in the Jovian broad-band kilometric radiation (nKOM) at frequency ranges of 30–70 kHz during its Jupiter flyby [Kurth et al., 2001]. Kuznetsov and Vlasov [2013] proposed the DPR as a possible mechanism for the formation of the stripped structures observed by the Cassini spacecraft in Jovian nKOM.

If we assume that the zebra patterns are generated by DPR in the frequency range from about 12.3 MHz to 29.7 MHz (as shown in Figure 4) then the required electron number densities along the magnetic field line to satisfy the DPR condition have to be 1.9×10^6 cm^{-3} $- 1.1 \times 10^7$ cm^{-3}. At the same time Voyager 2 radio occultation measurements showed that the main electron peak density in the Jovian ionosphere is around $2 - 2.3 \times 10^5$ cm^{-3} at altitudes 0.027 R_J [Hinson et al, 1998]. Therefore, the estimated electron number densities required for the DPR mechanism are significantly larger than the peak of the electron number density in the Jovian magnetosphere. Moreover, unlike the solar corona, Jupiter's plasma is strongly anisotropic, i.e. $f_{pe} << f_{ce}$ in most regions of the magnetosphere. Therefore, the mechanism of DPR with electrons cannot explain our observations since it requires an extremely high plasma density which is very unlikely in the Jovian magnetosphere.

Some proposed mechanisms of zebra pattern generation in the solar radio spectra involve the presence of energetic ions or ion structures in the source region. Treumann et al. [2011] discussed a model of the zebra in solar flare radio emission in which continuum radio bursts may be modulated by the harmonics of the ion cyclotron frequency f_{ci} under certain restrictive conditions (presence of strong field-aligned electric fields and weakly relativistic ions). In this case the distance between the stripes will correspond to the harmonics of f_{ci}. The typical values of f_{ci} in the inner Jovian magnetosphere are tens of kHz while the observed distances between zebra structures in DAM are 0.3–1.5 MHz. Therefore the theory proposed by Treumann et al. [2011] cannot explain the observed zebra patterns in the DAM.

Recently Zlotnik et al. [2016] proposed an alternative mechanism of zebra structure formation in Jovian kilometer radiation observed by Cassini at low frequencies (30–70 kHz) [Kurth et al., 2001]. The model is based on the double plasma resonance with ion cyclotron harmonics which involves the excitation of ion cyclotron waves at the lower hybrid frequency and then a non-linear transformation of this low frequency emission to high frequency waves due to a coalescence process with a high frequency mode, e.g. plasma upper hybrid frequency of the electrons. In the mechanism of DPR with ions the lower hybrid plasma waves are enhanced in regions where the lower hybrid resonance frequency f_{LH} coincides with the harmonics of the ion gyrofrequency f_{ci}. In contrast to DPR with the electrons DPR with ions can only be operated in regions where $f_{pe} << f_{ce}$. The last condition is fulfilled in most regions of the Jovian magnetosphere. Then $f_{LH} \approx f_{pi}$ and the resonance condition is $f_{pi} = sf_{ci}$ where f_{pi} and f_{ci} are plasma and cyclotron frequencies of the ions and $s = 2, 3, ...$ are harmonic numbers. Since in the DPR with ions the plasma waves are excited at low frequencies of the f_{ci} harmonics, the required densities of the ions are significantly lower than for DPR with the electrons.

The local f_{ce} along the magnetic field line can be calculated using the model of the Jovian magnetic field, e.g. VIP4 model [Connerney et al., 1998]. For example, for the field line with latitude 49.6° and longitude 170° (in System III (1965)) $f_{ce} = 12.3$ MHz will be at $\sim 0.34\ R_J$ above Jupiter's surface, and $f_{ce} = 29.7$ MHz at the altitude $\sim 0.054\ R_J$. At these altitudes the ion cyclotron frequencies are $f_{ci} = 6.8$ kHz (at 0.34 R_J) and $f_{ci} = 16.2$ kHz (at 0.054 R_J). Thus, using the resonant condition $f_{pi} = sf_{ci}$ the ion number densities for the second harmonic ($s = 2$, the minimal possible harmonic in the DPR) have to be $4.2 \times 10^3\,\mathrm{cm}^{-3}$ and $2.4 \times 10^4\,\mathrm{cm}^{-3}$ correspondingly for the altitudes 0.34 R_J and 0.054 R_J. These ion densities are more realistic. For example, Voyager 2 occultation measurements (Figure 4 in Hinson et al. [1998]) show that the number density of the electrons at an altitude of 0.054 R_J is $\approx 1.2 \times 10^4$ cm^{-3}, which is comparable to the densities estimated above.

Therefore, the DPR mechanism with ions can potentially exist in the upper Jovian ionosphere. Nevertheless there is a weak point in the model of the Jovian DAM zebra pattern generation at DPR with ions. According to the theory proposed by Zlotnik et al. [2016] the low plasma waves cannot escape the source and should be first transformed to the high frequency waves in a non-linear coalescence process $f = sf_{ci} + f_{ce}$. Since $f_{ce} >> f_{ci}$, the resulting frequency will be $f \approx f_{ce}$ and these high frequency waves can be observed as zebra stripes. The observed zebra is generally a strong radio emission with an intensity just 1–2 magnitudes lower than Jovian DAM – the strongest radio emission of Jupiter. Therefore the non-linear coalescence process $f = sf_{ci} + f_{ce}$ should explain how to reach the observed intensities.

Additional theoretical investigations will be needed to explain the zebra patterns in the Jovian DAM. The continuous observation is in progress, therefore we plan to analyze the other observations of 2016–2017. The performed analysis of the observations allows us to conclude that the observed zebra patterns are a new type of narrow band spectral structures in Jovian DAM.

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