DYNAMIC PROCESSES IN GROUPS OF SOLAR CORONAL MAGNETIC LOOPS OBSERVED IN MICROWAVES

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Abstract

The spectral and temporal evolutions of the low-frequency (LF) pulsations modulating the solar microwave radiation (37 GHz) recorded at the Metsähovi Radio Observatory were studied with the data analysis algorithm based on a fast Fourier transformation with a sliding window. Quite often the dynamic spectra of the LF pulsations contain several spectral tracks demonstrating a similar or slightly different temporal behaviour. These multi-track features of the LF spectra are interpreted as an indication that the radiation is produced in a system consisting of several closely located magnetic loops involved in a common global dynamical process. Application of the equivalent electric circuit models of the loops with inclusion of the effects of electromagnetic inductive interaction in groups of slowly growing current-carrying magnetic loops allows to explain and reproduce the main dynamical features of the observed LF modulation dynamic spectra.

1 Introduction

The solar corona has a highly dynamic and complex structure. It consists of a large number of continuously evolving loops and filaments, which interact with each other and are closely associated with the local magnetic field. The non-stationary character of solar plasma-magnetic structures is closely related to a variety of energetic phenomena, which range from tiny transient brightenings (micro-flares) and jets to large, active-region-sized flares and CMEs. They are naturally accompanied by different kinds of electromagnetic emission, covering a wide frequency band from radio waves to gamma-rays. Multi-frequency observations of flares, including soft X-ray, hard X-ray, and radio wavelengths

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indicate that quite often multiple loops are involved in a flare process [Nishio et al. 1997]. It is natural to expect that such structural complexity of a flaring region will manifest itself in peculiarities of the emitted radiation.

As a relatively new direction of investigations in the traditional branch of the microwave radio astronomy, appears the study of the Low-Frequency (LF) fluctuations of microwave radiation [Zaitsev et al. 2003]. For this purpose a "sliding window" Fourier (SWF) analysis is applied. Classic Fourier transform represents a signal as a sum of its spectral components and provides the information about a relative power of each of these components. However, the energetic spectrum says nothing about the appearance in time of particular spectral components. To obtain this type of information, the spectral analysis of a signal is performed within a certain time interval Δt (so-called "window"). Then the analysis interval is shifted along the time axis. This "sliding window" Fourier transform method is well known and appears now as a main algorithm for the analysis of non-stationary signals [Kharkevich 1957]. The dynamical spectra of the LF pulsations make possible the diagnostics of electric currents in the radiating source [Zaitsev et al. 2003] and allow to judge about parameters of the radiating magnetic loops [Khodachenko et al. 2005]. We pay attention to the fact that the microwave radiation from the solar active regions is produced by the electron gyrosynchrotron radiation mechanism. The intensity of this radiation in the case of a power-law distribution of electrons in energy $f(\mathcal{E}) \propto \mathcal{E}^{-\delta}$ (with $2 \leq \delta \leq 7$) is $I_\nu \propto B^{-0.22+0.9\delta} = B^{1.58 \div 6.08}$ [Dulk 1985]. Thus, any LF variations of the electric current in the radiating source (a flaring magnetic loop), which produce in their turn the LF disturbances of the magnetic field, will modulate the intensity of the gyrosynchrotron radiation. Particular values of the coronal magnetic field are provided below in the modeling section (Section 3.2).

2 Observations

To study the LF modulations of the solar microwave radiation the SWF analysis has been applied to the selected digital records of time profiles of the microwave radio bursts at 37 GHz obtained at the 14-m radio telescope of Metsähovi Radio Observatory (Finland). The width of the antenna beam pattern at 37 GHz is 2.4', the sensitivity of the receiver, about 0.1 sfu (10^{-23} W $\cdot$ m$^{-2}\cdot$ Hz^{-1}), and time resolution, 0.05...0.1 s. In principle, variations of the background magnetic field can cause not only the amplitude modulation of microwave radio emission from the solar active regions, but also may result in a certain frequency modulation (due to the influence on the electron gyrofrequency). The estimated width of the gyrofrequency variation interval due to this effect is from several tens to several hundreds MHz. At the same time, the bandwidth of the receiver at Metsähovi is much larger then this interval so that possible frequency modulation of the microwave radio emission cannot be resolved.

Quite often the dynamic spectra of the detected LF oscillations, modulating the microwave radiation from the solar active regions, contain several spectral tracks demonstrating a similar or slightly different temporal behaviour. We consider these multi-track features as an indication that the microwave radiation is produced within a system consisting of a

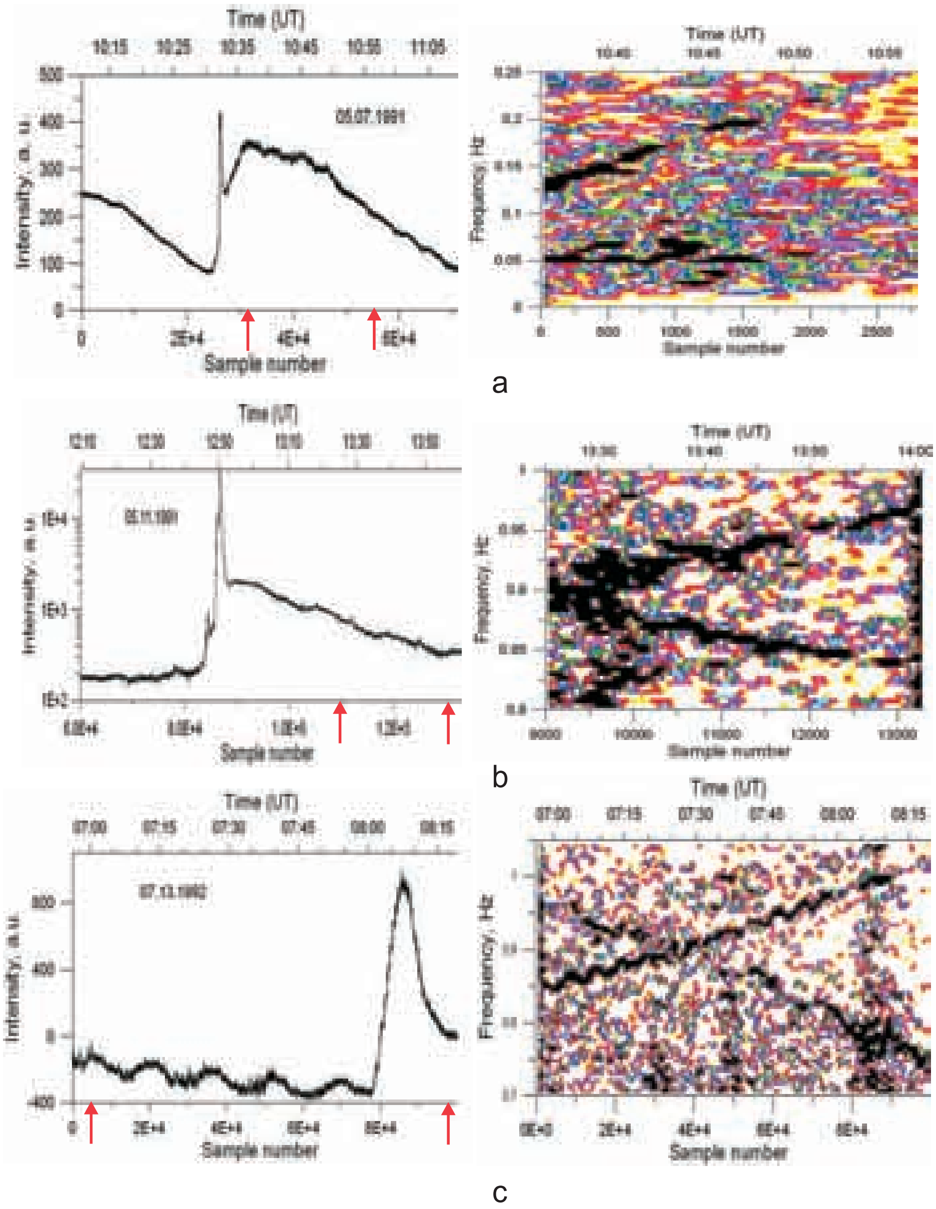


Figure 1: Microwave bursts (at 37 GHz) and dynamical spectra of the LF oscillations modulating the microwave flux (a) May 7, 1991 event; (b) May 11, 1991 event; (c) July 13, 1992 event. Red arrows in the microwave flux plots indicate time intervals for which the dynamic spectra are provided.

few separate, but closely located magnetic loops having slightly different parameters, and involved in a kind of common global dynamical process.

As the most typical examples, we consider here three microwave radio bursts recorded in 1991-1992. For all these events the applied data analysis algorithm allows to resolve in the LF modulation dynamical spectra two separate frequency modulated signals with typical frequencies from ≈ 0.04 to ≈ 1 Hz having either a positive or negative frequency drift.

May 7, 1991 event (Fig.1a): Relatively weak microwave burst with the flux of about 18 sfu, which took place at $10:30-11:08$ UT in the active region $S10W25$. The temporal interval of the LF spectrum corresponds to the time after the burst maximum.

May 11, 1991 event (Fig.1b): Microwave burst with the flux of about 600 sfu which took place at $13:19-13:57$ UT in the same active region as the burst of May 7, 1991. The center of this active region on May 11, 1991 had coordinates $S09W63$. The time interval of the LF spectrum corresponds to the decay phase of the burst.

July 13, 1992 event (Fig.1c): Microwave burst with the flux of about 10 sfu which has been observed at $07:00-08:20$ UT. LF modulation of the microwave radiation here is studied on the time interval before the maximum of the burst.

3 Interpretation and modeling

We interpret the observed multi-track spectra of the LF signal, modulating the microwave radiation, as the signatures of oscillating electric current running within the circuits of closely located coronal magnetic loops interacting with each other. The dynamics of currents can be described by means of the equivalent electric circuit (LCR-circuit) model of a magnetic loop [Zaitsev et al. 1998, Khodachenko et al. 2003].

3.1 LCR-circuit analog of a current-carrying magnetic loop

Complex dynamics of the loops together with action of possible sub-photospheric dynamo mechanisms cause the majority of coronal magnetic loops to be very likely as the current-carrying ones [Melrose 1995]. The current-carrying loops interact with each other via the magnetic field and currents. The simplest way to take into account this interaction consists in application of the equivalent electric circuit model of the loops which includes time-dependent inductances, mutual inductances, and resistances [Khodachenko 2003, 2005]. The equivalent electric circuit model is of course an idealization of the real coronal magnetic loops. A simple circuit model ignores the fact that changes of the magnetic field propagate in plasma at the Alfvén speed V_A. Therefore the circuit equations correctly describe temporal evolution of currents in a system of solar magnetic current-carrying loops only on a time scale longer than the Alfvén wave propagation time $\tau_A = \ell/V_A$, where ℓ is the loop length.

The LCR-circuit equation of the loop is obtained by the integration of the generalized Ohm's law [Khodachenko and Zaitsev 2002] across and along the loop [Zaitsev et al. 1998]. By this, two basic regions are distinguished inside the loop: *Region 1*, or the dynamo region, located in the photospheric footpoints of the loop, influenced by the converging supergranulation flows of the partially ionized photospheric plasma, and *Region 2*, corresponding to the coronal part of the loop. Below we use r_{01}, r_{02} and ℓ_1, ℓ_2 to denote the cross-sectional radii and the lengths of the loop fragments corresponding to the regions 1 and 2 respectively. The whole course of integration yields an equation for the relative variation $y = (I_z - I_{z0})/I_{z0}$ of the oscillating longitudinal current about its equilibrium value I_{z0}. [Zaitsev et al. 2001]. In the case of $|y| \ll 1$ this equation transforms to the equation of a linear oscillator

$$\frac{L}{c^2}\frac{\partial^2 y}{\partial t^2} + \left[R_\Sigma(I_{z0}) - \frac{|V_{r1}|\,\ell_1}{r_{01}c^2}\right]\frac{\partial y}{\partial t} + \frac{y}{C(I_{z0})} = 0, \tag{1}$$

where $L \simeq 2\ell_2\left(\ln\frac{4\ell_2}{\pi r_{02}} - \frac{7}{4}\right)$ is inductance of the LCR circuit of the loop [Landau and Lifshitz 1960]. The resistance term $R_\Sigma(I_{z0}) = R_0 + R(I_{z0})$ in Eq. (1) includes the resistance of the electric circuit of the loop caused by Coulomb conductivity $\sigma = 9 \times 10^6 T^{3/2}$ in the regions 1 and 2 (i.e. σ_1 and σ_2), $R_0 = \dfrac{\ell_1}{\pi r_{01}^2\sigma_1} + \dfrac{\ell_2}{\pi r_{02}^2\sigma_2}$, and the resistance $R(I_{z0}) = \dfrac{3F^2(1+b_1^{-2})\ell_1 I_{z0}^2}{2c^4 n m_i \nu'_{in}\pi r_{01}^4}$, caused by the ion-neutral collisions in the magnetized partially ionized plasma in the footpoints of the loop (region 1). Here $F = \rho_n/\rho$ defines the relative density of neutrals in the dynamo region, ν'_{in} is effective ion-neutral collision frequency connected with the real collision frequency ν_{in} as $\nu'_{in} = \nu_{in}m_n/(m_i + m_n)$, and $b_1 = \frac{2I_{z0}}{cr_{01}B_{z1}(0)}$, where $B_{z1}(0)$ is the longitudinal component of the magnetic field in the region 1 on the axis of the magnetic tube [Zaitsev et al. 2001]. The capacitance term in Eq. (1) has the following form:

$$\frac{1}{C(I_{z0})} = \frac{V_{A1}^2\ell_1}{c^2 r_{01}^2}\left(\frac{4I_{z0}^2}{c^2 r_{01}^2 B_{z1}(0)^2} + 1\right) + \frac{V_{A2}^2\ell_2}{c^2 r_{02}^2}\left(\frac{4I_{z0}^2}{c^2 r_{02}^2 B_{z2}(0)^2} + 1\right), \tag{2}$$

where $V_{A1} = B_{z1}(0)/\sqrt{4\pi\rho_1}$, $V_{A2} = B_{z2}(0)/\sqrt{4\pi\rho_2}$ are characteristic Alfvén speeds in the regions 1 and 2, respectively. Eq.(1) also includes the external electromotive force term which is proportional to $|V_{r1}| \ll \{V_A, C_s\}$, where C_s is the sound speed. It is connected to the convective motion of the partially ionized photospheric plasma in the loop footpoints (region 1). The EMF term causes a feedback in the system [Zaitsev et al. 2001].

Based on Eq. (1), taking into account the expressions for the inductance and capacitance one can obtain the formula for the eigen-frequency of the electric current oscillations in the LCR-circuit of the loop, which for the typical parameters of a coronal loop with $(B_{z1}(0)/B_{z2}(0))^2 < 10^3$, $\ell_1/\ell_2 \sim 10^{-3}$, $(r_{02}/r_{01})^2 > 10^2$, $\rho_2/\rho_1 \sim 10^{-6}$ has the following form [Zaitsev et al. 2001, Khodachenko et al. 2005]:

$$\nu_{LCR} = \frac{c}{2\pi\sqrt{LC(I_{z0})}} \approx \frac{1}{2\pi\sqrt{2\pi\Lambda}}\left(1 + \frac{c^2 r_{02}^2 B_{z2}^2(0)}{4I_{z0}^2}\right)^{1/2}\frac{I_{z0}}{cr_{02}^2\sqrt{nm_i}}, \tag{3}$$

where $\Lambda = \ln\frac{4\ell_2}{\pi r_{02}} - \frac{7}{4}$. As a very important consequence from the Eq.(3), appears the dependence of the eigen-frequency of LCR-oscillations ν_{LCR} on the value of the equilibrium current I_{z0}. Variations of I_{z0} result in a certain drift of the frequency of LCR-oscillations, which in turn modulate the microwave emission and can be detected in the LF spectra. Such an approach is valid, however, only in the case of slow variations of I_{z0} i.e. if $\tau_A < 1/\nu_{LCR} \ll \tau_{curr}$, where τ_{curr} is a characteristic time scale of the current I_{z0} variation [Khodachenko et al. 2005].

The Eq. (1) has been obtained for a coronal loop which is magnetically isolated from the surroundings, i.e. it does not include the effects of mutual inductance connected to a change of external magnetic flux through the circuit of the loop. These effects can be included in the course of integration of the generalized Ohm's law by adding of the mutual inductance electromotive force term $\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\left(\sum_j^N M_j I_j\right)$, where I_j is the current in the neighboring j-th circuit and M_j is the corresponding mutual inductance coefficient [Khodachenko et al. 2003, 2005]. The mutual inductance terms influence slow variation of the equilibrium current I_{z0} in the loop and they can be ignored during the study of relatively fast LCR-oscillations. In that connection one can distinguish between two different kinds of electric current dynamics in the circuit of the loop: 1) *"fast processes"*, i.e. LCR-pulsations of the electric current around the equilibrium value I_{z0}, and 2) *"slow processes"*, i.e. changes of the equilibrium current I_{z0} which, according to the Eq.(3), modulate the frequency ν_{LCR} of the LCR-oscillations.

3.2 Two-loop modeling of observations

Keeping in mind the two-track type of the LF spectra (Fig.1) we consider a system consisting of two inductively connected magnetic current-carrying loops. The major radii of the loops are assumed to increase linearly with time: $R^{(i)}_{\text{loop}} = R^{(i)}_{\text{loop}\ 0} + \upsilon_i t$, $i = 1, 2$. This relative motion of the loops creates significant inductive electromotive forces in their electric circuits which influence the dynamics of electric currents, which in their turn affect the thermal balance of plasma in the loops. Each loop in our model is described by two equations [Khodachenko et al. 2003, 2005]: 1) the equation for the electric circuit of the loop

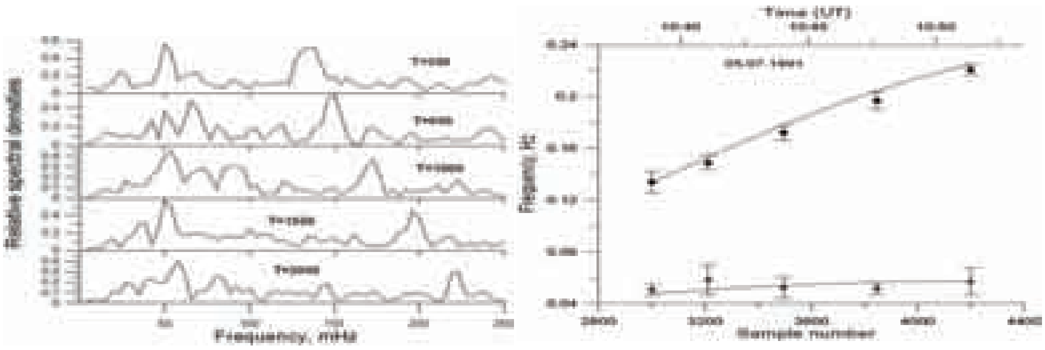
$$I_i R_{\Sigma\ i} = U_{0i} - \frac{1}{c^2}\left(L_i \dot{I}_i + I_i \dot{L}_i + M_{ij}\dot{I}_j + I_j \dot{M}_{ij}\right), \tag{4}$$

and 2) the energy equation

$$\dot{T}_i = \frac{1-\gamma}{2n_i k_B}\left(n_i^2 Q(T_i) - \frac{j_i^2}{\sigma(T_i)} - H_i\right) \tag{5}$$

where the indices i, j indicate the loop number (1 or 2), the dot means the time derivative, and the notation $I_{z0} \equiv I_i$ is applied. U_{0i} in the Eq.(4) is a drop of potential between the loop's footpoints and the resistance term $R_{\Sigma\ i}$ corresponds to $R_\Sigma(I_{z0})$ from the previous subsection, defined as a sum of the Coulomb resistance of a loop and the resistance of its footpoints. In the Eq.(5), T_i and n_i are the plasma temperature and density in the loop, $j_i = I_i/(\pi(r_0^{(i)})^2)$ is the current density, $\gamma = 5/3$ is the adiabatic constant, $Q(T_i)$, the radiative loss function for optically thin emission [Peres et al. 1982], and H_i is a stationary background heating introduced to provide thermal equilibrium in the initial steady state. Within the thin torus approximation, applied for the loops, we use for the mutual inductance coefficients $M_{ij} = M_{ji}$ in the Eq.(4) the approximate expression proposed by Aschwanden et al. [1999]: $M_{ij} = 8\,(L_i L_j)^{1/2}\left[\frac{R^{(i)}_{\text{loop}} R^{(j)}_{\text{loop}}}{(R^{(i)}_{\text{loop}} + R^{(j)}_{\text{loop}})^2 + d_{ij}^2}\right]\cos\varphi_{ij}$, where L_i, L_j are the inductances of the loops, d_{ij}, the distance between the centers of the loops' tori, and φ_{ij}, the angle between the normal vectors to the loops' planes.

The upward motion of the model loops appears as a prescribed feature of the system. The velocity of this motion is one of the free model parameters which, together with



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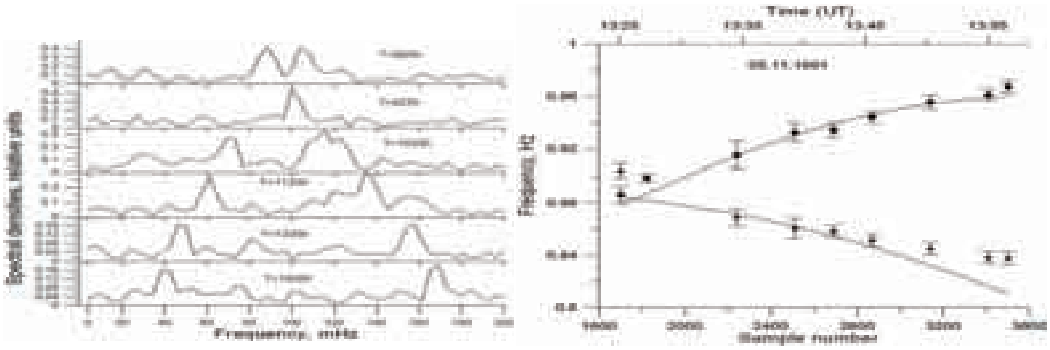

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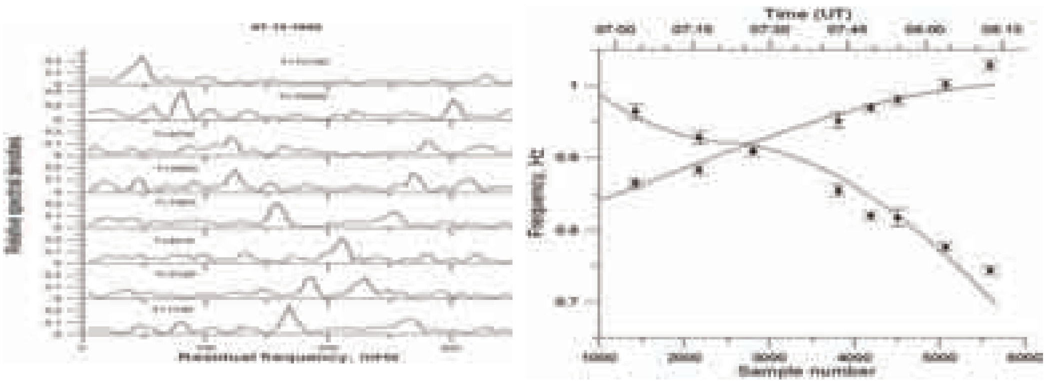

c

Figure 2: Instantaneous spectra of the LF modulation of the microwave flux and their simulation by the model of 2 interacting loops (a) May 7, 1991 event; (b) May 11, 1991 event; (c) July 13, 1992 event.

other model characteristics, finally influence the character of the LCR oscillations in the inductively connected electric circuits of the loops. The energy source for the upward motion is not included in the quantitative self-consistent consideration. It is assumed that the rising motion of the loops is not influenced by their electric currents and the plasma processes inside. In that sense the whole energetics of the system cannot be

Table 1: Two-loop model parameters used for simulation of the observed LF modulations of microwave bursts.

Event	May 7, 1991	May 11, 1991	July 13, 1992
$r_0^{(1)}$	600 km	700 km	590 km
$r_0^{(2)}$	550 km	700 km	510 km
$R^{(1)}_{\text{loop }0}$	$20,000$ km	$20,000$ km	$20,000$ km
$R^{(2)}_{\text{loop }0}$	$1,000$ km	$1,000$ km	$3,000$ km
υ_1	$0.5\ \text{km} \cdot \text{s}^{-1}$	$1.2\ \text{km} \cdot \text{s}^{-1}$	$0.5\ \text{km} \cdot \text{s}^{-1}$
υ_2	$4.5\ \text{km} \cdot \text{s}^{-1}$	$4.9\ \text{km} \cdot \text{s}^{-1}$	$2.5\ \text{km} \cdot \text{s}^{-1}$
T_{01}	10^7 K	10^7 K	2×10^6 K
T_{02}	10^7 K	5.0×10^6 K	1.0×10^6 K
n_1	$1.3 \times 10^9\ \text{cm}^{-3}$	$2.0 \times 10^8\ \text{cm}^{-3}$	$3.5 \times 10^8\ \text{cm}^{-3}$
n_2	$2.4 \times 10^9\ \text{cm}^{-3}$	$4.5 \times 10^8\ \text{cm}^{-3}$	$5.0 \times 10^8\ \text{cm}^{-3}$
I_{01}	1.7×10^8 A	-1.58×10^{10} A	-1.8×10^{10} A
I_{02}	1.7×10^8 A	1.58×10^{10} A	2.3×10^{10} A
B_1	85 G	120 G	170 G
B_2	85 G	120 G	100 G
d_{12}	$2,500$ km	$2,500$ km	$2,500$ km
φ_{12}	$\pi/20$	$\pi/4$	$\pi/4$

considered consistently. At the same time, by taking realistic values of the loop grow rates υ_i we include qualitatively, at the level of energetics of a separate loop, the action of an external energy source responsible for the loop motion.

The Eq.(4) differs from the LCR-circuit equation (1) derived in the previous subsection. The capacitance term $1/C_i \sim U_{0i}/\tau_{curr}$ has been neglected in Eq.(4) for the considered slow processes ($\tau_{curr} \gg 1/\nu_{LCR}$) [Khodachenko et al. 2005]. This allows to reduce the derivative order of the equation. The effects of plasma convection dynamo in the footpoints are included in the external potential term U_{0i}.

The dynamics of electric currents in the system of two inductively connected rising magnetic loops, described by the Eqs.(4),(5), depend on a number of model parameters, such as the initial main radii $R^{(i)}_{\text{loop }0}$ of the loops; the initial temperatures of plasma $T_i(t = 0)$ and electric currents $I_i(t = 0)$; cross-sectional radii of the magnetic tubes $r_0^{(i)}$; loop growing rates υ_i; the values of the longitudinal component of magnetic field in the loops B_i; plasma densities n_i; the distance d_{12} and the angle φ_{12} between the loops. Starting with parameter values typical for a coronal loop, and then varying them, we find those that provide the values of ν_{LCR} and their temporal behaviour in both loops similar to the observed ones in the LF dynamic spectra (Fig.1). The results of this simulation are shown on Fig.2a,b,c, and the corresponding model parameters are summarized in the Table 1. The simulation approach developed here can be considered as a method for the diagnostics of parameters of coronal magnetic loops, using their radiation features. On the other hand, it should be noted that the multi-parametric character of the applied model can result in a non-uniqueness of the sets of magnetic loop parameters corresponding to a particular type of observed LF modulations in microwaves. It is possible that in some cases different groups of model parameters will result in a similar behaviour of the system, i.e. further special study of this subject is needed.

4 Conclusion

The main idea in the background of our study here is that any temporal variations of the electric current and associated magnetic field in a source of solar microwave emission should modulate, because of its electron gyrosynchrotron nature, the intensity of the radiation. Thus, the LF modulations of the microwave radiation intensity can serve as an indicator and a diagnostic tool for the electric current evolution in a radiating source. The nature of the considered LCR oscillations of electric current in the circuit of a coronal magnetic loop is related to the existence of essentially different regions in the loop: 1) dynamo region, containing a moving partially ionized photospheric/chromospheric plasma, and 2) the coronal part of the loop. Convective motion of the partially ionized plasma in the magnetized dynamo region creates charge separation electric fields which in their turn contribute to the formation of Hall currents. In the course of general integration it was possible to express this complex interconnection between the material motions and the self-consistent quasi-stationary electromagnetic environment in terms of the non-linear capacitance. By this the coronal part of the loop works as a large inductance in the global equivalent electric circuit.

The number of two for the spectral tracks is, of course, not a limit. Thinking in terms of the proposed model and taking into account the observed multi-loop structure of the solar active regions, one can expect more low-frequency modulation features in the dynamical spectra. The character of particular spectral tracks will depend on the parameters of corresponding loops and on their dynamics. It is quite possible that these tracks will be located in other frequency intervals outside of the particular, considered here interval. The analyzed two-track spectra mean that there were probably only two current-carrying loops which could provide modulations detected in the considered LF interval $0.01 \ldots 1$ Hz, but this does not mean that there were no other loops which contribute into modulation at other frequencies. It is also necessary to remember that there exist other physical mechanisms which could also result in a slow variation of the background magnetic field and, consequently, in the LF modulation of the solar microwave radio emissions. Due to the known limitations of the model [Khodachenko et al. 2005], the inductive mechanism considered here, seems only to be applicable for the interpretation of modulations in the particular LF interval: $0.01 \div 1$ Hz.

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