Are chains of type I radio bursts generated by similar processes as drifting pulsation structures observed during solar flares?

M. Karlický

Astronomical Institute of the Czech Academy of Sciences, Fríčova 258, CZ – 251 65 Ondřejov, Czech Republic

Received ; accepted

ABSTRACT

Aims. Owing to similarities of chains of type I radio bursts and drifting pulsation structures a question arises if both these radio bursts are generated by similar processes.

Methods. Characteristics and parameters of both these radio bursts are compared.

Results. We present examples of the both types of bursts and show their similarities and differences. Then for chains of type I bursts a similar model as for drifting pulsation structures (DPSs) is proposed. We show that similarly as in the DPS model, the chains of type I bursts can be generated by the fragmented magnetic reconnection associated with plasmoids interactions. To support this new model of chains of type I bursts, we present an effect of merging of two plasmoids to one larger plasmoid on the radio spectrum of DPS. This process can also explain the "wavy" appearance of some chains of type I bursts. Then we show that the chains of type I bursts with the "wavy" appearance can be used for estimation of the magnetic field strength in their sources. We think that differences of chains of type I bursts and DPSs are mainly owing to different regimes of the magnetic field reconnection. While in the case of chains of type I bursts the magnetic reconnection and plasmoid interactions are in the quasi-separatrix layer of the active region in more or less quasi-saturated regime, in the case of DPSs, observed in the impulsive phase of eruptive flares, the magnetic reconnection and plasmoid interactions are in the current sheet formed under the flare magnetic rope, which moves upwards and forces this magnetic reconnection.

Key words. Sun: radio radiation – Sun: activity – Sun: flares

1. Introduction

Solar radio bursts are generally divided into five groups designated as type I, II, III, IV and V (Kundu 1965). Most of them show fine structures, especially type IV bursts: fibers, zebra patterns, spikes and pulsations (Krueger 1979).

In the present paper we study two types of bursts: type I bursts (Elgarøy 1977) and special type of the pulsations called drifting pulsation structures (DPSs) (Krueger & Benz 1994; Jiřička et al. 2001; Kliem et al. 2000; Karlický et al. 2001, 2002; Khan et al. 2002; Karlický 2004; Isliker & Benz 1994; Nishizuka et al. 2015; Khan et al. 2002). Type I radio bursts (noise storms) are quite common and they are associated with the active region passage over the solar disc (Elgarøy 1977; Krueger 1979). They appear in clouds of short duration and narrow bandwidth bursts (0.1 - 3 s; several MHz), superimposed on a broadband continuum. The polarization of type I bursts is in most cases the same as the background continuum polarization. While the polarization up to 100% is observed for the noise storms located close to the solar disc center, at the solar limb their polarization is lower (Kai et al. 1985). The type I bursts are structured, they form chains of type I bursts (in short type I chains) (Elgarøy & Ugland 1970). These chains preferentially drift towards lower frequencies and their drift is used for estimations of the magnetic field in their sources (Gopalswamy et al. 1986; Sarma 1994; Sodré et al. 2015). Sometimes the type I chains even oscillate in frequencies ("wavy" appearance on dynamic spectrum) (Elgarøy 1977).

Recently, Mercier et al. (2015) have found that noise storms consist of an extended halo and several compact cores which intensity is changing over a few seconds. Regions, where storms were originated, were much denser than the ambient corona and their vertical extent was smaller than estimated from hydrostatic equilibrium.

Moreover, Mandrini et al. (2015) have proposed that persistent magnetic reconnection along quasi-separatrix layers of the active region is responsible for the continuous metric noise storm.

Several models of type I bursts were proposed, see the book of Elgarøy (1977) and Kai et al. (1985). Among them the most promising models are those based on the plasma emission mechanism, e.g., the model by Spicer et al. (1982) connecting the type I chains with weakly super-Alfvenic shocks generated in the front of emerging magnetic flux.

In solar flares, in the decimetric range, pulsations are quite common (Aschwanden 1986; Krueger 1973; Aschwanden 2004). Among them a special type of the pulsations called now drifting pulsation structures (DPSs) have been recognized and interpreted (Kliem et al. 2000; Karlický et al. 2001, 2002; Khan et al. 2002; Karlický 2004; Isliker & Benz 1994; Jiřička et al. 2001; Nishizuka et al. 2015). They are relatively narrowband and drifting mostly towards lower frequencies. They are usually observed during the impulsive phase of eruptive flares in
Fig. 1. Examples of the chains of type I radio bursts observed in the metric range by the Callisto Trieste radiospectrograph.

Fig. 2. Examples of the drifting pulsation structures (DPSs) observed in the decimetric range during solar flares by the Ondřejov radiospectrograph [Jiricka & Karlický 2008].
the 0.6 - 3 GHz frequency range in connection with the plasmoid ejection.

Nice example of the plasmoid ejection, observed in soft X-rays during the 5 October 1992 event, is described in the paper by Ohyama & Shibata (1998). It is is shown that the plasmoid is a small part of the 3-D loop (Figures 2, 5a, and 10 in Ohyama & Shibata 1998). Further analysis showed that the plasmoid is a small part of the 3-D current-carrying loop which is embedded in the current sheet, where the flare magnetic reconnection takes place (see Figure 2 in Savage et al. 2012). The magnetic reconnection accelerates superthermal electrons (Drake et al. 2005, 2006; Pritchett et al. 2008, 2009) that are then trapped in a denser O-type magnetic structure, which thus becomes "visible" in the soft X-rays (Ohyama & Shibata 1998), EUV (Takahao et al. 2012) or at 17 GHz radio waves (Karlický & Kliem 2010) as the plasmoid. A limited extent of the plasmoid along the loop (i.e. trapping of superthermal electrons along the loop) can be explained by a complexity of magnetic field lines at the plasmoid as shown in the 3-D kinetic simulation of the magnetic reconnection (Guo et al. 2013) or by the distribution of superthermal electrons with the high-pitch angles only. Further possibilities of this trapping are discussed in the paper by Ohyama & Shibata (1998). The plasmoid in 3-D has a cylindrical form, which in its 2D models (invariant in the third coordinate) corresponds to circular magnetic structure having the plasma density greater than that in the surrounding plasma, see Bártá et al. (2008a) and the following Figure 3.

The model of DPSs was developed in papers by Kliem et al. (2000); Bártá et al. (2008a, 2011); Karlický et al. (2010); Karlický & Bártá (2011). In the 5 October 1992 event the frequency of DPS was found to be close to the plasma frequency derived from the plasmoid density, see Figure 1 in the paper by Bártá et al. (2008a). Therefore in the DPS model the plasma emission mechanism is considered. In the flare current sheet, during the magnetic reconnection plasmoids are generated due to the tearing mode instability. At X-points of the magnetic reconnection superthermal electrons are accelerated (Karlický 2008). Then these electrons are trapped in a nearby plasmoid (O-type magnetic field structure), where they generate plasma waves that after their conversion to electromagnetic waves produce DPSs (see Figure 9 in Karlický et al. (2010)). The narrow bandwidth of DPSs is given by the limited interval of the plasma densities (plasma frequencies) inside the plasmoid. In the flare current sheet plasmoids preferentially move upwards in the solar atmosphere (due to a tension of the surrounding magnetic field lines) in the direction, where the electron plasma density decreases, i.e. is consistent with the O-mode (Kai et al. 1985), for DPS it is unclear. Periods of repetition of type I bursts in chains and pulsations in DPSs are similar, from fractions of second to several seconds.

As shown in Table 1 some parameters of type I chains and DPSs are comparable (duration and brightness temperature), other parameters differ. However, type I chains are observed in metric range and DPSs in decimetric range, i.e. in different latitudes of the solar atmosphere with different densities, different density gradients and magnetic field strengths. Moreover, while DPSs are usually observed during the impulsive phase of eruptive flares (Nishizuka et al. 2013), type I chains are a part of noise storms connected with the reconnection activity at the quasi-separatrix layer in active region (Mandrini et al. 2015).

As concerns an appearance of the chains of type I bursts and DPSs (Figures 1 and 2) they look to be similar. The both types of bursts preferentially drift towards lower frequencies. In rare cases both reveal "wavy" appearance, see the chain of type I bursts observed in July 2, 2012 (Figure 1 the upper right part) and DPS observed in June 30, 2002 (Figure 2 the upper right part).

3. New model of type I chains

Considering all observational parameters of the both burst types and differences in conditions in their generation we propose that the type I chain is produced by very similar processes as DPS; they differ only in plasma parameters and initial conditions. Therefore the model of the drifting chain of type I bursts can be explained as follows:

During the magnetic reconnection in the current sheet formed in the quasi-separatrix layer of the active region the current-carrying loops are generated. In the magnetic reconnection between interacting current-carrying loops there are
Table 1. Typical parameters of the type I chains and DPSs. $T_b$ means the brightness temperature.

|                  | Frequency range (MHz) | Bandwidth (MHz) | Duration (s) | Drift rates (MHz s$^{-1}$) | Polarization | $T_b$ (K) | Size (arcsec) |
|------------------|-----------------------|-----------------|--------------|-----------------------------|--------------|----------|--------------|
| Type I chain     | 30 – 400              | 5 – 20          | 10 – 200     | -1.0 – +0.3                 | up to 100    | $\leq 10^{10}$ | $\sim 40$   |
| DPS              | 600 – 3000            | $\sim 200$     | $\sim 60$   | -10 – +5                    | $\sim 30$   | $\sim 8 \times 10^{9}$ | $\sim 10$   |

Fig. 3. Magnetic field lines and densities (grey shades) showing merging of two plasmoids ($P_1$ and $P_2$) into larger plasmoid $P$ which oscillates. The panels (from left to right) are shown for $t = 80, 90, 100$ and $110$ s, respectively.

are the X-magnetic points, where electrons are accelerated. These electrons penetrate into interacting loops at their interaction region. This region (plasmoid) is simultaneously rapidly heated. For the acceleration process and penetration of electrons to interacting current-carrying loops, see Figure 3 in the paper by Karlický (2008).

As seen in Figures 2, 5a, 10 in the paper by Ohyama & Shibata (1998), the observed plasmoid in the DPS case is a small part of the loop. We assume that a similarly spatially limited plasmoid is also formed in the case of the drifting chain of type I bursts. The limited extent of the plasmoid means that the hot plasma (observed in soft X-rays in the DPS case) is trapped by some processes in this plasmoid also in direction along its axis. Some processes explaining this trapping were proposed in the paper by Ohyama & Shibata (1998). But based on the papers by Guo et al. (2014) and Fujimoto (2016) we think that this trapping is mainly due a complexity of magnetic field lines in the plasmoid. Considering the observational evidence about the hot plasma confinement in the plasmoid, we assume that also superthermal electrons (accelerated during the interaction of the current-carrying loops) are trapped in the plasmoid. (Note that in the perpendicular direction to the plasmoid axis the hot plasma as well as superthermal electrons are kept by the magnetic field in the plasmoid.)

These trapped superthermal electrons generate in the plasmoid the Langmuir (electrostatic) waves, which are then transformed into the electromagnetic (radio) waves, observed as type I chains. These processes are shown in details in the paper by Karlický et al. (2010). There, using a 2.5-D particle-in-cell model, we self-consistently described not only the interaction of plasmoids, but also how the electrostatic (Langmuir) and electromagnetic (radio) waves are generated. We found that the distribution of superthermal electrons, penetrating the plasmoid, is unstable for the Langmuir waves (due to the bump-on-tail instability) and then these electrostatic waves are transformed to the electromagnetic (radio) waves, see Figure 9 in this paper. In agreement with the models of type I bursts based on the plasma wave theories (Elgarøy 1977), we assume that the emission of type I bursts is dominant on the fundamental frequency and the processes (e.g. the coalescence of two Langmuir waves) giving the emission on the harmonic frequency are not effective. The observed polarization of type I bursts is up to 100 percent. To reach such high polarization, in agreement with Takakura (1963), and Melrose (1980, page 271), we assume that the type I burst emission is in O-mode generated in the region where the emission frequency $\omega$ is greater than the plasma frequency $\omega_{pe}$ and smaller than the cutoff frequency for the X-mode $\omega_x$. This
O-mode (electromagnetic one) is generated from Langmuir waves by scattering on thermal ions and in such a case the frequency of the resulting emission is essentially equal to that of Langmuir waves \( \omega = \omega_{pe}(1+3\omega_{ce}/\omega_{pe})^{1/2} \), where \( \omega_{ce} \) is the thermal plasma velocity and \( \omega_{pe} \) is the phase velocity. Now using the commonly accepted assumption that in the type I burst source the electron gyro-frequency \( \omega_{ce} \) is much smaller that the plasma frequency, we have \( \omega_x \approx \omega_{pe} + 1/2 \omega_{ce} \). Then the above mention condition \( \omega \geq \omega_{ce} \) gives a lower limit for the phase velocities of generated Langmuir waves, expressed as \( v_{\phi} \geq v_{ce}(3\omega_{ce}/\omega_{pe})^{1/2} \). Because the Langmuir waves with the phase velocity \( v_{\phi} \) are produced by electrons having velocities greater than \( v_{\phi} \), it also gives a lower limit for energies of energetic electrons.

Due to a limited interval of densities inside the plasmoid, the trapped superthermal electrons generate Langmuir waves in the limited interval of plasma frequencies and thus the instantaneous bandwidth of type I chain is limited. Because the plasmoid expands or moves upwards in the solar atmosphere, plasma densities inside the plasmoid decrease, and therefore most of type I chains drift towards lower frequencies. Similarly as in DPSs, the acceleration of superthermal electrons is quasi-periodic which leads to quasi-periodic repetition of type I bursts (which form the type I chain) with the typical period of about one second. If accelerated electrons are trapped in several plasmoids simultaneously then several type I chains are simultaneously generated. Thus, type I chains can be mutually superimposed in the radio spectrum (if there are similar densities in the plasmoids) or they are separated in frequencies in the radio spectrum, if densities inside plasmoids are different.

As already mentioned, in some cases of type I chains and DPSs there is also similarity in their "wavy" appearances. Up to now this feature was not explained in any model of type I chains. In the DPS model, during the flare magnetic reconnection below the rising magnetic rope, plasmoids are formed due to the tearing mode instability (Kliem et al., 2008; Karlický, 2014). The plasmoids can merge to larger plasmoids which after this merging (coalescence) process start to oscillate with the period \( P \sim L/v_\Lambda \), where \( L \) is the characteristic length in the merging process and \( v_\Lambda \) is the local Alfvén speed (Taijima et al., 1983). Oscillations of the plasmoid (compression and expansion) periodically change densities inside the plasmoid and thus periodically change the plasma frequencies and frequencies of DPS. Just this process was proposed for explaining of quasi-periodic variations of frequencies ("wavy appearance") of DPSs (Karlický et al., 2014). Here the same process is proposed for explanation of the "wavy" appearance of type I chains.

To illustrate it, we made similar numerical simulations as in the paper by Bártá et al. (2008b), see Figure 3, where two plasmoids (\( P_1 \) and \( P_2 \)) merge into one larger plasmoid \( P \). After merging the resulting plasmoid starts to oscillate. Figure 3 shows time evolution of this merging and oscillating process expressed by positions of the selected magnetic field lines (with fixed magnetic vector potential) at the top and bottom of the plasmoids at the axis of the vertical and gravitationally stratified current sheet \( (x = 0 \text{ in Figure 3}) \). In our case the period of the oscillation is about 22 s. From computations we know the maximal and minimal densities inside plasmoids (which are delimited by the selected magnetic field lines) and then assuming the emission based on the plasma emission mechanism we computed the artificial radio spectrum shown in Figure 5. The vertical lines in this DPS spectrum mimic pulses with the typical period of about one second. Namely, the pulses are generated on the kinetic level of the plasma description and thus their generation cannot be included into the used magnetohydrodynamic simulation.

As seen in Figure 5 the artificial drifting pulsation structure has the "wavy" appearance. When the oscillating plasmoid is compressed then the frequency band of the drifting pulsation structure is shifted to higher frequencies and vice versa. Compare this artificial drifting pulsation structure with that, observed in June 30, 2002, shown in Figure 2 (the upper right part). For details of computations, see Bártá et al. (2008b).

Because type I chains and DPSs with the "wavy" appearance are relatively rare, it indicates that the full merging of two plasmoids with comparable sizes into one larger and oscillating plasmoid is also relatively rare.

In previous models the frequency drift of type I chains is connected with the the Alfvén speed at the source of type I chain, e.g., in the model by Skjærven (1952) and thus used for the magnetic field estimations (Sodré et al., 2015). However, in the new model the speed of the plasmoid can be in the range from zero up to the local Alfvén speed, see Bártá et al. (2008b).

Type I chains are limited from the high-frequency side at about 400 MHz. It is commonly believed that it is due to the collisional optical depth of the emission increases with the frequency to the square (Benz, 1993). On the other hand, the range of type I chains (below \( \sim 400 \text{ MHz} \)) shows that these chains are generated at upper parts of the active-region loops located close to the quasi-separatrix layers of the active region as proposed by Mandrini et al. (2012).

DPSs are observed on higher frequencies than type I chains, at which in the "quiet" conditions of the solar atmosphere the plasma emission is fully absorbed. However, during solar flares the atmosphere becomes highly inhomo-geneous and thus transparent for the plasma emission even in the decimetric range.

If the size of the resulting plasmoid \( (L) \), formed during a merging process, is estimated (e.g. from the instantaneous frequency bandwidth of the chain and some density model of the solar atmosphere), then the period \( (P_W) \) of the chains with the "wavy" appearance can be used for further estimation of the magnetic field strength \( B \) in the chain radio source (the Alfvén speed is \( v_\Lambda = B/\sqrt{\mu_0 \rho} \sim L/P_\text{ch} \), where \( \mu_0 \) is the magnetic permeability of free space and \( \rho \) is the plasma density, that can be determined from the frequency of the chain, see also Taijima et al. (1987)).

There is an important difference in processes generating type I chains and DPSs. While, in DPSs the magnetic reconnection is forced by the positive feedback between the magnetic reconnection and plasma inflow, given by the ejection of the whole flare structure upwards, in the processes generating type I chains this positive feedback in the magnetic reconnection is missing.

These two regimes (without and with the positive feedback) of the magnetic reconnection together with plasmoids generating type I chains and drifting pulsation structures can be seen, e.g., in the 2012 July 12 flare (Dudík et al., 2014). Before the flare (at 15:00 – 16:16 UT) chains of type I bursts (noise storm) and then during the flare impulsive
phase (at 16:16 UT), when the flare magnetic rope was ejected, the drifting pulsation structures were observed.

Fig. 4. Plot showing the merging process of two plasmoids (P₁ and P₂) along the axis of the vertical and gravitationally stratified current sheet to one larger and oscillating plasmoid P; compare with Figure 3.

Fig. 5. The artificial radio spectrum of DPS with the "wavy" appearance corresponding to merging process of two plasmoids into one larger and oscillating plasmoid as presented in Figures 3 and 4. Vertical lines mimics pulses in DPS with the typical period of DPS (about 1 s).

4. Conclusions

As shown in previous section some parameters of type I chains and DPSs are similar (duration, repetition period of type I bursts in the type I chain and that of pulses in DPS, preference of the frequency drift towards lower frequencies, brightness temperature and "wavy" appearance in some cases) and other parameters like frequency range, bandwidth, frequency drift, source size and polarization are different. However, the differences can be caused by different conditions where type I chains and DPSs are generated (different altitude in the solar atmosphere, different densities, different density gradients and different magnetic field strengths).

Therefore, considering all these similarities and differences we propose a new model of chains of type I bursts that is very similar to the DPS model. Although the magnetic reconnection was already proposed for explanation of noise storms (Mandrini et al. 2015), this new model is more specific about the processes generating the chains of type I bursts, which are a part of noise storms. The chains of type I bursts are considered to be radio signatures of processes that heat the solar corona. Therefore, a correct model of these processes can contribute to a solution of the problem of the hot solar corona.

We show that the chains of type I bursts can be generated by the magnetic reconnection associated with plasmoids (parts of current-carrying loops). While a trapping of accelerated superthermal electrons in a single plasmoid leads to normal type I chain (without the "wavy" appearance), the trapping of superthermal electrons in an oscillating plasmoid, which can be the result of merging of two smaller plasmoids, produces the type I chain with the "wavy" appearance.

Similarly as in DPSs, individual type I bursts (forming the type I chain) are generated by quasi-periodic acceleration of superthermal electrons and their plasma emission. The frequency drift of these individual type I bursts can be caused by propagation of these superthermal electrons inside the plasmoid.

We think that differences of both these types of bursts are also owing to different regimes of the magnetic reconnection. While in the case of type I chains the magnetic reconnection and plasmoid interactions are in the quasi-separatrix layers of the active region in more or less quasi-saturated regime, in the case of DPSs the magnetic reconnection and plasmoids formation and their interactions are forced by the upward motion of the flare magnetic rope.

The new model can explain the "wavy" appearance of some chains of type I bursts by the merging of two plasmoids into one larger and oscillating one. This feature was not up to now explained.

We showed that the chains of type I bursts with the "wavy" appearance can be used for estimation of the magnetic field strength in their sources. Unfortunately, examples of the chains of type I bursts with the "wavy" appearance are rare.

DPSs are generated in deeper and denser layers of the solar atmosphere than chains of type I bursts. In the "quiet" coronal conditions the plasma radio emission from these deep and dense layers is absorbed. However, during the impulsive phase of solar flares these deep and dense layers are strongly disturbed and thus they become transparent also for the DPS emission.

This new model can also explain the finding that the vertical extent of the noise storm is smaller than estimated from hydrostatic equilibrium (Mercier et al. 2015). Namely, complicated magnetic field structure in the region with plasmoids can shorten the density scale-height similarly as was proposed for microwave type III pair bursts by Tan et al. (2016). Furthermore, this model explains an enhanced density in the noise storm source comparing to the ambient corona (Mercier et al. 2013). As was shown, the plasmoids, where the type I chains are generated, are denser than the surrounding plasma.

In this new model the plasmoid velocity, which is assumed to be connected with the frequency drift of the type I chain, is in the range from zero to the local Alfvén speed; contrary to previous models, where the velocity of the agent producing the frequency drift were strictly the Alfvén speed. It should be taken into consideration when the frequency drift of type I chains is used for magnetic field estimations.

There are still many questions, especially about the plasmoid formation, its magnetic structure and evolution of the superthermal electrons in real 3-dimensional config-
uration. For their answers new simulations in extended 3-D kinetic models are necessary.

Acknowledgements. The author thanks the referee for constructive comments that improved the paper. He acknowledges support from Grants 16-13277S and 17-16447S of the Grant Agency of the Czech Republic.

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