Solar Drift-Pair Bursts

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Accepted: 9 February 2017

Abstract In this paper a new sight on the study of solar bursts historically called drift pairs (DPs) is presented. Having a simple morphology on dynamic spectra of radio records (two short components separated in time, and often they are very similar) and discovered at the dawn of radio astronomy, their features remain unexplained totally up to now. Generally, the DPs are observed during the solar storms of type III bursts, but not every storm of type III bursts is linked with DPs. Detected by ground-based instruments at decameter and meter wavelengths, the DP bursts are limited in frequency bandwidth. They can drift from high frequencies to low ones and vice versa. Their frequency drift rate may be both lower and higher than typical rates of type III bursts at the same frequency range. The development of low-frequency radio telescopes and data processing provide additional possibilities in the research. In this context the fresh analysis of DPs, made from recent observations in the summer campaign of 2015, are just considered. Their study was implemented by updated tools of the UTR-2 radio telescope at 9-33 MHz. During 10-12 July of 2015, DPs forming the longest patterns on dynamic spectra are about 7% of the total number of recorded DPs. Their marvelous resemblance in frequency drift rates with the solar S-bursts is discussed.

Introduction

The drift-pair bursts have long been known, starting with pioneering work of Roberts (1958), where he firstly drew attention to a special shape of radiation observing from the solar corona. The DPs appear as two parallel drifting ridges, similar to each other, on the dynamic spectrum. Most of the radio observations of such bursts were performed at 60-80 years of the last century (Ellis, 1969; de la Noë and Møller-Pedersen, 1971; Abranin et al., 1977; Møller-Pedersen, Smith, and Mangeney, 1978; Suzuki and Gary, 1979; Thejappa et al., 1986). The manifestations of solar DP activity occur at decameter and meter wavelengths (up to 80 MHz) during the solar storms of the type III bursts. But the relationship between the DPs and the type III bursts are unclear so far, and the understanding of the mechanism of the DP generation is not as successful for the type III bursts or the type II bursts. The most recent papers (Melnik et al., 2005; Litvinenko et al., 2016) were devoted to the study of decameter drift-pair bursts by utilizing the radio telescope UTR-2 (Braude et al., 1978). However, the observations applied the analog multichannel receiver (10-30 MHz), tuned to selected 60 frequencies with the frequency bandwidth 10 kHz in each frequency channel, and DSP (Digital Spectral Polarimeter) was carried out the fast Fourier analysis in the continuous frequency band 17.6-29.8 MHz with frequency (12 kHz) and time (100 ms) resolution. In recent years, thanks to advances in low-frequency radio astronomy, the quality of radio observations of solar bursts by ground-based instruments has increased significantly (see, for example, Konovalenko et al., 2016 and references therein). The aim of this paper is to present results of new observations of DPs useful for the study of their properties as well as for finding interrelations between them.

Observations and Facilities

The solar radio emission was received with the UTR-2 antenna to the digital receiver/spectrometer operating with the time resolution of 50 ms and the frequency resolution of 4 kHz. This antenna array consists of wideband horizontal dipoles, and it is not appropriate for polarization measurements of radio emission. We used four section of the UTR-2 array. The total effective area of these sections is 50 000 m^2 with the beam pattern size of 1°×15° at 25 MHz. This is enough to cover the whole corona at low frequencies. On 10-12 July 2012 we observed some hundreds of solar DP bursts with both forward and reverse drift (see, as an example, the dynamic spectrum on Figure 1). For forward DPs (or briefly FDPs) the average frequency bandwidth was 3.6 MHz, whereas for reverse DPs (RDPs) it was 2.82 MHz. Most of the registered DPs were really pairs on the dynamic spectrum, but we have also detected some vertical DPs as well as several single and multiple bursts like DPs. The frequency drift rate of DPs varies from event to event in the frequency range 9-33 MHz and in time. The drift rate histogram of FDPs was a symmetric shape with the average equal to about -0.74±0.28 MHz s^{-1}, whereas for RDPs the mean becomes 1.36 MHz s^{-1} under the histogram with a long tail. Basically the flux of the DP bursts was about some hundreds s.f.u. Recall here that 1 s.f.u. = 10^{-22} W/(Hz m^2). In each drift pair we can distinguish two components almost identical in frequency-time properties. Each of them had the duration equal to

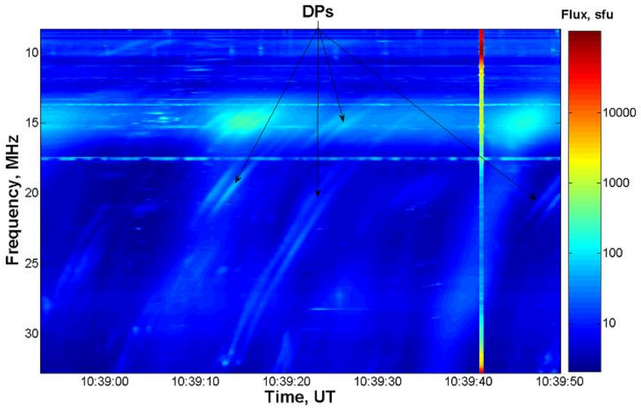

Figure 1: An illustrative dynamic spectrum of the drift-pair bursts (including long DPs) imposed on type III bursts obtained from the UTR-2 observations on 11 July of 2015. Here the bright vertical line indicates a phase shifter switching, and the conspicuous horizontal line was caused by intensive interferences due to broadcast radio stations. Note that SWPC/NOAA did not report any burst during the time of the drift-pair bursts observed by UTR-2.

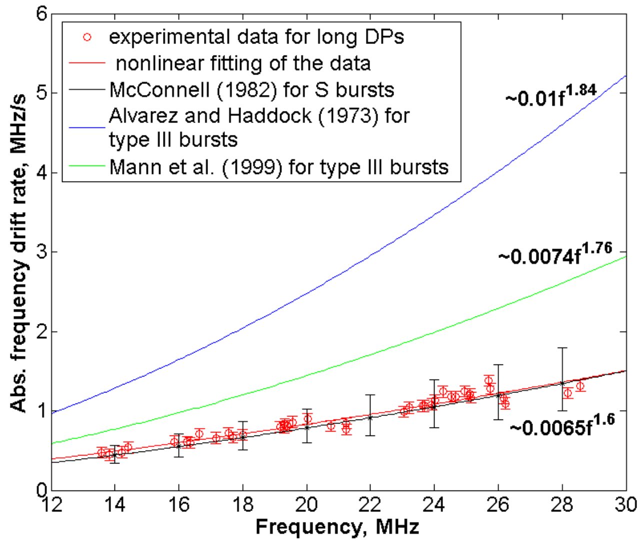

Figure 2: Comparative analysis of the absolute frequency drift rates for long DPs, type III bursts and solar S-bursts in dependence of frequency at decameter wavelengths with the use of data from various references (see them in the end of this report). Each circle corresponds to a single DP for which the frequency drift rate is determined on the central frequency of this chosen long DP.

about 1-2 s, and the time delay between the components was 1.5-2.5 s.

On 10-12 July of 2015, according to the space-based observations of STEREO, GOES and SOHO, the solar activity was weak, i.e. some C-class X-ray flares. The solar events were accompanied with the active regions NOAA AR 12381 located N14W25 on 10 July of 2015. The sunspot group belonged to the magnetic β class. Although SWPC/NOAA did not report any burst during the time of the drift-pair bursts observed by UTR-2, a few instruments of the e-Callisto network observed very short (in time and frequency) and weak bursts at the time of the drift-pair bursts.

Long Drift-Pair Bursts

To study the frequency drift rates of DPs, the long events are the most appropriate. The point is that their data processing permits us to provide the best fitting of the "centre" of the intensity hump for the DP burst under consideration on dynamic spectra. During the observations of 10-12 July 2012, we have detected 20 long FDPs and the only one long RDP. Their bandwidth was about 8-15 MHz. Particularly, Figure 1 demonstrates some examples of such events. As a fitting function, we have taken the form

$$f(t) = a(t-b)^{-\gamma}, \qquad (1)$$

where a,b,γ are the parameters leading to the best-fitting result. It is not difficult to show that in this case the frequency drift rate satisfies to the relation

$$\dot{f}(f) = Kf^{\nu}, \qquad (2)$$

where K and ν are constants, depending only on a and γ, namely $K=-\gamma a^{-1/\gamma}$ (sign means a negative drift rate) and $\nu=1+1/\gamma$. As usual, the doted symbol denotes the time derivative.

Based on the procedure, we have analyzed frequency-time properties of the long DPs. The results are presented in Figure 2. The frequency drift rate of long DPs is lower than the rates in the typical type III bursts at decameter wavelengths, but it is similar to the solar S-bursts in the same frequency range of observations according to McConnell (1982). In the case of the long DPs the best fitting of their frequency drift rate satisfies to the following equation (here the frequency in MHz and the frequency drift rate in MHz/s)

$$\dot{f}(f) = -0.01 f^{1.47}. \qquad (3)$$

According to the study, we have found that formula (1) is not only suitable for the description of frequency drift rates of the long DPs, but for all DPs observed in 10-12 July of 2015. Their detailed analysis of frequency drift will be held elsewhere.

Interpretations

The simplest interpretation of the DP generation was based on the assumption that the drift pairs are similar to the type III bursts in the mechanism of generation, but the first component escapes directly from the corona whereas the second component is a reflection (something like an echo) proposed by Roberts (1958). Unfortunately, any similar "echo" for other types of bursts is not observed. On the other hand, the scattering of the reflected radiation would produce the second element more diffuse (than the first component) not observed too. The contradictions have led to the development of other models for understanding the mechanism provoking the generation of DPs (Zheleznyakov, 1965; Abranin et al., 1977; Møller-Pedersen, Smith, and Mangeney, 1978; Zaitsev and Levin, 1978; Melrose, 1982). Their detailed comparison can be found in the papers of Thejappa (1988) and Melnik et al. (2005). The main outcome of their overview is that most of the interpretations can explain only a limited number of characteristics typical for DPs, and any simple interpretation based on one or two observational facts like frequency drift rate and so on will not explain all the features of the DPs self consistently.

In this context the theory of Zaitsev and Levin (1978) could be considered as promising. The model is based on the excitation of plasma waves in those layers of the corona where the condition of double plasma resonance is satisfied. This approach provides some very important clues to understand the strange implementations of DPs such as vertical DPs, DP chains and others. Any other model (Zheleznyakov, 1965; Abranin et al., 1977; Møller-Pedersen, Smith, and Mangeney, 1978; Melrose, 1982) cannot explain their generation totally. In fact, the vertical DPs, which occur simultaneously in all the frequencies, are difficult to interpret by means of a moving source, as any exciting agent responsible for such bursts will travel with velocities faster than velocity of light that is impossible. Nevertheless, the formula of frequency drift rate for DPs derived by Zaitsev and Levin (1978) contains the denominator tending to zero under certain conditions. First this feature has been noticed by Thejappa (1988). However, the general solution of that task has not been established yet. Thus, it would be useful to consider the problem below.

For this purpose, we write the denominator equal to zero as a differential equation (see more details in Zaitsev and Levin, 1978; Thejappa, 1988)

$$\frac{1}{2N_e}\frac{\partial N_e}{\partial z} - \frac{1}{H}\frac{\partial H}{\partial z} = A\frac{\sqrt{N_e}}{H}, \qquad (4)$$

where N_e is the electron density of the solar corona, H the magnetic field strength, A the constant (under assumptions of Thejappa, 1988 it was equal to 0. 00093), z the distance from the injection region. If we denote $M = \sqrt{N_e}/H$, then the above equation takes the simplest form

$$\frac{1}{M}\frac{\partial M}{\partial z} = AM. \qquad (5)$$

Its solution reads

$$M(z) = \frac{M(0)}{1 - AM(0)z^2}, \qquad (6)$$

where $M(0) = \sqrt{N_e(0)}/H(0)$ is the boundary condition. If, as a reasonable example, we use the model of magnetic field strength $H(z) = 0.5(z + a - 1)^{-1.5}$ (Dulk and McLean, 1978) and the model of electron density $N_e = 4.2 \times 10^4 \times 10^{4.2/(z+a)}$ (Newkirk, 1971) for the solar corona, then the formula (4.9) of Thejappa (1988) will be obtained right away whereas the formula (4.13) of Thejappa (1988) gives a rough estimate only. In particular, we take the parameter $a = 1.4$ corresponding to the plasma frequency equal to ~65 MHz in the Newkirk model (Thejappa, 1988). It should be pointed out that the derived solution includes two variables, $N_e(z)$ and $H(z)$. Only one of them may be independent whereas another will be dependent on the former. As $M = \sqrt{N_e}/H$ is a fraction, there are two different cases in the behavior of $N_e(z)$ and $H(z)$. Observe that the variable $M(z)$ tends to infinity as $z \to z_{cr}$. If the electron density (independent variable) decreases with height above the solar photosphere, then the magnetic field strength (dependent one) drops too. But if the magnetic field strength (independent variable in this case) falls with height, then the electron density (dependent one) will tend to infinity. In any case the result of this analysis will be the same, i.e. the frequency drift rate of such DPs tends to infinity in this approach (Zaitsev and Levin, 1978).

Now therefore, more accurate radio observations of DPs (with high resolution) require building a new model of DP generation. As it is not yet, any empirical study, i.e. the searching of empirical implicit dependences between DP properties, is of undoubted interest.

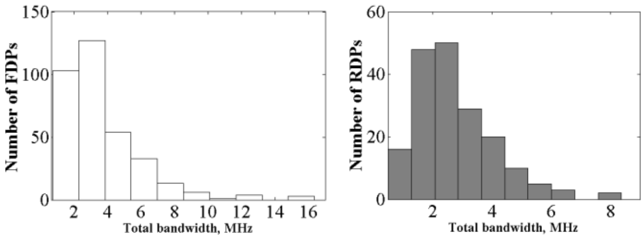

Figure 3: Frequency bandwidth histograms obtained for FDPs and RDPs according to the observations in 10-12 July of 2015.

Results

The total frequency bandwidth of DPs is one of simple parameters which are easy to measure in the radio data. In the frequency range of our radio instrument the DP bursts have clearly a limited frequency bandwidth. Their appearance in frequency-time plane (dynamic spectrum) has a random nature. The same goes for the central frequency of DPs. The total frequency bandwidth was determined for each component of any DP observed in our session of observations. This relative value is equal to the difference between the maximum frequency and minimum one, which we measured in each recorded DP. Unfortunately, our observations do not permit us to cover the entire radio band where the DPs originate. It is interesting to note that the observations clearly showed that high-frequency edges of the long DPs were located upward the frequency band of the UTR-2 radio telescope. This imposes certain restrictions on the results. This problem will be considered in more detail further. Figure 3 presents the frequency-bandwidth distributions of DPs observed in July of 2015.

The obtained histograms of random values (frequency bandwidth) are clearly asymmetric, i.e. they should be characterized at least by three moments (mean, variation and skewness). This case may correspond to the Gamma distribution (Meyer, 1970). This assumption has been verified by the quantile-quantile (Q-Q) plot used to compare experimental samples with a theoretical distribution sample (Wilk and Gnanadesikan, 1968). At first we have compared two random samples (FDPs and RDPs) by the Q-Q plot. From this it follows that the samples have almost the same distribution for the values of FDPs from the smallest bandwidths up to ~10 MHz as well as in RDPs from the smallest ones up to ~7 MHz. However, the long DPs (with the bandwidth about 8-15 MHz) have different distributions in these species. This is not surprising because in our experimental data, as a rule, the long DPs had a forward drift. This is confirmed, if the long DPs are removed from the samples.

The next important step is to detect the distribution itself for bandwidths of FDPs and RDPs, respectively. With this in mind we compare the collections of data with samples governed by the theoretical Gamma distribution. The corresponding Q-Q plots are seen in Figure 4. Indeed, the experimental samples obey the Gamma distribution, especially it concerns to RDPs. By numerical simulations (see Figure 5) we can explain the influence of the truncation of sample observations on the Q-Q plot. Consequently, the truncation leads to the deviation of the left picture shown in Figure 3.

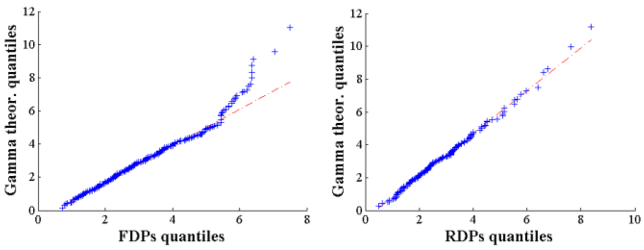

Figure 4: Q-Q plot used to compare both FDPs and RDPs samples with a theoretical Gamma distribution sample.

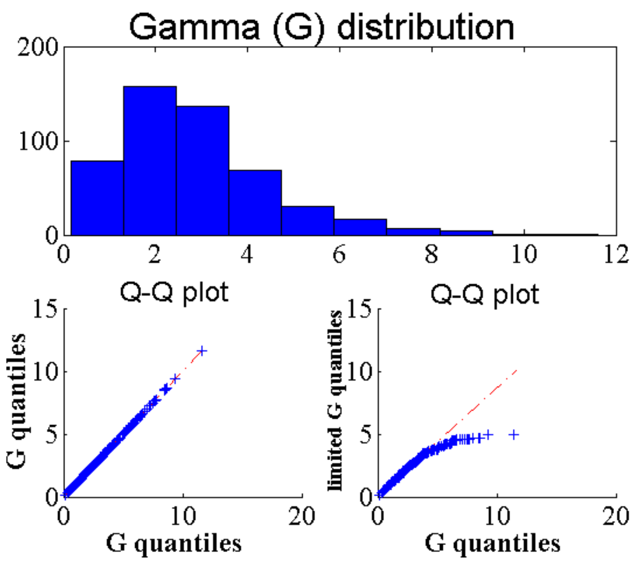

Figure 5: Numerical simulation of random samples with the Gamma distribution (histogram drawing top). The Q-Q plots present two cases: the left picture compares two ordinary Gamma theoretical samples whereas the right panel indicates a difference between the theoretical Gamma sample and its truncated one.

Discussion

Our comprehensive analysis has shown clearly that the functional form of the frequency drift rate of DPs in dependence of frequency is very similar to the case of the type III solar bursts (Alvarez and Haddock, 1973; Mann et al., 1999), but the fitting parameters are obtained different. If we consider the value at 20 MHz, then the typical frequency drift rate of type III bursts is expected either -2.48 MHz/s (according to the model of Alvarez and Haddock, 1973) or -1.44 MHz/s (following the model of Mann et al., 1999), respectively, whereas the long DPs tend to -0.82 MHz/s.

From the study we have found that the total frequency bandwidth of DPs has a random nature and satisfies the Gamma distribution. Some deviations from this distribution take place because the observations had a limited frequency band. Therefore, a part of the DP sample was not received by our instrument. Nevertheless, this did not prevent to fulfill the statistical analysis of DP properties. In the future we plan to provide our observations of DPs by means of a new Ukrainian radio telescope GURT (Giant Ukrainian Radio Telescope) being built now in Ukraine (Konovalenko et al., 2016). It has a wider frequency band for solar observations (from 10 to 80 MHz) that will be enough to cover almost the entire frequency range of solar radio emission where DPs occur.

Acknowledgements

This research effort was partially supported by Research Grant 0116U002841 from the National Academy of Sciences of Ukraine. We would like to thank the e-Callisto teams for developing and operating the instruments as well for their open data policy. We are also grateful the anonymous referees for his/her constructive comments and useful suggestions, which helped improve the quality of this paper.

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