On the Issue of the Origin of Type II Solar Radio Bursts

Gennady Chernov and Valery Fomichev
Pulkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of Russian Academy of Science (IZMIRAN), Russia; gchernov@izmiran.ru

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Abstract

Type II solar radio bursts are among the most powerful events in the solar radio emission in the meter wavelength range. It is generally accepted that the agents generating type II radio bursts are magnetohydrodynamic shock waves. But the relationship between the shock waves and the other manifestations of the large-scale disturbances in the solar atmosphere (coronal mass ejections, Morton waves, EUW waves) remains unclear. To clarify a problem, it is important to determine the conditions of generation of type II radio bursts. Here, the model of the radio source is based on the generation of radio emission within the front of the collisionless shock wave where the Buneman instability of plasma waves is developed. In the frame of this model, the Alfvén magnetic Mach number must exceed the critical value, and there is a strict restriction on the perpendicularity of the front. The model allows us to obtain the information about the parameters of the shock waves and the parameters of the medium by the parameters of type II bursts. The estimates, obtained in this paper for several events with the band splitting of the fundamental and harmonic emission bands of the type II bursts, confirm the necessary conditions of the model. In this case the registration of type II radio bursts is an indication of the propagation of shock waves in the solar atmosphere, and the absence of type II radio bursts is not an indication of the absence of shock waves. Such a situation should be taken into account when investigating the relationship between type II radio bursts and other manifestations of solar activity.

Unified Astronomy Thesaurus concepts: Solar physics (1476); Radio bursts (1339)

1. Introduction

Type II solar radio bursts are among the most powerful events in the solar radio emission in the meter wavelength range. On the dynamic spectrum, they appear as two harmonically related bands (in a ratio of 2/1) slowly drifting in frequency from high frequencies to low frequencies (Wild et al. 1954; Zheleznyakov 1964; Kundu 1965). In addition to the harmonic structure, bursts of this type have various fine structures of the dynamic spectra—splitting of each of the harmonic bands into two sub-bands, a herringbone structure characterized by the appearance of rapidly drifting bursts toward both low and high frequencies, patchy structure, etc.

At present, it is generally accepted that the agents generating type II radio bursts are magnetohydrodynamic (MHD) shock waves. Such MHD shock waves in the solar corona can be generated by solar flares, coronal mass ejections (CMEs), and fast plasma flows in the regions of reconnection of magnetic field lines (termination or quasi-stationary shock waves). In recent years, the spacecraft observations have shown (Cane & Erickson 2005) that shock waves and type II radio bursts are also observed in the interplanetary plasma (they are called interplanetary shock waves and decimeter and kilometer type II radio bursts, respectively).

Numerous studies of the relationship between coronal shock waves and coronal (in the meter wavelength range) radio bursts of type II with interplanetary shock waves and decimeter and kilometer radio bursts of type II, as well as the identification of the type of shock waves (explosive or piston, in front of the CME), still did not give a clear picture.

In studies of solar radio bursts of type II, a difficult situation has now emerged, when many papers appeared with a detailed investigation of the relationship between shock waves (sources of type II bursts) and CMEs, but without taking into account the mechanisms of radio emission, without which it is impossible to understand the fragmented structure of the dynamic spectra, the connection between type II bursts in the meter range and type II interplanetary bursts (in decimeter and kilometer wavelengths), and the relationship of type II radio bursts with other manifestations of large-scale disturbances in the solar atmosphere (Moreton waves, EUV waves).

In a recent article by Cairns et al. (2020) it was shown that all the shock waves are piston waves at the leading edge of the CME, and only the bursts with very high initial frequencies (~800 MHz) could be connected with explosive shock waves. At the heights of decimeter-range sources, only waves in the EUV radiation are usually observed, and CME formation occurs higher in the corona. The detailed analysis of the unique set of the observational data on the event of 2015 November 4 (ground-based and space-based observations in optic, X-ray, and UV ranges, and in wide radio diapason from 1000 MHz to 40 kHz), during which three meter type II bursts were observed in the same active region, showed that only the last (and the weakest of the three) had continuation as an interplanetary burst up to frequencies of ~20 kHz. Type II bursts are interpreted in terms of shock-drift acceleration and magnetic-mirror reflection at shocks; development of a beam distribution of reflected electrons; growth of Langmuir waves via the beam instability; and nonlinear wave—wave processes that convert Langmuir wave energy into radio emission near the electron plasma frequency $f_{pe}$ and near $2f_{pe}$ (Knock et al. 2001).

In Maguire et al. (2020), questions were raised not only about the relationship of type II bursts with CME (explosive or piston type of shock wave?) but also on the evolution of the Alfvén Mach number $M = V_{sh}/V_A$ ($V_{sh}$ and $V_A$ are the shock...
wave velocity and the Alfvén velocity, respectively) and on the initial and final frequencies of bursts. The Mach number was determined in three different ways: (1) from the geometry of the shock front propagation (in the CME images in the EUV and LASCO), where the key parameter is the distance between the shock front and the CME nose; (2) by ratio of the CME velocity to the Alfvén velocity; and (3) by value of the band splitting in type II bursts according to the method proposed by Vršnak et al. (2002), where the origin of the splitting branches is interpreted in terms of the plasma emission from the upstream and downstream shock regions (behind and ahead of the shock front) in accordance with the model of Smerd et al. (1974). Analysis of the event of 2017 September 2, when the type II burst was observed at frequencies of 80–20 MHz (according to the Irish Low Frequency Array (I-LOFAR) data), showed that all three methods give consistent results and the same tendency of evolution of the Alfvén Mach number: the type II radio emission emerged from near the nose of the CME when \( M_A \) was in the range 1.2–1.4 at a heliocentric distance of \( \sim 1.6 \) radius of the Sun (Rs), and the emission ceased when the CME reached \( \sim 1.7 \) Rs, despite an increasing Alfvén Mach number up to 4. It was suggested that the radio emission cessation is due to a lack of quasi-perpendicular geometry at this altitude, which inhibits efficient electron acceleration and subsequent radio emission.

The work of Zucca et al. (2014) showed a detailed correspondence between CME and the shock front as a piston in the phenomenon of 2013 November 6. The interpretation of the splitting of the second harmonic at frequencies of 550–150 MHz as radiation ahead of and behind the front is confirmed by observations of radio sources with the radioheliograph in Nançay. However, the authors do not continue their analysis of the continuation of the burst at lower frequencies of 80–40 MHz (shown in their Figures 2 and 11). It was suggested that at these distances the shock front of blast type was formed as a result of interaction of the CME with the coronal hole, was propagated independently of CME, and had no continuation at kilometer waves.

In Corona-Romero et al. (2015) it is affirmed that all the interplanetary shock waves associated with kilometer type II bursts were explosive, at least beyond \( \sim 21 \) Rs (i.e., at frequencies \( \leq 1 \) MHz). A blast regression technique is used to determine the speed and position of the front. It was found that the velocity of shocks near Earth’s orbit in all eight of the considered phenomena (CME/shock front) was higher than the speed of the corresponding CMEs, and the calculated time and velocity agree with their values measured in Earth’s orbit.

The first concepts, that type II radio bursts are observed only at meter wavelengths, have changed in recent years with the expansion of qualitative observations. In particular, the bursts have been observed with the initial frequencies far in the decimeter range, \( \sim 800 \) MHz (Cairns et al. 2020), or even \( \sim 1200 \) MHz (Pohjolainen et al. 2008), that is, at the altitudes where type II bursts can only be caused by explosive shock waves.

An intermediate case is the work of Zimovets et al. (2012), which presented the results of unique observations of a type II burst on 2010 November 3: simultaneous observations of the radio spectrum in the range 550–150 MHz, the positions of radio sources at 10 frequencies between 445 and 151 MHz with the Nançay radiotelescope, plasma emissions in the EUV lines (AIA/SDO), and hard X-ray source (RHESSI). It has been shown that the onset of the type II burst was associated with a shock wave at the leading edge of the plasma ejection, i.e., unambiguously with a piston shock wave. But after about 20 s, the velocity of the shock front doubled; it moved away from the ejection and then propagated like an explosive front. The authors estimated the Mach number from the parameters of the splitting of the second harmonic bands and obtained very small values, \( M = 1.06–1.16 \). The authors conclude that in this case the particles were somehow accelerated since the type II burst was observed.

The results of a statistic study of the relationship between shock waves and their velocities with CME for 1997–2005 were given in the work of Rahman et al. (2012). It was found that out of 101 CMEs, 52 phenomena did not contain both meter and kilometer type II bursts. In 38 events, both meter and kilometer bursts were observed. But the continuation of the meter burst in the kilometer range was observed only in 23 phenomena. Twelve interplanetary CMEs (ICMEs) had high velocities, \( \gtrsim 2000 \) km s\(^{-1}\). It is noteworthy that velocities of the interplanetary shock waves in all the phenomena exceeded the velocities of the corresponding interplanetary (MP) CMEs. In all 101 events the shock wave arrived at Earth’s orbit before (MP) CME, and the distance between shock wave and (MP) CME was minimum (\( \sim 17 \) Rs) in the events with high velocity, but the distance was maximum (\( \sim 35 \) Rs) in the events in which CME was accompanied only by a kilometer type II burst (without the meter one).

The issue of the relationship between meter type II bursts and interplanetary bursts was considered in the work of Cane and Erickson (2005). Over 3 yr of observations on WIND/WAVES, 31 km type II bursts were detected as a direct continuation of meter bursts. The most important result is the different nature of the bursts, since all kilometer bursts were characterized by the absence of a clear harmonic structure and clumpy parameters. All the interplanetary bursts were associated with piston shock waves in the front of fast CMEs, and meter bursts with other shock waves (possibly explosive). Thus, they were not their direct continuation in the interplanetary space.

Dependence of the different manifestation of type II radio bursts in decimetric, metric, and kilometric ranges on power of the solar flares was discussed in Pick et al. (2006). It was remarked that the blast-wave shocks, connected with the metric type II burst, did not propagate in the interplanetary space. In most cases the type II radio bursts in the decimetric and kilometric range were connected with the piston shocks. The unclear connection of type II radio bursts in decimetric and metric ranges with different eruptive events observed in white light, radio, optical lines, UV, and X-rays was also noted.

Although the idea that a driver for type II radio bursts is shock waves is generally accepted, all the estimations of their parameters (velocity, Alfvén number, \( M \)) and plasma parameters (magnetic field, density) were done in many works only from kinematic considerations in terms of plasma parameters and the shock front velocity without considering a specific mechanism of radio emission. For example, Bacchini et al. (2015) consider the acceleration of particles to speeds above the ion-acoustic speed sufficient for type II radiation. Their calculations show that a perpendicular wave can exist at the beginning, and it becomes parallel with distance in the corona. Obviously, such estimates cannot unambiguously explain the beginning and end of the emission from a type II burst.
Similar estimates were made by Mann et al. (1995). The critical values of the Mach number \( M_{cr} \) for quasi-parallel fronts are between 1.2 and 2.3, and those for quasi-perpendicular fronts are between 1.5 and 2.8. It was concluded that a longitudinal wave is considered preferable, but the possibility of a perpendicular wave is not excluded.

It is necessary to note also that type II radio emission exhibits often burst-like and irregular (fragmented) dynamic spectra, which means that the conditions for the radio emission to be generated are fulfilled irregularly and in distinct regions along the large-scale shock front.

Below, for clarification of these issues, we discuss the possibility of obtaining information on the parameters of solar plasma and shock waves necessary for generation of type II radio bursts.

2. Discussion of the Mechanism of Radio Emission

Experimental data on type II bursts (high effective radiation temperature \( T_{eff} \gg T_e \), sharp nonstationarity and a narrow frequency band, the complexity of the dynamic spectrum, short duration) indicate a coherent generation mechanism, since it is coherent radiation that is closely related to wave amplification that is realized only in limited frequency intervals and with special types of plasma particle velocity distribution that exist for a limited time. At present, it is generally accepted that the agent generating type II radio bursts is MHD shock waves. Such MHD shock waves in the solar corona can be generated, for example, by solar flares and CMEs. This connection is supported by the numerous studies of the connection between type II radio bursts and these eruptive phenomena (CMEs, ultraviolet waves, Morton waves; e.g., Smith & Harvey 1971; Harvey et al. 1974; Thompson et al. 2000; Klassen et al. 2000; Tripathi & Rao 2007; Warmuth 2010; Zhukov 2011), as well as a proximity of the estimated velocities of agents exciting type II radio bursts and the Alfvén velocities in the solar corona. In constructing the theory of type II radio bursts, the most difficult problem was the generation of plasma waves, in particular, the implementation of nonequilibrium electron distribution functions in the shock front. A number of theories have been put forward to address this problem.

In Cairns et al. (2020) and Knock et al. (2001) the generation of type II bursts is associated with the drift acceleration of electrons at the perpendicular shock front, the formation of fluxes of accelerated electrons, the excitation of Langmuir waves in the region ahead of the shock front, and their transformation through nonlinear wave–wave processes into radio emission at frequencies close to the electron plasma frequency \( f_{pe} \) and its second harmonic \( 2f_{pe} \). Such a model was used in many papers (Knock et al. 2001; Vršnak et al. 2001, 2002; Zucca et al. 2014; Maguire et al. 2020; Cairns et al. 2020) in their analyses of type II radio bursts. However, within the framework of such a model, a number of the problems remain in the interpretation of such characteristics of bursts as the narrow bandwidth of the emission bands in frequency and the fine structure of the bands of the splitting type. This model explains the acceleration and the formation of fluxes of accelerated electrons and the excitation of Langmuir waves in the upstream region of the shock front, but the issue of formation of fluxes of accelerated electrons in the downstream region remained unclear. Therefore, the origin of split structure in the frame of this model also remains unknown.

Another approach for explanation of the complex structure of type II radio bursts is based on the possibility for radio emission to be generated in different parts of the shock front (McLean 1967). Particularly, Holman & Pesess (1983) suggested that the electrons that are responsible for the type II bursts might get accelerated from the shock flanks. In a recent paper (Majumdar et al. 2021) it was shown that in the event of 2014 January 26 (with CME and type II burst) the source of radio emission was indeed located in the flank of the shock front. Nevertheless, the geometrical interpretation with several emission sources cannot account for the behavior of the splitting structure (synchronized intensity and frequency drift variation) because of the space separation of such sources and their moving in different coronal regions.

The most consistent theory of the generation of type II radio bursts was put forward by Pikelner & Guntzburg (1963) and later developed in various works (Zheleznyakov 1965; Zaitsev 1965; Zaitsev & Kaplan 1966; Zaitsev 1968, 1977). It is based on the laminar theory of weak collisionless shock waves (\( M < 2 \)) propagating perpendicular to the magnetic field.

If the number of collisions in plasma is sufficiently small (as occurs in the solar atmosphere—chromosphere and corona), the shock front is an oscillatory structure consisting of a sequence of solitons of compression or rarefaction (Sagdeev 1964). The type and scale of this structure depend on the Alfvénic Mach number \( M = V_{sw}/V_A \) (here, \( V_{sw} \) is the shock wave speed and \( V_A = H_0/(4\pi N_0 m_e)^{1/2} \) is the Alfvén velocity), the angle \( \theta \) between the front plane and the direction of undisturbed magnetic field \( H_0 \), and the parameter \( \alpha = H_0^2/(4\pi N_0 m_e c^2) = \omega_{\theta 0}^2/\omega_{A 0}^2 \), where \( \omega_{\theta 0} = eH_0/m_e c \), \( \omega_{A 0} = (4\pi e^2 N_0/m_e)^{1/2} \); \( N_0 \) and \( H_0 \) are the electron density and magnetic field strength of the upstream magnetic field, respectively; and \( c \) is the speed of light. Here the value \( \theta = 0 \) corresponds to transverse propagation of the shock wave relative to the upstream magnetic field, and \( \theta = \pi/2 \) corresponds to longitudinal propagation. As shown by Zaitsev (1970), shock waves differ qualitatively at \( \theta < \theta_{cr} \) and \( \theta > \theta_{cr} \) (\( \sin \theta_{cr} = V_{sw}/c \)). The shock transition occurs through a sequence of solitary compression waves at \( \theta < \theta_{cr} \) and through a sequence of rarefaction waves at \( \theta > \theta_{cr} \). The characteristic scale of a solitary wave, e.g., for compression waves at \( \theta = 0 \) (quasi-transverse propagation), is \( \delta = c/\omega_{\theta 0} (1 + \omega_{\theta 0} c / \omega_{A 0}^2 m_e/m_i) \). The inhomogeneity of the magnetic field in solitons makes the electrons drift in the plane of the shock front. The relative drift velocity of electrons and ions \( V_{se} = 4 \cdot 2^{1/2} \cdot 3^{-3/2} \cdot c \cdot \omega_{\theta 0} \cdot (\omega_{\theta 0}^2 + \omega_{A 0}^2)^{-1/2} (M^2 - 1)^{-1/2} \) exceeds the thermal electron velocity \( V_{Te} = (kT/m_e)^{1/2} \) if

\[
M > M_{cr} = 1 + [8\pi N_0 kT (1 + \alpha) H_0^2]^{1/3} \quad (1)
\]

\( k = 1.38 \times 10^{-16} \) erg K\(^{-1} \) is the Boltzmann constant; Zaitsev 1969). This leads to the generation of plasma oscillations (the Buneman instability) and, as a result of the induced scattering of plasma waves on fast electrons, to the generation of electromagnetic radiation. This mechanism made it possible to develop a comprehensive model of the source of classical type II bursts (Zaitsev 1977) and to explain all the parameters of radio bursts including the fine structure.

Within the frame of this theory, the observed characteristics of type II radio bursts are related both to the parameters of the solar corona and to the parameters of shock waves: (1) the observed frequency of the fundamental tone of type II radio bursts \( f \) is close to the plasma frequency of plasma waves...
concluded that the onset of the burst is associated with the fact that each phenomenon is purely individual, it was / The Astrophysical Journal, Alfvénic Mach number $M$ shock relative frequency drift velocity $f$ determined from the dynamic spectrum with unknown values of the concentration $N_0$, magnetic field $H_0$, and Mach number $M$ (Zaitsev 1968; Fomichev 1972).

This system of equations includes not only the effects associated with the inhomogeneity of the concentration and magnetic field in the solar corona but also effects caused by changes in the intensity of shock waves. This means that from the observed characteristics of type II bursts one can obtain important information on the nature of the propagation of shock waves in the inhomogeneous plasma of the solar corona, as well as the parameters of the latter (magnetic field, density). The first such estimates were given in Zaitsev (1968) and Fomichev (1972). The obtained calculations for $M$, $H_0$, and front velocity $V_p$ for nine bursts were very diverse. Despite the fact that each phenomenon is purely individual, it was concluded that the onset of the burst is associated with the achievement of the Mach number of the critical value, and the end of the burst with a possible overturning of the front, when the Mach number continues to grow ($M > 2$). The absence at that time of information about the trajectory of the shock front relative to the magnetic field lines did not allow the association of the interruption or termination of radio emission generation with the type of shock wave (perpendicular or longitudinal).

The laminar structure of shock waves moving along the magnetic field in a plasma with $\beta = 8 \pi N_0 kT / H_0^2 \ll 1$ exists in the range $1 < M < 1.5$. The front of the shock wave also involves a drift current directed across the disturbed magnetic field. However, the relative velocity of electrons and ions $V_d$ in this case is much lower than the electron thermal velocity $V_{Te}$, therefore, the ordinary Buneman instability occurring in transverse shock waves does not develop. Instead, a modified Buneman instability with a very low excitation threshold $V_d > V_{Te}$ develops in longitudinal shock wave at $Te \approx Ti$. The excitation condition begins to be satisfied in front sections at Alfvénic Mach number $M > 1 + (V_{Te}/2V_{A})^{1/2}$ (Zaitsev & Ledenev 1976). As a result, longitudinal waves are excited at the lower hybrid frequency $\omega \approx (\omega_{li} + \omega_{hi})^{1/2}$ with an energy density of about $W \approx N_0 m_e V^2$ in the saturation mode (Galeev & Sagdeev 1973). The energy of these waves is transferred to particles; electrons are heated to the temperature $Te \approx Ti \approx H_0^2 / 8\pi N_0$, i.e., acquire an average thermal velocity $V_e \approx 1/2 (m_e m_i)^{1/2} V_A$. In the solar corona, $V_A \approx 5 \cdot 10^8$ cm s$^{-1}$, therefore, $V_e \approx (1 - 2) \times 10^8$ cm s$^{-1}$ significantly exceeds the thermal velocity of electrons in the undisturbed corona ($V_{Te} \approx 5 \cdot 10^8$ cm s$^{-1}$), and the concentration of fast electrons escaping beyond the front can reach $N_e / N_0 \approx 1 / 2$ ($m_e / m_i)^{1/2} N_0 \approx 10^2 N_0$ according to the conclusions made by Zaitsev & Ledenev (1976). In other words, the front of a longitudinal shock wave at $\beta \ll 1$ and at sufficiently large Mach numbers is an emitter of fast electrons, which, falling into a cold plasma behind the front, can excite coherent plasma waves and be a source of radio emission. But in this case, it remains difficult to explain the narrow frequency range of radio emission and the appearance of split components of each of the harmonics of type II bursts. The lower efficiency of longitudinal shock waves for generating type II bursts fully explains the statistics in the work of Rahman et al. (2012): only in 23 events out of 101 did the meter burst continue at kilometer waves, since the appearance of longitudinal shock waves in the interplanetary medium is more likely than the perpendicular ones.

Thus, in the frame of the discussed model of the source of type II radio bursts, the following conditions must be fulfilled: (1) the shock wave must be relatively intense, since the excitation of turbulence in shock waves requires that the Mach number exceed a certain critical value $M_{cr}$, and (2) the shock wave must be perpendicular, a slight deviation $\Theta$ from $\Theta = 0$ makes the conditions for the excitation of plasma waves in the shock front more stringent, and at $\Theta \geq V_{sw}/c \approx 0.033 \approx 2^{\circ}$ the generation of plasma waves stops almost completely. This means that the source of radio emission can be formed at any part of the shock front (bow or flanks) simultaneously or in different times, depending on where and when the specified conditions are fulfilled (sufficient intensity and perpendicularity of the shock front, that is, $M > M_{cr}$ and $\Theta = 0$), and the dynamic spectrum of type II radio bursts can either represent continuously drifting stripes or have an interruptive and a blob structure.

The important role of the variation of this angle is confirmed by the two-dimensional MHD modeling of the filament explosion accompanied by coronal EIT waves, diming, and CME formation, carried out by Pomoell et al. (2008). Figure 6 in their paper shows the geometry of the magnetic field and the shock front, where it can be seen that the leading edge of the front propagates strictly perpendicularly to the force lines, and on the side parts the front crosses the force lines four times; therefore, on these parts of the front, radiation can be interrupted.

Another interesting type II burst is considered by Chrysaphi et al. (2020). The burst observed on 2017 July 15 at LOFAR’s LBA station in the 3–50 MHz range, at the initial stage (the first 30 s), was without frequency drift and then continuously transformed into a type II-like burst with the negative frequency drift. The authors attribute this phenomenon to the formation of a shock front during the interaction of CME with a coronal ray. Here, the radiation was not interrupted, and the front remained perpendicular only on the flanks of the front. But at the first stage, it spread the coronal beam, and the radiation source moved almost along the levels of equal density. Subsequently, the front shifted almost across the levels, which is responsible for the appearance of the frequency drift.

Thus, although the question of shock waves as drivers of type II solar radio bursts is considered as generally accepted, many questions, such as the relationship of shock waves with flares and CMEs, the type of shock waves (perpendicular or longitudinal), the relationship of meter type II radio bursts with kilometric type II bursts, and coronal shock waves with interplanetary shock waves, are awaiting their decision. In this connection, it is of interest to analyze the origin of the fragmented structure of type II bursts. Such a structure may be
connected with propagation of shock waves in the inhomogeneous (density, magnetic field) solar atmosphere. Because the characteristics of type II bursts depend on the characteristics of the medium where shock was propagating, it is possible to find out what the parameters of the medium and their variations can lead to appearance of such peculiarities of dynamic spectra (with interruptions and reactivations of radio emission).

To make this issue clear, it is important to determine an adequate mechanism for the generation of type II radio bursts. Below we will try to get the additional answers to these questions using the data from observations of several type II bursts in the frame of the generation mechanism within the front of a collisionless shock wave (based on the development of Buneman instability of plasma waves), which makes it possible to obtain estimates of the parameters of the corona and shock waves. We will be interested, in particular, in estimations of the Alfvén Mach number, the critical value $M_{cr}$, and their variation during type II radio bursts (or their fragments), that is, the parameters that can determine a duration of the radio emission.

3. Observations and Results

Dynamic spectra of the type II radio bursts are very diverse, associated primarily with the diffuseness of the spectrum and the clumpy structure of the spectrum, when it is difficult to trace both harmonic bands and their clear splitting into two sub-bands. Therefore, it is necessary to choose suitable type II bursts and, based on their parameters, to answer the questions why intensive bursts in the meter range after powerful flares sometimes do not extend in the decimetric and kilometric ranges, and, vice versa, less expressive bursts after moderate flares are observed in the interplanetary space. The complexity of unambiguous judgments on these issues is discussed in the review by Pick et al. (2006). There, it was noticed that the blast wave associated with a meter type II burst rarely passes into the interplanetary space. And most of the type II radio bursts in the decimeter and kilometer ranges are associated with piston shock waves. It is also noted that the picture sometimes becomes more complicated when the radiation is clearly emanating from the flanks of the shock front. However, the generation mechanism in this paper is only mentioned, that this becomes more complicated when the radiation is clearly excited in the shock front, which is determined by the value concentration of electrons $N$ in that section of the front, where the supercriticality (the ratio of the relative drift velocity of electrons and ions) is maximum, it is essential that the value $N > N_0$ (concentration of electrons in upstream region of the shock),

$$f = 1/2\pi(N_0Z4\pi e^2/m_e)^{1/2},$$

where $Z = 0.94(1 + 0.28M_2)^{1/2} - 0.06$.

(2) Time differentiation of Equation (2) (neglecting the changing of Mach number in comparison with the changing of electron density) gives the expression for relative frequency drift velocity

$$f^{-1}df/dt = 1/2V_{sh} \cdot L^{-1}(N_0) \cdot (\cos \alpha)^{-1},$$

where $\alpha$ is the angle between the density gradient and the direction of the shock motion, and $L = N_0 (dN_0/dR)^{-1}$ is a scale of inhomogeneity of density in the undisturbed solar atmosphere.

(3) The splitting of the dynamic spectra $\delta f$ of fundamental and harmonic bands of type II bursts in two sub-bands (low frequency $f_{l}$ and upper frequency $f_{u}$) is due to the fact that the maximum supercriticality on the forward slope of the leading soliton is realized at lower values of the plasma concentration than on the trailing slope owing to the heating of electrons by the Buneman instability. The expression of the dependence of relative value of splitting $\delta f/f$ on Mach number $M$ is rather cumbersome (Zaitsev 1968; Fomichev 1972; Zaitsev 1977). Such a dependence is shown in Figure 1.

It is important to note that the observed frequency of the fundamental tone of type II radio bursts (or the frequency of the low-frequency line in bursts with splitting $f_{s}$) is close to the plasma frequency of plasma waves excited within the shock front, which is determined by the value of concentration of electrons $N$ in that section of the front, where the ratio of the relative drift velocity of electrons and ions is maximum, but not by the value of concentration of electrons $N_0$ in the upstream region of the shock.

Derived a self-consistent system of equations describes dependence of the quantities $f$, $f^{-1}df/dt$, and $\delta f/f$ on the concentration $N_0$, magnetic field $H_0$, and Mach number $M$. It means the observable parameters of dynamic spectrum ($f$, $f^{-1}df/dt$, and $\delta f/f$) can be a basis for determination of the unknown parameters of the solar atmosphere and shock wave (the concentration $N_0$, magnetic field $H_0$, and Mach number $M$).

The procedure of estimation of the parameters of the shocks and of the plasma parameters is as follows. First, for each frequency $f$, Mach number $M$ is evaluated by the observable relative value of splitting $\delta f/f$ from the known dependence of $\delta f/f$ on $M$ (or from Figure 1) and $Z$. Then, from Equations (2) and...
Radioheliograph, dynamic spectra from a number of ground-based observatories covering the range 20–800 MHz and 0.8–4.5 GHz, radio emission spectrum in the range 1075–13,825 MHz from the Wind spacecraft did not allow us to get a clear answer on the question whether the shock waves (generating the type II bursts) are the CME-driven shocks or are the flare-initiated shocks (Vršnak et al. 2006).

Here we will be interested in the parameters of shock waves generating the type II bursts. By IZMIRAN’s data the type II burst started at 09:49 UT at 270 MHz (Figure 2). The dynamic spectrum shows a complex pattern with several type II emission bands and multilane structure. For analysis we chose the fragment of the dynamic spectrum in the time interval 10:00–10:08 UT in the frequency range 90–28 MHz, where it is possible to measure the parameters of the splitting lanes (oblique dark lines in Figure 3). Consider the segment of the burst at the fundamental band in the time interval 10:00:30–10:01:30 UT in the frequency range 66–48 MHz. This segment started at about 10:00:30 UT in the frequency range 62–54 MHz, and at this moment (beginning of the segment) the frequency drift \((df/dt)\) of the band at the fundamental frequency between 10:00:30 and 10:01 UT turns out to be about 0.11 MHz s\(^{-1}\), the relative drift rate amounts to \((df/dt) \cdot f^{-1} \sim 0.002\) s\(^{-1}\), the frequency of the low-frequency sub-band \(f_1 \sim 54\) MHz, the frequency of the upper-frequency sub-band \(f_2 \sim 62\) MHz, and the splitting of the dynamic spectra \(\delta f\) is about 8 MHz. Following the procedure of estimation of the parameters of the shocks and of the plasma parameters (Zaitsev 1968; Fomichev 1972), using these data we obtain the Alfvén magnetic number \(M \sim 1.33\) and \(Z \sim 1.1\). This means that the electron density in the upstream of the shock \(N_0 \sim 3 \cdot 10^7\) cm\(^{-3}\) corresponds to the plasma frequency \(\sim 50\) MHz. For the standard 2 Newkirk coronal density model we obtain then the estimates of the full shock velocity \(V_{sh} \sim 2200\) km s\(^{-1}\) and the magnetic field \(H_0 \sim 3.3\) G. At last, we have estimates of the critical value of the Alfvén magnetic numbers \(M_{cr} \sim 1.15\) and 1.2 for the coronal temperatures \(T \sim 10^6\) K and 2 \cdot 10^6 K, respectively.

At the moment of the end of this segment (10:01:30 UT) the parameters of the radio burst were as follows: the frequency drift \((df/dt) \sim 0.08\) MHz s\(^{-1}\), the relative drift rate \((df/dt) \cdot f^{-1} \sim 0.0016\) s\(^{-1}\), the frequency of the low-frequency sub-band \(f_1 \sim 48\) MHz, the frequency of the upper-frequency sub-band \(f_2 \sim 54\) MHz, and the splitting of the dynamic spectra \(\delta f\) is about 6 MHz. Then, we obtain the estimates \(M \sim 1.27\), \(Z \sim 1.07\), \(N_0 \sim 2.5 \cdot 10^7\) cm\(^{-3}\), \(V_{sh} \sim 2000\) km s\(^{-1}\), \(H_0 \sim 2.5\) G, and the critical values of the Alfvén magnetic numbers \(M_{cr} \sim 1.14\) and 1.18 for the coronal temperatures \(T \sim 10^6\) K and 2 \cdot 10^6 K, respectively. The estimates presented above show that the parameters of the shock remain practically constant, and the condition \(M > M_{cr}\) is fulfilled during the entire duration of the segment. Therefore, the most probable reason of the end of the segment is that the shock wave enters a region where the magnetic field orientation was very different and the shock wave became a parallel (that is, a condition of the perpendicularity was violated).

It should be noted that in accordance with the observations on SOHO/LASCO C2 (Solar and Heliospheric Observatory: https://cdaw.gsfc.nasa.gov/movie/make_javamovie.php?date=20031103&img1=las2rdf&img2=wwaves) the velocity of the CME was about \(\sim 1500\) km s\(^{-1}\) in the beginning of the event, with a low slowing-down up to distances 30 Rs.
According to Vršnak et al. (2006), the shock front overtook the CME. The estimates of the velocity of the shock wave obtained above (∼2000 km s⁻¹) are in good agreement with these data.

Event of 1999 February 21.

This event was included in the list of 18 coronal type II bursts recorded in the decimetric to metric wavelength range and was discussed in Vršnak et al. (2002). The dynamic spectrum of the type II burst (their Figure 1) showed the fundamental and harmonic emission bands, both frequency bands split into two sub-bands at frequencies below 100 MHz. The measurements were performed at the harmonic emission band because of stronger intensity, and only a part of the fundamental band could be seen in this event. The upper-frequency (f_u) and low-frequency (f_l) bands of the band-split emission are marked there by the lines that follow the two emission ridges. In this dynamic spectrum three consecutive fragments can be seen with interruption of the radio emission between the fragments. Following the method in the previous section, we determine the parameters of the shock wave and the solar corona during all the fragments. For the estimates we used the two-fold Newkirk density model (2N model), and all the parameters of radio emission will be given for the fundamental band.

Fragment 1 (∼10:00:30–10:02:00 UT):

The beginning: \(f_l\sim36.5\) MHz, the relative frequency splitting \(\delta f\cdot f^{-1}\sim0.13\), the Alfvén magnetic number \(M\sim1.27\), and \(Z\sim1.07\). This means that the electron density and the plasma frequency in the upstream region of the shock \(N_0\sim1.28\cdot10^9\) cm⁻³ and \(f_0\sim32.5\) MHz. For the relative drift rate \((df/dt)\cdot f^{-1}\sim0.0013\) s⁻¹ we obtain the estimates of the shock velocity \(V_{sh}\sim1000\) km s⁻¹ and the magnetic field \(H_0\sim1.25\) G. At last, we have the estimates of the critical values of the Alfvén magnetic numbers \(M_{cr}\sim1.15\) and 1.2 for the coronal temperatures \(T\sim10^6\) K and \(2\cdot10^6\) K, respectively.

The end: \(f_l\sim32\) MHz, the relative frequency splitting \(\delta f\cdot f^{-1}\sim0.14\), the Alfvén magnetic number \(M\sim1.32\), and \(Z\sim1.086\), the electron density and the plasma frequency in the upstream region of the shock \(N_0\sim1.08\cdot10^9\) cm⁻³ and \(f_0\sim29.5\) MHz, respectively. For the relative drift rate \((df/dt)\cdot f^{-1}\sim0.0012\) s⁻¹ we obtain the estimates of the shock velocity \(V_{sh}\sim1050\) km s⁻¹ and the magnetic field \(H_0\sim1.1\) G. At last, the estimates of the critical values of the Alfvén magnetic numbers are \(M_{cr}\sim1.15\) and 1.19 for the coronal temperatures \(T\sim10^6\) K, and \(2\cdot10^6\) K, respectively.

Fragment 2 (∼10:03:30–10:04:45 UT):

The beginning: \(f_l\sim28.5\) MHz, the relative frequency splitting \(\delta f\cdot f^{-1}\sim0.13\), the Alfvén magnetic number \(M\sim1.28\), and \(Z\sim1.07\), the electron density and the plasma frequency in the upstream region of the shock \(N_0\sim9.4\cdot10^9\) cm⁻³ and \(f_0\sim27.5\) MHz, respectively. For the relative drift rate \((df/dt)\cdot f^{-1}\sim0.0012\) s⁻¹ we obtain the estimates of the shock velocity \(V_{sh}\sim1100\) km s⁻¹ and the magnetic field \(H_0\sim1.0\) G, and the estimates of the critical values of the Alfvén magnetic numbers are \(M_{cr}\sim1.15\) and 1.19 for the coronal temperatures \(T\sim10^6\) K and \(2\cdot10^6\) K, respectively.

The end: \(f_l\sim27.0\) MHz, the relative frequency splitting \(\delta f\cdot f^{-1}\sim0.14\), the Alfvén magnetic number \(M\sim1.34\), and \(Z\sim1.09\), the electron density and the plasma frequency in the upstream region of the shock \(N_0\sim8.2\cdot10^9\) cm⁻³ and \(f_0\sim25.8\) MHz, respectively. For the relative drift rate \((df/dt)\cdot f^{-1}\sim0.0012\) s⁻¹ we obtain the estimates of the shock velocity \(V_{sh}\sim1150\) km s⁻¹ and the magnetic field \(H_0\sim1\) G, and the estimates of the critical values of the Alfvén magnetic
numbers are \( M_{\text{cr}} \sim 1.14 \) and 1.17 for the coronal temperatures \( T \sim 10^6 \) K and 2 \( \cdot 10^6 \) K, respectively.

Fragment 3 (\( \sim 10:05:30 \)–10:07:00 UT):

The beginning: \( f_L \sim 26 \) MHz, the relative frequency splitting \( \delta f \cdot f^{-1} \sim 0.14 \), the Alfvén magnetic number \( M \sim 1.3 \), and \( Z \sim 1.08 \), the electron density and the plasma frequency in the upstream region of the shock \( N_0 \sim 7.7 \cdot 10^9 \) cm\(^{-3} \) and \( f_0 \sim 25 \) MHz, respectively. For the relative drift rate \( (df/dt) \cdot f^{-1} \sim 0.0012 \) s\(^{-1} \) we obtain the estimates of the shock velocity \( V_{sh} \sim 1000 \) km s\(^{-1} \) and the magnetic field \( H_0 \sim 0.94 \) G, and the estimates of the critical values of the Alfvén magnetic numbers are \( M_{\text{cr}} \sim 1.13 \) and 1.16 for the coronal temperatures \( T \sim 10^6 \) K and 2 \( \cdot 10^6 \) K, respectively.

The end: \( f_L \sim 24.0 \) MHz, the relative frequency splitting \( \delta f \cdot f^{-1} \sim 0.14 \), the Alfvén magnetic number \( M \sim 1.3 \), and \( Z \sim 1.08 \), the electron density and the plasma frequency in the upstream region of the shock \( N_0 \sim 6.6 \cdot 10^9 \) cm\(^{-3} \) and \( f_0 \sim 23 \) MHz, respectively. For the relative drift rate \( (df/dt) \cdot f^{-1} \sim 0.001 \) s\(^{-1} \) we obtain the estimates of the shock velocity \( V_{sh} \sim 1090 \) km s\(^{-1} \) and the magnetic field \( H_0 \sim 0.9 \) G, and the estimates of the critical values of the Alfvén magnetic numbers are \( M_{\text{cr}} \sim 1.12 \) and 1.15 for the coronal temperatures \( T \sim 10^6 \) K and 2 \( \cdot 10^6 \) K, respectively.

The obtained estimates of the parameters of shock waves (Alfvén magnetic number \( M \) and of the solar corona (density, magnetic field, and the critical value of the Alfvén magnetic numbers \( M_{\text{cr}} \)) show that the condition \( M > M_{\text{cr}} \) is fulfilled during the entire duration of all three segments. Moreover, the relatively small variability of these parameters during the entire burst allows us to assert that the most possible reason of the origin of such fragmented structure in a type II radio burst (with the attenuation or cessation of emission between the fragments) is that the shock wave enters a region where the magnetic field orientation was very different, and the shock wave became a longitudinal (that is, a condition of the perpendicularity was violated).

By the data of SOHO/LASCO C2, C3 (https://cdaw.gsfc.nasa.gov/CME_list/), the velocity of the corresponding CME was \( \sim 480 \) km s\(^{-1} \) in the beginning of the event with a low slowing-down, and the velocity became \( \sim 345 \) km s\(^{-1} \) at 20 Rs.

Event of 1997 October 9.

The dynamic spectrum of the band-split type II burst in this event is given in Vršnak et al. (2001, their Figure 3(a)). It is an example of a metric (i.e., coronal) type II burst in the 80–50 MHz range with well-defined band splitting. The obtained values of the relative split \( (df \cdot f^{-1}) \) and the relative frequency drift \( (df/dt) \cdot f^{-1} \) are also shown there as a function of time \( t \) (at six time moments). It can be noted that the relative split was approximately constant, and the relative frequency drift showed a slight decrease. Below, following our model, we give the estimates of the parameters of shock waves and the medium at the same time moments as given in the paper.

Moment 1: the Alfvén magnetic number \( M \sim 1.4 \), and \( Z \sim 1.16 \), the electron density and the plasma frequency in the upstream region of the shock \( N_0 \sim 6.3 \cdot 10^7 \) cm\(^{-3} \) and \( f_0 \sim 69.5 \) MHz, the shock velocity \( V_{sh} \sim 680 \) km s\(^{-1} \) and the magnetic field \( H_0 \sim 1.65 \) G, the estimates of the critical values of the Alfvén magnetic numbers are \( M_{\text{cr}} \sim 1.24 \) and 1.3 for the coronal temperatures \( T \sim 10^6 \) K and 2 \( \cdot 10^6 \) K, respectively.

Moment 2: the Alfvén magnetic number \( M \sim 1.35 \), and \( Z \sim 1.1 \), the electron density and the plasma frequency in the upstream region of the shock \( N_0 \sim 5.7 \cdot 10^7 \) cm\(^{-3} \) and \( f_0 \sim 67 \) MHz, the shock velocity \( V_{sh} \sim 600 \) km s\(^{-1} \) and the magnetic field \( H_0 \sim 1.45 \) G, the estimates of the critical values of the Alfvén magnetic numbers are \( M_{\text{cr}} \sim 1.24 \) and 1.3 for the coronal temperatures \( T \sim 10^6 \) K and 2 \( \cdot 10^6 \) K, respectively.

Moment 3: the Alfvén magnetic number \( M \sim 1.37 \), and \( Z \sim 1.15 \), the electron density and the plasma frequency in the upstream region of the shock \( N_0 \sim 4.7 \cdot 10^7 \) cm\(^{-3} \) and
$f_0 \sim 62$ MHz, the shock velocity $V_{sh} \sim 670$ km s$^{-1}$ and the magnetic field $H_0 \sim 1.4$ G, the estimates of the critical values of the Alfvén magnetic numbers are $M_{sh} \sim 1.24$ and 1.3 for the coronal temperatures $T \sim 10^6$ K and $2 \cdot 10^8$ K, respectively.

Moment 4: the Alfvén magnetic number $M \sim 1.34$, and $Z \sim 1.09$, the electron density and the plasma frequency in the upstream region of the shock $N_0 \sim 4 \cdot 10^7$ cm$^{-3}$ and $f_0 \sim 57$ MHz, the shock velocity $V_{sh} \sim 690$ km s$^{-1}$ and the magnetic field $H_0 \sim 1.37$ G, the estimates of the critical values of the Alfvén magnetic numbers are $M_{sh} \sim 1.23$ and 1.29 for the coronal temperatures $T \sim 10^6$ K and $2 \cdot 10^8$ K, respectively.

Moment 5: the Alfvén magnetic number $M \sim 1.35$, and $Z \sim 1.1$, the electron density and the plasma frequency in the upstream region of the shock $N_0 \sim 3.1 \cdot 10^7$ cm$^{-3}$ and $f_0 \sim 53$ MHz, the shock velocity $V_{sh} \sim 675$ km s$^{-1}$ and the magnetic field $H_0 \sim 1.3$ G, the estimates of the critical values of the Alfvén magnetic numbers are $M_{sh} \sim 1.23$ and 1.29 for the coronal temperatures $T \sim 10^6$ K and $2 \cdot 10^8$ K, respectively.

Moment 6: the Alfvén magnetic number $M \sim 1.25$, and $Z \sim 1.07$, the electron density and the plasma frequency in the upstream region of the shock $N_0 \sim 3 \cdot 10^7$ cm$^{-3}$ and $f_0 \sim 49.2$ MHz, the shock velocity $V_{sh} \sim 700$ km s$^{-1}$ and the magnetic field $H_0 \sim 1.65$ G, the estimates of the critical values of the Alfvén magnetic numbers are $M_{sh} \sim 1.23$ and 1.28 for the coronal temperatures $T \sim 10^6$ K and $2 \cdot 10^8$ K, respectively.

These estimates show an approximate constancy of the intensity (the Alfvén magnetic number) and shock velocity practically during the entire duration of this type II burst. However, the estimates at the six moments (end of the last segment of the band) give the Alfvén magnetic number $M \leq M_{cr}$; therefore, the end of radio emission can also be interpreted as a consequence of the relative weakening of shock waves.

By the data of SOHO/LASCO C2, C3 (https://cdaw.gsfc.nasa.gov/CME_list/), the velocity of the corresponding CME was $\sim 247$ km s$^{-1}$ in the beginning of the event with a small acceleration, and the velocity became $\sim 456$ km s$^{-1}$ at 20 Rs.

Event of 1997 November 4.

This event was also discussed in Vršnak et al. (2001), and it is an example of a type II burst in the dekameter to kilometer wavelength range associated with the shock detected by in situ measurements at 1 au. The dynamic spectrum of this burst in the frequency range 250–120 kHz is shown in their Figure 2, and it shows a fragmented, patchy emission pattern. For our analysis we used the fragment at 19:30:00–20:15:00 UT. To estimate the parameters of shock waves and the parameters of the interplanetary plasma, the density model and normalization procedure of Leblanc et al. (1998) was adopted, and the radial motion of the radio source was assumed as presumably corresponding to the shock velocity in the range of radial distances from the Sun $R > 10$ Rs.

The beginning: $f_1 \sim 137$ kHz, the relative frequency splitting $\Delta f \cdot f_1^{-1} \sim 0.33$, the Alfvén magnetic number $M \sim 1.85$, and $Z \sim 1.25$, the electron density and the plasma frequency in the upstream region of the shock $N_0 \sim 1.84 \cdot 10^2$ cm$^{-3}$ and $f_0 \sim 122$ kHz. For the relative drift rate $(df/dt) \cdot f_1^{-1} \sim 3.9 \cdot 10^{-5}$ s$^{-1}$ we obtain the estimates of the shock velocity $V_{sh} \sim 1000$ km s$^{-1}$ and the magnetic field $H_0 \sim 3 \cdot 10^{-3}$ G, and the estimates of the critical values of the Alfvén magnetic numbers are $M_{cr} \sim 1.1$ for the temperatures $T \sim 10^5$ K.

The end: $f_2 \sim 122$ kHz, the relative frequency splitting $\Delta f \cdot f_1^{-1} \sim 0.3$, the Alfvén magnetic number $M \sim 1.85$, and $Z \sim 1.25$, the electron density and the plasma frequency in the upstream region of the shock $N_0 \sim 1.46 \cdot 10^2$ cm$^{-3}$ and $f_0 \sim 110$ kHz. For the relative drift rate $(df/dt) \cdot f_1^{-1} \sim 3.9 \cdot 10^{-5}$ s$^{-1}$ we obtain the estimates of the shock velocity $V_{sh} \sim 900$ km s$^{-1}$ and the magnetic field $H_0 \sim 3 \cdot 10^{-3}$ G, and the estimate of the critical value of the Alfvén magnetic number is $M_{cr} \sim 1.08$ for temperature $T \sim 10^5$ K.

In this event the constancy of the parameters of the shock wave is in accordance with the connection of the shock wave with the CME. Under such conditions, the fragmented structure of radio emission can be observed when the specified conditions (sufficient intensity and perpendicularity of the shock front, that is, $M > M_{cr}$ and $\theta < \theta_{cr}$) are not satisfied during the propagation of shock in some regions of the solar atmosphere.

Note also that, by the data of SOHO/LASCO C2, C3 (https://cdaw.gsfc.nasa.gov/CME_list/), the velocity of the corresponding CME was $\sim 700$ km s$^{-1}$ at 20 Rs, that is, the shock front overtook the CME.

It can be noted that the estimated values of the strength of the upstream magnetic field in general are in good agreement with the results of Vrsnak et al. (2002), namely, the magnetic field strength is about 5–1 G at $R \sim (0.6–1)$ Rs. The estimates of parameters of the shock wave and, especially, of the magnetic field strength in the interplanetary space (at distances > 10–20 Rs) by the parameters of the kilometer type II bursts were obtained for the first time.

4. Conclusion

The presented analysis shows that the physical relationship between CMEflare and the coronal waves (Moreton waves, EUV waves, shock waves) is quite complex. The comparison of observations with the theoretical analysis provides evidence that the coronal shock and the associated type II burst emission can be due to the energy release in the flare, as well to the CME expansion. The investigations of the parameters of type II radio bursts can give valuable information about the MHD shock evolution in the inhomogeneous coronal and interplanetary plasma, as well as on the parameters of the medium where the shock wave is propagating. But when analyzing such radio bursts, it is important to take into account the generating mechanism of radio emission. In many papers the generation of type II bursts is associated with the drift acceleration of electrons at the perpendicular shock front, the formation of fluxes of accelerated electrons, the excitation of Langmuir waves in the region ahead of the shock front, and their transformation through nonlinear wave−wave processes into radio emission at frequencies close to the electron plasma frequency $f_{pe}$ and its second harmonic $2f_{pe}$. However, within the framework of such a model, a number of the problems remain in the interpretation of such characteristics of bursts as the narrow bandwidth of the emission bands in frequency and such a fine peculiarity of the structure of the bands as the band splitting. This model explains the acceleration and the formation of fluxes of accelerated electrons and the excitation of Langmuir waves in the upstream region of the shock front, but the issue of formation of fluxes of accelerated electrons in the downstream region remains unresolved. Therefore, the origin of split structure in the frame of the model, where the lower-frequency and higher-frequency bands are emitted from the upstream and downstream regions of the shock, remains unknown.
Here we used the model of the classical type II bursts based on the generation of plasma oscillations (the Buneman instability) within the front of collisionless shock waves and the induced scattering of plasma waves on fast electrons. This mechanism allows us to explain all the main parameters of radio bursts, including the fine structure. In the frame of this model of the source of type II radio bursts, two conditions must be fulfilled: (1) the shock wave must be relatively intense (the Mach number must exceed a certain critical value $M_c$), and (2) the shock wave must be perpendicular, a slight deviation from perpendicularity $\theta (\sim 2^\circ)$ results in cessation of the generation of plasma waves. This means that the shock wave is not a source of radio emission if any of these conditions are not satisfied. This also means that the source of radio emission can be formed at any part of the shock front (bow or flanks) simultaneously or in different times, depending on where and when the specified conditions are fulfilled, and the dynamic spectrum of type II radio bursts can either represent continuously drifting stripes or have an interruptive and a blob structure. In particular, the analysis of the fragmented dynamic spectra in a number of events showed that the condition $M > M_c$ was fulfilled during the entire duration of the fragments, and the most possible reason of the end of the radio emission in the fragments was the transition a shock wave from a perpendicular shock to a longitudinal shock (that is, a condition of the perpendicularity was violated).

The investigation of band splitting presented in this paper shows that it can be consistently interpreted in terms of the emission from the regions within the forward slope and the trailing slope of the leading soliton of collisionless shock waves. In the frame of such a model it is possible to estimate the parameters of the shock and their evolution during the propagation in the inhomogeneous magnetoplasma, as well as the parameters of the medium (density and magnetic field) where the shock is propagating. The results obtained here show that the reason for fragmented structure of the type II bursts can be both the variation of intensity of the shock wave during propagation in a strongly inhomogeneous and turbulent plasma and the transiting of the shock from perpendicular to longitudinal and vice versa.

It should be remarked that the dynamic spectra of the type II bursts have very diverse fine structure. Besides the fundamental and harmonic bands, their split into two sub-bands, the herringbones, and fragmentation of the radio emission, there are many another types of fine structure of the dynamic spectra. A number of types of the fine structure in the meter range were observed with ZMIRAN’s radio spectrographs and in several papers (e.g., Korolev et al. 1973 Urbarz et al. 1977; Fomichev & Chertok 1977 Markeev et al. 1981; Ishkov et al. 1985). Many of these types of fine structure were confirmed by the high-resolution LOFAR observations of a strongly fragmented type II burst on 2014 August 25 (Magdalenic et al. 2020). In addition, in this paper the first observation of a peculiar splitting of the already split harmonic band was reported. Now it is not clear whether such a peculiarity is intrinsic (common) for the type II radio bursts or not. In the frame of the model used here the reason for such a double splitting can be a collisionless shock wave that has the second source of emission connected with the second well-formed soliton. Such a situation needs a special theoretical analysis. But it is also very likely that such a structure can appear if several sources of the radio emission are formed along the large-scale shock front, where the conditions for generation of radio emission are fulfilled. Taking into account the various locations and spacings of these sources (with various parameters), the simultaneous presence of these sources can result in forming of the different types of fine structure (double splitting, many lines, blobs, and others).

Our analysis allows us to conclude that meter bursts starting at frequencies $<200$ MHz usually turn into intermittent bursts as long as the perpendicularity of the shock front remains. Bursts starting in the decimetric wavelength range ($>500$ MHz) do not go into the long wave range; they are usually associated with explosive shock fronts that slow down even in the meter range. Thus, registration of a type II burst is evidence of the propagation of a perpendicular shock wave, but the absence of a type II burst is not evidence of the absence of a shock wave. Such a situation can be one of the reasons for the ambiguous relationship between type II radio bursts and other manifestations of the solar activity (Hα wave, Moreton wave, EUV wave).

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ORCID iDs
Gennady Chernov https://orcid.org/0000-0003-3525-6746

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