Theory and Interpretation of Solar Decimetric Radio Bursts

(doctoral thesis)

Miroslav Bárta
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Abstract

Solar radio emission represents an important source of direct information about many physical processes related to particle acceleration in the solar atmosphere. Namely, the radio bursts – intense and highly variable component of solar radio radiation – bear many signatures of underlying physics related to primary energy release in solar flares and eruptions. Indeed, decimetric (dm) radio bursts and their careful analysis provide the closest observational insight into the region of magnetic reconnection and the particle acceleration sites. On the other hand, emission mechanisms of solar dm radio bursts are typically non-thermal, involving various plasma micro-instabilities and wave-mode transformations. High non-linearity of the radio emission process thus put strong demands on correct physical interpretation of the observed bursts and on finding the relations between observed features (e.g., intensity, frequency profile and its dynamics) and underlying physics. This doctoral thesis addresses two particular areas of research in the solar radio bursts and their utilization in the flare plasma diagnostics: (1) Physical interpretation of two particular classes of radio bursts related to solar flares, and, (2) Contribution to the theory and modeling of wave-mode conversion as an important part of the plasma radio emission physics. These two main contributions follow immediately after a brief introduction to the solar flare physics and advanced theory of waves and instabilities in plasmas.

Interpretation part concerns two specific classes of radio bursts: The *lace burst* (discovered by the *Ondřejov Solar Radio Group* at the Astronomical Institute AS CR in 2001), and much more known *decimetric spikes*. Interpretation is based on the model of *double-resonance instability* of upper-hybrid waves acting in the turbulent environment as it can be expected, e.g., in the reconnection outflow jets. Based on this assumption a multi-step forward-fit numerical model for the dynamic spectra is consecutively built. The model calculates saturated energy density level of upper-hybrid (UH) waves in the simulated turbulent environment of reconnection jet. Then, assuming (for the sake of simplicity) a fixed ratio of the UH wave energy is being transformed by the wave-mode conversion processes into the modeled escaping electromagnetic mode, the resulting radio emission is estimated, dependent on frequency and time. Constructed radio dynamic spectra are then compared with observations. It was found that action of the turbulence on the UH waves generation is double: (i) It rapidly changes spatial positions of resonant surfaces, where the double-resonance condition is fulfilled. This leads to the characteristic intermittent time variations of the resonant emission “line” frequency in the lace bursts. Conversely, the spectrum of frequency variations in the observed lace bursts can be used as a unique tool for estimation of the MHD turbulence properties (e.g., spectrum of the turbulent variations of plasma density and magnetic field, plasma density r.m.s.,...) in the radio source. (ii) Presence of shortest-scale and therefore fastest variations (controlled by the high-spatial-frequency cut-off in the simulated turbulence spectra) in the turbulent environment can effectively suppress the instability of UH waves and consequently make the emission itself very intermittent and of spiky nature. Resulting emission as seen in modeled spectra then resembles quite well the properties of *decimetric spikes*. Not only the first-glance impression from the modeled dynamic spectra reminds the typical dm spikes’ observation, but even the time and frequency profiles of individual spikes are very well reproduced by the model. This model thus – on the base level of emission mechanism – relates the dm spikes to the lace bursts: Just the position of high-frequency cut-off in the spectrum of turbulent variations in the reconnection jet (i.e., presence or lack of small-scale density/magnetic-field structures in the jet) controls, what type of radio emission will we observe. This unified model naturally explains – in addition to properties of individual spikes – also their organization into chains and lines observed frequently in the radio spectra. Moreover, relative rareness of lace bursts to spikes is thus quite natural as the lace bursts originate – according to this model – from not yet fully developed turbulence. This intermediate state, after the turbulence on-set and before the dissipation scale is reached in the turbulent energy cascade, likely lasts just for a short moment. On the other hand, rare observations of the lace burst, or even its transition to the dm spikes, thus opens advanced diagnostic possibilities for study of the MHD turbulence properties in the flare jets. Let us note, that the UH-instability based model may relate the lace bursts and the dm spikes also to the well known *zebra-structure* radio bursts: The double-resonance model in a stratified solar atmosphere is

assumed by many authors as an explanation for observed zebra structures. In this sense, the multi-line lace bursts represent an extension of emission model of multi-line zebra structures to the turbulent environment.

The last part of the thesis addresses an important part of the plasma radio emission mechanism – the conversion of wave energy from unstable electrostatic plasma modes to the escaping electromagnetic radio emission. Using the set of generalized Zakharov equations and their Green functions, the non-linear dispersion relations for interacting Langmuir (L), ion-sound (S) and electromagnetic/transverse (T) waves are found and solved. Exact solutions are found assuming Lorentz type particle velocity distribution functions what allows for the analytical integration in the complex plane. Assumption of the Lorentz-like distributions is not motivated merely by the possibility of analytical integration but also from observational reasons. The Lorentz-type distributions exhibit the high-energy tails in comparison to standard Maxwell statistics, which is in line with in-situ measurements in the solar wind (and via indirect evidence provided by the UV/EUV spectroscopy this holds also in the solar corona and the transition region). The exact solutions for non-linear dispersion equations using Lorentz-like distributions is not a single novel approach to this frequently studied problem of (spoace) plasma physics that can be found in the thesis: For the first time not merely frequencies and wave vectors of electromagnetic radiation generated by the parametric and modulation instabilities of initial Langmuir waves has been found, but – using the Green functions of Zakharov equations combined with solutions of the dispersion relation – the phase energy density (in the k-space) for all daughter wave modes was calculated, which is the quantity much closer to the application of this model to the *quantitative* diagnostics based on *intensities* of observed radio emission. Calculation of energy density of generated ion-sound daughter waves has also shown that frequently used *plasmatic approximation* n_e=n_i is not valid for specific regimes of instabilities and the exact solution of generalized Zakharov equations must be used.

The very last section of the thesis continues in this direction and develops the theory of wave-mode conversion in the turbulent environment as it can be expected namely in the flare jets. An author's adaptation of the quantum theory of scattering (up to the first order of expansion) is used for description of Langmuir wave-packet transmission through the ion-sound turbulence region. It is shown, that presence of such regions in the space, where Langmuir waves propagate, can lead to the strongly enhanced radio emission of *noise-storm* type.

The research part of the thesis is based on the three articles published in impacted journals whose is the candidate author or co-author.