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Editorial: solar radiophysics — recent results on observations and theories

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Abstract Solar radiophysics is a rapidly developing branch of solar physics and plasma astrophysics. Solar radiophysics has the goal of analyzing observations of radio emissions from the Sun and understanding basic physical processes operating in quiet and active regions of the solar corona. In the near future, the commissioning of a new generation of solar radio observational facilities, which include the Chinese Spectral Radio Heliograph (CSRH) and the upgrade of the Siberian Solar Radio Telescope (SSRT), and the beginning of solar observations with the Atacama Large Millimeter/submillimeter Array (ALMA), is expected to bring us new breakthrough results of a transformative nature. The Marie-Curie International Research Staff Exchange (MC IRSES) "RadioSun" international network aims to create a solid foundation for the successful exploitation of upcoming solar radio observational facilities, as well as intensive use of the existing observational tools, advanced theoretical modeling of relevant physical processes and observables, and training a new generation of solar radio physicists. The RadioSun network links research teams from China, Czech Republic, Poland, Russia and the UK. This mini-volume presents research papers based on invited reviews and contributed talks at the 1st *RadioSun* workshop in China. These papers cover a broad range of research topics and include recent observational and theoretical advances in solar radiophysics, MHD seismology of the solar corona, physics of solar flares, generation of radio emission, numerical modeling of MHD and plasma physics processes, charged-particle acceleration and novel instrumentation.

Key words: editorials, notices — Sun: corona — Sun: radio radiation — Sun: flares

Nowadays, solar physics is one of the most rapidly developing fields of astrophysics. The new ground-based and spaceborne observational facilities provide researchers with the means for unprecedented time, spatial and spectral resolution to study features and phenomena on our closest enigmatic star, the Sun, in different observational bands.

The interest in solar physics is connected with the central role, in all aspects, the Sun plays in the solar system, being the source of energy and also producing the overwhelming part of the magnetic field and the plasma filling the heliosphere. In the context of geophysics, the Sun is known to heavily influence Earth's climate, and cause magnetic storms and other extreme events that are part of space weather. The solar-terrestrial interaction can have violent and costly technological implications, such as energy supply blackouts, and disturbances and total disruption of communication and navigation systems. Moreover, the Sun is a natural plasma laboratory where one can find plasma in very different conditions and configurations, which is directly relevant to international efforts at controlled fusion.

An important band for solar observations is the radio part of the electromagnetic spectrum. On one hand, this band is one of two spectral windows in which the Earth's atmosphere is transparent and hence the Sun can be observed with ground-based facilities. Ground-based observations are not constrained by the data transfer limitations and a number of other problems intrinsic to observations from space. On the other hand, in this band the Sun is a very loud object, with its radio brightness increasing by several orders of magnitude during solar flares. Moreover, the radio emission brings us direct information about the plasma density and magnetic field, the parameters that are vitally important for understanding the structure and dynamics of the solar atmosphere. Indeed, coherent radio emission that is generated in magnetized plasma peaks at the electron plasma frequency and gyrofrequenciy and their harmonics, and the upper hybrid frequency. Non-coherent solar radio emission gives us information about thermal plasma density and the interaction of mildly-relativistic electrons accelerated in solar flares with the background plasma. An astonishing recent development is the observational detection of an unexpected peak of solar flaring emission in the sub-THz band, and ongoing efforts in its interpretation (e.g. see Fleishman & Kontar 2010). This justifies the continuous observational and theoretical efforts in solar radiophysics. The recent discovery of ultra-low frequency electromagnetic waves in the solar corona, which are usually referred to as magnetohydrodynamic (MHD) waves (e.g. see De Moortel & Nakariakov 2012), extended the area of interest and area of applicability of solar radiophysics. Coronal MHD waves have been detected as modulations of white-light, extreme-ultraviolet (EUV), X-ray and gamma-ray emission, as well as of radio emission. Confident identification of observed modulations as various MHD modes of solar atmospheric plasma non-uniformities have created a solid foundation for a new branch of plasma astrophysics, MHD seismology. Observations of MHD oscillations in the solar plasma, as well as in stellar flares and other dynamical processes in astrophysical objects (e.g. in accretion disks and magnetospheres of neutron stars) and in magnetospheres of the Earth and other planets, combined with the advanced theory of MHD wave interaction with plasma non-uniformities, allow us to get unique information about physical conditions and processes in these objects. Analysis of MHD oscillations, supplemented by the mainstream analysis of solar radio emission, opens up very promising opportunities that have yet to be explored.

A major reinforcement in solar radio observations is expected with the new generation of upcoming observational facilities. The Chinese Spectral Radio Heliograph (CSRH) will bring us a unique possibility of simultaneous 2D observations within a wide range of heights in the solar atmosphere and excellent spectral resolution in the 400 MHz–15 GHz band (Yan et al. 2009). These first routine implementations of solar imaging radiospectroscopy will give us a unique opportunity to trace height evolution and fine height structure of dynamical processes in bursty energy releases. This information is vital for revealing the basic mechanisms operating in solar (and stellar) flares, the knowledge necessary for improving forecasting of extreme events of space weather. The upgraded Siberian Solar Radio Telescope (SSRT) will be able to obtain 4–8 GHz images of the solar atmosphere with up to 1 second time resolution and up to $13''$ spatial resolution (Lesovoi et al. 2012). The heliograph supplemented with a complex of spectropolarimeters placed in the same observatory, will allow researchers to study physical processes with high time, spectral and spatial resolution within the most enigmatic levels of the solar atmosphere. The Atacama Large Millimeter/submillimeter Array (ALMA) will provide us with a unique new band of solar observations, 30–900 GHz, which allows directly probing the electron temperature in the solar atmosphere. This information is vital for understanding the thermal response of the low chromosphere to waves and shocks from the interior.

One of the major difficulties in the height tomography of MHD waves in the lower layers of the solar atmosphere is connected with the intrinsic uncertainties in the formation of emission or absorption lines, associated with the effects of the departure from local thermodynamic equilibrium (LTE). On the other hand, solar sub-THz emission has a thermal bremsstrahlung origin. The electrons are in LTE, allowing the use of the Planck source function. Thus, ALMA can be considered as a high-resolution solar chromospheric "thermometer." In addition, ALMA will disclose the high-frequency part of the non-coherent radio emission generated in solar flares (Karlický et al. 2011). The anticipated implications of this new information are crucial for revealing the enigmatic processes of high-energy particle acceleration, explosive releases of magnetic energy, and heating of solar and stellar atmospheric plasmas.

The Marie-Curie International Research Staff Exchange (MC IRSES) network "Radiophysics of the Sun" (*RadioSun*[1]) is a collaborative research project funded by the EU 7th Framework Programme, that links internationally-recognized and well-respected research teams at the National Astronomical Observatories of the Chinese Academy of Sciences (NAOC), the Astronomical Institute of the Academy of Sciences of the Czech Republic, the University of Maria Curie-Skłodowska, Poland, the Central Astronomical Observatory at Pulkovo of the Russian Academy of Sciences, the Institute of Solar-Terrestrial Physics of the Siberian Branch of the Russian Academy of Sciences, and the University of Glasgow and the University of Warwick, United Kingdom. The research teams specialize in observations and analysis of solar radio emission, MHD seismology, and theoretical modeling of relevant physical processes. The collaborating teams host CSRH and SSRT, and lead in the preparation of the solar research program with ALMA. The aim of the *RadioSun* project is to establish close research interaction and collaboration between the key EU and non-EU research groups involved in research about the Sun in the radio band; qualitatively advance our knowledge of the physical processes operating in the solar atmosphere, the basic mechanisms responsible for its evolution and dynamics and its effect on the Earth; provide young researchers with extensive training in relevant research techniques and with universally transferrable skills. Apart from qualitatively advancing solar and plasma astrophysics research, the *RadioSun* project has the goal to create a new generation of solar radio physicists that will exploit the data gained with these new facilities. The four-year collaborative project began in June 2012, and is expected to develop into a long-standing international partnership.

The first 20 months of the *RadioSun* collaboration have brought a number of important scientific results already published in thirty papers in leading astrophysical journals. Below we briefly summarize the main achievements.

Comprehensive analysis of zebra-patterns and spikes in microwave bursts emitted in solar flares, observed with the Chinese Solar Broadband Radio Spectrometer at Huairou and the Ondřejov Radiospectrograph in the Czech Republic was performed. Zebra-patterns (ZPs) are sequences of almost-parallel stripes of enhanced emission detected in the dynamical radio-spectra of type II and IV bursts. Three distinct types of ZPs, equidistant ZPs, variable-distant ZPs and growing-distant ZPs, were identified (Tan et al. 2014). Arguably, these different types correspond to different modulation mechanisms: the Bernstein wave model, whistler wave model and double plasma resonance model, respectively. In certain examples of microwave ZPs, solid evidence of the double-plasma resonance effect was found (Tan et al. 2012). The appearance of fibers and sporadic ZP stripes in flaring solar radio spectra, exhibiting the frequency splitting, was linked with the coalescence of plasma waves with whistlers (Chernov et al. 2012). One-second periodic modulation of the spectral location of ZP stripes was found and interpreted in terms of MHD oscillations in the emission source regions (Yu et al. 2013). This result supports the association of ZPs with the effect of the double plasma resonance.

[1] *http://www2.warwick.ac.uk/fac/sci/physics/research/cfsa/people/valery/radiosun/*

A novel semi-empirical model of the radio continuum modulation in pulsar radio emission based upon an analogy with ZPs in solar flares was created. ZPs in the pulsar and flare radio spectra were successfully reproduced in numerical simulation of the plasma emission mechanism in the presence of slow magnetoacoustic waves or turbulence (Karlický 2013).

Theoretical modeling of recently-discovered standing and propagating MHD waves in solar coronal plasma structures was performed. It was shown that the period of long-wavelength sausage oscillations, which are believed to be responsible for the quasi-periodic pulsations in solar and stellar flare light curves, may be independent of the wavelength (Nakariakov et al. 2012). Typical periods of these oscillations are then in the range of a few seconds to about a minute for typical flaring loops. The formation of rapidly-propagating EUV wave trains in coronal funnels was interpreted in terms of the dispersive evolution of guided fast magnetoacoustic wave trains (Pascoe et al. 2013). The wave trains of EUV intensity perturbations propagate along the magnetic field at a speed exceeding a few thousand km s^{-1}, have a typical period of about one minute (Yuan et al. 2013) and are associated with radio bursts. These wave trains can be used as natural probes of the magnetic connectivity in the solar atmosphere.

Detailed observational study and theoretical modeling of tadpole wavelet spectra of dm radio bursts was performed. Theory of the formation of tadpole spectral signatures, based on the effect of geometric dispersion of fast magnetoacoustic wave trains guided by field-aligned plasma non-uniformities, was generalized for the important case of coronal current sheets (Jelínek et al. 2012) that are the intrinsic ingredient in the standard solar flare model.

Long-period quasi-periodic pulsations in white-light emission generated in a stellar megaflare were discovered, and their similarity with the well-known SUMER oscillations was demonstrated (Anfinogentov et al. 2013a). This result suggests that the mechanism for megaflare energy release may be similar to the mechanisms for solar flares. It opens up interesting perspectives for the comparative studies of solar and stellar flares, and forecasting solar megaflares.

Detailed observational study of the new, decay-less regime of kink oscillations of plasma loops in solar coronal active regions was performed with the use of EUV imaging data obtained with SDO/AIA (Anfinogentov et al. 2013b). This regime is surprisingly different from the well-known large-amplitude kink oscillations that decay in a few cycles of the oscillation. The decay-less kink oscillations were found to have the same phase along individual loops, and their periods are different for different loops, which range from 2 min to 10 min. The theory describing this phenomenon is absent and needs to be constructed.

The first simultaneous detection of ultra-long-period oscillations in sunspots, with two spatially-separated radioheliographs, SSRT at 5.7 GHz and the Nobeyama Radioheliograph at 17 GHz, was made (Bakunina et al. 2013). Significant periodicities in the range of 22–170 min were found in the variation of the radio emission intensity, polarization and degree of circular polarization. Oscillation periods are different in different sunspots and in the same sunspot on different days. The ultra-long-period oscillations are likely to be global oscillations of sunspots, and their theory needs to be developed.

Acceleration of electrons in solar flares during nonlinear electron-beam relaxation in a magnetized plasma was modeled with a state-of-the-art 3D particle-in-cell electromagnetic code (Karlický & Kontar 2012). It was established that apart from the plasma thermalization, a noticeable part of the electron population gets accelerated. The amount of energy in the accelerated electrons above the energy in the injected beam could reach 10%–30% of the initial beam's energy. This effect has important implications for energetics of solar and stellar flares.

A novel technique for the diagnostics of the magnetic field geometry in sunspots' magnetospheres by the variation of the acoustic cut-off frequency was developed and applied (Yuan et al. 2014). Shorter period oscillations dominate in the sunspot umbra, but longer period oscillations form an annular shape approximately concentric with the sunspot. This effect is associated with a decrease in the acoustic cut-off frequency that happens with an increase in the inclination of a sunspot's mag-

Fig. 1 Participants in the 1st *RadioSun* Workshop and Summer School on a field trip to the construction site of the Chinese Spectral Radio Heliograph at the Mingantu Observatory in Inner Mongolia, China.

netic field from the vertical. Inclinations of the magnetic field determined with the theory of cutoff frequency were found to be about 30%–40% larger than the values obtained by potential field extrapolation, supporting the concept of the returning magnetic flux in the outer penumbra.

Comparative analysis of the time series of full width at half-maximum (FWHM) of Hα and Hβ lines obtained by the Ondřejov Observatory's optical spectrograph with microwave and soft X-ray (SXR) fluxes revealed the occurrence of two phenomenologically distinct types of observations which differ significantly in the timing of FWHM and SXR/radio fluxes (Kotrč et al. 2013). Synthesis of all observed data supported the interpretation of the Hα broadening in the sense of regular macroscopic plasma motions, contrary to the traditional view that associated it with the emission from warm dense plasma. The timing and observed characteristics indicated that the initiation of a prominence eruption had been observed. This possible interpretation was tested against MHD modeling of the initial phase of the flux rope eruption, followed by the calculation of the modeled Hα emission and spectrum. The modeled and observed data were found to be in good agreement. A set of diagnostics based on the developed model was suggested to estimate the Alfvén speed and plasma-β in the prominence, which are hard to obtain in other ways.

The volume, broadness and quality of the research findings unequivocally demonstrate the great potential of the international collaboration in solar radiophysics, based upon the synthesis of the research expertise and experience of the participating research teams. It is important to point out that almost every research paper that resulted from activities associated with *RadioSun* has an early-career researcher.

The 1st *RadioSun* Workshop[2] took place on 2013/10/28–11/02 at the Mingantu Observatory, Inner Mongolia, and at NAOC in Beijing, and was hosted by members of the Key Laboratory of Solar Activity, NAOC (see Fig. 1). The five-day activity provided an international forum for intensive discussion of most recent research achievements in solar radiophysics, as well as comprehensive reviewing of strategy development, operational improvement and formulation of future plans. The scientific sessions were comprised of the following topics: new radio instruments, with a focus on achievements and new goals; application of new methods of modeling and data processing to study solar phenomena; dynamic processes of energy release and transport in solar flares, relating to the

[2] *http://beijingradiosun.csp.escience.cn*

fine structure of solar phenomena and evolution of plasma parameters; and dynamic processes of energy release and transportation in solar flares. The workshop was accompanied by a Summer School with six lectures to PhD students and early-career researchers on various aspects of physics of solar flares, MHD theory, advanced methods of data analysis and solar radio emission.

This mini-volume includes three review papers based on invited reviews delivered at the 1st *RadioSun* Workshop by world-renowned experts in the relevant fields (Karlický 2014; Reid & Ratcliffe 2014; Pascoe 2014), and four selected contributed papers (Chernov et al. 2014; Gao et al. 2014; Lesovoi et al. 2014; Chmielewski et al. 2014). This set of publications provides an excellent snapshot of the ongoing observational and theoretical research activities in solar radiophysics. The mini-volume may be of interest not only to solar physicists, but also for researchers and students that specialize in plasma astrophysics, space physics, geophysics and controlled fusion.

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