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Editorial

Solar Radio Emissions

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The radio emission from the Sun covers a very wide frequency band ranging from several hundreds of GHz (sub-millimeter wavelength) down to sub-MHz (kilometer wavelength). Generally, radio emissions at different frequencies come from different layers of the solar atmosphere: sub-millimeter waves may come from the photosphere, millimeter waves from the chromosphere and transition region, centimeter–decimeter waves from the lower corona, meter-wave emissions from the higher corona, and decameter–kilometer waves from the interplanetary space [1–3]. At the same time, solar radio emissions with different spectral patterns may be produced by different physical processes, such as thermal bremsstrahlung, cyclotron emission, non-thermal synchrotron emission, coherent plasma emission (PE), and electron cyclotron maser emission (ECME) [4–9]. They are very sensitive to particle acceleration and propagation, plasma instabilities, magnetic fields and their variations, magnetic reconnections and the violent energy releases, various scales of plasma ejections and shock waves, etc. [10–14]. Therefore, solar radio observations can be applied to diagnose magnetic fields in the very hot and dilute coronal atmosphere to reveal the mystery of coronal heating, detect energetic particle acceleration and propagation, explore the origin of solar violent eruptions (flares, CMEs, jets, etc.) and track their temporal and spatial evolutions, and provide crucial information for predicting disastrous space weather events [14–16].

Recently, a series of advanced solar radio telescopes were put into operation and have already obtained a large amount of observational data. These new instruments include MUSER, EVOSA, SRH, LOFAR, MWA, ALMA, and PSP [17–22]. Through their high-sensitivity and high-resolution solar radio observations, we have the opportunity to give new explanations to the above important problems, discover new physics knowledge, and make new scientific breakthroughs. In order to exhibit the most recent progress, we established this Special Issue of *Universe*, "Solar Radio Emissions", in 2022. This Special Issue has collected a total of seven papers, including two review papers, two communications, and three research articles (see the list of contributions). It covers the spectral fine structure classification of solar radio bursts, quasi-periodic pulsations (QPPs), the diagnosis of plasma parameters in the source region, radio signals of dark matter axions, and millimeter-wave radiation in the solar transition regions.

Alissandrakis et al. (contribution 1) reviewed the results of a series of observations of high-sensitivity, low-noise dynamic spectra obtained with the acousto-optic analyzer (Spectrographe Acousto Optique-SAO, 270–450 MHz) of the ARTEMIS-IV/JLS solar radiospectrograph, in conjunction with high-time-resolution images from the Nançay Radioheliograph at five frequencies (164, 236.6, 327, 410.5, and 432 MHz). They reported the fine structures embedded in type-IV burst continua (spikes and fibers) and spike-like structures detected near the front of type-II bursts, and summarized their spectral parameters, such as the duration, bandwidth, and frequency drift rate. Through a combined analysis of SAO and NRH observations, they found the type-II-associated narrow-band spikes constituted

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the predominant radio signature of the MHD shocks. The similar spectral parameters of type-II and type-IV spikes indicate that they could be produced by similar emission processes as type-IV spikes. They are the signature of energetic electrons accelerated by MHD shocks. With the emission model of fibers and the proposed density model, they presented an estimate of the magnetic field of the source and the scale along the exciter path.

The paper by Karlicky and Rybak (contribution 2) applied radio spectra to analyze a group of high-frequency type-III bursts, and found a multi-periodicity of these bursts that is interpreted by the electron beams accelerated in the fragmented magnetic reconnection in the rising magnetic rope. They proposed that each period in these type-III bursts is a result of the periodic interaction of sub-ropes formed in the rising magnetic rope. In each interaction, the period depends on the diameter of interacting sub-ropes and local Alfvén velocity. They also found that the flare deviates from the standard flare model, where the main magnetic reconnection is located below the rising magnetic rope. The paper by Xu et al. (contribution 3) reported a QPP with period of 40 s at soft X-ray, hard X-ray, radio, and UV wavelengths. Based on the SDO/AIA observation, QPPs seem to originate from the flare ribbons, the peaks of fast-varying components correspond to the bright spots on two ribbons, and the period of QPPs is closely related to the separation of flare ribbons. These observations tend to support the mechanism of periodic non-thermal electron injection during flare eruption. QPP is a very important signal of the physical processes related to solar eruptions.

One important aspect for understanding solar phenomena is to obtain the source conditions from observations. The paper by Zaitsev and Stepanov (contribution 4) proposed the diagnostics of plasma density, temperature, electric current, radius, loop-top altitude, and loop volume in flare loops using the data of multi-wavelength observations in both shrinkage and expansion phases of the flare loops. The paper by Chen et al. (contribution 5) proposed a new classification for solar radio spectra from the Swin Transformer method. Experiments show that the self-attentive mechanism can extract the global features of images well, which gives the model a strong generalization ability and greatly improves model classification. It is more accurate than previous methods. The observations of radio spectral observations contain abundant information on the emission process. The analyses of radio spectral observations and their models provide more detailed information on the plasma process in solar activities. Through a joint study with imaging data, we could learn more information on the emission process, which would help us understand the physics of various solar phenomena.

What and where is dark matter? This is a big question in modern physics. Recently, many researchers proposed that ultralight axions and dark photons are well-motivated dark matter candidates. Inside the plasma, once the mass of ultralight dark matter particles matches the plasma frequency, they will resonantly convert into electromagnetic waves due to the coupling between the ultralight dark matter particles and the standard model photons. The converted electromagnetic waves are monochromatic. The paper by An et al. (contribution 6) reviewed the development of using radio detectors to search for ultralight dark matter conversions in the solar corona and solar wind plasmas.

Many crucial questions, including those regarding coronal heating, solar eruptions (flares, CMEs, and various scales of jets), and the origin of solar winds, are closely related to the physical processes in the solar transition region, especially non-thermal processes. However, so far, there has been almost no observation of non-thermal processes in the transition region, and millimeter-wavelength broadband dynamic spectrum observation is almost an unique approach. Therefore, we propose a millimeter-wave dynamic spectrum observation scheme with ultra-wideband and very-high-time–frequency resolutions (space-based SUBMS plan with frequency of 20–100 GHz, and a ground-based tested Sub-SUBMS plan with frequency of 20–35 GHz), which will open a new avenue for the study of the important questions mentioned above (contribution 7).

Although the content of this Special Issue does not cover all aspects related to solar radio emission, it does present as many important advances in the field of solar radio astronomy as possible, which can provide valuable references for researches in solar physics, astrophysics, and space science.

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List of Contributions

1. Alissandrakis, C.; Hillaris, A.; Bouratzis, C.; Armatas, S. Fine structure of solar metric bursts: ARTEMIS-IV/JLS and NRH observations. *Universe* **2023**, *9*, 442. https://doi.org/10.3390/universe9100442.
2. Karlicky, M.; Rybak, J. Multi-periodicity of high-frequency type III bursts as a signature of the fragmented magnetic reconnection. *Universe* **2023**, *9*, 92. https://doi.org/10.3390/universe9020092.
3. Xu, J.; Ning, Z.J.; Li, D.; Shi, F.P. Quasi-periodic pulsations in an M-class solar flare. *Universe* **2023**, *9*, 215. https://doi.org/10.3390/universe9050215.
4. Zaitsev, V.; Stepanov, A. Diagnostics of flare loop parameters in shrinkage and ascent stages using radio, X-ray, and UV emission. *Universe* **2023**, *9*, 261. https://doi.org/10.3390/universe9060261.
5. Chen, J.; Yuan, G.W.; Zhou, H.; Tan, C.M.; Yang, L.; Li, S.Q. Classification of solar radio spectrum based on Swin Transformer. *Universe* **2023**, *9*, 9. https://doi.org/10.3390/universe9010009.
6. An, H.P.; Ge, S.L.; Liu, J. Solar radio emissions and ultralight dark matter. *Universe* **2023**, *9*, 142. https://doi.org/10.3390/universe9030142.
7. Tan, B.L.; Huang, J.; Zhang, Y.; Deng, Y.Y.; Chen, L.J.; Liu, F.; Fan, J.; Shi, J. The non-thermal radio emissions of the solar transition region and the proposal of an observational regime. *Universe* **2024**, *10*, 82. https://doi.org/10.3390/universe10020082.

References

1. Dulk, G.A. Radio emission from the Sun and stars. *Annu. Rev. Astron. Astrophys.* **1985**, *23*, 169–224. [CrossRef]
2. Bastian, T.S.; Benz, A.O.; Gary, D.E. Radio emission from solar flares. *Annu. Rev. Astron. Astrophys.* **1998**, *36*, 131–188. [CrossRef]
3. Klein, K.L. Radio Astronomical Tools for the Study of Solar Energetic Particles I. Correlations and Diagnostics of Impulsive Acceleration and Particle Propagation. *Front. Astron. Space Sci.* **2020**, *7*, 580436. [CrossRef]
4. Fleishman, G.D.; Kuznetsov, A.A. Fast gyrosynchrotron codes. *Astrophys. J.* **2010**, *721*, 1127–1141. [CrossRef]
5. Melrose, D.B. The emission mechanisms for solar radio bursts. *Space Sci. Rev.* **1980**, *26*, 3–38. [CrossRef]
6. Winglee, R.M.; Dulk, G.A. The electron-cyclotron maser instability as a source of plasma radiation. *Astrophys. J.* **1986**, *307*, 808–819. [CrossRef]
7. Aschwanden, M.J.; Benz, A.O. Electron Densities in Solar Flare Loops, Chromospheric Evaporation Upflows, and Acceleration Sites. *Astrophys. J.* **1997**, *480*, 825–839. [CrossRef]
8. Aurass, H.; Vourlidas, A.; Andrews, M.D.; Thompson, B.J.; Howard, R.H.; Mann, G. Nonthermal radio signatures of coronal disturbances with and without coronal mass ejections. *Astrophys. J.* **1999**, *511*, 451–465. [CrossRef]
9. Zirin, H.; Baumert, B.M.; Hurford, G.J. The Microwave Brightness Temperature Spectrum of the Quiet Sun. *Astrophys. J.* **1991**, *370*, 779–783. [CrossRef]
10. Aschwanden, M.J. Theory of Radio Pulsations in Coronal Loops. *Sol. Phys.* **1987**, *111*, 113–136. [CrossRef]
11. Benz, A.O. Radio Spikes and the Fragmentation of Flare Energy Release. *Sol. Phys.* **1985**, *96*, 357–370. [CrossRef]
12. Carley, E.P.; Vilmer, N.; Vourlidas, A. Radio Observations of Coronal Mass Ejection Initiation and Development in the Low Solar Corona. *Front. Astron. Space Sci.* **2020**, *7*, 551558. [CrossRef]
13. Chen, B.; Bastian, T.S.; Shen, C.C.; Gary, D.E.; Krucker, S.; Glesener, L. Particle acceleration by a solar flare termination shock. *Science* **2015**, *350*, 1238–1242. [CrossRef] [PubMed]
14. Su, W.; Li, T.M.; Cheng, X.; Feng, L.; Zhang, P.J.; Chen, P.F.; Ding, M.D.; Chen, L.J.; Guo, Y.; Wang, Y.; et al. Quantifying the magnetic structure of a coronal shock producing a Type II radio burst. *Astrophys. J.* **2022**, *929*, 175. [CrossRef]
15. Tan, B.L. Diagnostic functions of solar coronal magnetic fields from radio observations. *Res. Astron. Astrophys.* **2022**, *22*, 072001. [CrossRef]

16. Tan, B.L.; Yan, Y.H.; Huang, J.; Zhang, Y.; Tan, C.M.; Zhu, X.S. The physics of solar spectral imaging observations in dm-cm wavelengths and the application on space weather. *Adv. Space Res.* **2023**, *72*, 5563–5576. [CrossRef]
17. Vourlidas, A.; Carley, E.P.; Vilmer, N. Radio observations of coronal mass ejections: Space weather aspects. *Front. Astron. Space Sci.* **2020**, *7*, 43. [CrossRef]
18. Yan, Y.; Chen, Z.; Wang, W.; Liu, F.; Geng, L.; Chen, L.; Tan, C.; Chen, X.; Su, C.; Tan, B.; et al. Mingantu Spectral radioeliograph for solar and space weather studies. *Front. Astron. Space Sci.* **2021**, *8*, 584043. [CrossRef]
19. Fu, Q.; Ji, H.; Qin, Z.; Xu, Z.; Xia, Z.; Wu, H.; Liu, Y.; Yan, Y.; Huang, G.; Chen, Z.; et al. A New Solar Broadband Radio Spectrometer (SBRS) in China. *Sol. Phys.* **2004**, *222*, 167–173. [CrossRef]
20. Altyntsev, A.; Lesovoi, S.; Globa, M.; Gubin, A.; Kochanov, A.; Grechnev, V.; Ivanov, E.; Kobets, V.; Meshalkina, N.; Muratov, A.; et al. Wultiwave Siberiran Radioheliograph. *Sol.-Terr. Phys.* **2020**, *6*, 30–40.
21. Tapping, K.F.; Morton, D.C. The Next Generation of Canadian Solar Flux Monitoring. *J. Phys. Conf. Ser.* **2013**, *440*, 012039. [CrossRef]
22. Gary, D.E.; Chen, B.; Dennis, B.R.; Fleishman, G.D.; Hurford, G.J.; Krucker, S.; McTiernan, J.M.; Nita, G.M.; Shih, A.Y.; White, S.M.; et al. Microwave and hard X-ray observations of the 2017 September 10 solar limb flare. *Astrophys. J.* **2018**, *863*, 83. [CrossRef]