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Editorial: Sources and propagation of ultra-low frequency waves in planetary magnetospheres

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Editorial on the Research Topic
Sources and propagation of ultra-low frequency waves in planetary magnetospheres

1 Introduction

Ultra-low frequency (ULF) waves, with frequencies from 1 mHz to 1 Hz, play a crucial role in the dynamics of planetary magnetospheres throughout our Solar System (e.g., Glassmeier and Espley, 2006; Volwerk et al., 2013; Liljeblad and Karlsson, 2017). They mediate the transfer of electromagnetic energy from the solar wind into the magnetosphere and are important drivers of particle acceleration and transport in planetary radiation belts (e.g., Zong et al., 2017). At Earth, enhanced ULF wave activity is typically associated with geomagnetic storms (Sandhu et al., 2021). High ULF wave power results in efficient electron acceleration to relativistic energies in the radiation belts, posing a risk to satellites orbiting in this region of space (e.g., Baker et al., 2018). Understanding ULF wave physics is thus critical both from the viewpoint of fundamental space physics and for space weather forecasting, and important efforts are being made to address the major open questions in the field.

This Research Topic compiles new results and comprehensive reviews of key aspects of ULF wave research. Here, we summarise the key points of these articles, sorted into four categories: transmission of externally-driven ULF waves, properties of field line resonances, new methodologies for ULF wave investigations and impact of ULF waves on radiation belt particles.

2 Transmission of ULF waves into the magnetosphere

Magnetospheric ULF waves can either be generated internally by local plasma instabilities, or originate from outside of the magnetosphere. External wave sources include fluctuations in the solar wind parameters, magnetopause surface waves, and waves driven by cyclotron instabilities upstream of the bow shock. It is still unclear how these externally-generated waves enter the magnetosphere and how their properties control the resulting ULF wave activity inside the magnetosphere.

Villante et al. emphasise the challenges encountered in connecting magnetospheric ULF waves with their external sources. Simultaneous observations by different solar wind monitors reveal that the dominant frequencies of the plasma density fluctuations vary depending on the exact parcel of solar wind probed by the spacecraft. Furthermore, the obtained frequencies are dependent on the selected spectral analysis technique and one must be cautious when interpreting the data. Numerical simulations can help alleviate some of these issues, as the exact conditions just upstream of the magnetosphere can be known at all times (Zhou et al.). Using a 2D global hybrid-Vlasov simulation, Zhou et al., investigate the interaction of solar wind density fluctuations with the Earth's outer magnetosphere. The varying upstream conditions lead to motion of both the magnetopause and the bow shock, as well as changes in the magnetosheath wave activity. In another numerical study, Turc et al., focus on ULF waves generated in the foreshock, comparing their properties for different solar wind conditions. They find that the wave power strongly depends on the Alfvén Mach number, from the foreshock to the magnetosphere, suggesting wave transmission.

3 Field line resonances

Field line resonance (FLR) is a very basic process through which the magnetosphere establishes standing Alfvén waves with position dependent frequencies, which can be detected by a variety of experimental techniques. The Research Topic includes three papers on the latest development in different aspects of FLR. The review article by Elsden et al. provides a comprehensive overview of the recent theoretical development of FLR in 3D magnetosphere geometry. In the traditional theoretical studies of FLR, a simple geometry such as a box model is often adopted for the magnetosphere to make the mathematics tractable (Southwood, 1974). In the real magnetosphere, the magnetosphere is dominated by the dipole magnetic field but the mass density structure is far from axially symmetric. Despite the asymmetry, FLR signatures are ubiquitous. Elsden et al. describe how this is possible. The review article by Lysak compares FLRs in the terrestrial and Jovian magnetospheres. The models for the FLR at Jupiter illustrate how the plasma structures unique to that planet, such as the plasma torus formed by Io, produce spatial and frequency structures of FLR that are vastly different from those found at Earth. The research paper by Warden et al. presents a detailed comparison of techniques to evaluate the latitudinal width of FLR using ground magnetometer data. The resonance width has a significant relevance to the widely used technique to determine the field line eigenfrequencies using data from latitudinally separated ground magnetometers.

4 A new method to study ULF waves: Sonification

Archer et al. employs techniques from audio and music, and applies them to the sonification of magnetospheric ULF waves. A variety of sonification methods are applied, and assessed through a public dialogue with stakeholder groups. The study presents recommendations on applying sonification to magnetic field timeseries. In particular, they discuss how sonification enables data to be more accessible and is well-suited for citizen science studies and public engagement. The study draws upon previous examples of where this has been successful for identifying and exploring ULF wave activity, although there remains a broad scope for sonification to understand the wealth of wave activity within the magnetosphere, as well as meaningfully engaging a broad range of audiences.

5 Impact of ULF waves on radiation belt particles

In planetary radiation belts, ULF waves can influence energetic electron dynamics through radial diffusion. Significant efforts are directed at computing radial diffusion coefficients, which quantify the amount of radial diffusion experienced by a particle population and are crucial for radiation belt modelling. Here George et al., present a new method to compute radial diffusion coefficients directly from the time derivative of the Roederer L^* coordinate. They apply it to a 2D hybrid-Vlasov simulation in which radial diffusion is driven by Pc3 waves. The proposed method only requires knowledge of the global magnetic field structure, and is thus applicable to any global simulation.

In summary, this Research Topic provides a good overview of the different aspects of ULF wave research and ongoing developments of the field including new methodologies, pointing towards future avenues of research.

Author contributions

LT wrote the introduction of this editorial and the sections on ULF wave transmission and impact on the radiation belts. KT wrote the section on field line resonances. JKS wrote the section on ULF wave sonification. All co-authors proofread and contributed to improving the entire editorial.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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