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Editorial: Kinetic plasma dynamics in the light of novel *in situ* heliospheric observations: synergistic view with theories and simulations

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Editorial on the Research Topic
Kinetic plasma dynamics in the light of novel *in situ* heliospheric observations: synergistic view with theories and simulations

The solar wind, a plasma stream emanating from the Sun, consists of various ion species, primarily protons (H^+), alpha particles (He^{2+}), and minor heavier ions such as O^{6+} and Fe^{12+}. Despite the presence of dynamic ion populations, which show variable abundances that fluctuate within the background solar wind as well as in structures (e.g., coronal mass ejections, stream interaction regions, etc.), the physics of heating and acceleration of each ion population remains elusive (Robbins et al., 1970; Marsch et al., 1982; von Steiger et al., 1995; Marsch, 2010; Verscharen et al., 2019; Ďurovcová et al., 2019; Mostafavi et al., 2022; Mostafavi et al., 2024). Moreover, energetic non-thermal pickup ions (PUIs), which predominantly originate from charge exchanges between interstellar neutral atoms and solar wind ions within the heliosphere (Semar, 1970), play a significant role in the transport of energy, momentum, and mass throughout the outer heliosphere (Burlaga et al., 1996; Zank, 2015; McComas et al., 2017; Zank et al., 1996), yet remain poorly understood.

Each plasma species often exhibits complex distribution functions that deviate from a simple Maxwellian profile, displaying non-Maxwellian features that are critical to understanding their kinetic behavior. These non-Maxwellian distributions are sources of free energy that can drive various kinetic instabilities and wave-particle interactions, processes essential to the heating and acceleration of solar wind ions. Understanding how the solar wind and energetic PUIs react, particularly in relation to turbulence, collisional processing, and large-scale heliospheric dynamics, is key to advancing our knowledge of solar wind behavior and its interactions across different regions of the heliosphere. Space missions such as Parker Solar Probe and Solar Orbiter (near the Sun), IBEX, WIND, and STEREO (at 1 AU), and New Horizons (currently in the outer heliosphere) have opened new windows into these processes, offering unprecedented *in situ* and remote measurements from the Sun's vicinity to the far reaches of the heliosphere.

The primary aim of this Research Topic was to expand our understanding of the science questions related to the heating and acceleration of solar wind ions and energetic PUIs, particularly through non-Maxwellian velocity distributions, wave-particle interactions, and turbulence in both the inner and outer heliosphere. This Research Topic hosts four significant contributions that enhance our understanding of these effects in the solar wind.

Previous observations revealed that solar wind ions exhibit distinct kinetic non-thermal features such as the differential flows that suggest preferential acceleration of alpha particles compared to protons (Ryan and Axford, 1975; Marsch et al., 1982; Ďurovcová et al., 2019; Mostafavi et al., 2022). Additionally, Coulomb collisions during a transit time of a particle can be crucial in reducing the ion non-thermal features (Kasper et al., 2008; Mostafavi et al., 2022; Ran et al., 2024). In this Research Topic, Johnson et al. introduce an application of collisional analysis to the alpha-proton differential flow. By comparing *in situ* observations from the Parker Solar Probe and the Wind spacecraft, they find strong evidence that Coulomb collisions play significant roles in shaping the differential flow through the inner heliosphere. These results underscore the importance of considering collisional processes in models of solar wind acceleration and heating.

While the role of Coulomb collisions in shaping ion dynamics is crucial, understanding the mechanisms of energy dissipation and turbulence in collisionless plasmas is equally important (Bourouaine et al., 2013). Here, Guerrero Guio et al. advance this understanding through a detailed investigation into the probability distribution functions of magnetic field increments, employing both single-spacecraft and multi-spacecraft approaches. Their study reveals a transition from Gaussian to non-Gaussian distributions at smaller scales, indicating the presence of intermittency within the turbulent cascade. Moreover, they demonstrate that the multi-point approach tends to underestimate intermittency due to its focus on larger scales, highlighting the needs for high-resolution measurements in capturing the true nature of heliospheric turbulence. This finding is particularly relevant to the upcoming Helioswarm mission (Klein et al., 2023).

In the outer heliosphere, beyond the ionization cavity which is about 4 au from the Sun, PUIs become an important source of turbulence (Zank et al., 1996; Isenberg et al., 2023; Adhikari et al., 2023). In this Research Topic, Wang et al. explore the temporal and latitudinal dependence of turbulence driven by PUIs in the outer heliosphere. Utilizing a latitude-dependent solar wind speed model and an advanced ionization rate model, this study provides a comprehensive analysis of the temporal and spatial variation in the strength of low-frequency turbulence driven by PUIs from 1998 to 2020. They highlight the significant variability in turbulence driving rates with solar activity and latitude, emphasizing the need for turbulence transport models to incorporate these dynamic factors to accurately predict solar wind heating and cosmic ray modulation.

Finally, Odstrcil advances the field of predictive modeling for space weather events, with a particular focus on multi-CME interactions within the heliosphere. This paper enhances our understanding of how multiple coronal mass ejections interact as they propagate through the heliosphere, a complex process that can lead to significant space weather impacts on Earth and throughout the solar system. While this paper primarily addresses space weather forecasting, its relevance to kinetic plasma dynamics cannot be understated. The improved modeling tools and interpretations presented are crucial for understanding how large-scale heliospheric disturbances affect the solar wind's kinetic properties, thereby linking space weather events to the broader theme of solar wind dynamics.

Together, these papers illustrate the significant advancements in the study of plasma dynamics within the heliosphere, from inner to outer regions. They reflect a growing synergy between observational data, theoretical models, and numerical simulations, offering a more integrated understanding of the solar wind ions, turbulence, non-thermal energetic PUIs, and space weather phenomena. As we continue to explore the heliosphere with the current and future missions and advanced models, the insights from these studies will be instrumental in guiding future research and improving predictive models of space physics.

Author contributions

PM: Writing–original draft, Writing–review and editing. RK: Writing–review and editing. TB: Writing–review and editing. DT: Writing–review and editing.

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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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