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Editorial: Thermal imbalance and multiphase plasmas across scales: from the solar corona to the intracluster medium

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Editorial on the Research Topic
Thermal imbalance and multiphase plasmas across scales: from the solar corona to the intracluster medium

Thermodynamically non-equilibrium multiphase plasmas, featuring a continuous interplay of heating and cooling processes and a range of temperatures from thousands to millions of K, are ubiquitous in both laboratory and diverse astrophysical plasma environments. The main interest in thermodynamically active plasmas has been traditionally connected with radiative (condensation) instability responsible for the formation of cool dense structures (see the seminal paper of Field, 1965). Nowadays, this research extends to the formation of coronal rain, prominences, and thermal non-equilibrium (TNE) cycles in the solar atmosphere (e.g., Antolin, 2020; Antolin and Froment, 2022), modified dynamics and stability of magnetohydrodynamic (MHD) waves (e.g., Nakariakov and Kolotkov, 2020; Kolotkov et al., 2021), and cool cluster cores and associated feedback cycles in the circumgalactic and intracluster medium (CGM & ICM) that regulate the formation of galaxies (e.g., Dunn and Fabian, 2008; Voit et al., 2015). These phenomena demonstrate striking similarities across scales, offering insights into the mechanisms behind coronal and ICM heating and instabilities of thermal or other nature (e.g., Hood, 1992). This interdisciplinary Frontiers Research Topic aims to consolidate recent advances in observational and theoretical studies of thermodynamically non-equilibrium plasmas across these fields and promote knowledge exchange.

Motivated by the insights from laser–plasma theory and responding to recent observational findings that the thermal transport in the solar corona may be significantly suppressed relative to the standard *Spitzer* prediction (Spitzer, 1962), the review of Arber et al. addresses the question of when the fluid approach and local approximation for the description of thermal transport in solar and space plasmas break down. It is articulated that non-local transport effects should be taken into account if the temperature perturbation scale length is comparable to the electron mean-free path. Arber et al. show that the standard fluid-based local *Spitzer* approach fails for the temperature scale length less than 5 Mm and 500 Mm for a 1-MK and 10-MK coronal plasma, respectively. The latter estimations are crucial for an accurate modelling of the dynamic processes in coronal loops, such as MHD waves and coronal rain, and assessing their role in coronal heating (e.g., Van Doorsselaere et al., 2020).

The work of Kolotkov presents a gold standard for the application of the method of coronal seismology in strongly non-adiabatic conditions to probe such fundamental parameters as thermal transport coefficient and effective adiabatic index of the coronal plasma, through numerical simulations and analysis of essentially non-adiabatic slow magnetoacoustic waves. In particular, it is shown that the use of a polytropic assumption for the estimation of the effective coronal adiabatic index is justified in a weakly conductive regime only. In realistic coronal conditions with strong field-aligned conductivity, the observable slow wave parameters such as the amplitude ratio and phase shifts between plasma density and temperature perturbations become coupled with the thermal conduction coefficient and effective adiabatic index. Zavershinskii et al. extends this study by obtaining an exact analytical solution for linear slow-mode oscillations in coronal loops with field-aligned thermal conduction. It is shown that the initial perturbation energy partitions between slow and entropy modes, and the efficiency of this partitioning depends on the properties of the thermal conduction process and coronal loop parameters. It is also shown that the phase shifts between density and temperature perturbations, caused by conduction, increase with the harmonic number of the standing slow wave, but always remain smaller than $\pi/2$, which can be used as an important constraint for the interpretation of observations.

Waters and Proga perform a study of nonlinear stabilisation of thermal instability and derive several general identities that reveal the mechanism by which thermal instability saturates. The exponential growth of condensations is slowed down by a pressure reversal, which causes the dynamics to deviate from the linear solution. For isobaric perturbation (associated with the entropy mode), a steady state is quickly reached. For non-isobaric regime (associated with the acoustic mode), pressure oscillations arise which eventually damp and bring the medium to mechanical equilibrium. Moreover, Waters and Proga address a semantic question of the conceptual difference between the phenomenon of thermal instability and thermal non-equilibrium.

Ganguly et al. measure the velocity structure functions (VSFs) in ~10 clusters using Hα and CO-emitting cold (~10^4, $\lesssim 100$ K) gas. Turbulence is one of the important heat sources that can compensate for the cooling losses (radiated away in X-rays) in dense ($n \gtrsim 0.01\,\mathrm{cm}^{-3}$) cluster cores. In this work, the cold gas, assumed to trace the local velocity of the hot ICM at large scales, is used to constrain turbulence in the ICM. The observed (projected) VSFs are steeper than the expectations from subsonic and supersonic turbulence ($v_l \propto l^{1/3,1/2}$) but show a sign of consistency with $l^{1/3}$ at smaller scales. The flattening of VSFs at large scales indicates the energy injection scale, that matches the bubble/cavity sizes. The turbulent dissipation rate estimated at smallest scales is only $\lesssim 10\%$ of the rate required to offset cooling losses in the core. This paper corroborates the previous results and provides impetus to future work on constraining turbulence in the ICM.

Choudhury presents an overview of multiphase plasmas in diffuse, extended atmospheres of galaxies and clusters of galaxies (CGM and ICM). They motivate the theoretical basis of thermal instability, its isobaric and isochoric regimes and their applicability to CGM/ICM. They also discuss the nonlinear processes such as the interplay of thermal instability and gravitational stratification, and the interaction of a dense cloud with a wind. Interesting analogies and differences between galactic atmospheres and the solar coronal phenomena, such as prominences and coronal heating, are highlighted. Important plasma physics questions related to heating, weak collisionality and gyro-radius scale instabilities are briefly mentioned. This mini-review is an excellent place to learn about fascinating non-equilibrium phenomena across ~10 orders of magnitude in scales.

The publication of this Frontiers Research Topic was inspired by a dedicated session "Non-equilibrium thermodynamics across scales: from the solar corona to the intracluster medium" at the National Astronomy Meeting 2022, convened by P. Antolin, P. P. Choudhury, T. Duckenfield, A. Fabian, M. Jardine, D. Kolotkov, P. Sharma, and by the international webinar and research team "Effects of Coronal Heating/Cooling on MHD Waves" chaired by D. Kolotkov. See also a white paper on this Research Topic, submitted to the NASA Decadal Survey for Solar and Space Physics (Heliophysics) 2024–2033 (Antolin et al., 2023).

Author contributions

DK: Writing–original draft, Writing–review and editing. PA: Writing–review and editing. PS: 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.

Publisher's note

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