

突発的な力によって駆動される太陽プロミネンスの形成
Formation of solar prominence driven by impulsive forces

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担当 : 研究の指導監督助言

研究目的 (Research Objective):

The primary purpose of this research is to achieve a comprehensive understanding of the formation mechanisms of solar prominences—cool, dense plasma suspended in the hot, tenuous corona. While previous studies have proposed theoretical models such as the evaporation-condensation model and the direct-injection model, their underlying physical drivers and the transition between them remain unclear. Our earlier one- and two-dimensional simulations have led to a unified model that identifies the height of localized heating (linked to magnetic reconnection at the footpoint) as the key distinguishing factor between the two scenarios. However, due to the limitations of low-dimensional simulations, we have so far been restricted to studying single filament threads, unable to capture the collective dynamics and fine structures that characterize real prominences. Therefore, the central goal of this study is to overcome these limitations by developing a high-resolution three-dimensional simulation framework. Specifically, we aim to construct a complete model that explains how impulsive forces, magnetic reconnection, and thermal processes work together to form and sustain prominences. Through this three-dimensional approach, we seek to bridge the gap between theoretical models and observed prominence complexity, thereby providing deeper insight into solar activity and its impact on coronal mass ejections and flares.

計算手法 (Computational Aspects):

In this study, we employ the MPI-AMRVAC framework to perform three-dimensional magnetohydrodynamic (MHD) simulations of solar prominence formation. The numerical setup is designed to capture both the large-scale magnetic configuration and the thermodynamic evolution of the plasma.

We first construct the initial magnetic field configuration using the magneto-frictional (MF) method, which allows the system to relax toward a force-free equilibrium consistent with the prescribed boundary conditions. This approach provides a realistic three-dimensional magnetic topology containing dipped field lines that are capable of supporting cool, dense prominence material.

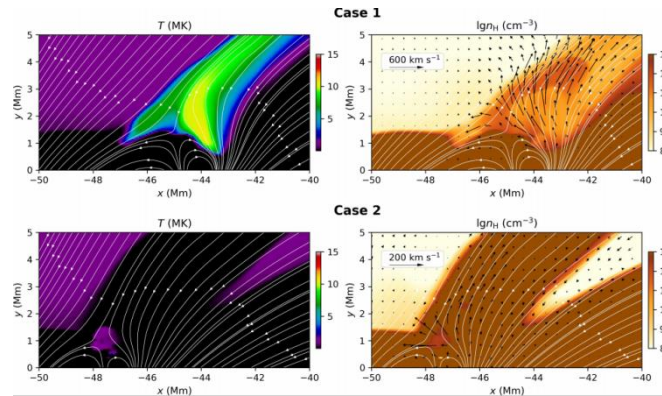
Based on this pre-configured magnetic structure, we then carry out time-dependent MHD simulations. The formation of the prominence is driven by localized and impulsive heating applied near the chromospheric footpoints, which induces chromospheric evaporation and subsequent thermal instability in the corona. The simulations self-consistently evolve the plasma density, temperature, and velocity, enabling us to track the condensation process and mass accumulation along magnetic field lines.

Adaptive mesh refinement (AMR) is utilized throughout the simulation to ensure sufficient resolution in regions with strong gradients, such as condensation sites and transition regions.

研究成果 (Accomplishments) :

The main results of this study can be divided into two parts, based on two-dimensional (2D) and three-dimensional (3D) simulations.

In the 2D simulations, we successfully reproduce two distinct prominence formation mechanisms driven by magnetic reconnection (seen in the figure below). By self-consistently incorporating reconnection-induced energy release into the system, the simulations demonstrate how localized heating near the footpoints can trigger both evaporation - condensation processes and direct plasma injection into coronal magnetic structures. These two mechanisms exhibit clearly different evolutionary pathways, thermodynamic properties, and mass supply processes. In particular, we analyze the dynamical evolution of the resulting filament plasma, including the formation, growth, and drainage of cool dense material along magnetic field lines. Furthermore, we quantitatively investigate the mass circulation process during prominence formation, evaluating how chromospheric plasma is transported into the corona and how a significant fraction of this material subsequently returns to the lower atmosphere. This provides a coherent picture of the mass exchange between different atmospheric layers and highlights the role of reconnection in regulating this cycle.



In the 3D simulations, we extend the analysis to a more realistic magnetic configuration and successfully reproduce the formation of a prominence within a coronal flux rope system. The results reveal that the formation process follows a hybrid scenario, in which both plasma injection and in-situ condensation contribute simultaneously to the buildup of cool material. These two processes are not independent; instead, they interact and influence each other throughout the evolution. For example, injected plasma can modify the local thermodynamic conditions and facilitate thermal instability, while condensation can alter the magnetic and flow structures, thereby affecting subsequent mass transport. In addition, we examine the dynamical structure of the prominence during its formation, including the evolution of flow patterns, density distribution, and magnetic support. The simulations also allow us to investigate the mass circulation between the corona and the lower solar atmosphere in a fully three-dimensional context, providing new insights into the global mass budget and the coupling between magnetic topology and plasma thermodynamics.

公表状況 (Publications) :

1. C.J. Huang, Y.W. Ni, J.H. Guo, P.F. Chen, A self-consistent model of solar prominence formation, *The Astrophysical Journal*, Volume 991, Issue 2, id.215, 9 pp.
2. C.J. Huang, Formation of solar prominence driven by impulsive forces (Doctoral thesis)

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1. C.J. Huang, Yokoyama takaaki, Formation of solar prominence driven by impulsive forces, JSPC, Kyoto, March 2026
2. C.J. Huang, Yokoyama takaaki, Formation of solar prominence driven by impulsive forces, ASJ annual meeting spring, Kyoto, March 2026