

太陽プロミネンス形成の 3D 磁気流体力学シミュレーション

3D numerical simulation of solar prominence formation

研究代表者 : Huang Chujie (Department of astronomy, Graduate school of Science, Kyoto University)

研究分担者 : 横山央明 (京都大学理学研究科附属天文台)
担当 : 研究の指導監督助言

研究目的 (Research Objective):

Solar prominence (or filament) - cool, dense plasma suspended in the hot corona above magnetic neutral lines - represent a captivating solar atmospheric phenomenon. Their formation, governed by thermal instability (TI) and/or thermal non-equilibrium (TNE), directly opposes coronal heating processes. These structures serve as critical indicators of coronal magnetic fields and play a pivotal role in triggering solar flares and coronal mass ejections (CMEs). Our research aims to unravel the fundamental mechanisms behind prominence formation through advanced numerical modeling.

Three primary theoretical models exist for prominence formation: the evaporation-condensation model, direct-injection model, and levitation model. Our work focuses on the first two observationally supported mechanisms. The evaporation-condensation paradigm proposes that chromospheric plasma undergoes heating-induced evaporation, and subsequent coronal condensation to form prominence. Conversely, the direct-injection model posits that cold chromospheric plasma is magnetically injected and trapped in coronal structures by gravity.

Our unified framework, derived from 1D simulations, identifies the localized heating height (equivalent to magnetic reconnection height at footpoints of magnetic flux rope(MFR)) as the key difference between these models. This work intend to extend the unified model from 1D to 2D&3D cases. We will replace the artificial heating in 1D simulation with real magnetic reconnection, discover how the footpoints' reconnection affect the formation process and make a comprehensive model of solar prominence formation process

計算手法 (Computational Aspects):

In this work, we are going to use MPI-AMRVAC to do the simulation work. The

main computational aspects of 2D&3D are as followed:

In our 2D simulation, we will establish a time-independent background magnetic arcade and introduce an emerging magnetic flux at one of its footpoints. This emerging flux will undergo magnetic reconnection with the background field, generating hot evaporation flows and cold injection flows to form a prominence. An Adaptive Mesh Refinement (AMR) grid will be implemented to achieve a maximum resolution of $500 \text{ km} \times 125 \text{ km}$ (or higher) cell size, ensuring sufficient detail to resolve and analyze the reconnection process.

Our 3D simulation involves three key phases: First, we initialize a background magnetic flux rope (MFR) via magnetic friction (MF) simulations in isolation from the solar atmosphere. The preformed MFR is then embedded into a realistic solar atmosphere environment, where full magnetohydrodynamic (MHD) simulations with thermal conduction, gravity, and radiative cooling drive the system toward equilibrium. Finally, inspired by the 2D approach, an emerging magnetic flux is introduced near the MFR's footpoint. The inherent 3D twisted magnetic geometry enables the prominence formation process to exhibit multi-scale fine structures and dynamic thread interactions, thereby refining the unified model through three-dimensional insights. However, due to the simulation resources, the resolution in 3D is lower with $198 \text{ km} \times 198 \text{ km} \times 198 \text{ km}$ smallest cell size and the analyze will be mainly qualitatively.

研究成果 (Accomplishments) :

In 2D simulation (completed), we set the magnetic emerging flux at different horizontal location to trigger the reconnection at different heights (Fig 1):

Case 1 demonstrates the formation process of the evaporation-condensation model, while Case 2 illustrates the direct-injection model. (the main result is not published yet, therefore will not be introduced)

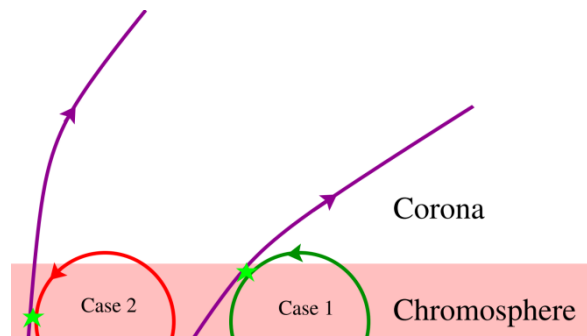


Fig.1 2D simulation: Magnetic reconnection at different heights

In 3D simulation (in progress), We have already completed the first two steps: forming a magnetic flux rope in MF simulation by setting an initial magnetic sheared arcade, introducing a bottom driving velocity to twist the magnetic field into a quadrupole field, and finally relaxing it to a force-free state, as seen in Fig.2

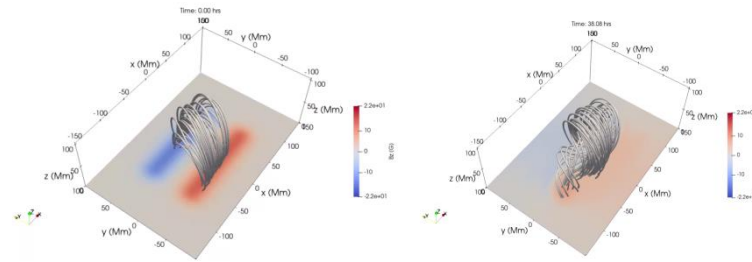


Fig.2 3D MF simulation, Left: magnetic sheared arcade before shearing and converging flow,
Right: Magnetic flux rope (MFR) after the driving velocity and relaxing

Subsequently, we introduce the MFR into the solar atmosphere and allow it to reach a state of static, thermal, and magnetized equilibrium, as depicted in Fig.3. This sets the stage for the ultimate phase involving the emergence of magnetic flux. Currently, the final step still need more parameter tests to complete.

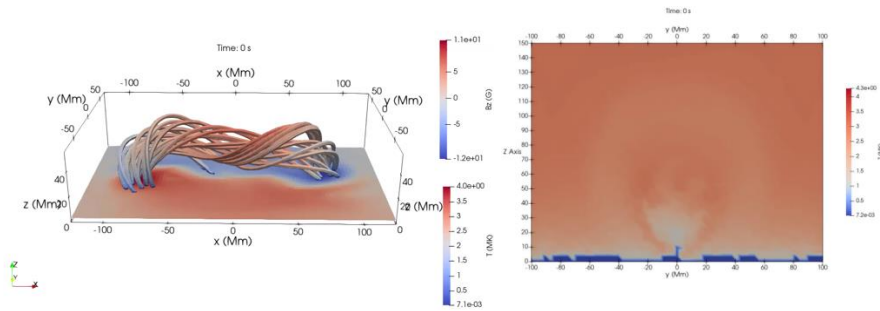


Fig.3 3D MHD simulation, Left: MFR in the solar atmosphere
Right: Temperature distribution at x=0 panel

公表状況 (Publications) :

(論文)

1. C.J.Huang, Y.W.Ni, J.H.Guo, P.F. Chen, A self-consistent model of solar prominence formation(submitted)

(口頭)

1. C.J. Huang, A self-consistent model of solar prominence formation, ASJ annual meeting, 2024,9
2. C.J. Huang, T. Yokoyama, Simulations of solar prominence formation driven by magnetic emerging flux: I.Setup of background flux rope and emergence fields, ASJ annual meeting, 2025,3