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Flux Rope Eruptions and Shocks: 2.5D Numerical Modeling

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As manifestations of solar storms, solar flares, eruptive prominences (EPs), and coronal mass ejections (CMEs) affect Earth's environment and human habitability. Sometimes, solar energetic particle events (SEPs) are associated with CME-driven interplanetary shocks that propagate through the turbulent solar wind. We explore these phenomena in a gravitationally stratified solar atmosphere using 2.5D MHD combining particle simulations as shown in Figure 1.

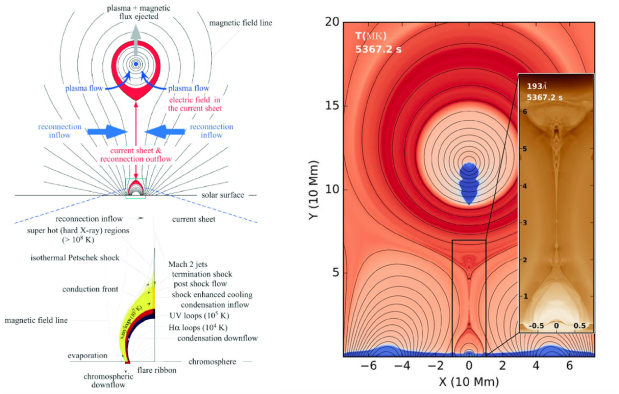

Figure 1: The left side shows a schematic diagram of the solar eruption Lin-Forbes model [1], adapted from [2]. The right side presents a comparative image from our 2.5-dimensional magnetohydrodynamic (MHD) simulations of solar eruptions, adapted from [3-6]. A zoomed-in view of the current sheet is also plotted on the right side, displaying a synthetic extreme ultraviolet (EUV) observation image obtained through forward modeling, which reveals "mesoscale" phenomena within the current sheet, such as magnetic island motion, waves, and shocks. Our simulation also incorporates the prominence formation process during flux rope eruption. Solar prominences are relatively cool and dense structures in the solar atmosphere, as depicted on the right side within the flux rope.

Our research includes three key topics:

(1) MHD simulations of solar flux rope eruptions and prominence formation [3, 4, 5, 6]: We employed 2.5D MHD simulations to investigate two scenarios of flux rope and prominence eruptions within a gravitationally stratified solar atmosphere. We further developed the levitation model for prominence formation and proposed a novel mechanism involving plasmoid-fed processes in the current sheet. These models describe the formation of flux ropes during eruption and pre-existing flux ropes beforehand, respectively. Additionally, we explored "mesoscale" phenomena during flux rope eruption and their association with Quasi-Periodic Pulsations (QPPs).

(2) Shock-Turbulence Interactions Associated with CMEs [7]: When CMEs propagate through the solar wind, they drive interplanetary shocks that interact with solar wind turbulence, which is one of the sources of SEPs. These interactions result in a turbulent downstream fluid. We found that after shocks propagate across turbulence, the downstream occurrence of plasmoids (i.e., small magnetic flux ropes in the solar wind) increases, saturates to a peak value for a certain interval, and then gradually decreases away from the shock. These plasmoid structures are important for plasma heating and particle acceleration. Besides, the flux rope eruption within a turbulent coronal environment, resulting in distorted, curved coronal shocks, will also be discussed.

(3) Particle Accelerations During Solar Eruptions [7, 8]: We investigated particle acceleration during solar eruptions, focusing on: 1) test-particle modeling of non-adiabatic particle motion in 2D magnetic islands; 2) particle propagation through turbulent flux tubes in the solar wind; and 3) preliminary tests to study particle acceleration at interplanetary shocks using a PIC-MHD approach. This approach accounts for electromagnetic interactions between non-thermal particles and the background magnetofluid, potentially leading to upstream self-excited turbulence enhancing particle acceleration through various mechanisms.

References

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