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Modeling Solar Prominences with Frozen-Field Hydrodynamic (ffHD) Equations

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Large-scale dynamics in the solar corona's plasma can be effectively modeled using magnetohydrodynamics (MHD) equations. However, full-scale, multi-dimensional MHD simulations require immense computational resources. Given the low plasma β in the solar corona, treating the magnetic field as static is often sufficient, simplifying the problem to 1D hydrodynamic (HD) simulations. This approach is particularly useful for studying coronal loops and their tendency for condensation due to thermal instability. While 1D HD simulations along magnetic field lines are efficient, they do not fully capture multi-dimensional effects. To address this, we solve the multi-dimensional MHD equations with a static field, converting them into frozen-field HD (ffHD) equations for simulations [1].

We integrated the ffHD module into the open-source code MPI-AMRVAC [2] and employed it in a 2D model to investigate prominence formation driven by thermal instability. The results of these 2D ffHD simulations were compared with those from true 2D MHD and pseudo-2D HD simulations, which incorporate the effects of field line expansion, to analyze the differences and their underlying causes. This comparison demonstrated the efficiency and reliability of the ffHD approach.

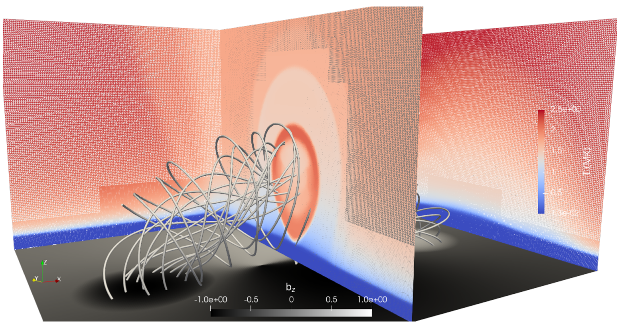

Fig1. 3D Titov-Demoulin flux rope

Further, we applied the ffHD module to a 3D Titov-Demoulin flux rope model to evaluate its effectiveness in detailed 3D simulations. We also performed forward modeling for EUV synthetic imagery to enhance the comparison with observational data, further showcasing the model's capability.

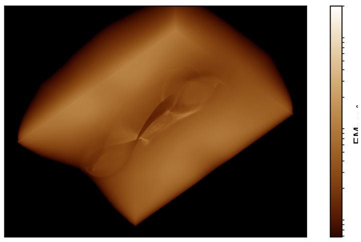

Fig2. Synthetic image of the simulated prominence in SDO/AIA 193 Å

Additionally, we extended the application of the ffHD model to magnetic fields extrapolated from solar magnetograms. We simulated filament formation using these extrapolated fields and compared the results with observations, achieving a close match. This further validated the effectiveness and broad applicability of the ffHD model in simulating solar phenomena.

These comprehensive efforts underline the ffHD module's efficacy, reliability, and wide-ranging utility in modeling solar prominences and related structures.

References

[1] Zhou, Y. et al. 2024, ApJ, 968.
[2] Keppens, R. et al. 2023, A&A, 673