Solar prominence modeling: 3D modeling progress

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Abstract

We present numerical simulations of solar prominences, the cool, macroscopic (order 100 Mm) 'clouds' in the million degree solar corona. Observations show that even quiescent prominences are continuously perturbed by hot, rising bubbles, and show Rayleigh-Taylor instabilities. Our simulated prominences rapidly establish fully non-linear (magneto)convective motions where hot bubbles interplay with falling pillars. We cover chromospheric to coronal heights, and demonstrate that Rayleigh-Taylor fingers reflect on transition region plasma, ensuring that cool, dense chromospheric material gets mixed with prominence matter up to very large heights [3]. Extensions to twin-layered prominence models show that their magnetic connectivity ensures strongly coherent evolutions and also leads to field-aligned fine structure formation. We produce synthetic views in extreme ultraviolet wavelengths, and contrast these dynamical models with ab initio computations where also the thermal instability driven formation process is incorporated. Then, depending on the chromospheric evaporation processes and the prevailing magnetic topology, we can encounter coronal rain-like dynamics, or a more gradual growth into macroscopic filaments. When coronal rain develops, Rayleigh-Taylor and interchange dynamics controls the complex motions of individual condensation blobs [4]. All our simulations use the magnetohydrodynamic module in our open-source, parallel, block-adaptive MPI-AMRVAC software [5].

The study of quiescent solar prominences, seen as filaments on the solar disk and surviving for weeks on end, usually adopts a magnetostatic viewpoint: a gravitationally modified, Grad-Shafranov force equilibrium gets established in a flux rope [1]. In direct analogy with tokamak fusion plasmas, this allows to compute the collection of eigenoscillations and magnetohydrodynamic (MHD) instabilities that are accessible to this plasma configuration, which starts by charting the essential (especially the continuous) part of the full spectrum of MHD eigenfrequencies [2]. This identified the convective continuum instability as a viable route to more turbulent, Rayleigh-Taylor like dynamics, where magnetic field-projected variation of the Brunt-Väisäläa frequency is key. However, truly nonlinear evolutions must be explored by direct numerical simulations, where also a realistic temperature stratification of the solar atmosphere (through a chromosphere, transition region and corona) can be incorporated. In this contribution, we highlight recent findings from such multidimensional simulations, which can directly confront actual prominence observations.

3D magnetoconvection studies

Using our open-source MPI-AMRVAC code [5], we performed ideal MHD simulations that achieve a 50 km resolution in a 30 Mm domain size, focusing especially on the nonlinear dynamics in Rayleigh-Taylor unstable prominence segments [3]. These are modeled as cold, dense sheets supported by magnetic pressure against solar gravity. Contrary to earlier studies, the vertical extent of our model has a transition region temperature variation at about 2.5 Mm height, where the coronal region with 2 MK temperatures connects to the underlying denser and cooler chromosphere. At all times in our simulation, which covered about 15 minutes of actual prominence evolution, the entire prominence is embedded in hot coronal plasma. The density inversion at the lower prominence boundary spontaneously develops falling fingers and upwelling arches, on timescales (minutes) and spatial scales (several Mm) that resemble observational findings. The magnetic configuration we assume in these studies is largely perpendicular to the initial prominence sheet, with a small shear layer in the initial magnetic stratification.

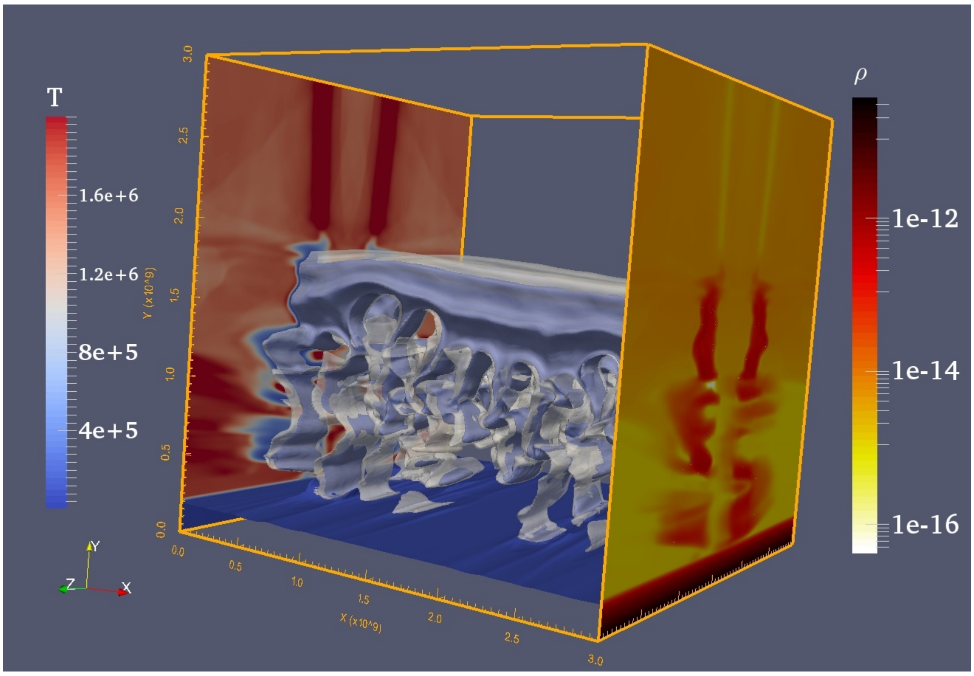

Figure 1: *A twin-layer prominence, showing Rayleigh-Taylor dynamics.*

Most recently [7], we extended this model to twin-layered structures, where multiple parallel cool sheets are supported by the same magnetic field topology. In figure 1, we show a snapshot of such a twin-layered prominence evolution, where the back and front cutting planes denote the temperature and density, respectively, while (blue) isosurfaces at transition region temperature show the (at this time yet unperturbed) transition region horizontal plane, along with the prominence-corona interface. A grey isosurface identifies the relocated prominence matter as found by an added tracer, and this isosurface is seen to surround the cold and dense prominence matter. The finger structures are seen to develop in an analogous fashion on both prominence sheets, and the field lines show concave up and down deformations in the upwelling cavities and falling fingers, respectively. When we mimick line-integrated density views from atop, we note that the fingers show up as thread-like, field-aligned structures of about 0.5 Mm thickness, consistent with observations. The vigorous magnetoconvective motions also include material that is swept up from the chromosphere to large heights, as the fingers impact the denser chromosphere and thereby get deflected.

Ab initio computations of coronal condensations

The models discussed above do not address prominence formation aspects, which require to incorporate optically thin radiative losses, anisotropic thermal conduction, and an unknown heating source for the solar coronal plasma. To do so in earnest, we investigated the long-term fate of an arcade system in a gravitationally and thermally stratified corona, subject to continued footpoint heating [4]. This type of simulation first establishes a realistic transition region variation whose precise location is mediated by the heat flux from the corona downwards into the chromosphere, along with the temperature dependent conduction coefficient. The magnetic arcade is characterized by the presence of a central dipped region, relating to a quadrupolar configuration. Additional footpoint heating ultimately leads to thermal instability in the sheared arcade system. We found that blob-like structures condense and ultimately show field-line guided dynamics, reminiscent of coronal rain. When using the linear stability criteria for convective continuum instabilities, we found a nice correlation between the instantaneously unstable regions, with regions where coronal rain blobs show complex, but overall downward motions. The simultaneous effects of thermal runaway (leading to condensations) and Rayleigh-Taylor activity (giving the impression of coronal rain) are nicely seen in Extreme Ultraviolet views: cooler blobs show up prominently in 304 Å channels. In figure 2, taken in the 171 Å channel instead, we especially see the heated arcade loops, while the (edges of) the coronal rain blobs show up as fine-structure in between these loops and the horizontal edge marking the transition region (at $y \approx -3.5$ in the figure units). Up to 20-30 rain blobs are present at all times.

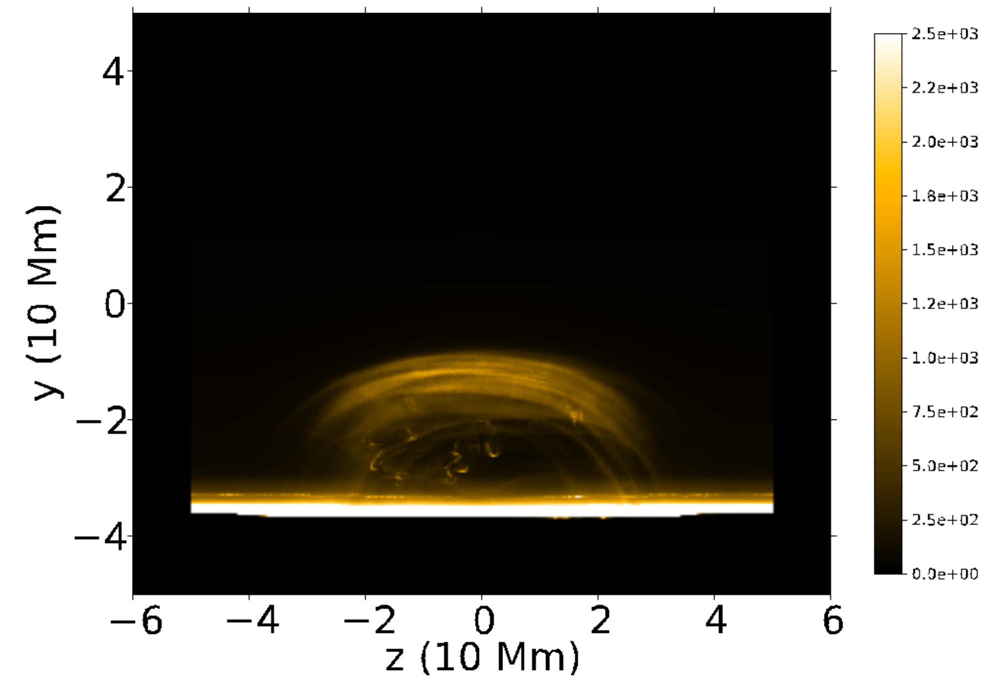

Figure 2: *A synthetic Extreme Ultraviolet view on a footpoint-heated magnetic arcade, where we see heated loops, along with small-scale condensations that resemble coronal rain.*

Conclusions

Using 3D MHD simulations, we have been able to simulate coronal condensation phenomena in arcade setups, as well as the vigorous mixing processes in more large-scale prominence segments. These represent different aspects of how convective processes manifest themselves in the solar corona, and this on rather different spatial scales. To combine the insights gained from these studies, we are currently pursuing ab initio modeling of full prominences in actual flux rope structures. It is then found that the dynamic, fragmented nature of the coronal rain can be recovered in a more macroscopic full-scale prominence, where chromospheric matter that gets evaporated into the corona, and prominence fragments that descend down from the corona, establish a stable mass recycling [6].

References

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