

Sources of Coronal Heating and Formation of Solar Wind Switchbacks as Revealed by 3D Radiative MHD Simulations

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Abstract Understanding the evolution of magnetic activity and plasma dynamics from the photosphere to the corona is of great interest. Tracking the plasma's thermodynamic properties and structuring is essential to understand how to relate in-situ observations from the Parker Solar Probe to observations of the low corona and solar surface. Realistic high-resolution radiative MHD simulations reveal complex multiscale structuring and dynamics above the photosphere. We present a detailed study of how photospheric magnetic fields affect properties of the transition zone and corona, based on an analysis of 3D radiative MHD simulations made with StellarBox. In this presentation, we discuss a heating mechanism of the chromosphere and low corona originating in the transition zone. We also discuss the formation of funnel-like structures and eruptive dynamics in the low corona and how these processes might initiate the observed solar wind switchbacks.

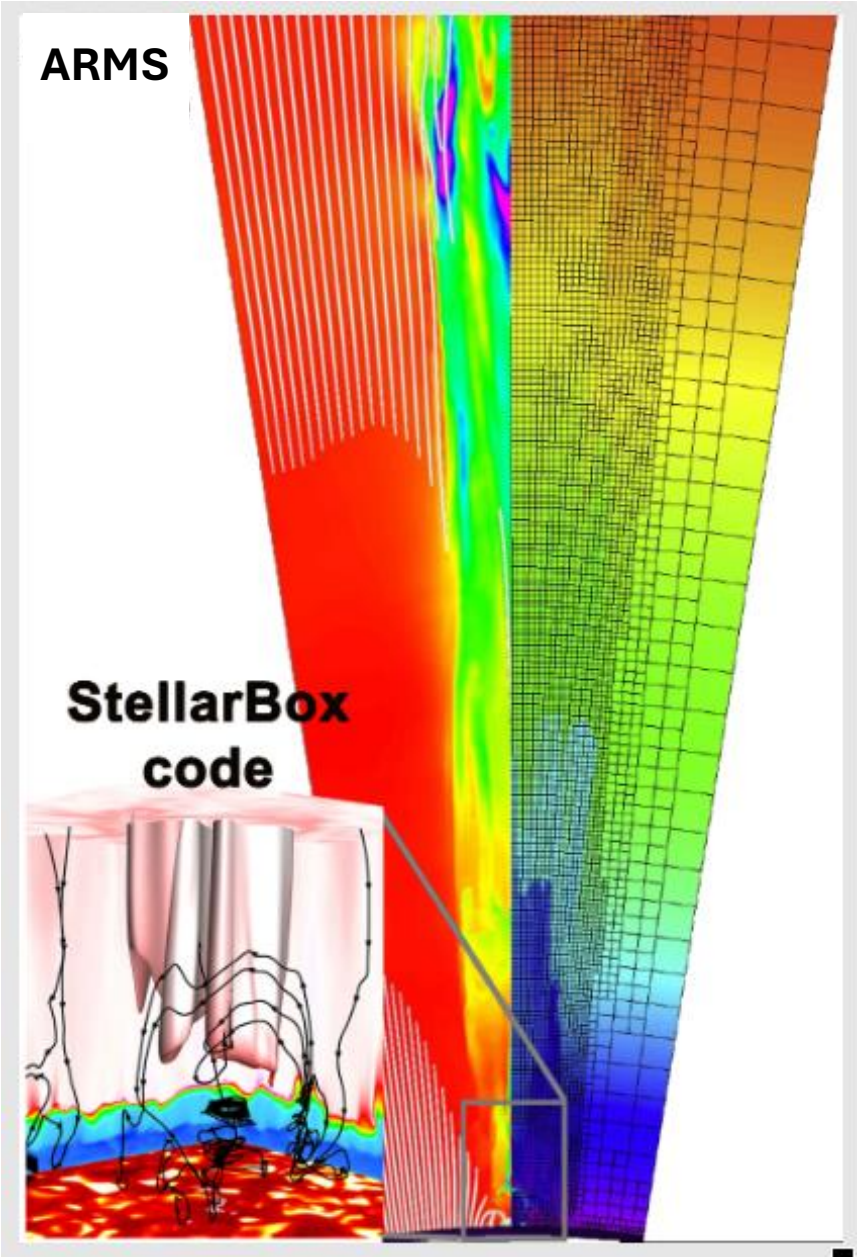
StellarBox & ARMS codes:

StellarBox code:

The 3D radiative MHD code is widely used to study a variety of phenomena, such as self-formation of highly magnetized structures, the turbulent dynamics of the Sun from the interior to the corona, eruptive activity, and the interpretation of observations from NASA space missions (e.g., SDO, Hinode, IRIS) and ground-based observations. The code formulation includes the fully compressible MHD equations coupled with the radiative transfer equations. In the simulations, sub-grid scale turbulence is modeled using the Large-Eddy Simulation (LES) approach using the compressible dynamic turbulence model. Radiative transfer between fluid elements is calculated using a 3D, multi-spectral-bin, long-characteristics method to integrate the radiative transfer equation; ray-tracing transport is calculated for 18 directional rays. The current version of the code includes capabilities to increase the size of the computational domain in the horizontal directions as well as deeper into the convection zone and the corona, mesh refinement in user-specified layers, modeling with different initial magnetic field configurations, modeling of emerging flux, shear flow, effects of rotation and the Coriolis forces, and others.

ARMS code:

The 3D Adaptively Refined Magnetohydrodynamics Solver (ARMS) code was developed by C. Richard DeVore and Spiros Antiochos (2008). The code can model dynamic phenomena in the solar corona and solar wind, such as jets, interchange reconnection, formation of coronal mass ejections (CMEs), and pseudo-streamers. The code can use either Cartesian or Spherical coordinates and is capable of capturing waves and shocks. It utilizes the PARAMESH technology for adaptive mesh refinement. The code has a large degree of flexibility in the selection of boundary and initial conditions and the capability to apply uniform electrical resistivity and thermal conduction.

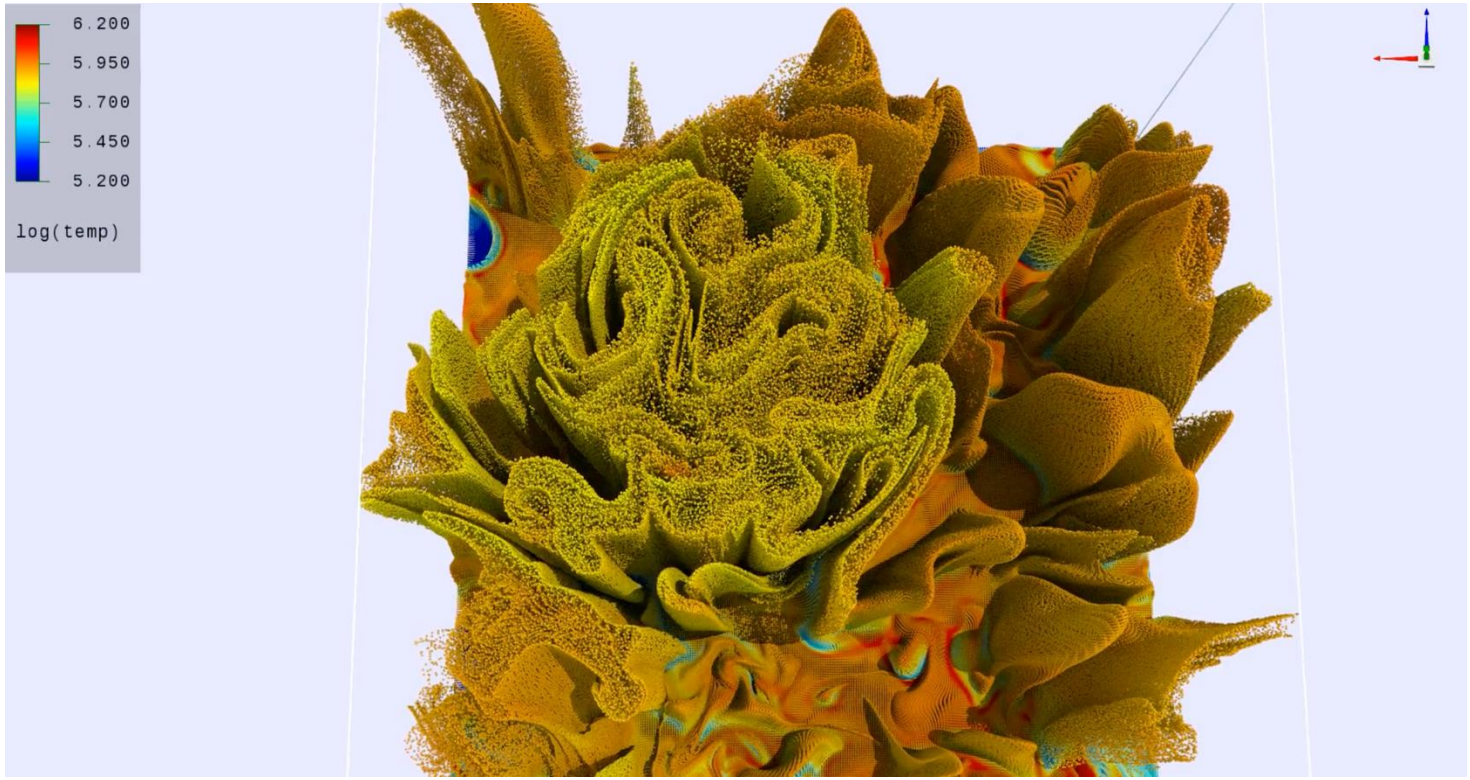


Schematic representation of the use of the ARMS (DeVore & Antiochos, 2008) and StellarBox (Wray et al., 2015; 2018) codes to model magnetic switchback formation and evolution. The ARMS model (top and right side of figure) shows the jet-propagation phase on the left half with magnetic field lines (white) and the magnitude of velocity in the background. The right part shows an adaptively refined grid and the logarithm of the mass density in the background. The mesh distribution corresponds to an early moment for visualization purposes. The StellarBox model illustrates the pre-eruptive stage of a solar tornado (black streamlines) originating in the photosphere. Pink/white colors show the temperature in the corona, where white colors correspond to temperatures of 1 MK and higher. The sharp transition to green/blue colors (cooler plasma, below 30,000 K) shows the transition zone. The grey box shows the overlap of the ARMS and StellarBox models.

Coronal Heating in Quiet Sun Regions

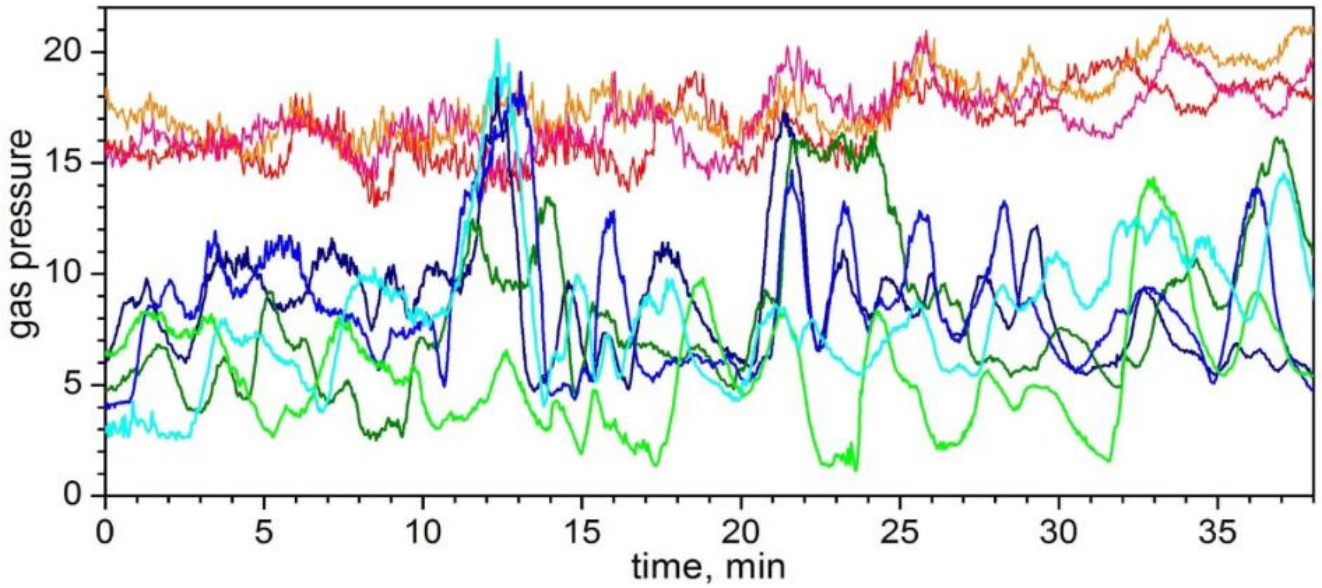
The simulation results show a self-formation of a magnetic structure in the solar corona that is connected with a kilogauss magnetic field in the photosphere through the chromosphere and transition zone.

Evolution of a Magnetized Funnel-Like Structure in the Corona and Heating Episodes in the Transition Zone



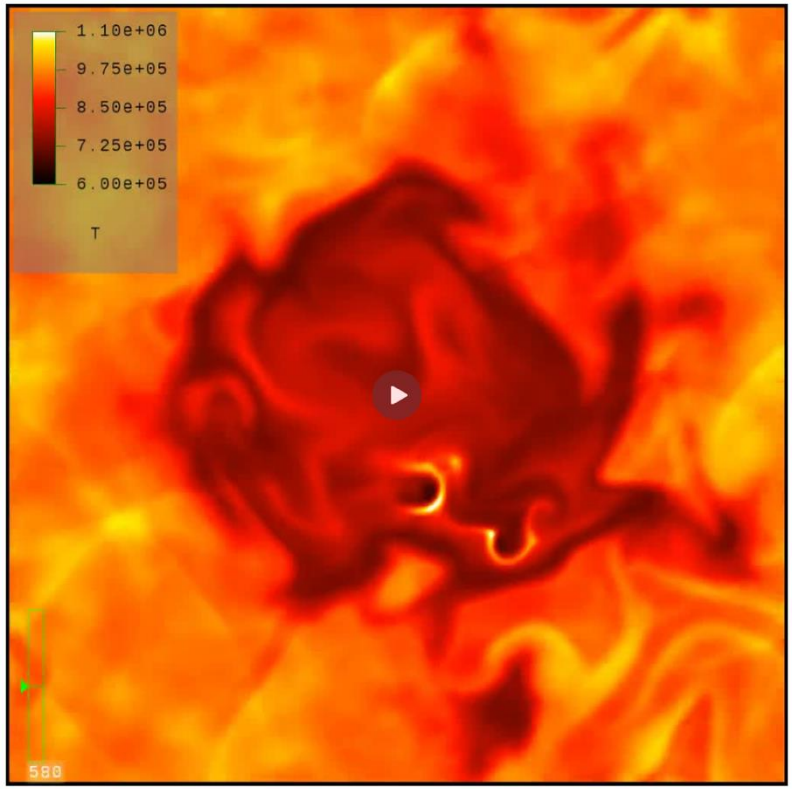
View of the log temperature and particle streams through the solar atmosphere from above looking towards the transition zone and corona. Visualization is performed by advecting particles seeded at a height of 2.4Mm above the solar surface.

Temporal Variations of the Plasma Gas Pressure in Corona



The colors correspond to the probes located inside (cold colors) and outside (warm colors) of the funnel structure at a height of 6 Mm above the photosphere (Kitiashvili et al., 2020).

Coronal Heating by Shock Waves and Small-Scale Currents

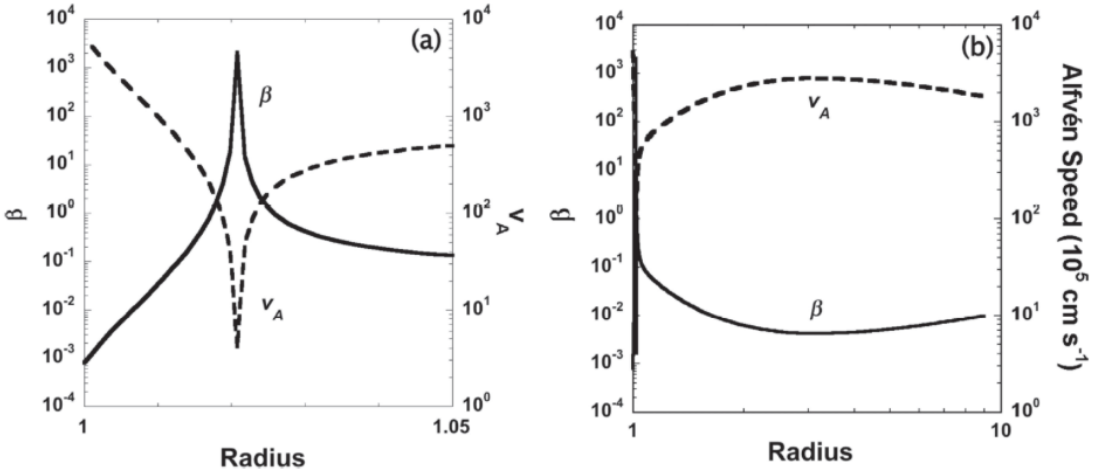


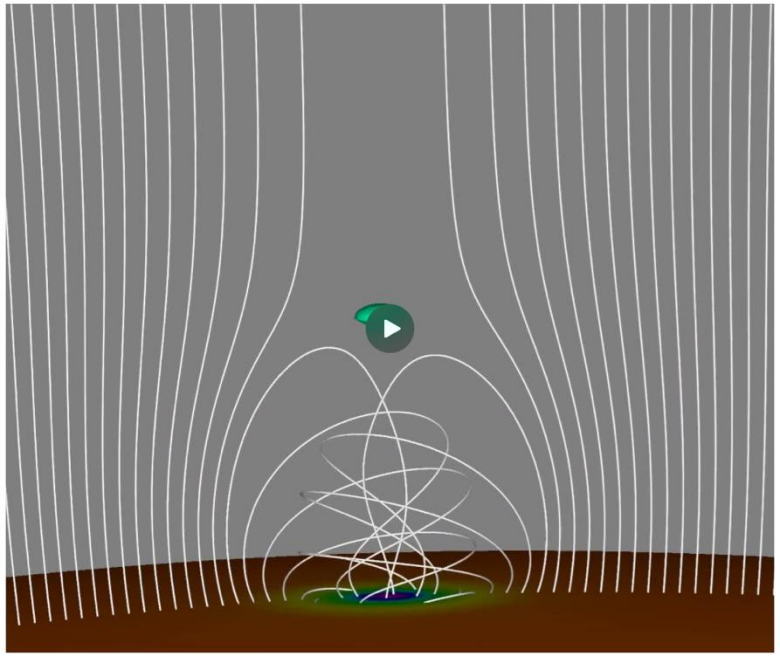
The animation shows the temperature change in the solar corona (heights 10Mm) during the evolution of the funnel structure driven by a small-scale kG patch at the photosphere.

Origin of the Magnetic Field Lines Deflection

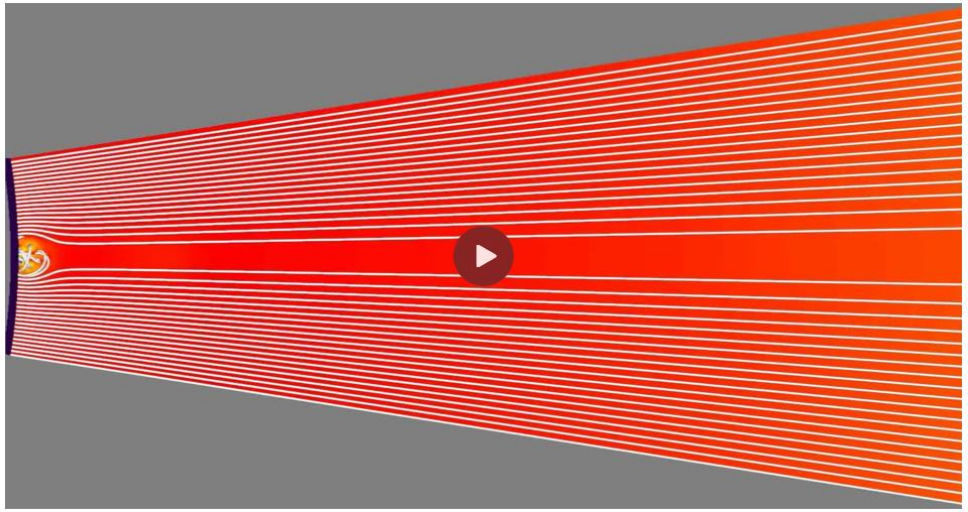
Simulation results of the 3D MHD model obtained with ARMS code show significant magnetic field lines deflection caused by a jet-like eruption. However, it was found that deflected field lines are losing this property in the low-plasma beta corona. Therefore, the current study targets evaluating the past and recent models to uncover conditions that slow down this process and allow the deformation of the field lines at larger distances.

The initial conditions for plasma β (solid curve) and Alfvén speed (v_A; dashed curve) as a function of distance from the solar surface (r/Rsun) that passes through the coronal null point.





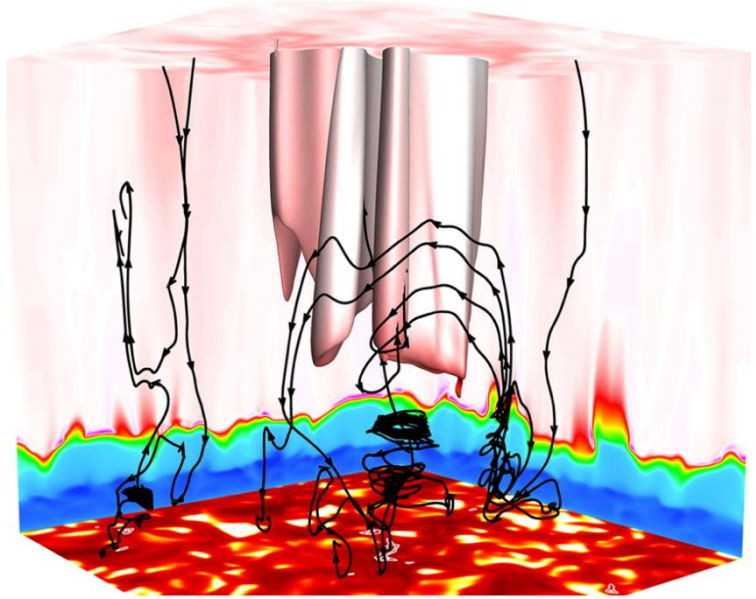
Evolution of the corona properties during the energy buildup and jet-propagation phase. White curves are magnetic field lines drawn from fixed footpoints at the lower boundary. The color scale is saturated at 500km/s to highlight lower speeds. The outer (right) boundary is at 2.5 Rsun at the midpoint; the side boundaries are at θ = ±9° (Karpen et al., 2017).



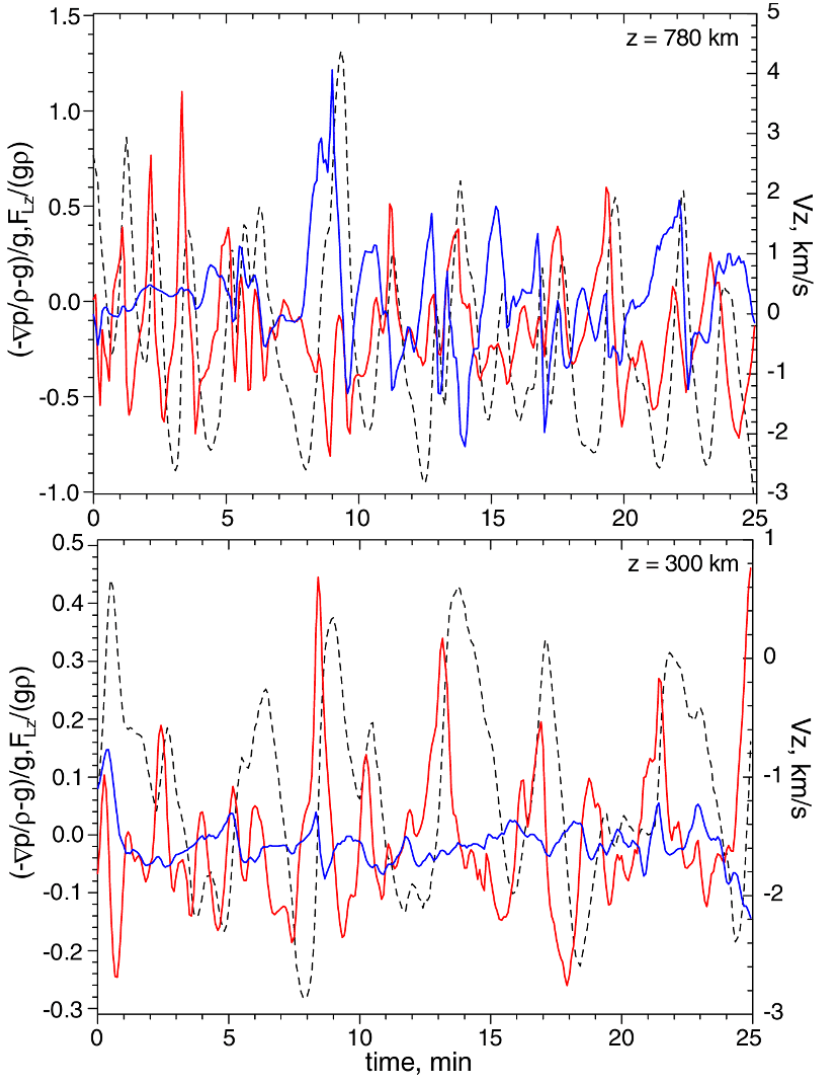
The jet source region during the energy buildup and release phases. White curves are magnetic field lines drawn from fixed footpoints at the lower boundary; color shading on the lower boundary indicates the sign and magnitude in Gauss of the vertical magnetic field varying from -3 G (orange) to 33G (magenta); the green-colored spheroid is an isosurface of plasma β = 2 indicating the location of the null point and associated current patch (Karpen et al., 2017).

Dynamical Coupling of the Photosphere and Corona

3D radiative MHD simulations with the StellarBox code show a connection between turbulent flows at the photosphere and corona. The vortical flows originate at the near photospheric layers with strong magnetic field patches and can produce highly twisted jets. The erupted flows are accelerated by the Lorentz force. Because the twisted jets carry mass to higher atmospheric layers (Kitiashvili et al., 2013), they can cause local perturbations in the plasma, allowing the field lines to be deflected.

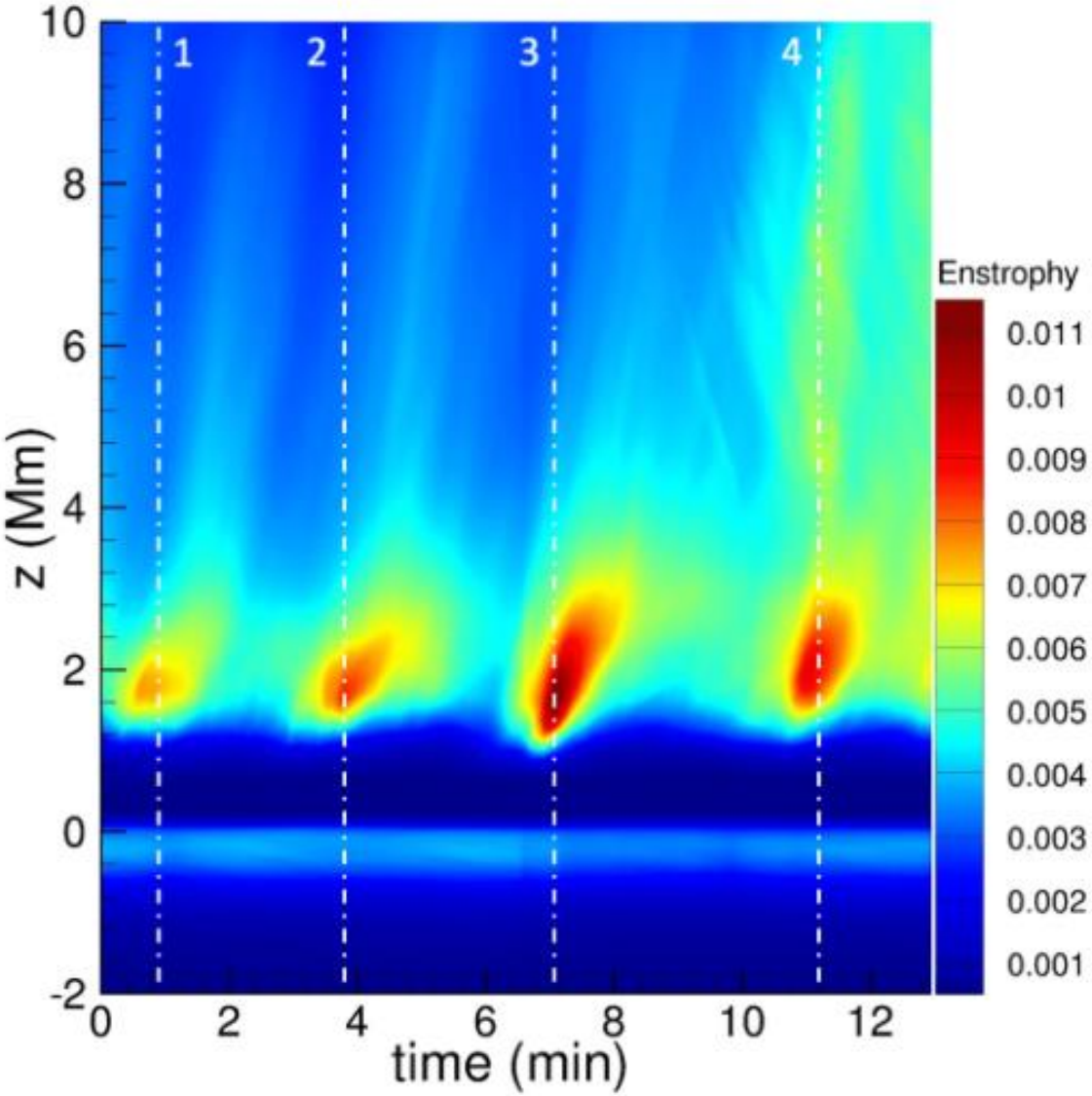


The 3D radiative MHD simulations show helical flows (twisted streamlines in the middle) driven by highly magnetized vortex tubes at the photosphere (horizontal plane). These helical flows in the presence of a magnetic field cause the formation of a funnel-like structure in the solar corona. Colors on the vertical planes and isocontour show the logarithm of temperature.

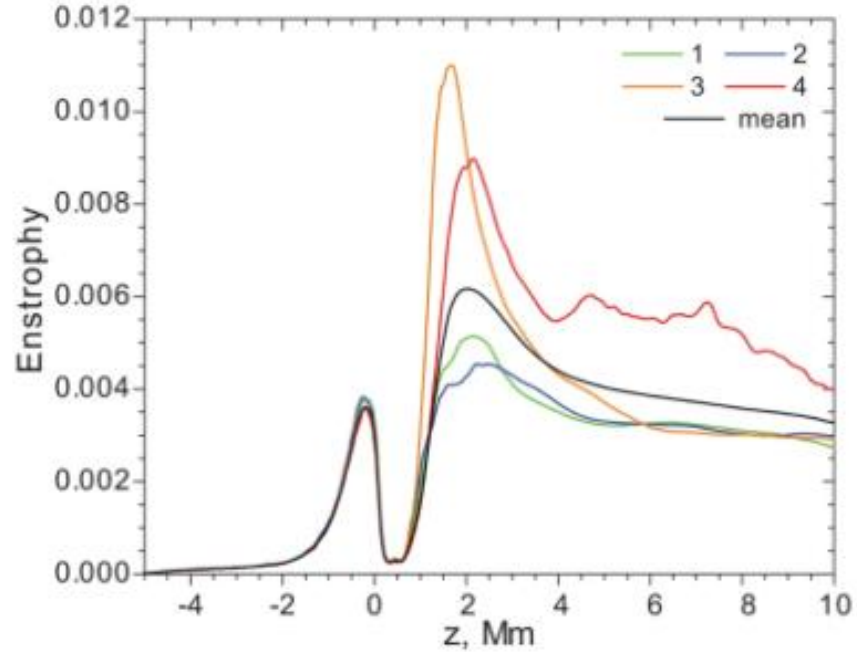


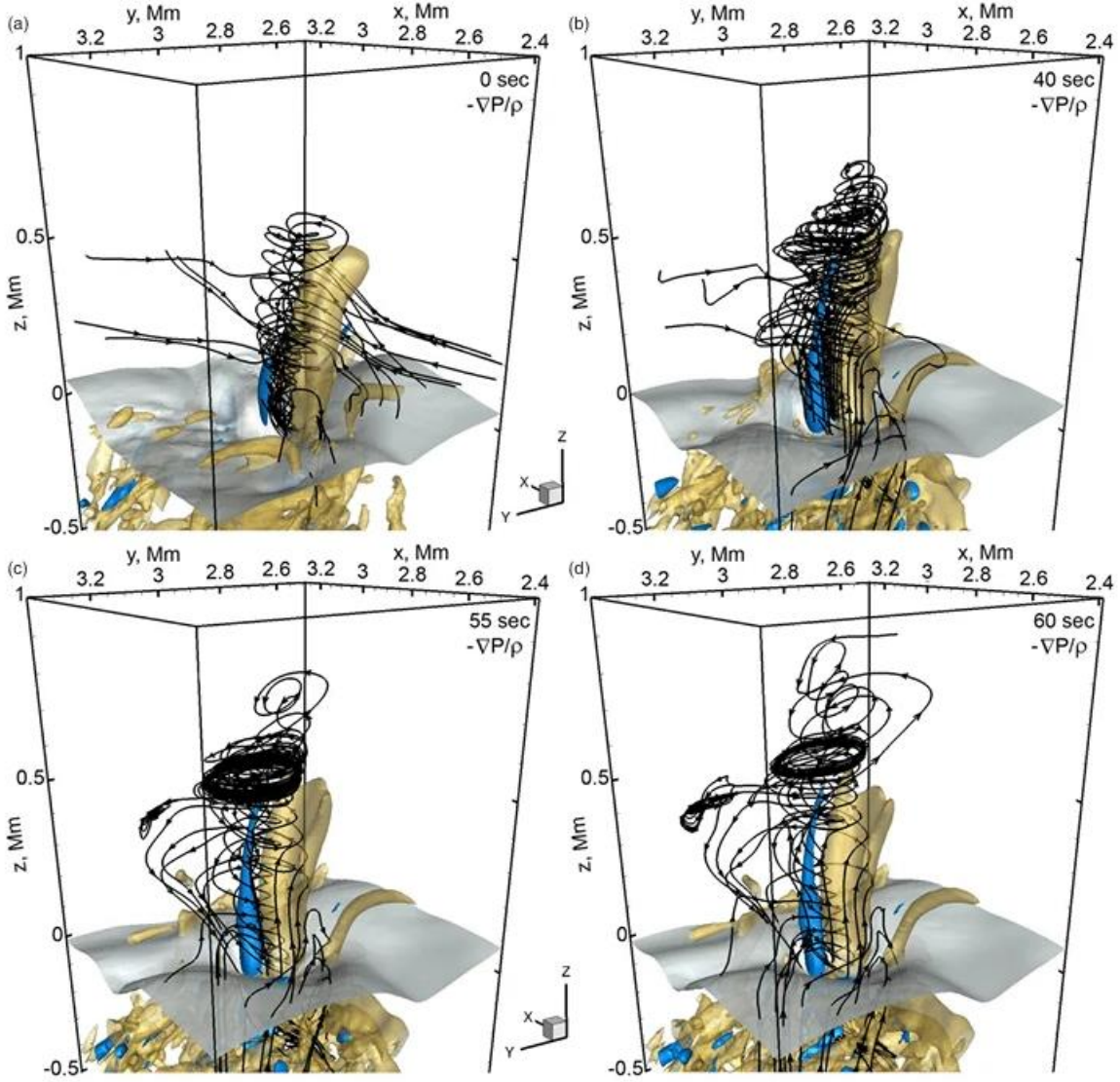
Comparison of the contributions to the flow ejection of the hydrodynamic ((−∇p/ρ−g)/g, red curves) and magnetic (Lorentz force, $F_L/(\rho g)$, blue curves) vertical accelerations (normalized by the gravity acceleration) at different altitudes: h = 780km, and h = 300 km. The dashed curves correspond to the vertical velocity, Vz, given for reference at the same layers.

Enstrophy transport from the transition zone to the corona



# Eruption	Enstrophy transport speed, km/s	
1	16	110
2	16	76
3	30	79
4	35	115





Different stages of the flow ejection: (a) vortex tube penetration into the atmosphere layers, (b) intensification of the swirling motions, (c) concentration of the swirling motion in a ring-like structure, and (d) flow ejection along the vortex tube. Black streamlines illustrate the velocity field in the vicinity of the vortex tube. Semitransparent light gray surface corresponds to a constant temperature of 6400 K. Yellow and blue isosurfaces correspond to the normalized-by-density vertical pressure gradient ($-\nabla p/\rho$) for the values of 5.e4 cm/s^2 (yellow color) and −5.e4 cm/s^2 (blue color).

Conclusions

Revealing the origin of the coronal heating and the magnetic switchbacks (also so-called microstreams because they correlate with fluctuations of the solar wind speed and density) are critical for understanding the structure and thermodynamical properties of the solar atmosphere for monitoring and interpretation of the evolution of disturbances driven by solar magnetic activity.

In the current study, we interlink the advances of two subfields covering subsurface layers to the low corona (StellarBox code), with extension to the outer corona and solar wind (ARMS code). This approach allows us to investigate changes in the thermodynamic properties of the solar atmosphere up to several solar radii.

Using advanced 3D radiative MHD code “StellarBox,” we have performed the first high-resolution simulations of the Sun from the deep convection zone to the corona. It is found that the transition zone between the low temperature (10,000 K) chromosphere and hot (1 MK) corona is substantially more turbulent and dynamic than previously assumed. The simulations revealed new processes of generation shocks and plasma eruptions and showed that the transition region dynamics is a source of the corona expansion and formation of the solar wind, as well as heating of the corona and the transition region.

Utilizing ARMS’s capability to model eruption from the solar surface to dozens of solar radii, we perform a cross-analysis of modeling results between these codes to optimize the computational effort. In particular, the ARMS code is capable of modeling magnetic field deflection during eruptive activity. However, understanding conditions that allow the magnetic field to be deflected requires significantly increased spatial resolution to be able to reproduce turbulence in the corona better and develop an approach to couple StellarBox and ARMS codes.

Acknowledgements:

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References

- DeVore C. R., Antiochos S. K. 2008. Homologous Confined Filament Eruptions via Magnetic Breakout. ApJ 680, pp. 740-756
- Karpen J.T., DeVore C.R., Antiochos S.K., Pariat E. 2017. Reconnection-Driven Coronal-Hole Jets with Gravity and Solar Wind. ApJ, 834:62 (16pp).
- Kitiashvili I. N., Kosovichev A.G., Lele S.K., Mansour N.N., Wray A.A. 2013. Ubiquitous Solar Eruptions Driven by Magnetized Vortex Tubes. ApJ, 770 (1), article id. 37, 10 pp.
- Kitiashvili I.N., Wray A.A. Sadykov V., Kosovichev A.G., Mansour N.N. 2020. Realistic 3D MHD modeling of self-organized magnetic structuring of the solar corona. IAU Proceedings, Vol. 354, pp. 346-350.
- Wray A.A., Bensassi K., Kitiashvili I. N., Mansour N. N., Kosovichev A. G. 2015. Simulations of Stellar Magnetoconvection using the Radiative MHD Code ‘StellarBox’. ArXiV: 1507.07999.
- Wray A.A., Bensassi K., Kitiashvili I.N., Mansour N.N, Kosovichev A.G. Realistic simulations of Stellar Radiative MHD. In Book: “Variability of the Sun and Sun-like Stars: from Asteroseismology to Space Weather”. Eds: J.-P. Rozelot, E.S. Babaev, EDP Sciences, 2018. p.39-62.
- Wyper P.F., DeVore C.R., Antiochos S.K. 2018. A Breakout Model for Solar Coronal Jets with Filaments. ApJ. 852:98 (16pp).