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Realistic 3D MHD modeling of self-organized magnetic structuring of the solar corona

Irina N. Kitiashvili[1], Alan A. Wray[1], Viacheslav Sadykov[1], Alexander G. Kosovichev[1,2] and Nagi N. Mansour[1]

[1]NASA Ames Research Center Moffett Field, MS 258-6, Mountain View, USA
email: irina.n.kitiashvili@nasa.gov

[2]New Jersey Institute of Technology, Newark, NJ 07102, USA
email: alexander.g.kosovichev@njit.edu

Abstract. The dynamics of solar magnetoconvection spans a wide range of spatial and temporal scales and extends from the interior to the corona. Using 3D radiative MHD simulations, we investigate the complex interactions that drive various phenomena observed on the solar surface, in the low atmosphere, and in the corona. We present results of our recent simulations of coronal dynamics driven by underlying magnetoconvection and atmospheric processes, using the 3D radiative MHD code StellarBox (Wray *et al.* 2018). In particular, we focus on the evolution of thermodynamic properties and energy exchange across the different layers from the solar interior to the corona.

Keywords. convection; plasmas; shock waves; turbulence; waves; (magnetohydrodynamics:) MHD; Sun: corona, magnetic fields; methods: numerical, Sun: transition region

1. Introduction

High interest in solar coronal structure and dynamics is primarily driven by interest in the episodic massive energy releases that can cause significant impacts on the Earth's space environment and in fundamental physical problems such as coronal heating and energy transport.

Recent achievements in realistic 3D radiative MHD modeling, in combination with multiwavelength observations, have provided a solid basis for investigating complex dynamical interactions in the solar atmosphere, from the upper layers of the convection zone to the corona. Realistic modeling, which takes into account the nonlinear coupling of turbulence, magnetic fields, and radiation, provides a physics-based interpretation of the observed phenomena and allows us to determine their primary physical mechanisms. An important feature of this approach is building the models from first physical principles, such that the physical processes develop spontaneously driven by dynamical energy flow from the solar interior. These models can reproduce a wide range of phenomena observed on different spatial scales, such as heating events in the chromosphere and transition region, small-scale dynamos, generation of different types of waves, jets, pore formation, sunspot-like and tornado-like structures, loops, etc. (e.g. Rempel *et al.* 2009; Cheung *et al.* 2010, 2019; Kitiashvili *et al.* 2010, 2013, 2015, 2019b; Stein & Nordlund 2012; Carlsson *et al.* 2016; Chen *et al.* 2017; Iijima & Yokoyama 2017; Snow *et al.* 2018).

Extension of the computational domain into the solar corona provides a unique opportunity to trace disturbances from subsurface layers through many layers of the atmosphere and allows investigation of the realistic structure and dynamics of the transition region and corona, which are critically important for understanding variations in space weather. Currently only a few realistic models of the solar corona have been developed (Gudiksen & Nordlund 2005; Rempel 2017; Cheung *et al.* 2019; Kitiashvili *et al.* 2019a, 2020) that allow detailed comparisons with observed phenomena. In this paper, we present 3D MHD simulations of the solar corona that reveal the spontaneous formation of a funnel-like magnetic structure. Such structures can play a significant role in the fine structuring of the corona and the formation of the solar wind.

2. Structure and dynamics of the solar corona

Generation of the 3D radiative MHD model, which covers dynamics of the solar plasma from the subsurface to the corona, is performed using the StellarBox code (Wray *et al.* 2018). The StellarBox code simulates the fully compressible MHD equations with radiative transfer and includes a large-eddy simulation (LES) treatment of subgrid turbulent transport. The StellarBox code includes subgrid turbulence models for flows (Smagorinsky 1963; Moin *et al.* 1991) and magnetic fields (Theobald *et al.* 1994) that are critical to obtain a more accurate description of small-scale energy dissipation and transport.

The computational domain of $12.8 \times 12.8 \times 15.2$ Mm includes a 10-Mm high layer from the photosphere to the corona. The grid spacing is 25 km in the horizontal directions, with a variable vertical grid-spacing of similar size in the photosphere. The lateral boundary conditions are periodic. The top boundary is open to mass, momentum, and energy fluxes, and also to radiation flux. The bottom boundary in these simulations is open only for radiation, to simulate the energy input from the interior of the Sun. The simulation is initialized from a standard solar model of the interior structure and the lower atmosphere (Christensen-Dalsgaard *et al.* 1996). For the initial conditions of the chromosphere and corona, the model by Vernazza *et al.* (1981) is used.

In these simulations, we introduced an initially uniform vertical magnetic field of $B_{z0} = 10$ G. The boundary conditions conserve the total flux but the field freely evolves inside the computational domain. In the near-surface layers, the magnetic field amplifies and concentrates into magnetic patches due to a small-scale dynamo and collapsing field in the intergranular lanes. Magnetic field concentrations with a field strength of about 1 kG are strong enough to hold their magnetized structure extending into the corona. The complexity of the structure and its dynamics increases with hight as it often splits into the substructures. In particular, there are spontaneously-formed helical patterns of different scales, which appear and disappear with time. The vertical velocity distribution is highly inhomogeneous (Figure 1a) and reveals strong upflows, exceeding 100 km/s, and downflows with speeds of tens kilometers per second. Notably, complex flows and numerous strong shock waves are excited during the formation and 'active' evolution of the structure. During the structure's decay phase, the amplitude of fluctuations associated with shock waves decreases.

The self-organized magnetic structure in the solar corona is primarily associated with cold plasma (Figure 1b). However, the numerous current sheets that are in the coronal structure are able to heat the plasma to a few million degrees. The magnetic field strength drops significantly with height. However, inside the magnetized region the field is still relatively strong, $24 - 27$ G (Fig. 1c) at a height 10 Mm above the photosphere.

In addition to the ubiquitous shock waves in the corona, the simulations reveal high-frequency oscillations initiated in the transition zone. Figure 1d shows a vertical slice through a fraction of the computational domain. The color-scale corresponds to divergence of the velocity field. It illustrates small-scale perturbations associated with the propagation of the high-frequency perturbations from the transition region (the location of which is indicated by two constant temperature curves for 0.1MK (black) and

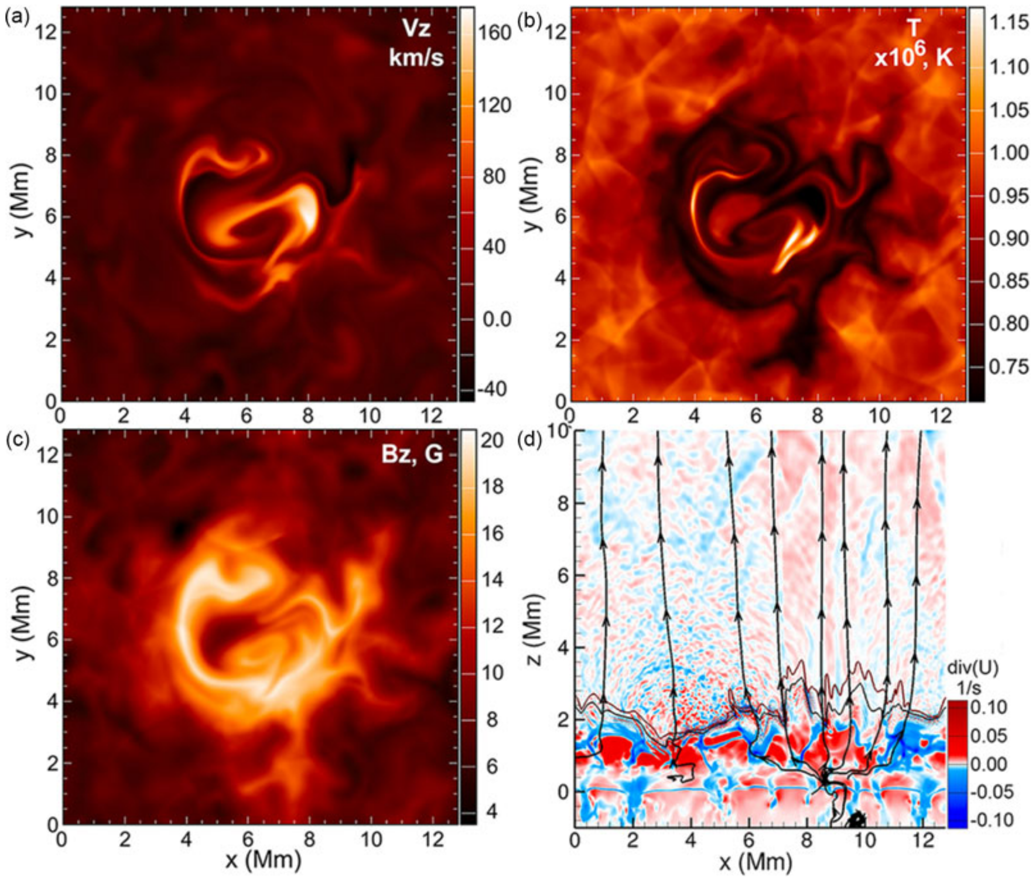

Figure 1. Distributions of (a) vertical velocity, b) temperature, and c) magnetic field in a quiet Sun region at height 10 Mm above the photosphere. The vertical slice of divergence of the velocity in panel d) shows propagation of high-frequency perturbations from the transition zone to upper layers of the corona. Two thin color curves (black and red) in panel d) show the temperature levels of 0.1MK and 0.5MK, respectively, in the transition region. Black lines with arrows indicate magnetic field lines.

0.5MK (red curve)) into the high corona. To characterize the gas pressure perturbations, we selected several areas inside and outside the magnetic structure at a height of 9 Mm above the photosphere and plotted their variations as a function of time in Figure 2. Outside the magnetic structure (warm colors) the plot reveals the high-frequency oscillations of low amplitude superimposed on a high mean, whereas in the area inside where there is a stronger magnetic field (cold colors), the variations have a lower frequency higher amplitude with low mean values. At times inside the magnetized structure, high-frequency oscillations are also present and in such cases reflect a local decrease of the magnetic field strength.

The model reveals frequent eruptive activity on small scales. Therefore there is particular interest in the associated helicity and vorticity transport. Figure 3a shows a time-height diagram (averaged over horizontal plains) of the flow enstrophy, which shows quasi-periodic enstrophy perturbations with a period about of 3 min generated near the transition region (panel b). Near the transition zone, the enstrophy transport speed is in the range of 16 – 35 km/s for different events, whereas above 4 Mm height, the speed reaches 76 – 115 km/s.

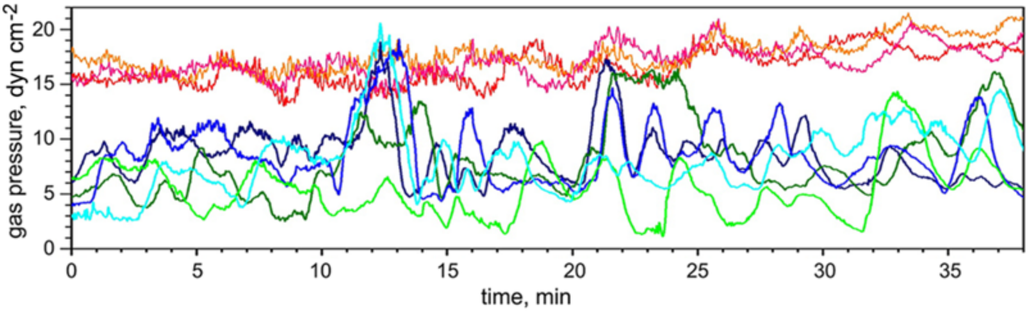

Figure 2. Temporal variations of gas pressure inside (cold colors) and outside (warm colors) the funnel structure at a height of 6Mm above the photosphere.

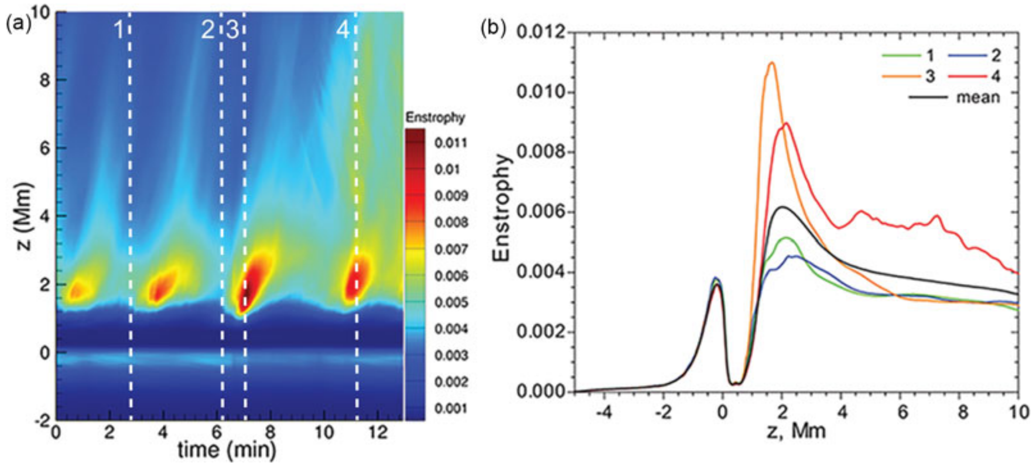

Figure 3. Enstrophy transport from the transition zone to the corona. Panel (a) Time-height diagram of the enstrophy shows propagation of the helical flows from the transition region into the corona. The numbered white dashed lines corresponds to the vertical enstropy profiles shown in the panel b) for selected moments of time.

3. Conclusions

Understanding the fine thermodynamical and magnetic structure of the solar corona is an essential basis for interpreting observational data. The performed 3D radiative MHD simulations performed, which cover layers from the convection zone to the corona, reveal complex multi-scale dynamics, which causes formation of self-organized magnetic coronal structures originating from kG magnetic patches at the photosphere. In the solar corona, the magnetic field strength drops to several tens of Gauss, and the plasma inside the magnetized structure is colder. However, there are episodic strong plasma heating events, where the temperature reaches a few million degrees, produced by small-scale current sheets. Numerous shock waves are excited due to the dynamics of this magnetic funnel-like structure, and these also contribute to coronal heating. In addition, the simulation results predict high-frequency oscillations in weak magnetic field regions, originating in the transition zone. The mechanism of these oscillations is currently under investigation.

Acknowledgments

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References

Carlsson, M., Hansteen, V. H., Gudiksen, B. V., Leenaarts, J., & De Pontieu, B. 2016, *A&A*, 585, A4

Chen, F., Rempel, M., & Fan, Y. 2017, *ApJ*, 846, 149

Cheung, M. C. M., Rempel, M., Title, A. M., & Schüssler, M. 2010, *ApJ*, 720, 233

Cheung, M. C. M., Rempel, M., Chintzoglou, G., *et al.* 2019, Nature Astronomy, 3, 160

Christensen-Dalsgaard, J., Dappen, W., Ajukov, S. V., *et al.* 1996, Science, 272, 1286

Gudiksen, B. V. & Nordlund, Å. 2005, *ApJ*, 618, 1031

Iijima, H. & Yokoyama, T. 2017, *ApJ*, 848, 38

Kitiashvili, I. N., Kosovichev, A. G., Wray, A. A., & Mansour, N. N. 2010, *ApJ*, 719, 307

Kitiashvili, I. N., Kosovichev, A. G., Lele, S. K., Mansour, N. N., & Wray, A. A. 2013, *ApJ*, 770, 37

Kitiashvili, I. N., Couvidat, S., & Lagg, A. 2015, *ApJ*, 808, 59

Kitiashvili, I., Wray, A. A., Kosovichev, A. G., Sadykov, V. M., & Mansour, N. N. 2019a, in American Astronomical Society Meeting Abstracts, Vol. 234, American Astronomical Society Meeting Abstracts #234, 106.15

Kitiashvili, I. N., Kosovichev, A. G., Mansour, N. N., Wray, A. A., & Sandstrom, T. A. 2019b, *ApJ*, 872, 34

Kitiashvili, I. N., Wray, A. A., Kosovichev, A. G., Sadykov, V. M., & Mansour, N. N. 2020, in preparation

Moin, P., Squires, K., Cabot, W., & Lee, S. 1991, Physics of Fluids A, 3, 2746

Rempel, M., Schüssler, M., & Knölker, M. 2009, *ApJ*, 691, 640

Rempel, M. 2017, *ApJ*, 834, 10

Smagorinsky, J. 1963, Monthly Weather Review, 91, 99

Snow, B., Fedun, V., Gent, F. A., Verth, G., & Erdélyi, R. 2018, *ApJ*, 857, 125

Stein, R. F. & Nordlund, Å. 2012, *ApJ*, 753, L13

Theobald, M. L., Fox, P. A., & Sofia, S. 1994, Physics of Plasmas, 1, 3016

Vernazza, J. E., Avrett, E. H., & Loeser, R. 1981, *ApJS*, 45, 635

Wray, A. A., Bensassi, K., Kitiashvili, I. N., Mansour, N. N., & Kosovichev, A. G. 2018, Realistic Simulations of Stellar Radiative MHD, ed. J. P. Rozelot & E. S. Babayev, 39

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