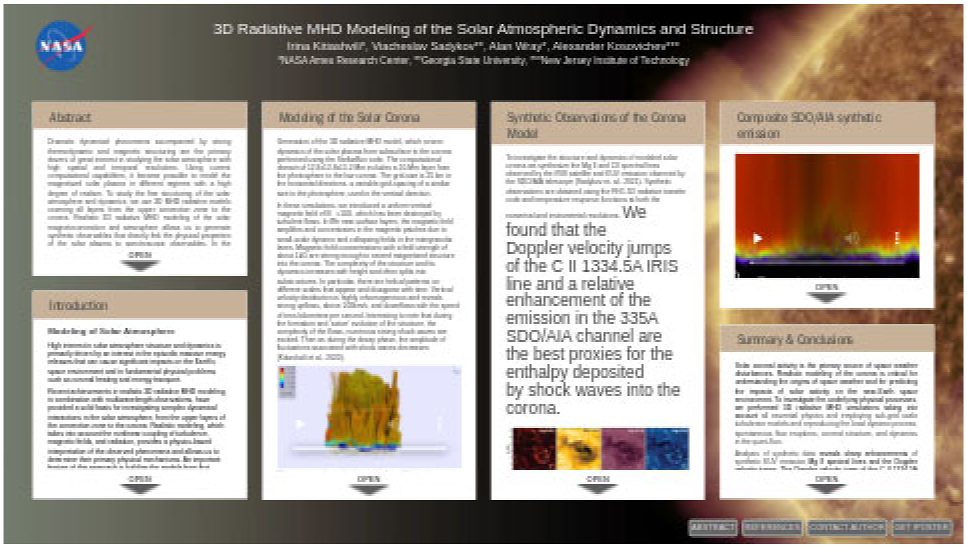
3D Radiative MHD Modeling of the Solar Atmospheric Dynamics and Structure



3D Radiative MHD Modeling of the Solar Atmospheric Dynamics and Structure

Irina Kitiashvili*, Viacheslav Sadykov**, Alan Wray*, Alexander Kosovichev***

*NASA Ames Research Center, **Georgia State University, ***New Jersey Institute of Technology

Abstract

Introduction

Modeling of Solar Atmosphere

Modeling of the Solar Corona

Synthetic Observations of the Corona Model

We found that the Doppler velocity jumps of the C II 1334.5A IRIS line and a relative enhancement of the emission in the 335A SDO/AIA channel are the best proxies for the enthalpy deposited by shock waves into the corona.

Composite SDO/AIA synthetic emission

Summary & Conclusions

Irina Kitiashvili*, Viacheslav Sadykov, Alan Wray*, Alexander Kosovichev*****

***NASA Ames Research Center, **Georgia State University, ***New Jersey Institute of Technology**

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ABSTRACT

Dramatic dynamical phenomena accompanied by strong thermodynamic and magnetic structuring are the primary drivers of great interest in studying the solar atmosphere with high spatial and temporal resolutions. Using current computational capabilities, it has become possible to model the magnetized solar plasma in different regimes with a high degree of realism. To study the fine structuring of the solar atmosphere and dynamics, we use 3D MHD radiative models covering all layers from the upper convection zone to the corona. Realistic 3D radiative MHD modeling of the solar magnetoconvection and atmosphere allows us to generate synthetic observables that directly link the physical properties of the solar plasma to spectroscopic observables. In the presentation, we discuss qualitative and quantitative changes of the atmospheric structure and dynamics at different layers of the solar atmosphere, properties of acoustic and surface gravity waves, sources of local heating in the chromosphere-corona transition region, formation of shocks, and high-frequency oscillations in the corona, as well as manifestation of these phenomena in the modeled observables.

INTRODUCTION

Modeling of Solar Atmosphere

High interest in solar atmospheric 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 regions, small-scale dynamos, generation of different types of waves, jets, pore formation, sunspot-like and tornado-like structures, loops, etc.

StellarBox code

We use a 3D non-linear radiative MHD code to simulate the upper solar convection zone and lower atmosphere.
The StellarBox code (Wray et al., 2015 (https://arxiv.org/pdf/1507.07999.pdf); 2018 (https://ui.adsabs.harvard.edu/abs/2018vsss.book...39W/abstract)) includes the fully compressible MHD equations with radiative transfer and large-eddy simulation (LES) treatment of subgrid turbulent transport. The code supports several sub-grid scale turbulence models: hyperviscosity model, compressible Smagorinsky model, compressible dynamic model (Smagorinsky 1963 (https://journals.ametsoc.org/view/journals/mwre/91/3/1520-0493_1963_091_0099_gcewtp_2_3_co_2.xml); Moin et al., 1991 (https://aip.scitation.org/doi/10.1063/1.858164)), and MHD sub-grid scale models (Theobald et al., 1994 (https://aip.scitation.org/doi/10.1063/1.870542); Balarac et al., 2010 (https://arxiv.org/pdf/1010.5759.pdf)). These models are critical to obtaining an accurate description of small-scale energy dissipation and transport. Because of the subgrid-MHD model, the turbulent magnetic Prandtl number varies with the plasma properties (Kitiashvili et al., 2015 (https://iopscience.iop.org/article/10.1088/0004-637X/809/1/84/pdf)). The current version of the StellarBox code supports the effects of electron heat conductivity following Braginskii’s formulation (Braginskii, 1965 (https://ui.adsabs.harvard.edu/abs/1965RvPP....1..205B/abstract)).

Basic characteristics of “StellarBox” code (Wray et al., 2018)

- ✓ 3d rectangular geometry
- ✓ Fully conservative compressible
- ✓ Fully coupled radiation solver:
    - – LTE using 4 opacity-distribution-function bins
    - – Ray-tracing transport by Feautrier method
    - – 18 rays (2 vertical, 16 slanted) angular quadrature
- ✓ Non-ideal (tabular) EOS
- ✓ 4th order Padé spatial derivatives
- ✓ 4th order Runge-Kutta in time
- ✓ Different Turbulence models
    - LES: Smagorinsky model (including its dynamic form)
    - DNS + Hyperviscosity approach
    - MHD subgrid models

Numerical Model: Governing Equations

The equations we solved are the grid-cell average conservation of mass:

$$\frac{\partial \rho}{\partial t} + (\rho u_i)_{,i} = 0$$

Conservation of momentum:

$$\frac{\partial \rho u_i}{\partial t} + \left(\rho u_i u_j + P_{ij}\right)_{,j} = -\rho \phi_{,i}$$

Conservation of energy:

$$\frac{\partial E}{\partial t} + \begin{pmatrix} E u_i + P_{ij} u_j - \kappa T_{,i} + \\ + \left(\frac{c}{4\pi}\right)^2 \frac{1}{\sigma}\left(B_{i,j} - B_{j,i}\right) B_j + F_i^{\mathrm{rad}} \end{pmatrix}_{,i} = 0$$

with

$$P_{ij} = \left(p + \frac{2}{3}\mu u_{k,k} + \frac{1}{8\pi} B_k B_k\right)\delta_{ij} - \mu\left(u_{i,j} + u_{j,i}\right) - \frac{1}{4\pi} B_i B_j$$

Conservation of magnetic flux:

$$\frac{\partial B_i}{\partial t} + \left(u_j B_i - u_i B_j - \frac{c^2}{4\pi\sigma}\left(B_{i,j} - B_{j,i}\right)\right)_{,j} = 0$$

$$\kappa^t = \rho c_p \nu^t / Pr^t$$

$$\sigma^t = c^2 / 4\pi \eta_m^t$$

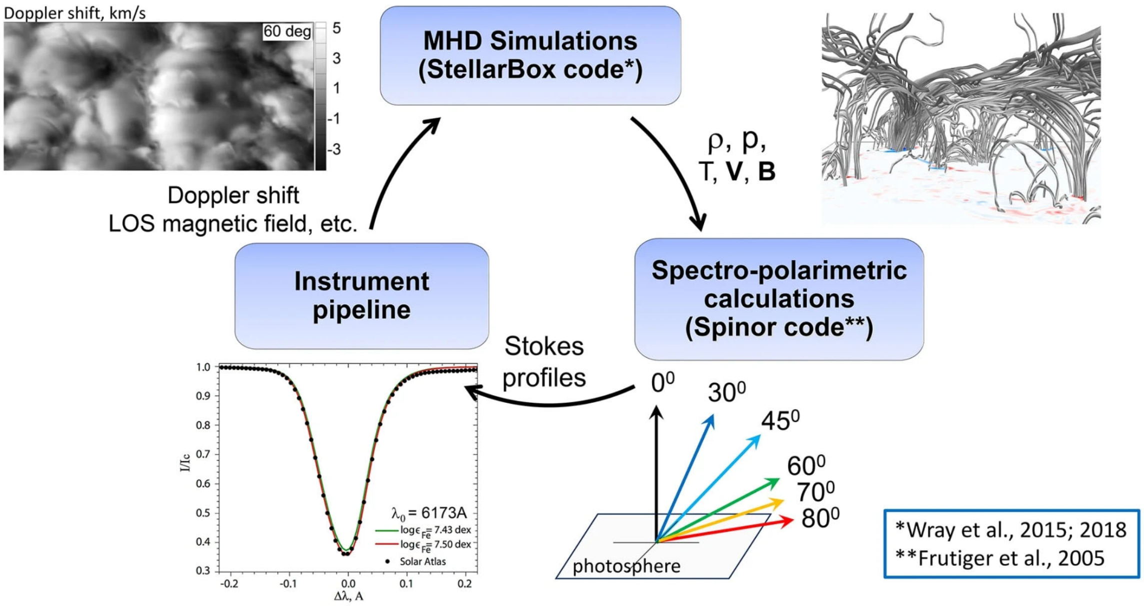
$$\eta_m^t = a \Delta^2 |\nabla \times \bar{\mathrm{B}}| / \sqrt{\rho}$$

$Pr = \eta_m / \kappa$

$$\nu^t = \mu^t / \rho$$

ρ denotes the average mass density,
u_i, the Favre-averaged velocity

Modeling of synthetic observations workflow



MHD Simulations (StellarBox code*)

ρ, p, T, **V**, **B**

Spectro-polarimetric calculations (Spinor code)**

Stokes profiles

Instrument pipeline

Doppler shift
LOS magnetic field, etc.

*Wray et al., 2015; 2018
**Frutiger et al., 2005

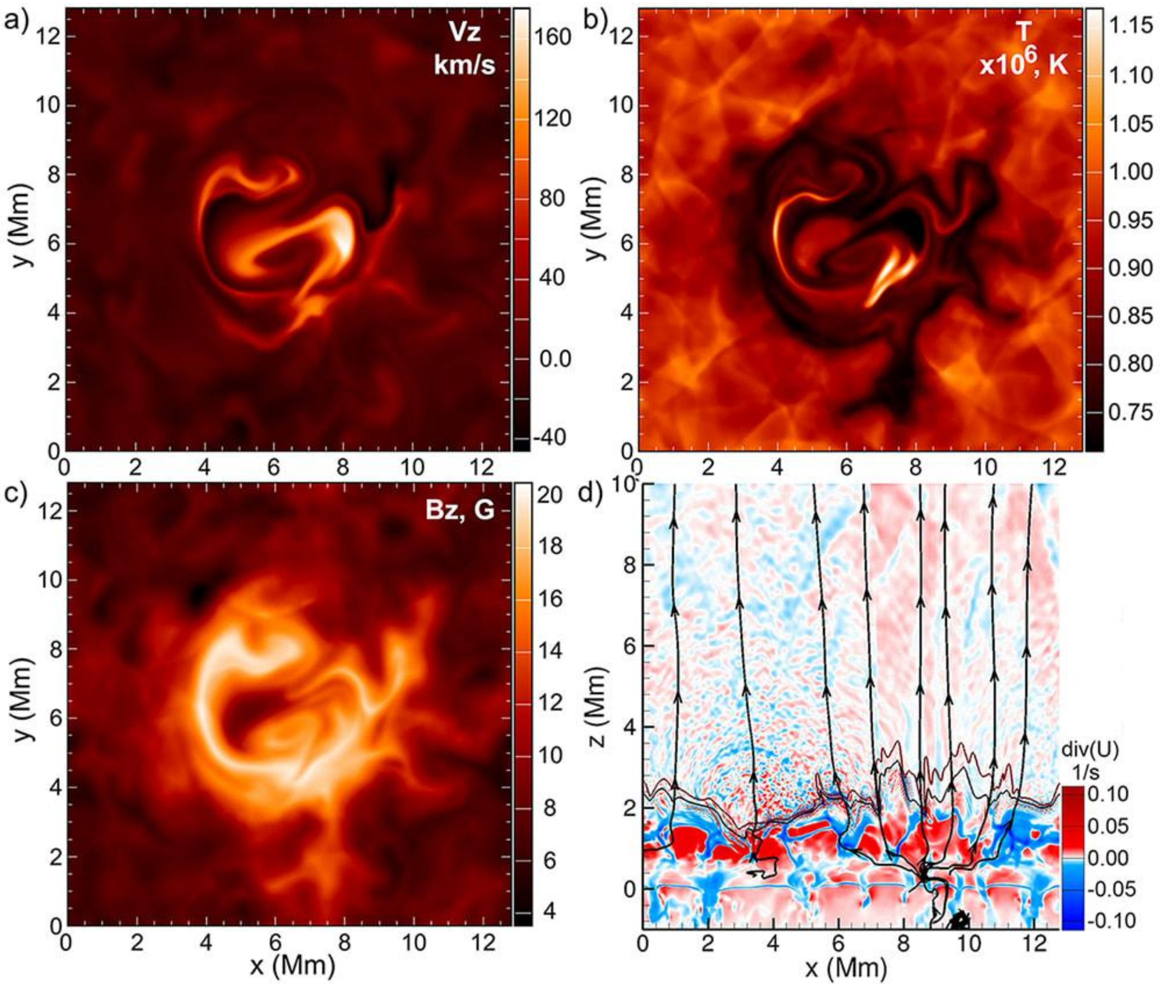
MODELING OF THE SOLAR CORONA

Generation of the 3D radiative MHD model, which covers the dynamics of the solar plasma from subsurface to the corona, was performed using the StellarBox code. The computational domain of 12.8x12.8x15.2 Mm includes a 10-Mm layer from the photosphere to the low corona. The grid-size is 25 km in the horizontal directions, and a variable grid-spacing, of similar size in the photosphere, is used in the vertical direction.

In these simulations, we introduced an initial uniform vertical magnetic field B_{z0}=10 G; this field is completely restructured by turbulent flows as time advances. In the near-surface layers, the magnetic field amplifies and concentrates into magnetic patches due to small-scale dynamo and collapsing fields in the intergranular lanes. Magnetic field concentrations with a field strength of about 1 kG are strong enough to extend a magnetized structure into the corona. The complexity of this structure and its dynamics increases with height and often splits into substructures. In particular, there are helical patterns on different scales that appear and disappear with time. The vertical velocity distribution is highly inhomogeneous and reveals strong upflows, above 100 km/s, and downflows with speeds of tens of kilometers per second. It is interesting to note, during the formation and 'active' evolution of the structure, the high complexity of the generated flows and the numerous strong shock waves that are excited. Then, during the decay phase, the amplitudes of the fluctuations associated with shock waves decreases (Kitiashvili et al., 2020 (https://www.cambridge.org/core/journals/proceedings-of-the-international-astronomical-union/article/abs/realistic-3d-mhd-modeling-of-selforganized-magnetic-structuring-of-the-solar-corona/AF2250F92287CDD8C274C789E9926E67)).

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1639067815/agu-fm2021/66-EE-D5-0D-71-2F-52-6A-E5-D0-72-B7-BC-BC-57-C4/Video/corona_logT_v04_zaowxj.mp4

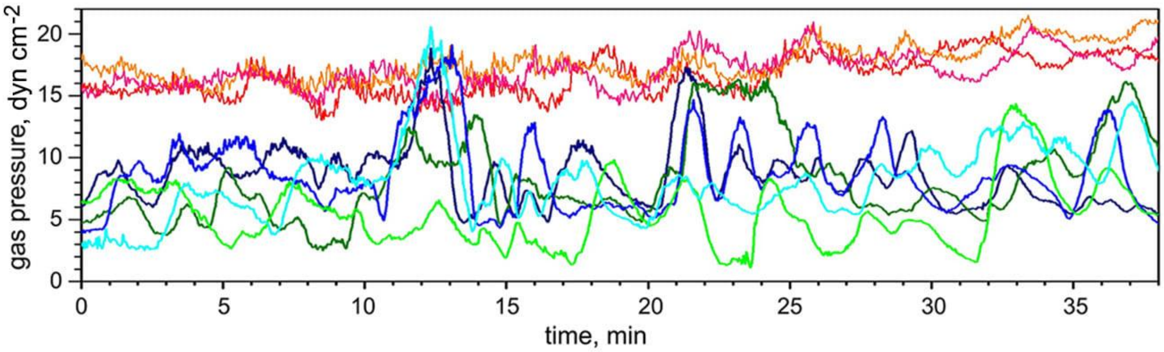
The animation shows the dynamics of a self-formed magnetic structure in the corona that is connected, through the chromosphere and transition zone, with kilogauss magnetic field in the photosphere. Visualization is performed by advecting particles seeded at a height 2.4 Mm above the solar surface.



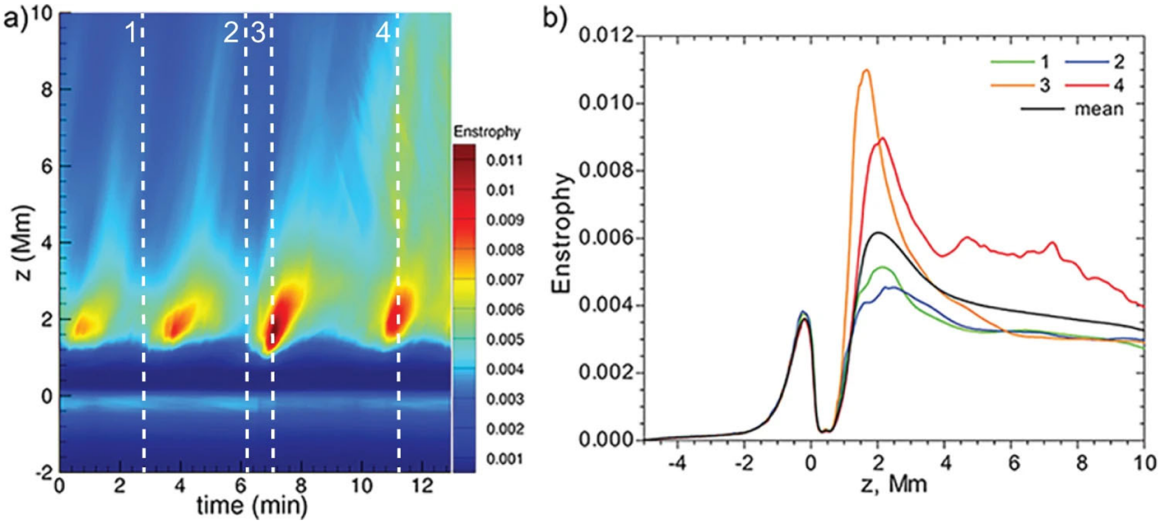
Distributions of a) vertical velocity, b) temperature, and c) magnetic field in a quiet Sun region at height 10 Mm above the photosphere. The vertical slice in panel d) shows propagation of high-frequency perturbations of divergence of the velocity from the transition zone to the upper layers of the corona. Color curves in panel d) correspond to temperatures of the transition *region of 0.1 MK and 0.5 MK. Black streamlines with arrows indicate magnetic field lines. Kitiashvili et al., 2020 (https://www.cambridge.org/core/journals/proceedings-of-the-international-astronomical-union/article/abs/realistic-3d-mhd-modeling-of-selforganized-magnetic-structuring-of-the-solar-corona/AF2250F92287CDD8C274C789E9926E67).*

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1639069878/agu-fm2021/66-EE-D5-0D-71-2F-52-6A-E5-D0-72-B7-BC-BC-57-C4/Video/Kitiashvili_IN_corona-temperature_vmmipq.mp4

Temperature structure of the solar corona at a height of 10 Mm above the solar surface. This image shows regions of strong plasma heating to several million degrees Kelvin (yellow-white colors), caused by the dissipation of small-scale electric currents spontaneously generated in the magnetic structure (center) as well as by shocks propagating across the solar atmosphere.



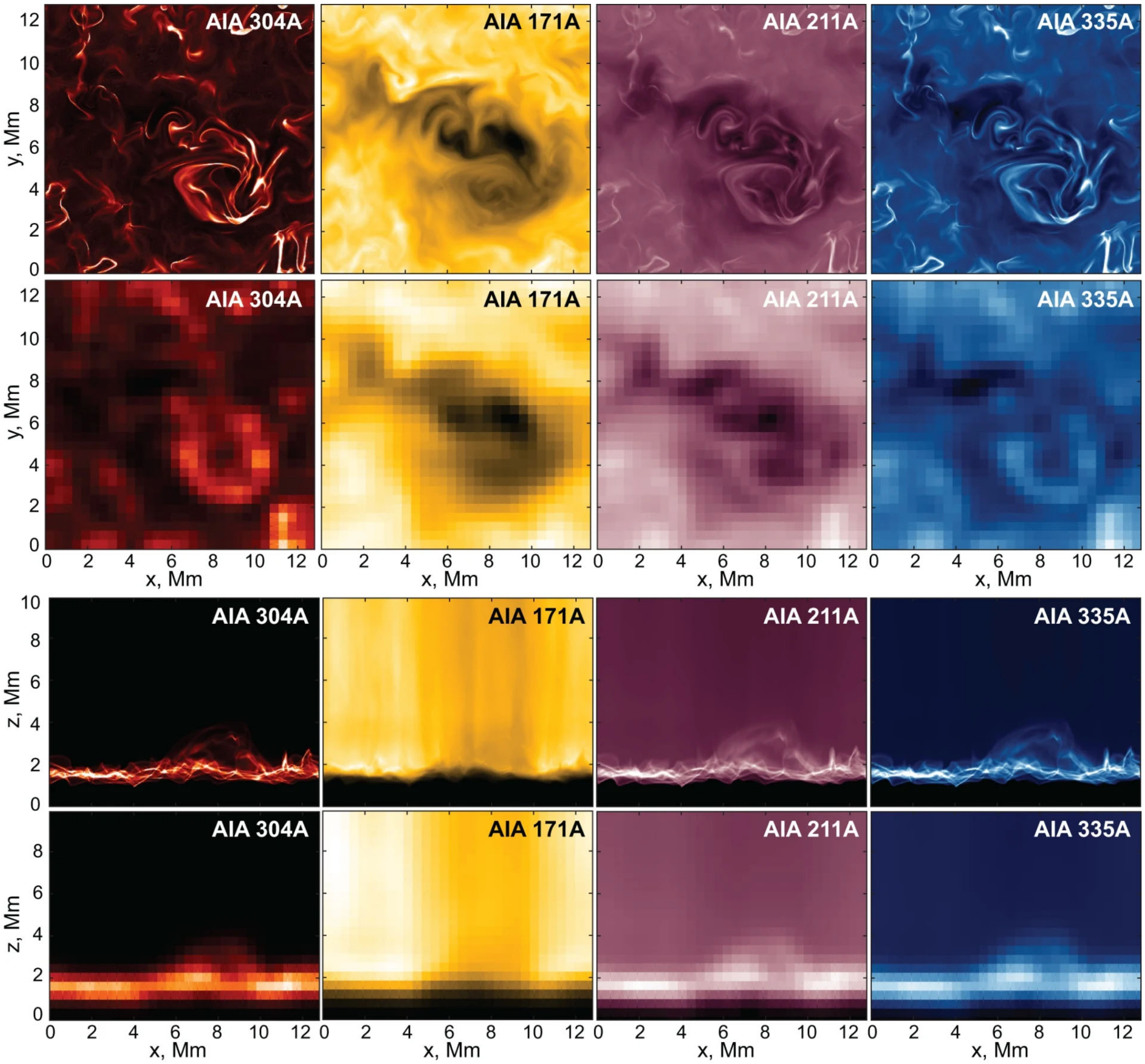
Temporal variations of the gas pressure inside (cold colors) and outside (warm colors) the funnel structure at a height of 6 Mm above the photosphere.



Enstrophy transport from the transition zone to the corona.

SYNTHETIC OBSERVATIONS OF THE CORONA MODEL

To investigate the structure and dynamics of the modeled solar corona we synthesize the MgII and CII spectral lines observed by the IRIS satellite and EUV emission observed by the SDO/AIA telescope (Sadykov et. al., 2021 (https://iopscience.iop.org/article/10.3847/1538-4357/abd9c7/pdf)). Synthetic observations are obtained using the RH1.5D radiative transfer code and temperature response functions at both the numerical and instrumental resolutions. We found that the Doppler velocity jumps of the C II 1334.5 A IRIS line and a relative enhancement of the emission in the 335 A SDO/AIA channel are the best proxies for the enthalpy deposited by shock waves into the corona.



Synthetic AIA emission in four channels calculated with the full numerical and instrumental resolution, and for two views at the disc center and the limb.

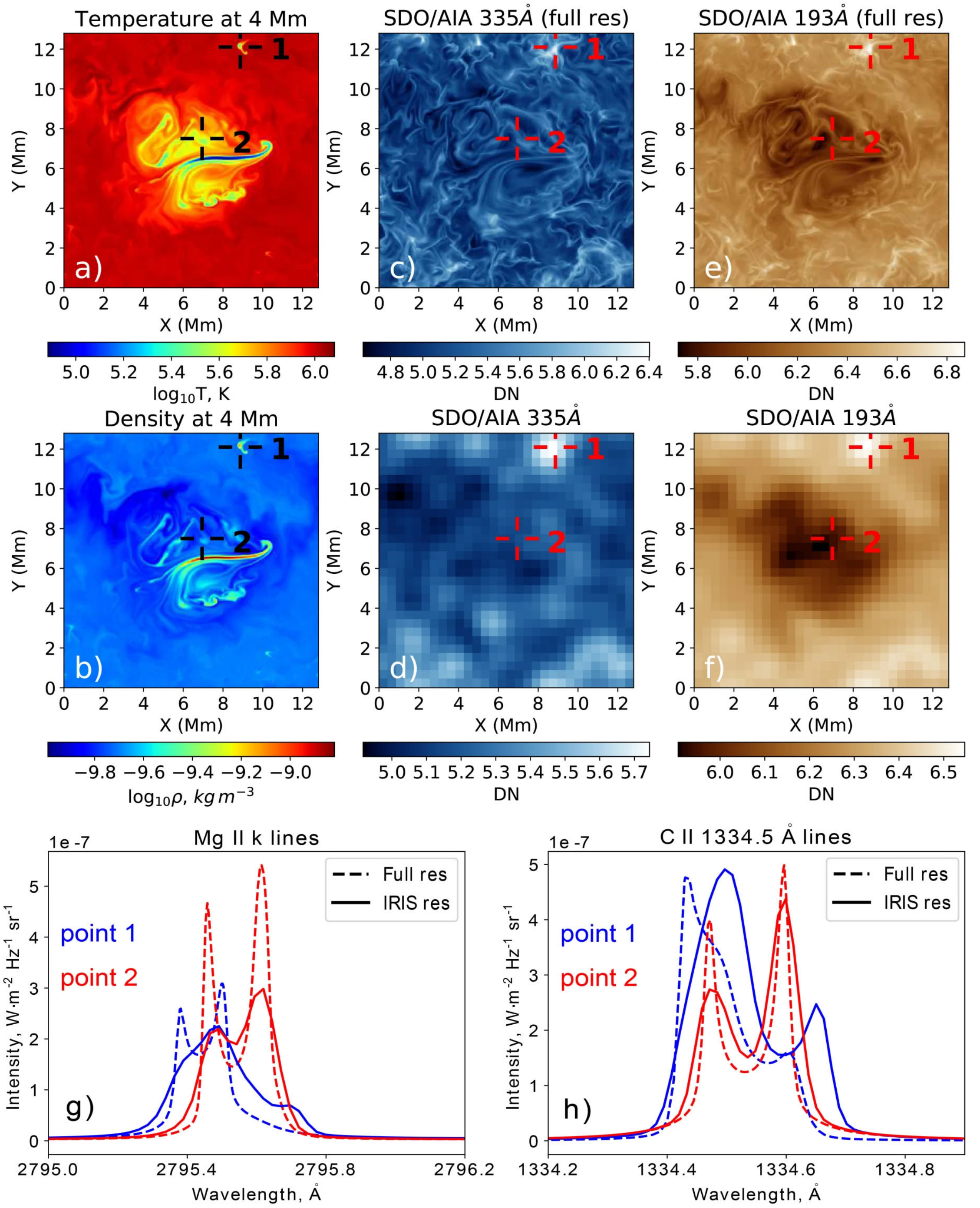
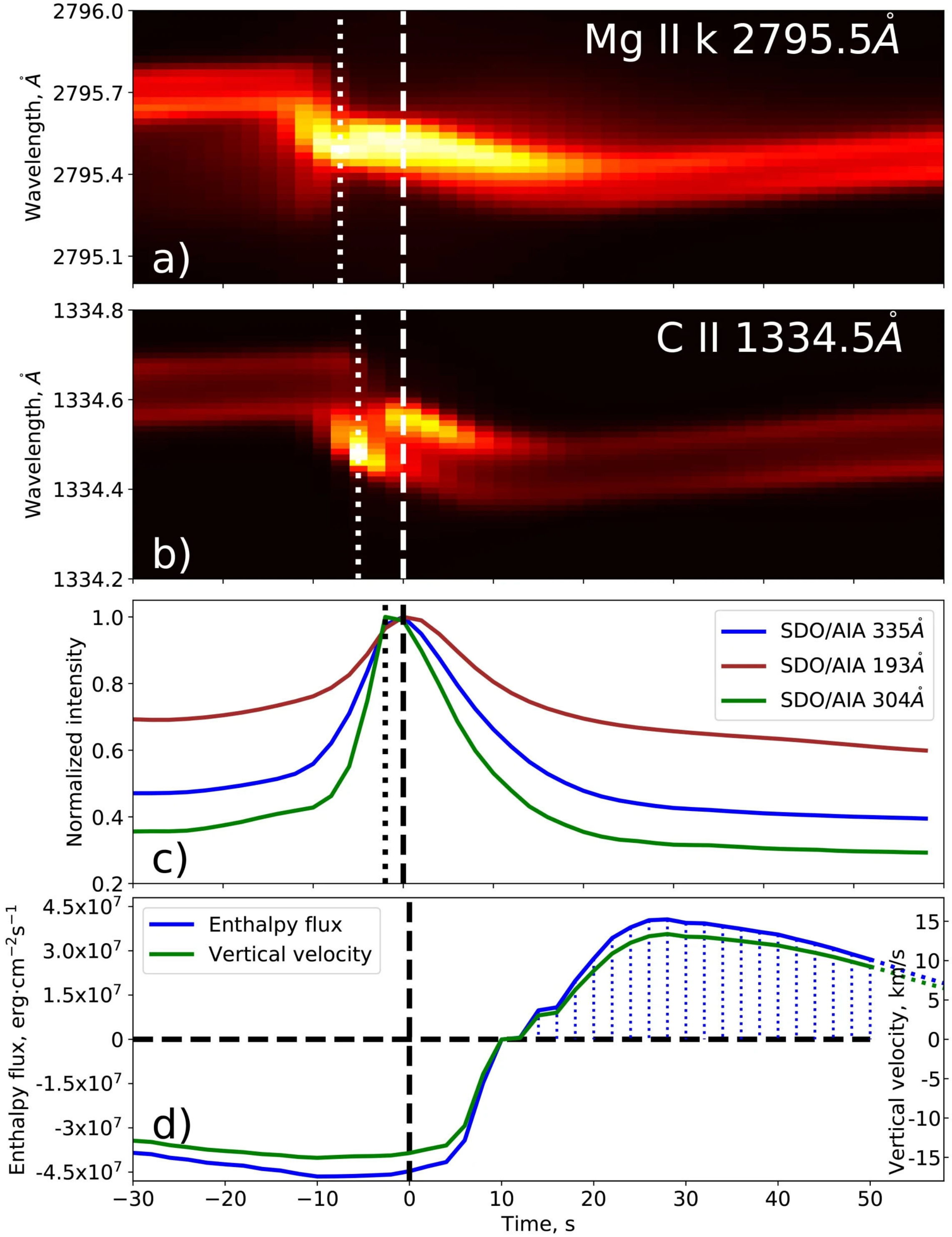


Illustration of physical properties and synthetic emission at the starting time of the considered simulation series: a) temperature, and b) density distributions at 4 Mm height; synthetic SDO/AIA 335 A emission at c) computational, and d) instrumental resolutions; synthetic SDO/AIA 193 A emission at e) computational and f) instrumental resolutions; g) MgII k and h) CII 1334.5 A line profiles derived in points 1 (blue) and 2 (red) at computational (dashed) and instrumental (solid) resolutions. Points 1 and 2 are marked by crosshairs in panels a-f (Sadykov et. al., 2021 (https://iopscience.iop.org/article/10.3847/1538-4357/abd9c7/pdf)).

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1639069744/agu-fm2021/66-EE-D5-0D-71-2F-52-6A-E5-D0-72-B7-BC-BC-57-C4/Video/Animation_SDOAIA_335_bqv8g6.mp4

In synthetic emission of 335 A, the propagating shock waves are visible as fast-moving bright features.



Evolution of a) the MgIIk line spectra, b) CII 1334.5 A line spectra, c) normalized SDO/AIA emission, and d) physical parameters in the transition region (at the height corresponding to 0.5 MK). The vertical dashed lines mark the time moment corresponding to the strongest SDO/AIA 335 A emission during the shock. The vertical dotted lines mark the time moments of the Mg II k intensity peak (panel a), CII 1334.5 A intensity peak (panel b), and SDO/AIA 304A peak (panel c). The dotted area in panel (d) indicates the positive enthalpy flux. Sadykov et. al., 2021 (https://iopscience.iop.org/article/10.3847/1538-4357/abd9c7/pdf)

COMPOSITE SDO/AIA SYNTHETIC EMISSION

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1639067416/agu-fm2021/66-EE-D5-0D-71-2F-52-6A-E5-D0-72-B7-BC-BC-57-C4/Video/video_sideview_p1_s1_wa_T_30FPS_o4or9q.mp4

Visualization of the Solar Dynamics Observatory Atmospheric Imaging Assembly (SDO/AIA) synthetic emission for the side view of the simulated quiet Sun region. Red corresponds to the synthetic SDO/AIA 171 Å emission (T = 0.79 MK); green corresponds to 131 Å (0.56 MK); blue corresponds to 304 Å (0.079 MK). The domain has a horizontal size of 12.8 Mm and includes 10 Mm of the solar atmosphere from the surface to corona. The sporadic heating events in the solar transition region and a self-organized magnetic structure are seen in the center of the region.

SUMMARY & CONCLUSIONS

Solar coronal activity is the primary source of space weather disturbances. Realistic modeling of the corona is critical for understanding the origins of space weather and for predicting the impacts of solar activity on the near-Earth space environment. To investigate the underlying physical processes, we performed 3D radiative MHD simulations taking into account all essential physics and employing sub-grid scale turbulence models, thereby reproducing the local dynamo process, spontaneous flow eruptions, coronal structure, and dynamics in the quiet-Sun.

Analysis of synthetic data reveals sharp enhancements of synthetic EUV emission Mg II spectral lines and Doppler velocity jumps. The Doppler velocity jump of the C II 1334.5A (IRIS line) and relative enhancement of 335A emission (SDO/AIA) is the best proxy for the enthalpy deposited by shocks in the corona with Kendall's τ correlation coefficients of 0.59 for 1334.5 A and 0.38 for 335 A.

It is found that the transition zone between the low temperature (0.01 MK) chromosphere and hot (1 MK) corona is substantially more turbulent and dynamic than previously assumed. The simulations revealed new processes of generation of shocks and plasma eruptions and showed that the transition region dynamics is a source of coronal expansion and formation of the solar wind. Our simulation results reveal that initially uniform weak magnetic fields are greatly amplified due to small-scale dynamo action below the visible surface of the Sun and cause the spontaneous formation of tornado-like plasma structures and eruptions. The strongest helical flows originate in strong, 1 kG magnetic field patches formed on the solar surface. These helical magnetized structures extend into the corona and produce Alfvén waves that drive plasma eruptions. The simulations also reveal many important details that are unresolved in observational data, such as the Kelvin-Helmholtz instability of the magnetic structures and plasma downflows in the corona.

ABSTRACT

Dramatic dynamical phenomena accompanied by strong thermodynamic and magnetic structuring are the primary drivers of great interest in studying the solar atmosphere with high spatial and temporal resolutions. Using current computational capabilities, it has become possible to model the magnetized solar plasma in different regimes with a high degree of realism. To study the fine structuring of the solar atmosphere and dynamics, we use 3D MHD radiative models covering all layers from the upper convection zone to the corona. Realistic 3D radiative MHD modeling of the solar magnetoconvection and atmosphere allows us to generate synthetic observables that directly link the physical properties of the solar plasma to spectroscopic observables. In the presentation, we discuss qualitative and quantitative changes of the atmospheric structure and dynamics at different layers of the solar atmosphere, properties of acoustic and surface gravity waves, sources of local heating in the chromosphere-corona transition region, formation of shocks, and high-frequency oscillations in the corona, as well as manifestation of these phenomena in the modeled observables.

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