Data-constrained MHD simulation of solar corona including solar wind effects

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Coronal mass ejections (CMEs) are one of the most important events within the solar system, releasing large amounts of magnetized plasma from the Sun into interplanetary space, influencing the heliosphere and magnosphere of the Earth. Magnetohydrodynamic (MHD) simulations are often used to investigate initiations and propagations of CMEs.

To conduct more realistic MHD simulations from the solar surface to several solar radii to interplanetary space, the effects by solar wind have to be considered, which can produce more accurate magnetic field configuration, velocity and energy evolution[1], give a profound understanding of the physics of the Sun-Earth transients, and predict space weather.[2] There are multiple data-constrained simulation softwares that incorporate the effects of the solar wind including both in the domain of solar corona and heliosphere, including COolfluid COroNa UnsTructured (COCONUT)[2,3], the Alfven Wave Solar Model-Realtime (AWSoM-R)[4], and ICARUS[5] under the Message Passing Interface Adaptive Mesh Refinement Versatile Advection Code (MPI-AMRVAC). They employ different numerical meshes and account for complex heating mechanisms.

Therefore, we implement a corona model constrained by observed magnetograms using MPI-AMRVAC, taking effects of the solar wind into accounts, with relatively strong magnetic field intensity allowed and more accurate polar-region schemes. It also allows for advanced adaptive mesh refinement (AMR) operations and finer grid settings under this framework. We conduct an MHD simulation with energy equation and $\gamma = 1.05$ of the solar corona on 2024 April 8. The computation domain is $[r_{min}, r_{max}] \times [\theta_{min}, \theta_{max}] \times [\phi_{min}, \phi_{max}] = [1.001R_{sun}, 2.500R_{sun}] \times [0°, 180°] \times [0°, 360°]$. The domain is resolved by $400 \times 180 \times 360$ cells and uniform in r, θ, ϕ directions. For initial conditions, we start from a global magnetic field which reaches the equilibrium of magneto-frictional method with a solar wind profile inserted with the highest order of spherical harmonics $l_{max} = 10$, and the density and velocity are from the Parker solar wind solution using Lambert functions. We have tested multiple input magnetograms, including the HMI synoptic maps, HMI synchronic frames, GONG maps, and GONG-ADAPT maps, and it turns out that the HMI synchronic frames include more up-to-date radial magnetic field information and are therefore better to reproduce the streamer structures. For boundary conditions, we adopt the pole conditions in θ boundaries and periodic conditions in ϕ boundaries. The bottom radial boundary is line-tied for density, velocity, thermal pressure and magnetic field in the inner ghost layer, and zero-gradient extrapolation for the outer ghost layer. For the top radial boundary, all radial components are constrained by the zero-gradient extrapolation, and transverse component are fixed to zero, which are referred to non-slipping boundaries.

We successfully simulate the global solar corona with solar wind effects on 2024 April 8. We quantitatively analyze simulation results in terms of magnetic field configuration, magnetic topology, velocity distribution and radiation synthesis. In conclusion, large-scale closed magnetic loops evolve to streamers and yield relatively reliable velocity and density distributions. Comparison between white-light radiation synthesis and observations from the total solar eclipse and coronagraphs will be further explored to verify this corona model.

References

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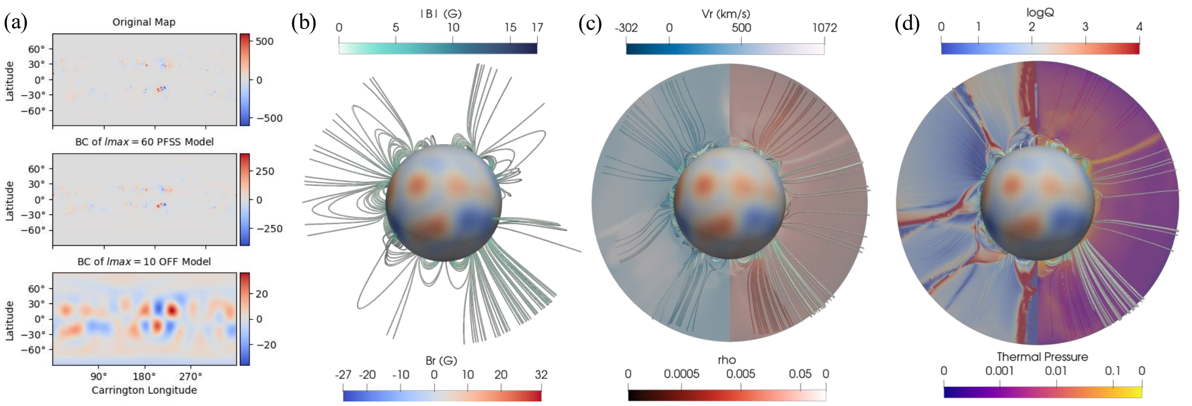

Figure 1 MHD simulation setup and results. (a) bottom boundary for initial magnetic field model. (b) the initial magnetic field configuration. (c) solar corona at t=21 mins, with radial velocity and density displayed. (d) similar to (c), with log(Q) and pressure displayed.