

HERCORE: Highly Efficient and quasi-Realistic CORonal and coronal mass Ejection modeling



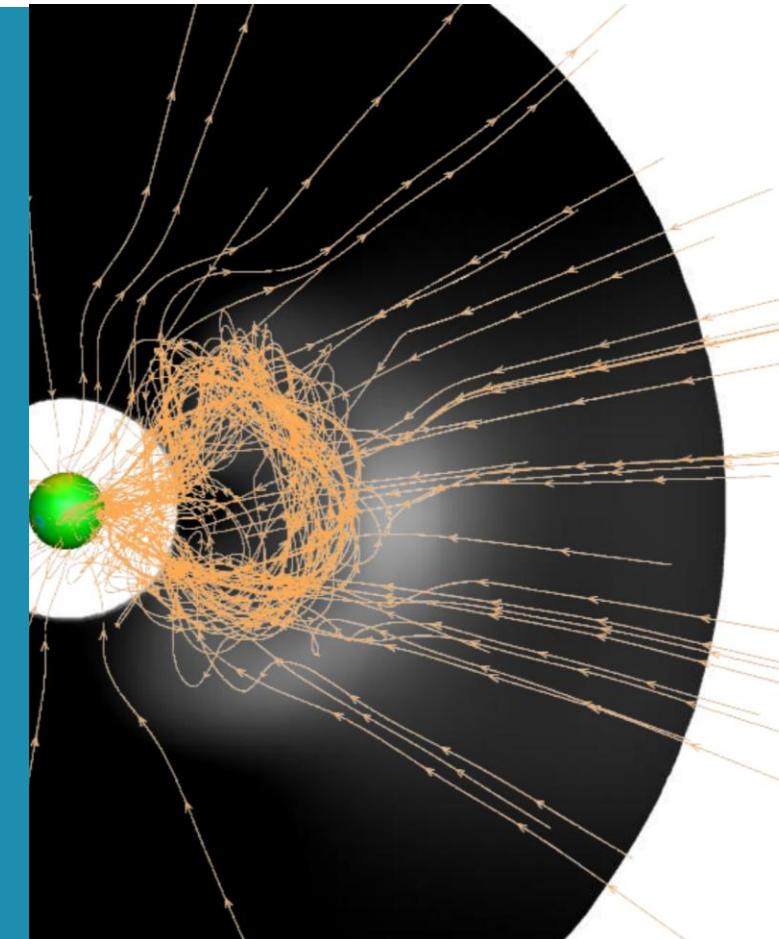
Dr. Haopeng Wang

KU Leuven, 02/10/2025

Postdoctoral Researcher, KU Leuven (Supervisor: Stefaan Poedts)

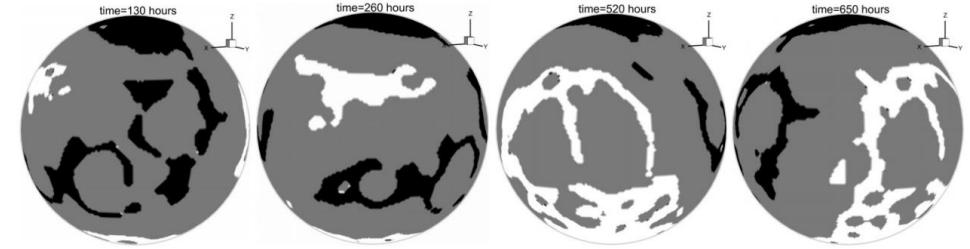
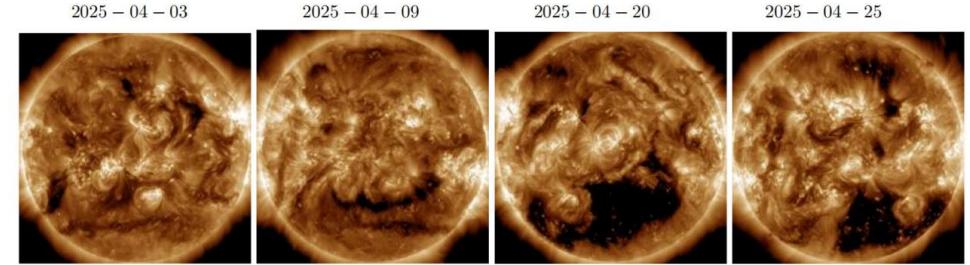
Ph.D., National Space Science Center, UCAS (Supervisor: Xueshang Feng)

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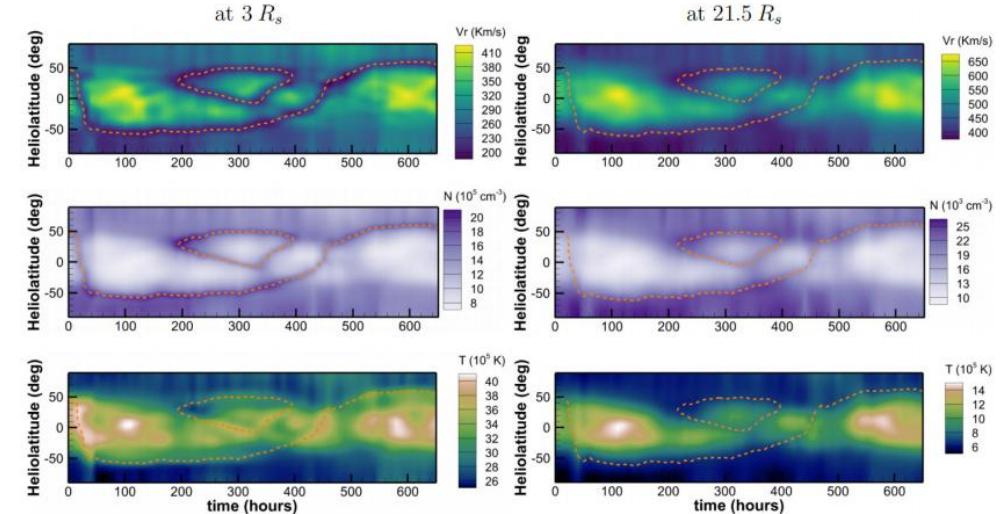


Outline

- Background: Why **COCONUT**?
- Fully implicit, quasi-steady-state MHD coronal model **COCONUT**
- Faster-than-real-time MHD modeling of the coronal evolutions by **COCONUT**
- In prep research works based on **COCONUT**

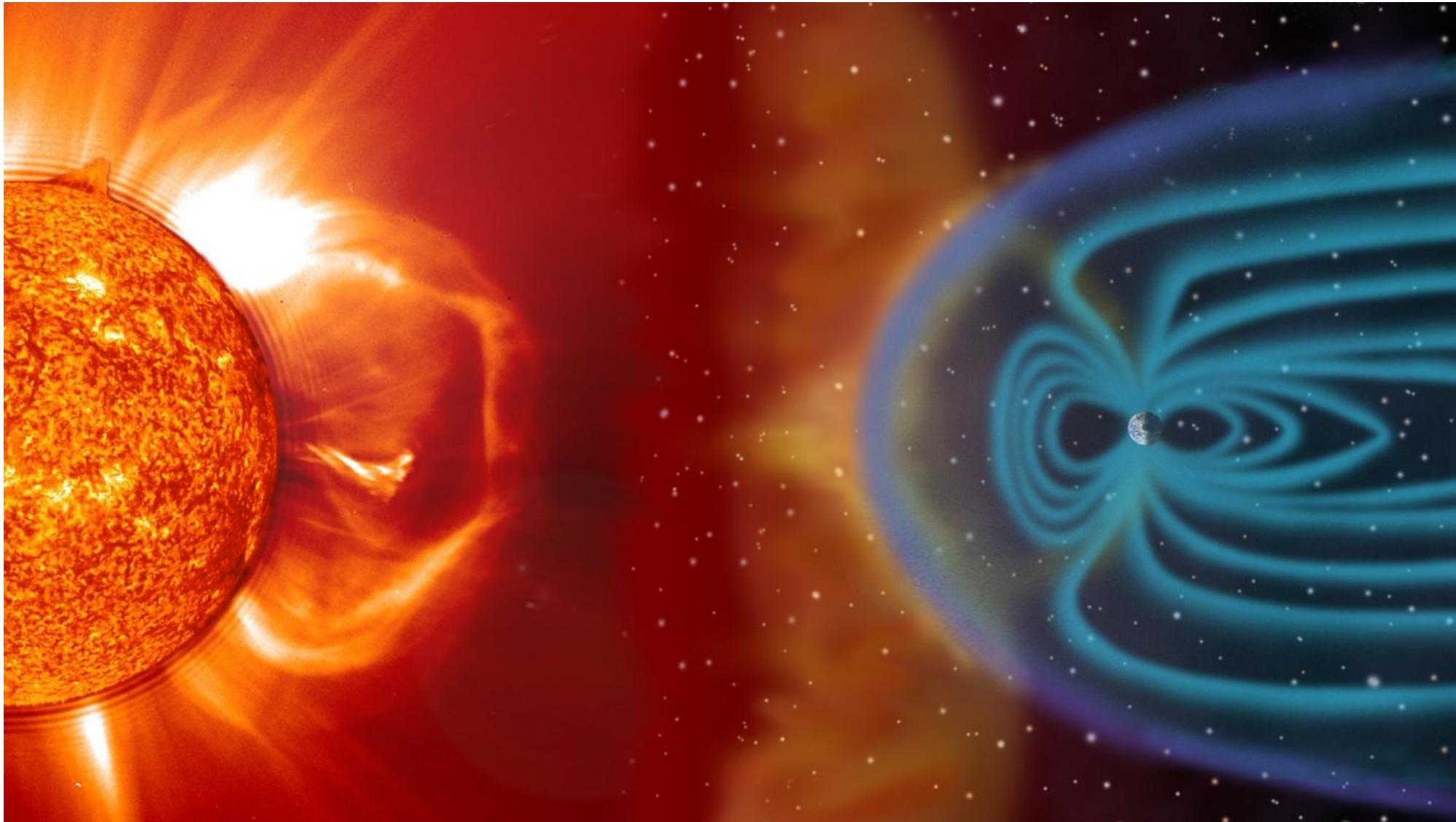


SDO/AIA observation and simulated open-field region from **COCONUT**



Timing diagrams of simulated plasma variables along the latitudes intersected by the Sun–Earth line at $3 R_S$ and 0.1 AU .

Our goal: Solar-terrestrial space and space weather forecasting



Our society suffers from severe space weather:

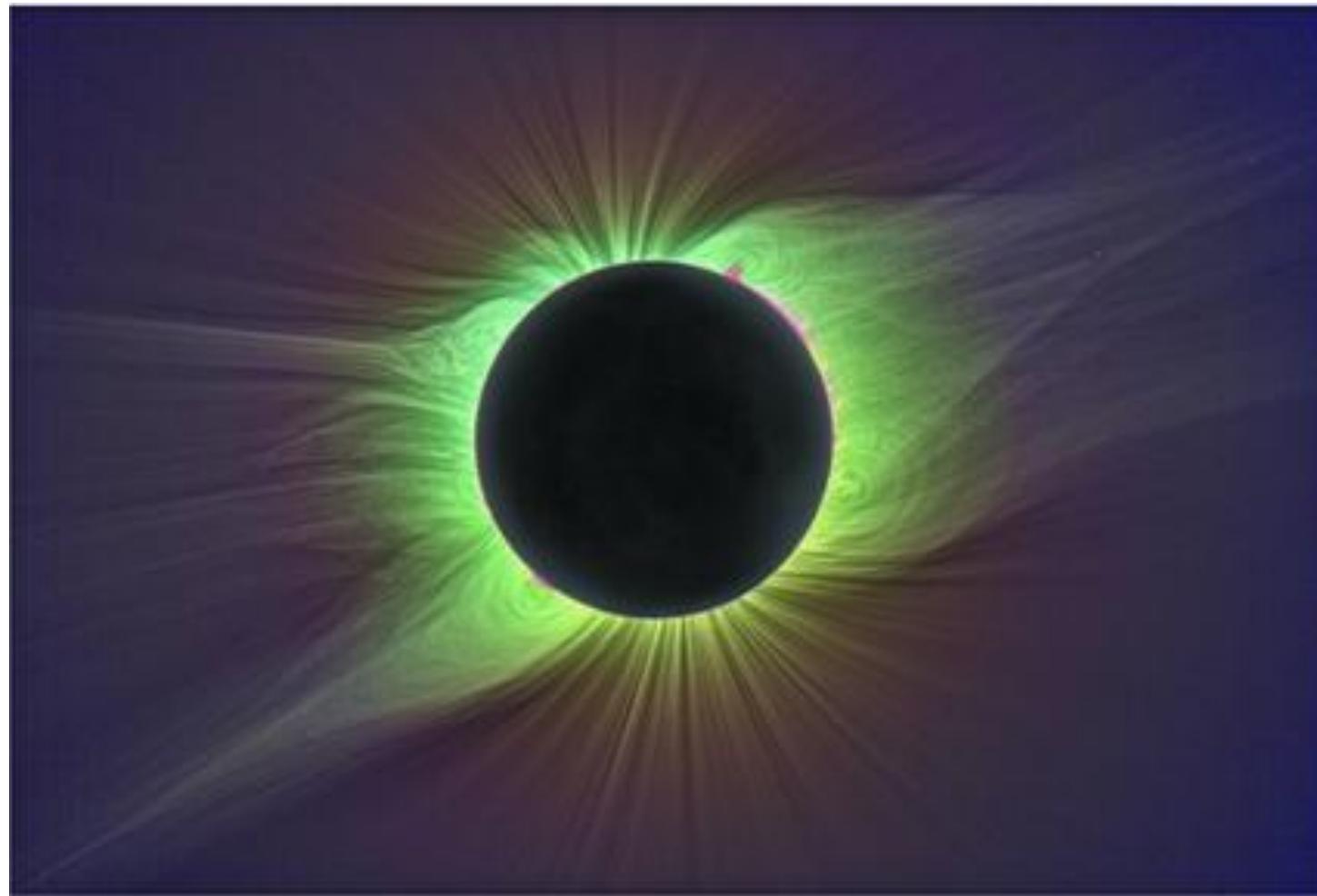
1989 Quebec blackout

Satellite electronics damage during the 2003 “Halloween Storm”

A geomagnetic storm in February 2022 caused loss of up to 40 out of 49 Starlink satellites.

et al.

Critical and extremely challenging work: Efficient time-evolving coronal modeling



Color-enhanced image (the saturation was increased by $50\times$) of the white-light observation of total solar eclipse of 2008 August 1 (Pasachoff et al. 2009)

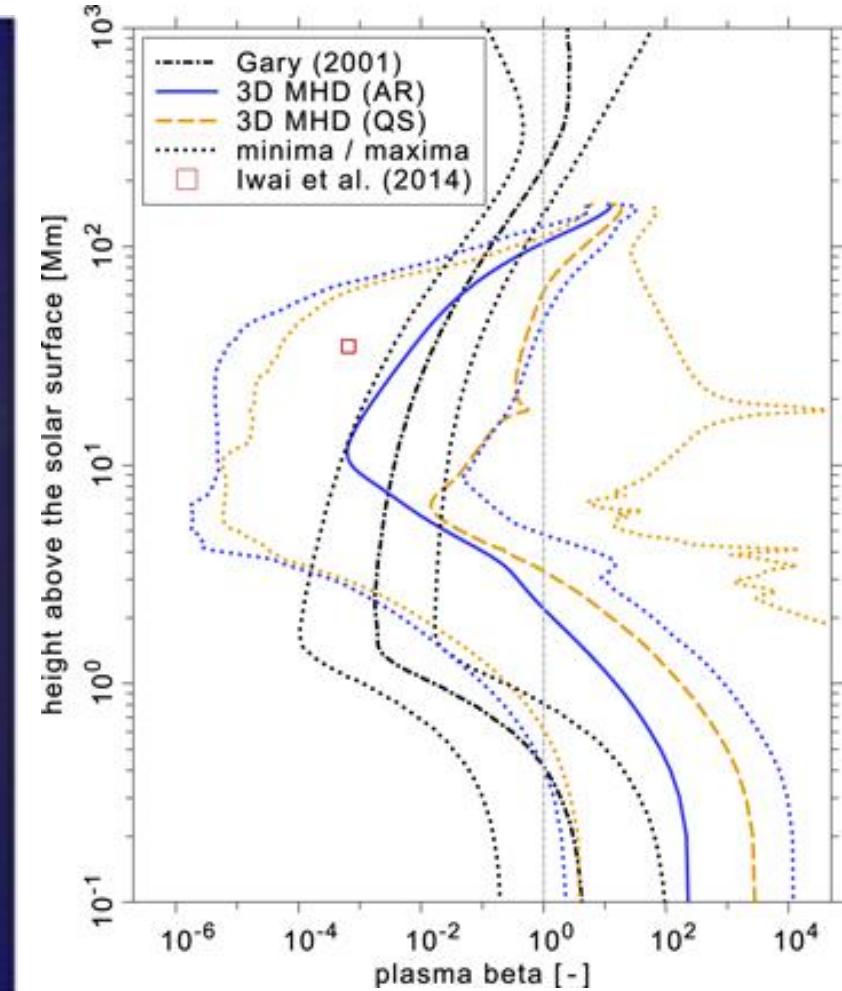


Illustration of the plasma β near the solar surface (Bourdin 2017).

Challenges and advantages of coronal and solar wind MHD modeling

Challenges

- Uncertain boundary data: incomplete and noisy solar magnetograms.
- Coronal heating problem: poorly understood mechanisms.
- Multi-scale physics: difficult to resolve both fine coronal structure and global solar wind.
- Numerical stability & efficiency: stiff low- β regions require costly schemes.
- Limited microphysics: small-scale or kinetic effects are not fully captured.
- CME initiation & propagation: hard to capture realistic reconnection and magnetic topology.
- Lower-atmosphere coupling: simplified treatment of chromosphere/transition region.

Advantages:

- Physics-based: self-consistent plasma dynamics (mass, momentum, energy, magnetic flux).
- Global coverage: Sun-to-Earth, capturing corona and heliosphere structures.
- Predictive: forecasts solar wind, CMEs, and space weather events.
- Flexible & diagnostic: integrates multiple processes and supports observational comparisons.
- Coupled processes: includes magnetic fields, waves, and thermodynamics simultaneously.
- Operational utility: supports space weather forecasting.
- Insightful: helps test hypotheses about coronal heating, solar wind acceleration, and heliospheric structures.

Challenges in MHD coronal modeling: low- β issues

- Nonphysical **negative thermal pressure** is prone to occur in the floating-point calculation process of deriving thermal pressure from energy density.
- Extremely **small time-step length** determined by the Courant-Friedrichs-Lowy (CFL) restriction.
- **Non-zero magnetic field divergence error** leads to anomalous Lorentz force parallel to the magnetic field, leading to severe stability problems.
- A solver suitable for **both the incompressible low- and compressible high-speed flows** is required.

$$\beta = \frac{p}{0.5 * \mathbf{B}^2}$$

Challenges in MHD coronal modeling: low- β issues

- Nonphysical **negative thermal pressure** is prone to occur in the floating-point calculation process of deriving thermal pressure from energy density.

- Positivity-preserving method implemented on density and thermal pressure
- Decomposed energy equation**

$$p = (\gamma - 1) \left(E - \frac{1}{2}(\rho V^2 + \mathbf{B}^2) \right)$$

$$\beta = \frac{2p}{\mathbf{B}^2}$$

catastrophic cancellation

$$(\mathbf{B} + \varepsilon \mathbf{B})^2 - \mathbf{B}^2 \equiv \varepsilon \mathbf{B}^2$$

$\varepsilon \mathbf{B}$ means the discretization error of \mathbf{B} .

During the 2nd or 3rd order spatial discretization procedure, $\varepsilon \mathbf{B}^2 \equiv p$ for low β cases.

Challenges in MHD coronal modeling: low- β issues

- Extremely **small time-step length** determined by the Courant-Friedrichs-Lowy (CFL) restriction.

- Implicit temporal integration method enable large time steps exceed CFL stability restriction

$$\Delta t = \text{CFL} \cdot \frac{dh}{c_f}$$

characteristic cell size

Maximum wave velocity
in current cell

Usually, $\text{CFL} < 1$ for explicit scheme.
The time step length Δt decreases with magnetic field strength increasing. Δt may be less than 10^{-4} hours for low- β MHD simulations.

Challenges in MHD coronal modeling: low- β issues

- Non-zero magnetic field divergence error leads to anomalous Lorentz force parallel to the magnetic field, leading to severe stability problems.

- Hyperbolic generalized Lagrange multiplier method

$$\frac{\partial \psi}{\partial t} + c_h^2 \nabla \cdot \mathbf{B} = 0$$
$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} + \nabla \psi = 0$$

$$\begin{aligned}\mathbf{F} &= \mathbf{J} \times \mathbf{B} = \nabla \times \mathbf{B} \times \mathbf{B} \\ &= -\nabla \left(\frac{B^2}{2} \right) + (\mathbf{B} \cdot \nabla) \mathbf{B} + \mathbf{B}(\nabla \cdot \mathbf{B})\end{aligned}$$

Fully implicit, time-evolving thermal dynamic MHD coronal models COCONUT

- Unstructured geodesic grid mesh
- Implicit: GMRES solver
- Decomposed energy strategy enhances stability for addressing **time-evolving low- β issues.**
- Multi-fluid module enables higher fidelity of the simulation results.

Fully implicit, time-evolving MHD coronal models COCONUT

- Implicit: Parallel GMRES solver

- Global matrix solving technique
- Converge with less iterations, require more memory
- Simulate the coronal evolution during **a full CR within only 9 hours** (1080 CPU cores, ~1.5M cells, time step is 10 minutes.)

$$V_i \frac{\Delta \mathbf{U}_i^n}{\Delta t} + \mathbf{R}_i^{n+1} = 0; \quad \mathbf{A} \Delta \mathbf{U}^n = \mathbf{R}^n, \Delta \mathbf{U}^n = \mathbf{U}^{n+1} - \mathbf{U}^n$$

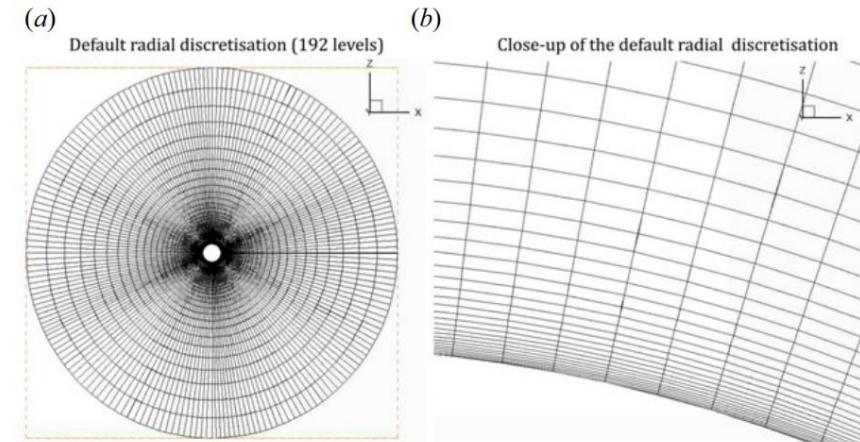
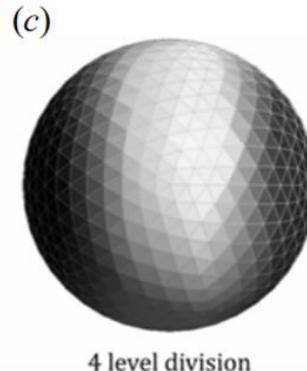
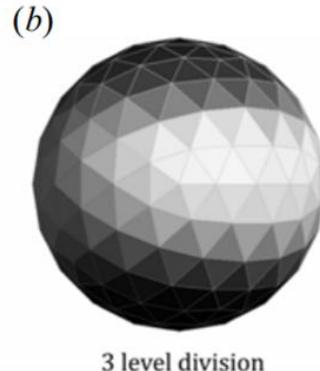
- \mathbf{A} is the Jacobian matrix, a large sparse coefficient matrix
- \mathbf{U} is the solution vector

Fully implicit, time-evolving MHD coronal models COCONUT and SIP-IFVM

● Unstructured geodesic grid mesh [Brchnelova et al. 2022]

Brchnelova, M., Zhang, F., Leitner, P., et al. 2022b, J. Plasma Phys., 88,
doi:10.1017/S0022377822000241

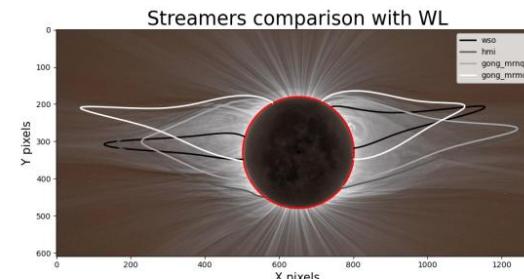
- Flexible in mesh division
- Avoid degeneracy at the poles



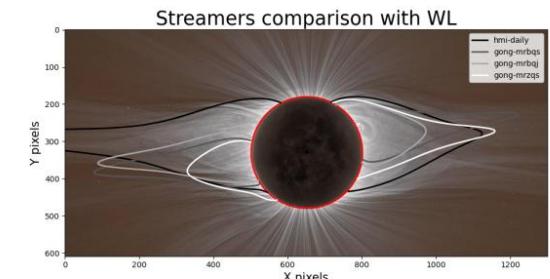
Fully implicit, time-evolving MHD coronal models COCONUT and SIP-IFVM

- Impact of the input magnetic map on simulation results [Perri et al. 2022]

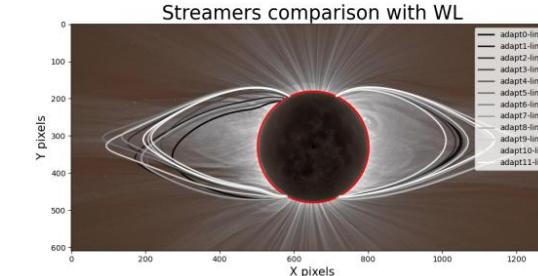
Barbara Perri et al 2023 ApJ 943 124, doi:10.3847/1538-4357/ac9799



(a) Carrington frame diachronic maps.



(b) Synchronic frame maps.

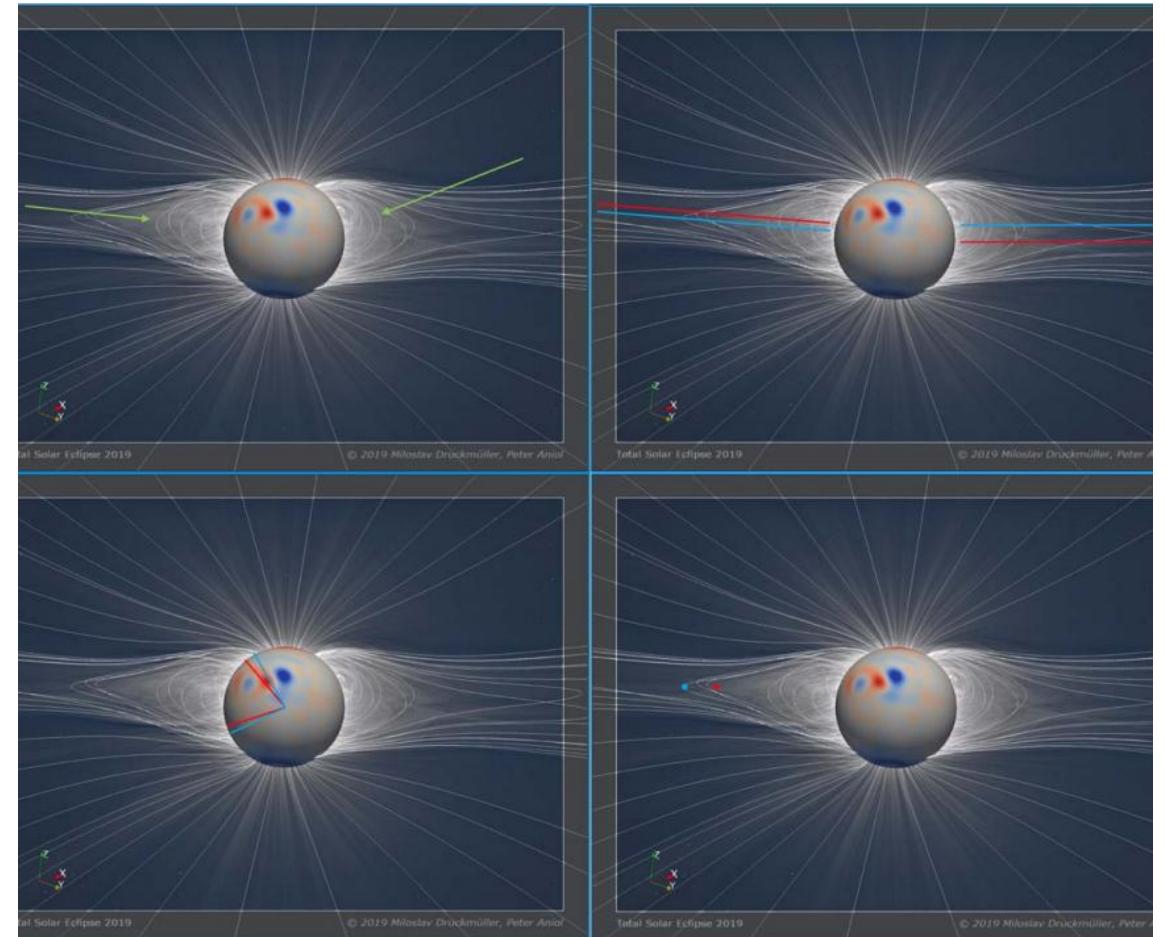


(c) GONG-ADAPT realisations.

Fully implicit, time-evolving MHD coronal models COCONUT and SIP-IFVM

- Validation method of Wagner et al. (2022) used in the case of the 2019 total solar eclipse [Kužma et al. 2023]

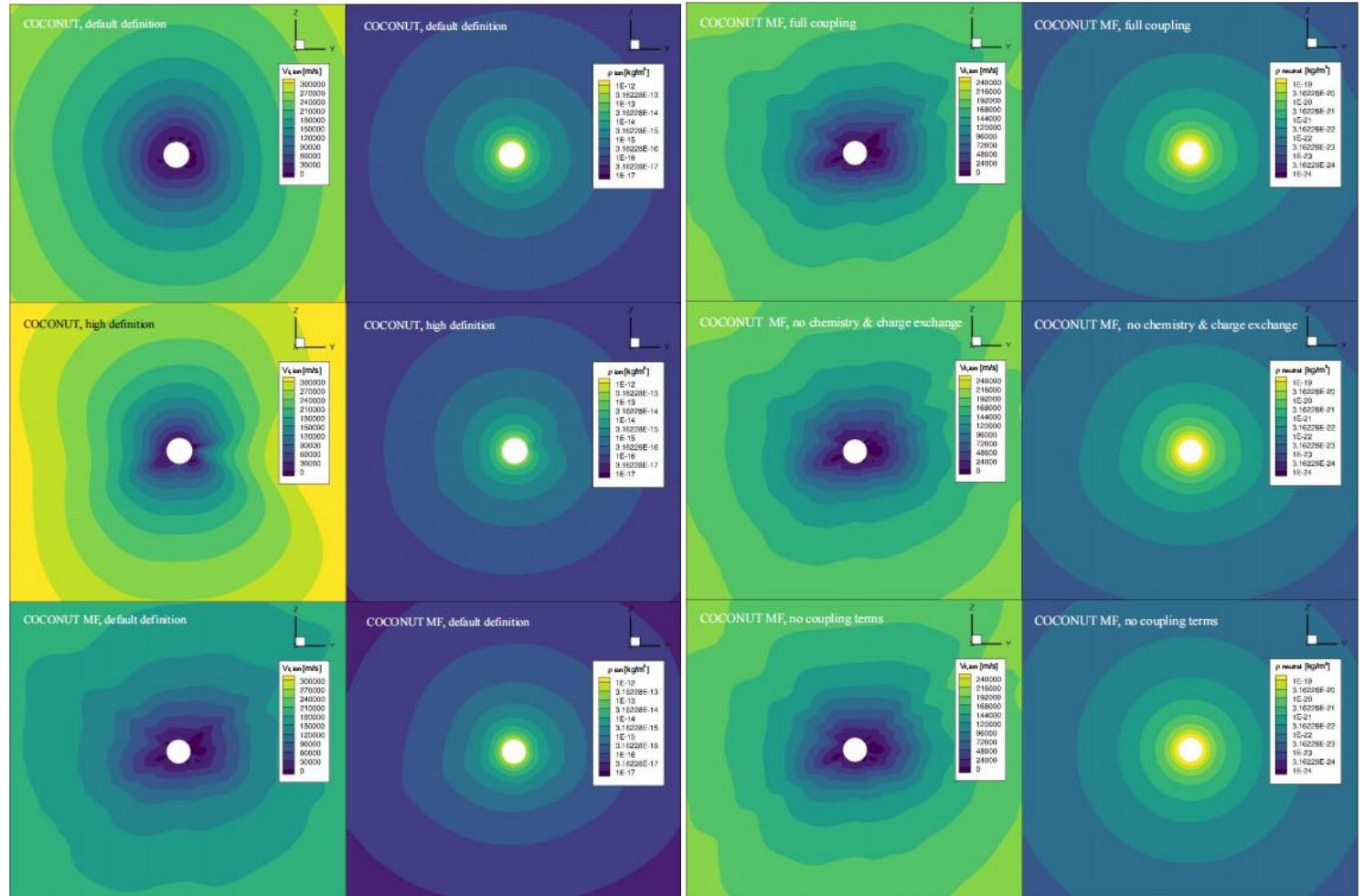
Błażej Kužma et al 2023 ApJ 942 31, doi:10.3847/1538-4357/aca483



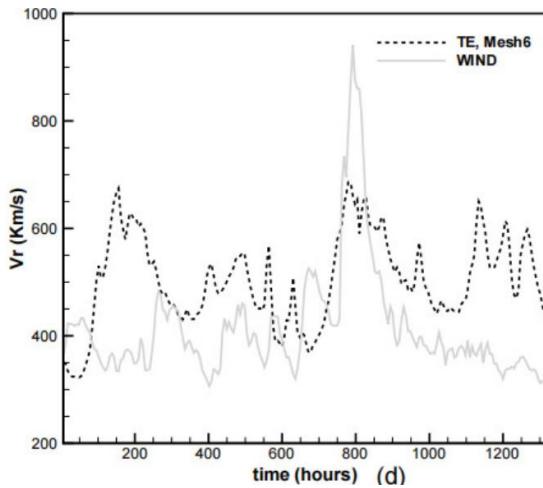
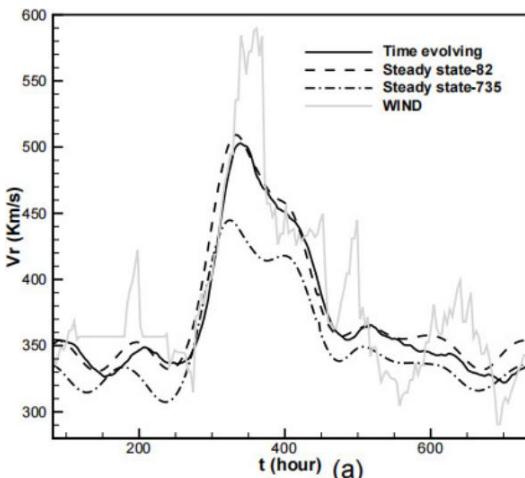
Fully implicit, time-evolving MHD coronal models COCONUT and SIP-IFVM

- Two-fluid ion-neutral global coronal modelling [Brchneleva et al. 2023]

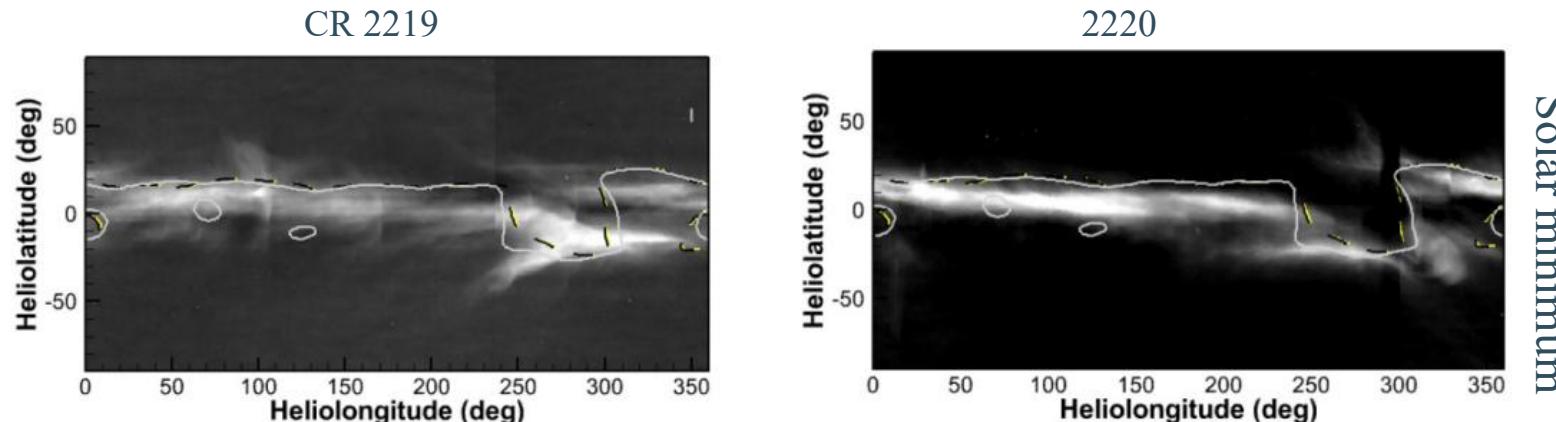
Brchneleva, Michaela et al 2023 A&A 678 A117, doi:
[10.1051/0004-6361/202346525](https://doi.org/10.1051/0004-6361/202346525)



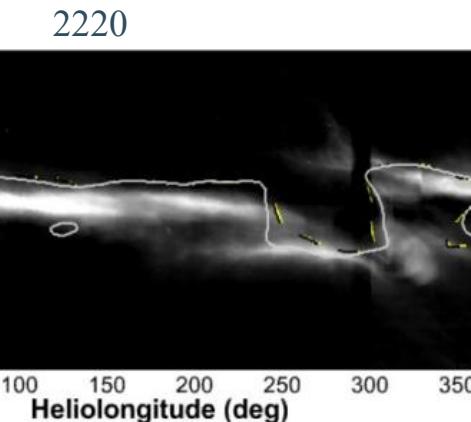
Time-evolving COCONUT



Timing diagram of the simulated and the observed radial velocity.

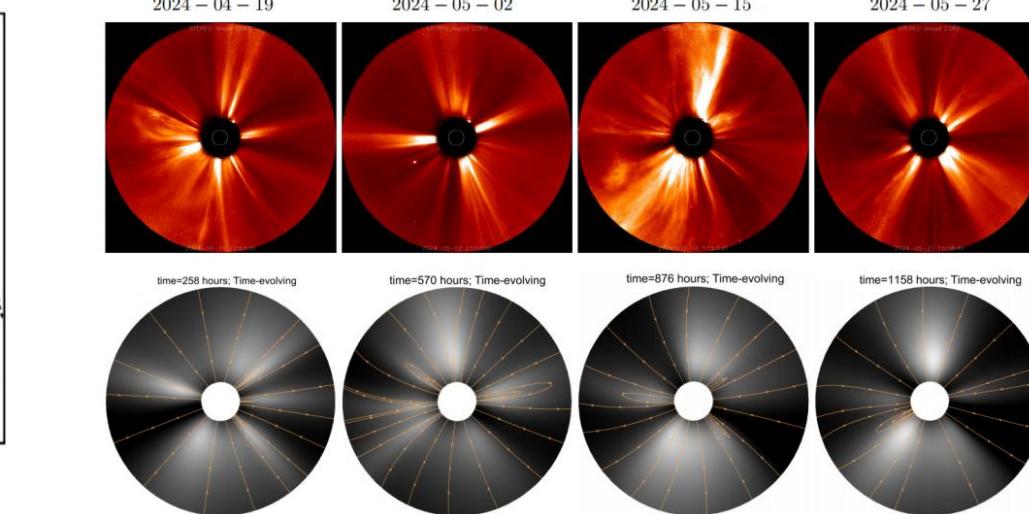


Observed synoptic pB images and simulated magnetic neutral lines at $3R_s$.



Solar minimum

Haopeng Wang, Stefaan Poedts, Andrea Lani et al.: 2025c, Time-evolving coronal modelling of the solar maximum around the solar storms in May 2024 by COCONUT. A&A:1-11.

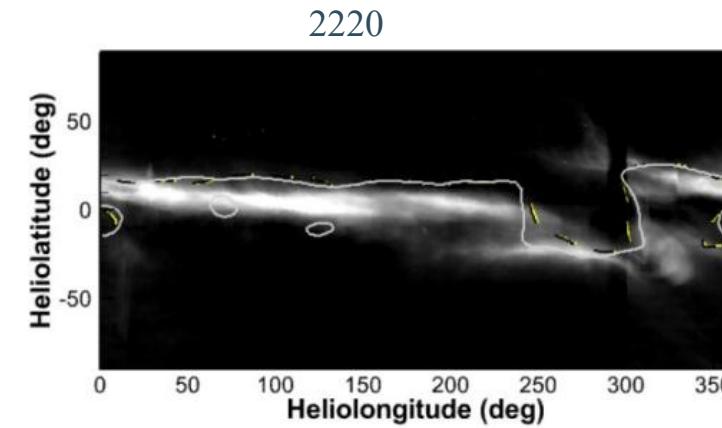
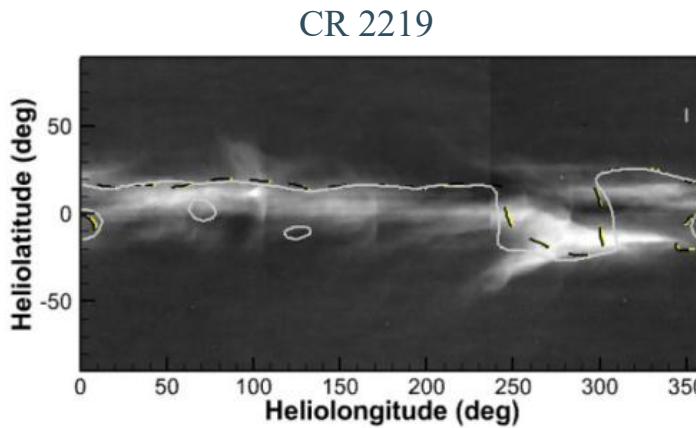
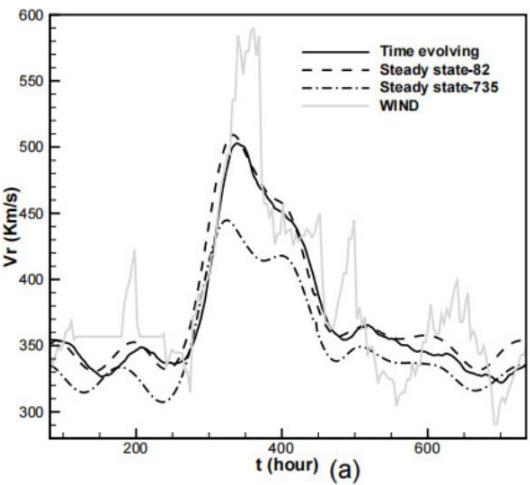


Solar maximum

STEREO-A COR2 pB observations and corresponding simulated pB images.

Haopeng Wang, Stefaan Poedts, Andrea Lani et al.: 2025b, Efficient MHD modelling of the time-evolving corona by COCONUT. A&A, 694(A234):1-14.

Time-evolving COCONUT



Observed synoptic pB images and simulated magnetic neutral lines at $3R_s$.

Solar minimum

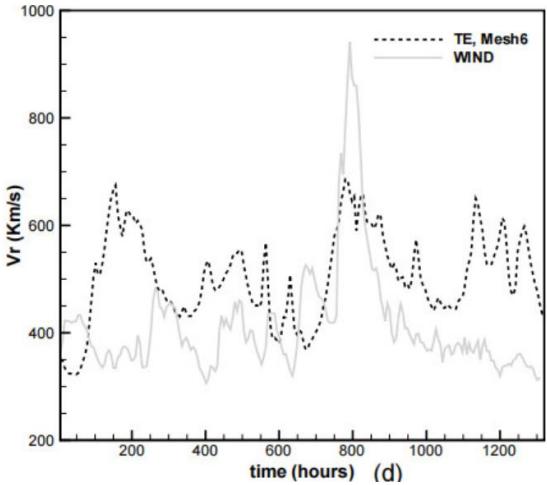
Haopeng Wang,
Stefaan Poedts,
Andrea Lani et
al.: 2025b,
Efficient MHD
modelling of the
time-evolving
corona by
COCONUT.
A & A,
694(A234):1-14.

TimeEvolving_COCONUT(FirstVersion)

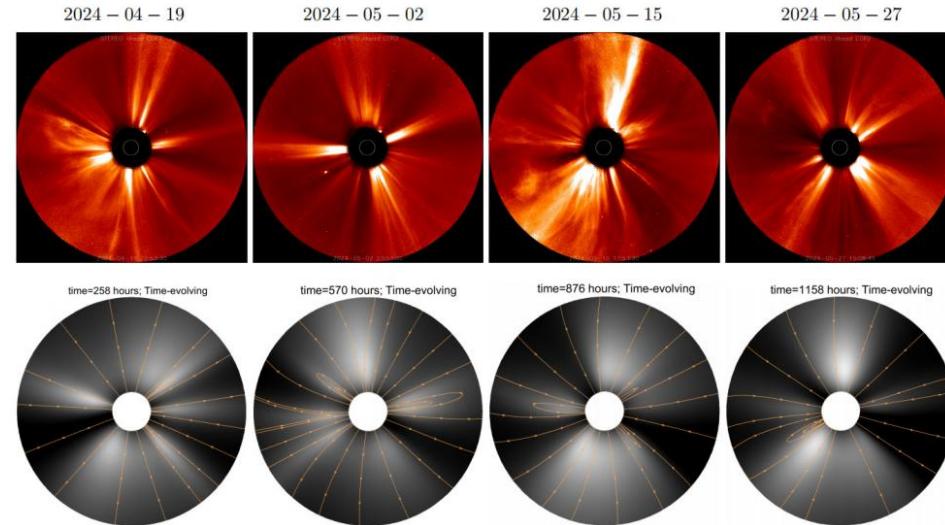
People in KU Leuven can visit them.

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	Installation	03月10日	Haopeng Wang	2 items
○	Manus	02月19日	Haopeng Wang	3 items
	script_to_replace	02月19日	Haopeng Wang	3 items
	30Rs_lv15.CFmesh	02月19日	Haopeng Wang	28.6 MB
	coconut_bcfile-3.py	02月26日	Haopeng Wang	33.1 KB
	map_steady.CFcase	02月19日	Haopeng Wang	23.1 KB

Time-evolving COCONUT



Timing diagram of the simulated and the observed radial velocity.



STEREO-A COR2 pB observations and corresponding simulated pB images.

[TestCaseAround2024MayEvent \(TheLatestVersion\)](#)

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Solar maximum

Haopeng Wang, Stefaan Poedts, Andrea Lani et al.: 2025c, Time-evolving coronal modelling of the solar maximum around the solar storms in May 2024 by COCONUT. A&A:1-11.

My files > Time-evolving COCONUT > TestCaseAround2024MayEvent(TheLatestVersion)			
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	Scratch_DiskSection	06月02日	Haopeng Wang
	CompleteCopyTest.zip	07月21日	Haopeng Wang
	788 MB		

Time-evolving COCONUT

Table 1. Average relative differences between quasi-steady-state and time-evolving coronal simulation results.

Parameters	$\text{RD}_{\text{ave},\rho}^t$	$\text{RD}_{\text{ave}, \mathbf{v} }^t$	$\text{RD}_{\text{ave}, \mathbf{B} }^t$
$t = 82 \text{ h}$	0.54%	1.06%	4.24%
$t = 735 \text{ h}$	4.53%	8.49%	35.35%

$$\begin{aligned}\text{RD}_{\text{ave},\rho} &= \frac{\sum_{i=1}^N |\rho_{i,\text{QSS}} - \rho_{i,\text{TE}}|}{\sum_{i=1}^N \rho_{i,\text{QSS}}}, \\ \text{RD}_{\text{ave},|\mathbf{v}|} &= \frac{\sum_{i=1}^N |\mathbf{v}_{i,\text{QSS}} - \mathbf{v}_{i,\text{TE}}|}{\sum_{i=1}^N |\mathbf{v}_{i,\text{QSS}}|}, \\ \text{RD}_{\text{ave},|\mathbf{B}|} &= \frac{\sum_{i=1}^N |\mathbf{B}_{i,\text{QSS}} - \mathbf{B}_{i,\text{TE}}|}{\sum_{i=1}^N |\mathbf{B}_{i,\text{QSS}}|}.\end{aligned}$$

$$\begin{aligned}B_{\text{BC,r}}(t, \theta, \phi) &= h_{00}(t') B_{\text{r}}(\theta, \phi)_m \\ &+ h_{10}(t') (t_{m+1} - t_m) \left(\frac{\partial B_{\text{r}}(\theta, \phi)}{\partial t} \right)_m \\ &+ h_{01}(t') B_{\text{r}}(\theta, \phi)_{m+1} \\ &+ h_{11}(t') (t_{m+1} - t_m) \left(\frac{\partial B_{\text{r}}(\theta, \phi)}{\partial t} \right)_{m+1}\end{aligned}$$

with $t' = \frac{t - t_m}{t_{m+1} - t_m}$.

Interpolated inner-boundary magnetic field for each time step

Table 2. Comparison of time-evolving coronal simulations with $dt = 10$ and 2 minutes for two CRs of physical time.

Wall-clock times for $dt = 2 \text{ min}$ & $dt = 10 \text{ min}$ (h)	$\text{RD}_{\text{ave},\rho}^{82 \text{ hr}}$ & $\text{RD}_{\text{ave},\rho}^{735 \text{ hr}}$	$\text{RD}_{\text{ave}, \mathbf{v} }^{82 \text{ hr}}$ & $\text{RD}_{\text{ave}, \mathbf{v} }^{735 \text{ hr}}$	$\text{RD}_{\text{ave}, \mathbf{B} }^{82 \text{ hr}}$ & $\text{RD}_{\text{ave}, \mathbf{B} }^{735 \text{ hr}}$
39.06 & 17.54	0.09% & 0.08%	0.10% & 0.09%	0.60% & 0.42%

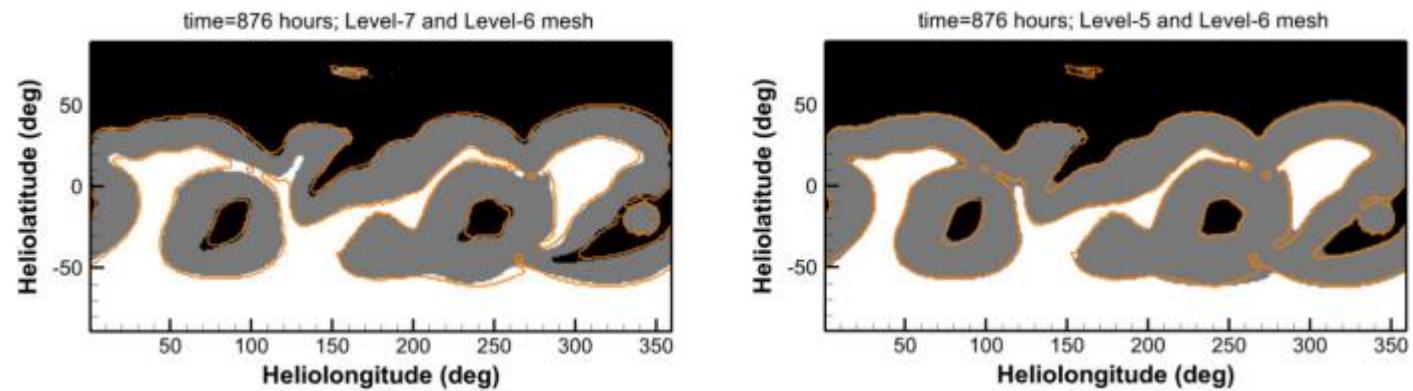
Haopeng Wang, Stefaan Poedts, Andrea Lani et al.: 2025b, Efficient MHD modelling of the time-evolving corona by COCONUT. A & A, 694(A234):1-14.

Time-evolving COCONUT

Table 1. Average relative differences between variables calculated on the Nth- and fifth-level meshes.

Parameters	LV _N =6	LV _N =7
RD _{ave, B} ^{LV_N} at 3 R _s	21.96%	35.08%
RD _{ave, B} ^{LV_N} at 21.5 R _s	23.78%	43.32%
RD _{ave,ρ} ^{LV_N} at 3 R _s	0.50%	-1.17%
RD _{ave,ρ} ^{LV_N} at 21.5 R _s	-1.90%	-4.37%
RD _{ave,V_r} ^{LV_N} at 3 R _s	3.70%	6.94%
RD _{ave,V_r} ^{LV_N} at 21.5 R _s	3.22%	6.83%

$$RD_{ave,\chi}^{LV_K} = \frac{1}{N^{LV_K}} \sum_{i=1}^{N^{LV_K}} \frac{\chi^{LV_K} - \chi^{LV_5}}{\chi^{LV_5}}.$$



Contours of open- and closed-field regions at the 876th hour of the time-evolving simulations, performed on the seventh- (left) and fifth level (right) subdivided geodesic meshes, respectively. The orange lines overlaid on these contours denote the edge of close-field regions derived from the corresponding result on the sixth-level mesh.

Haopeng Wang, Stefaan Poedts, Andrea Lani et al.: 2025c, Time-evolving coronal modelling of the solar maximum around the solar storms in May 2024 by COCONUT. A&A:1-11.

Time-evolving COCONUT

Accurately determining solar wind parameters is crucial for Sun–Earth space research, as they significantly affect spacecraft safety and ground-based power systems. Traditionally, solar wind conditions are derived using coupled coronal and heliospheric models, with the latter initialized by the former’s output at 0.1 AU, a computationally intensive and time-consuming process that limits real-time space weather forecasting. In this work, we propose a machine learning-based method for generating solar wind parameters at 0.1 AU. Specifically, we employ a U-Net neural network, trained using the output of the COolfluid COroNal UnsTructured (COCONUT) model as the learning target and Global Oscillation Network Group – Air Force Data Assimilative Photospheric Flux Transport (GONG–ADAPT) magnetograms as input. The model achieves correlation coefficients of 0.992 for radial velocity, 0.987 for number density, and 0.991 for radial magnetic field on the test set, with derived Alfvén speed and dynamic pressure reaching 0.996 and 0.769, respectively, demonstrating strong capability in reconstructing key solar wind parameters. Moreover, the model effectively captures the temporal evolution of these parameters within a single Carrington rotation. Once trained, the model generates full-surface solar wind predictions at 0.1 AU in 7.8 seconds on a CPU-only device and 0.065 seconds on a cluster with one GPU and 10 CPU cores, achieving 15 \times and 1800 \times speed-ups, respectively, over the COCONUT MHD simulation, which requires at least one hour to obtain a converged steady-state solution and over two minutes on 288 CPU cores per prediction.

Yucong Li, Haopeng Wang, Hyun-Jin Jeong et al.: Submitted to ApJS, Fast Reconstruction of Solar Wind MHD Parameters at 0.1 AU with Machine Learning.

Time-evolving COCONUT

- Decomposed energy strategy
- HLL solver with appropriately added dissipation term

$$\begin{cases} \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \\ \frac{\partial(\rho \mathbf{v})}{\partial t} + \nabla \cdot \left[\rho \mathbf{v} \mathbf{v} + \left(p + \frac{\mathbf{B}^2}{2} \right) \mathbf{I} - \mathbf{B} \mathbf{B} \right] = \mathbf{0}, \\ \frac{\partial E_1}{\partial t} + \nabla \cdot [(E_1 + p) \mathbf{v}] = - \mathbf{B} \cdot (\mathbf{v} \cdot \nabla \mathbf{B}) + \mathbf{v} \cdot (\mathbf{B} \cdot \nabla \mathbf{B}) \\ \frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{v} \mathbf{B} - \mathbf{B} \mathbf{v} + \psi \mathbf{I}) = \mathbf{0}, \\ \frac{\partial \psi}{\partial t} + V_{\text{ref}}^2 \nabla \cdot \mathbf{B} = 0. \\ E_1 = \frac{p}{\gamma - 1} + \frac{\rho \mathbf{v}^2}{2} \end{cases}$$

$$\mathbf{F}_n(\mathbf{U}_{i,L}, \mathbf{U}_{j,R}) = \frac{\mathbf{F}_n(\mathbf{U}_{i,L}) + \mathbf{F}_n(\mathbf{U}_{j,R})}{2} - \frac{1}{2} \mathbf{D}'_{\text{HLL}}(\mathbf{U}_{i,L}, \mathbf{U}_{j,R})$$

$$\begin{aligned} \mathbf{D}_{\text{HLL}}(\mathbf{U}_{i,L}, \mathbf{U}_{j,R}) &= \frac{(S_L + S_R)(\mathbf{F}_n(\mathbf{U}_{j,R}) - \mathbf{F}_n(\mathbf{U}_{i,L}))}{S_R - S_L} \\ &\quad - \frac{2S_R S_L}{S_R - S_L} (\mathbf{U}_{j,R} - \mathbf{U}_{i,L}). \end{aligned}$$

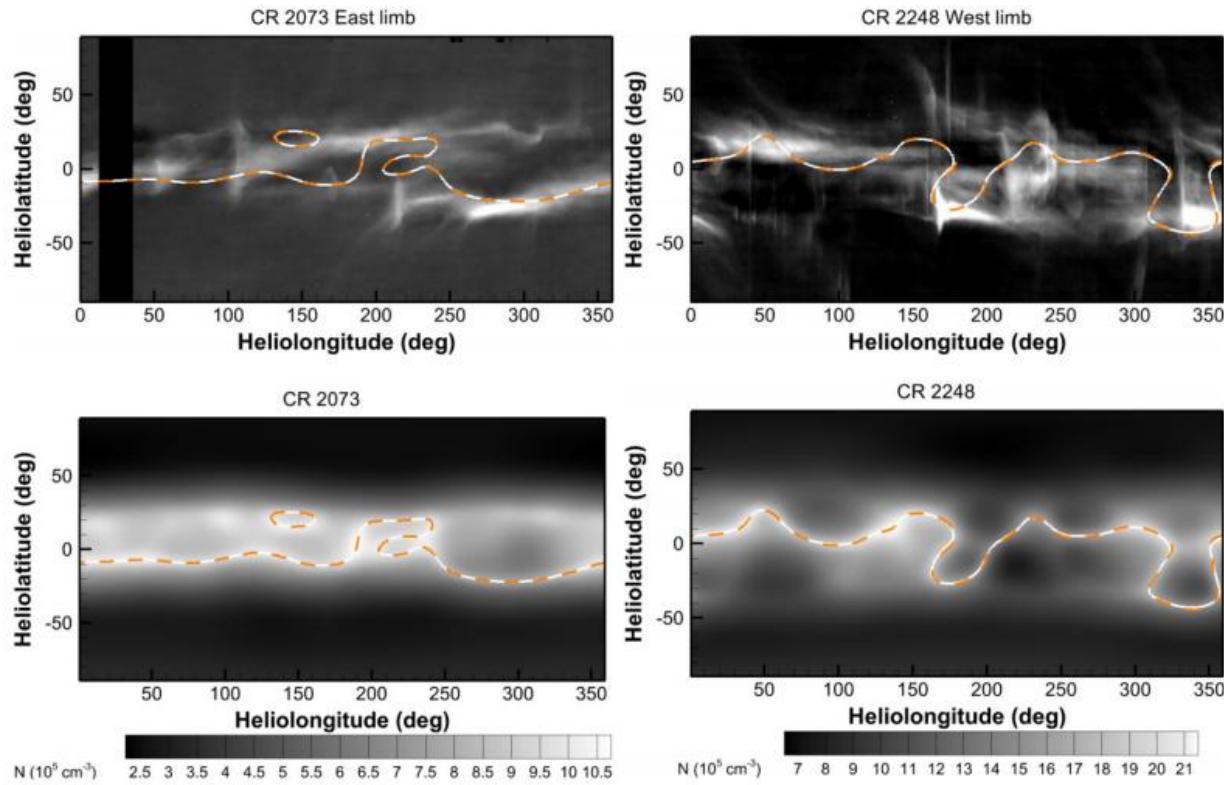
$$\mathbf{D}_{\text{LLF}}(\mathbf{U}_{i,L}, \mathbf{U}_{j,R}) = \max(|S_R|, |S_L|) (\mathbf{U}_{j,R} - \mathbf{U}_{i,L})$$

$$\begin{aligned} \mathbf{D}'_{\text{HLL}}(\mathbf{U}_{i,L}, \mathbf{U}_{j,R}) &= \mathbf{D}_{\text{HLL}}(\mathbf{U}_{i,L}, \mathbf{U}_{j,R}) \\ &\quad + \alpha \mathcal{R} \mathbf{D}_{\text{LLF}}(\mathbf{U}_{i,L}, \mathbf{U}_{j,R}) \end{aligned}$$

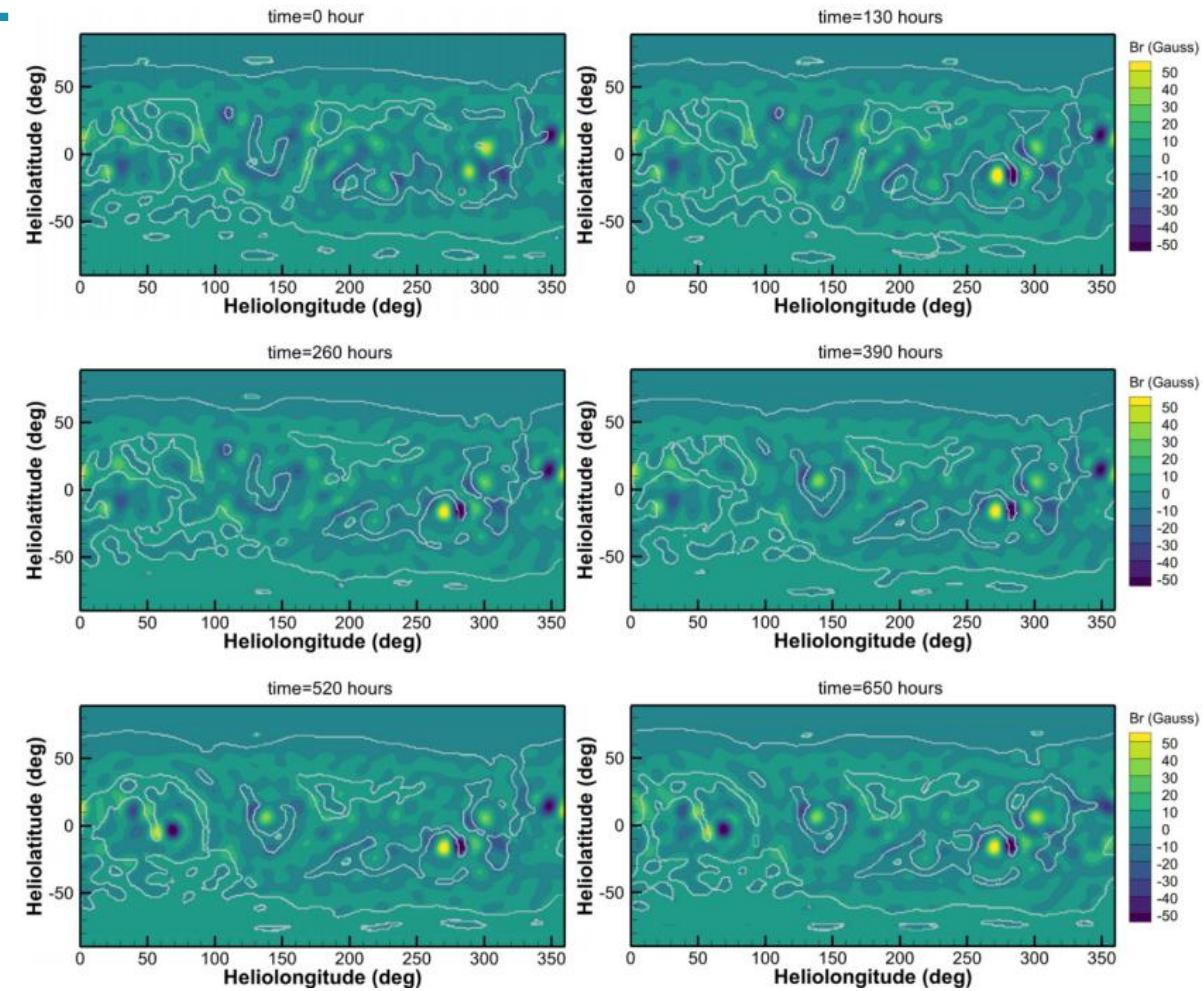
$$\mathcal{R} = \begin{pmatrix} \mathbf{0}_{7 \times 7} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Haopeng Wang, Stefaan Poedts, Andrea Lani et al., 2025, COCONUT: A time-evolving coronal model with an energy decomposition strategy. 1-12. [arXiv:2508.20423]

Time-evolving COCONUT



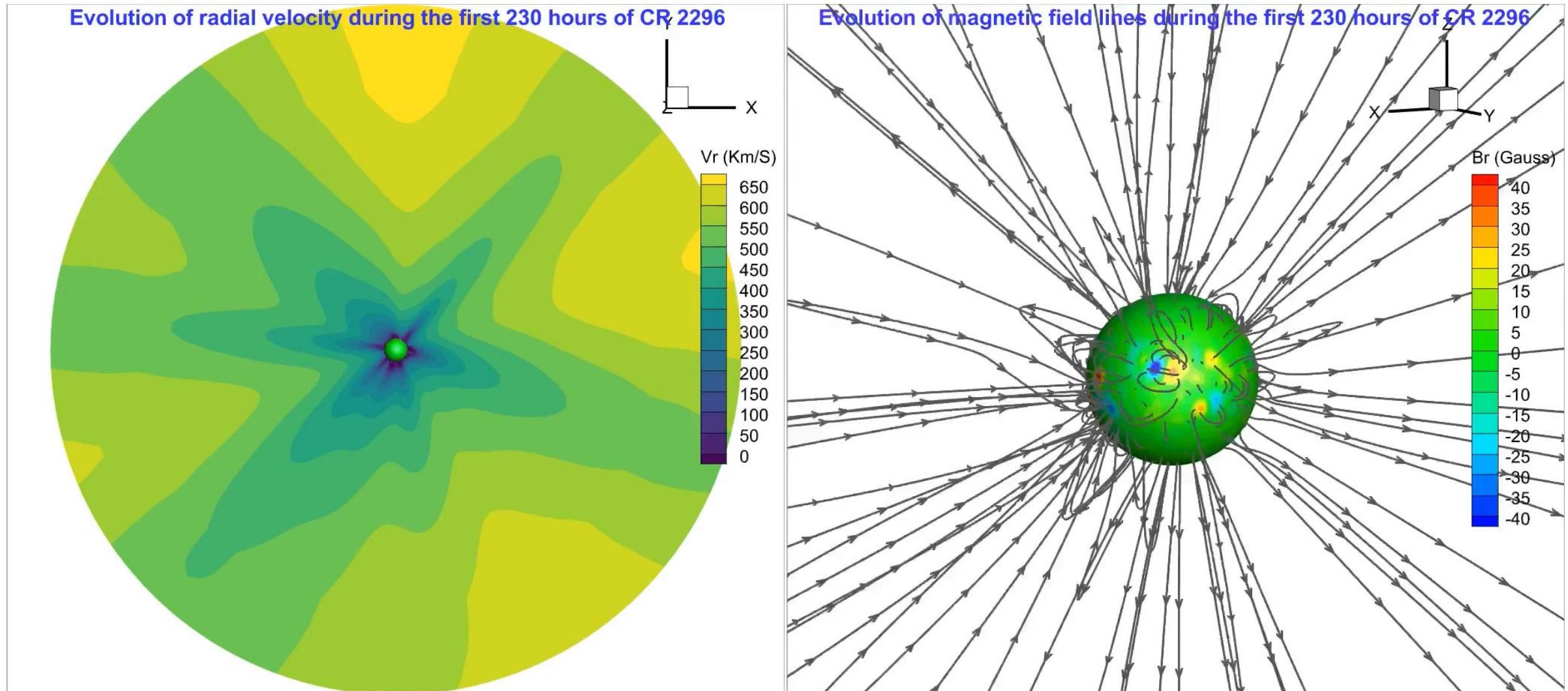
Observed Pb at $3 R_s$ and plasma density at $3 R_s$ simulated by COCONUT with decomposed energy equation.



Time-evolving inner-boundary magnetic field and open-field regions for CR 2296 simulated by COCONUT with decomposed energy equation.

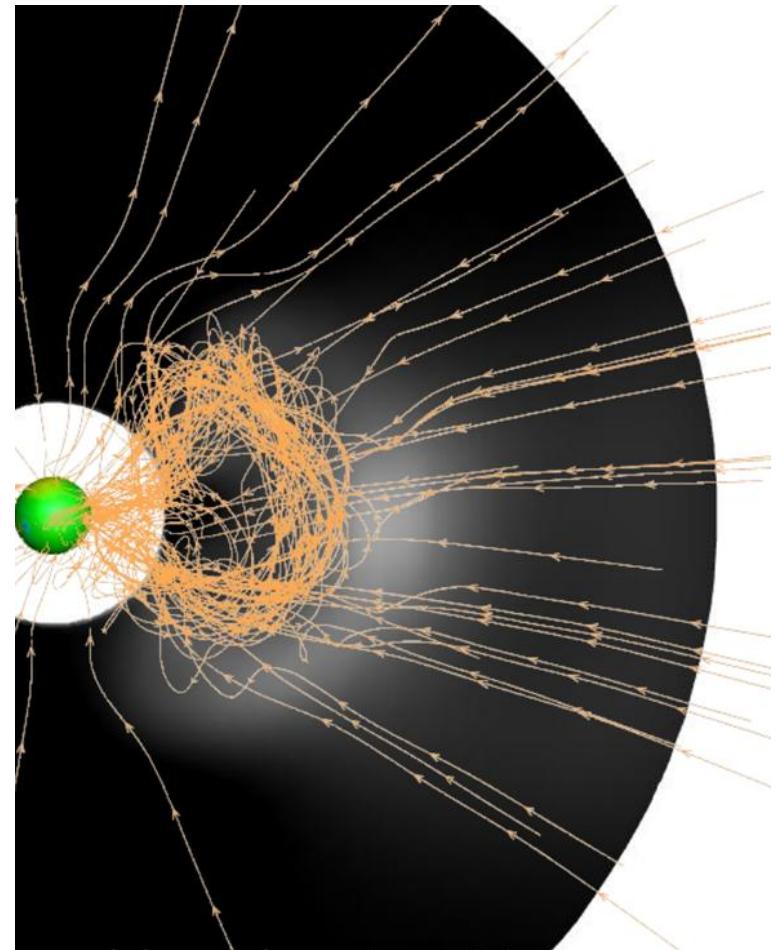
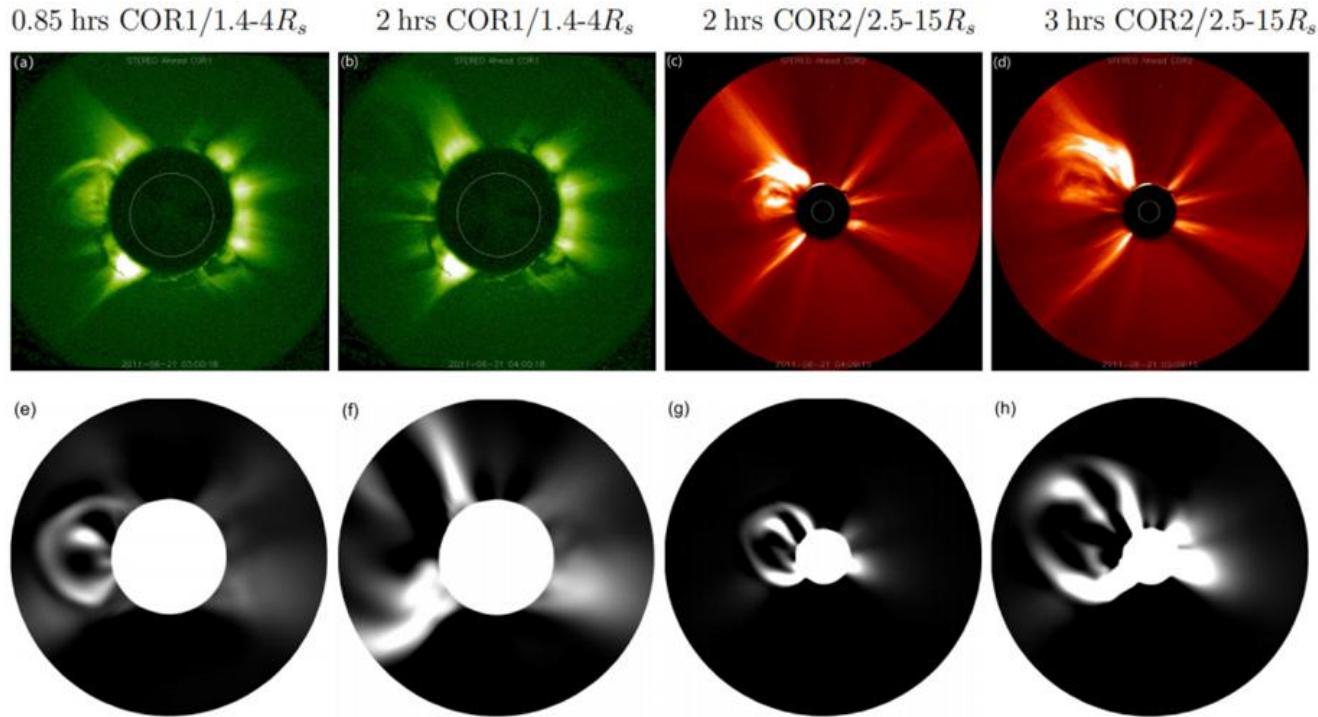
Wang et al. 2025.

Time-evolving COCONUT (1.5M cells, 360 CPUs, achieving $\sim 24 \times$ speedup)



Outline

- Fully implicit, quasi-steady-state MHD coronal model COCONUT
- **Faster-than-real-time MHD modeling of the coronal evolutions by COCONUT and SIP-IFVM**



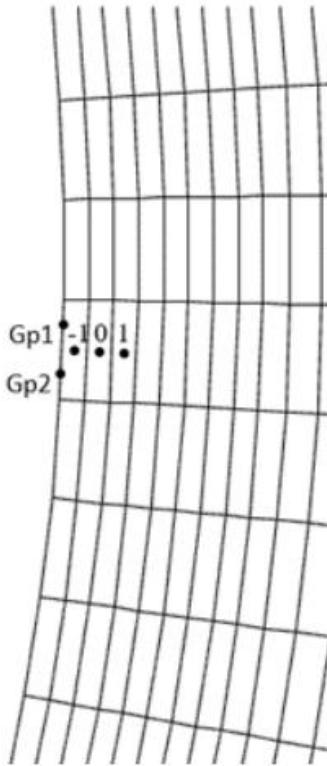
CME simulation in global background corona: **SIP-IFVM**

- Highly efficient: **Less than 1 hour** for background coronal and 6 hours of CME simulations (192 CPU cores, $\sim 1M$ cells, from $1 R_S$ to 0.1 AU).
- Simulation results calculated at large time-step lengths can be consistent with those calculated at small time-step lengths.
- Results are basically **in agreement with the observations** from SDO, SOHO and STEREO-A/B.

Haopeng Wang, Jinghan Guo, Liping Yang et al.: 2025d, SIP-IFVM: Efficient time-accurate magnetohydrodynamic model of the corona and coronal mass ejections. A&A 693(A257):1-17.

Haopeng Wang, Jinghan Guo, Stefaan Poedts et al.: Accepted by ApJS, SIP-IFVM: An observation-based magnetohydrodynamic model of coronal mass ejection. 1-25, [arXiv:2506.19711].

CME simulation in global background corona: SIP-IFVM



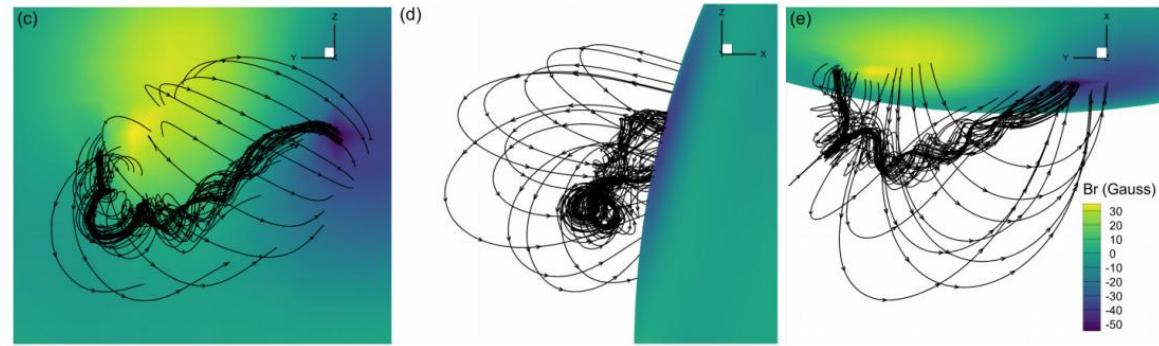
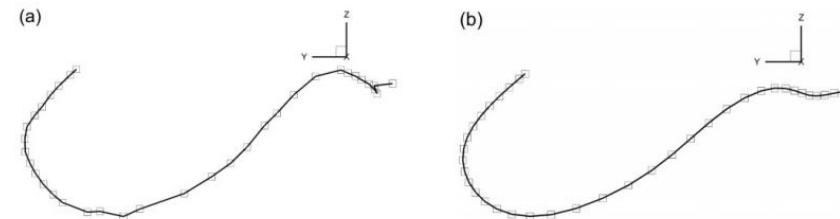
Initial magnetic field
for CME propagation
simulation

Regularised Biot-Savart Laws
(RBSL) flux rope magnetic field

$$\mathbf{B}_{FR}(\mathbf{x}) = \nabla \times \mathbf{A}_I(\mathbf{x}) + \nabla \times \mathbf{A}_F(\mathbf{x})$$
$$\left\{ \begin{array}{l} \mathbf{A}_I(\mathbf{x}) = \frac{\mu_0 I}{4\pi} \oint_{C \cup C^*} K_I(r) \mathbf{R}'(l) \frac{dl}{a(l)} \\ \mathbf{A}_F(\mathbf{x}) = \frac{F}{4\pi} \oint_{C \cup C^*} K_F(r) \mathbf{R}'(l) \times \mathbf{r} \frac{dl}{a(l)^2} \end{array} \right.$$

Wang et al. 2025d.

2D illustration of the inner
boundary cells which lay on the
left-most layer of this picture.



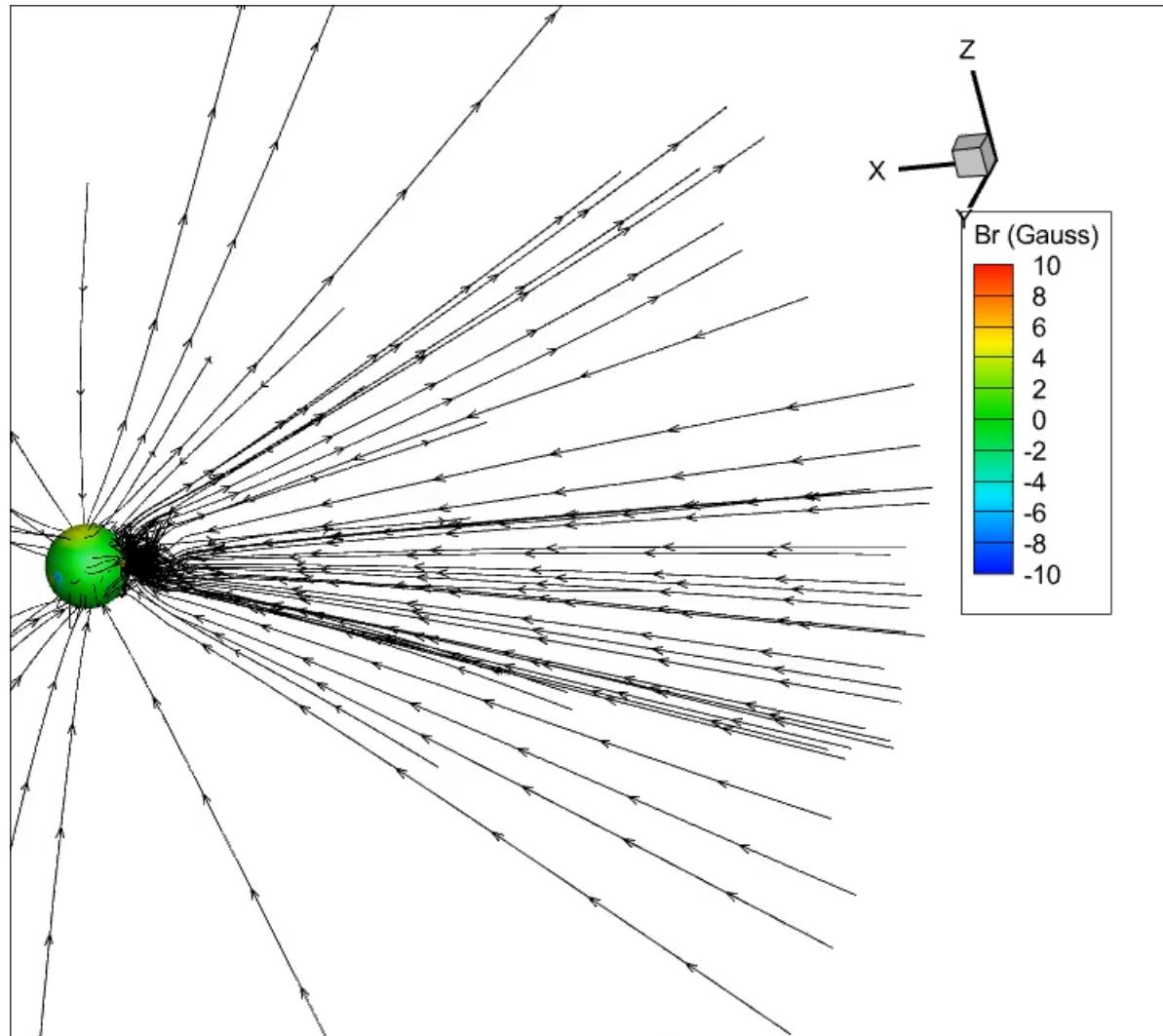
The RBSL flux rope axis path derived from the original observed (a) and the smoothed (b) sample points. (c, d, e) shows selected magnetic field lines of the flux rope and the background corona, viewed from three mutually perpendicular perspectives. (Wang et al. Accepted by ApJS)

CME simulation in global background corona: COCONUT

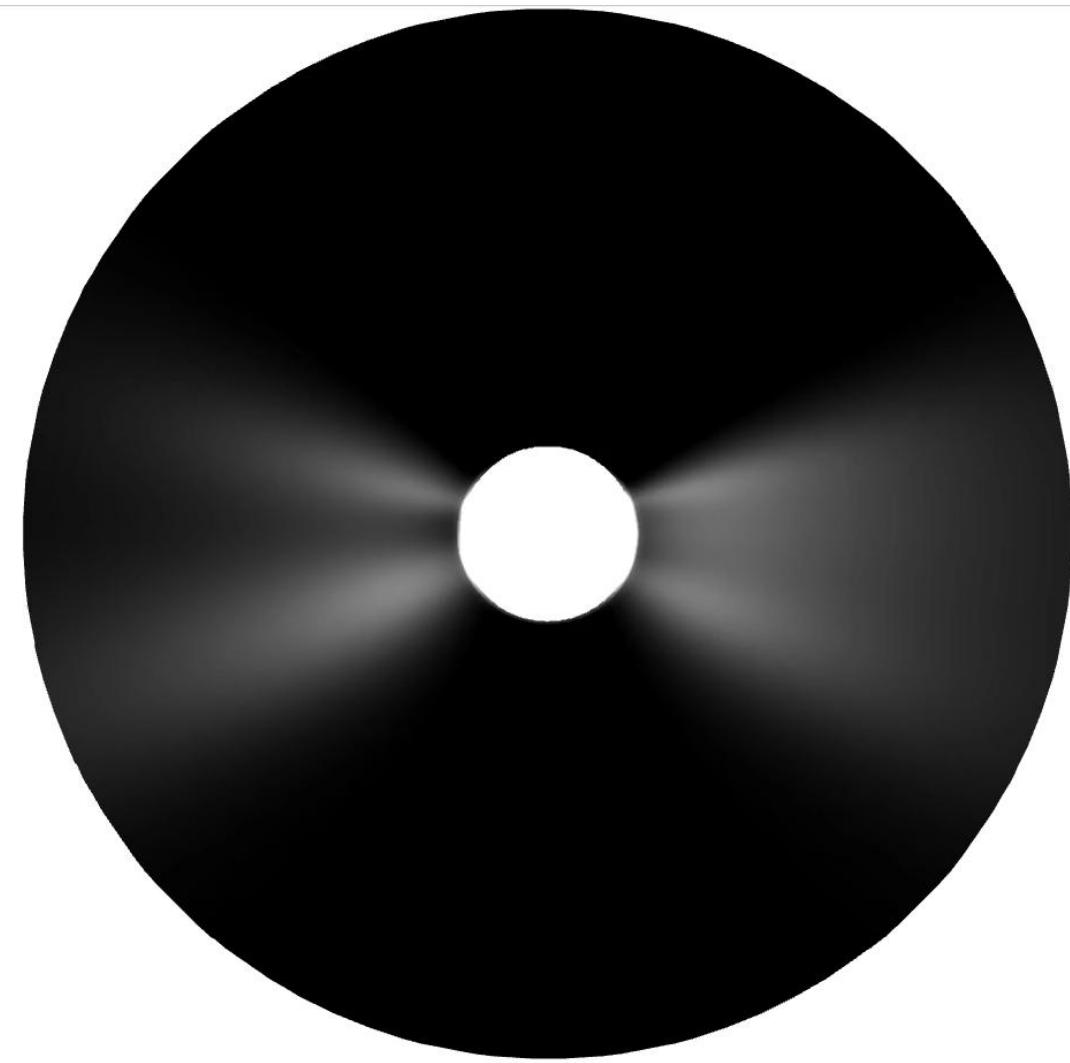
Employ the time-evolving COCONUT to simulate the CME events (in prep).

- The inner-boundary magnetic field also evolves during the CME propagation
- Evaluate the impact of coronal background evolution on CME propagation
- Conduct more realistic CME simulations

CME propagation calculated by time-evolving COCONUT



Evolution of simulated magnetic field lines in the time-evolving background corona.



Evolution of simulated white-light pB image in the time-evolving background corona.

Conclusion and discussion

1. The implicit time-evolving coronal models **COCONUT** and **SIP-IFVM** show great promise for **practical space weather forecasting** due to their efficiency and stability. (Providing inner-boundary conditions for inner-heliosphere models, improve efficiency of CME simulations with required accuracy, ...)
2. The extended magnetic field decomposition strategy and energy decomposition strategies improve the numerical stability of the MHD coronal and CME models in addressing **time-evolving low- β issues**.
3. We are **extending** the coronal model to 1 AU or **coupling** the coronal model with an inner heliosphere model to conduct some **faster-than-real-time** and more **realistic** CME simulations from the solar surface to 1 AU.
4. We plan to integrate active region models into global coronal model COCONUT.

Planned research works based on COCONUT for the upcoming months

COCONUT+EUFORIA: Magnetohydrodynamic Modeling of Time-Evolving Sun-to-Earth Solar Wind Background

COCONUT: A time-evolving coronal model with an energy decomposition strategy (For ApJS)

1. Two quasi-steady-state cases, one time-evolving solar maximum case and one MHD vortex case are considered.
2. The solar minimum case confirms the consistency of the decomposed method with the full energy method, while the increasing-phase case, which shows relatively larger differences, indicates the decomposed equation really make difference. Then we mention the benchmarking for further validation.
3. An Orszag–Tang case and a rotor case will be used as a benchmark listed in Appendix to validate both the decomposed energy equation and the hybridized HLL–Friedrichs solver. (With help from Rayan)
4. The time-evolving solar maximum case demonstrates the improved numerical stability of COCONUT in handling strong and complex magnetic fields under low- β conditions.

(1,2, and 4 is already finished in the A&A work, 3 required to do next week.)

Planned research works based on COCONUT for the upcoming months

COCONUT+EUHFORIA: Magnetohydrodynamic Modeling of Time-Evolving Sun-to-Earth Solar Wind Background

Numerical modeling of magnetic flux evolution by coronal model COCONUT (A&A revision)

1. Modify the previous positivity-preserving measures on density to correct higher density results at 0.1 AU. (Time-evolving 2019 eclipse case and 2024 May event case without filter.)
2. 2024 May event case, $l_{\max} = 25$ with and without filter, evaluate impact of neglected small scale magnetic structure, usually adopted in global coronal simulations, on the simulated magnetic flux (**Underestimated magnetic flux in coronal simulation**).
3. Trace simulated magnetic field from 0.1 AU to solar surface, calculate total magnetic flux, total positive and total negative magnetic flux at inner boundary and at original magnetograms, at 1.1 R_s (maybe not necessary), at 2.5 R_s and at 0.1 AU. (Calculate them with a cadence of 6 hours.)

We need to incorporate a scientific issue as the referee said, maybe the magnetic flux evolution can be one required issue.

Planned research works based on COCONUT for the upcoming months

COCONUT+EUHFORIA: Magnetohydrodynamic Modeling of Time-Evolving Sun-to-Earth Solar Wind Background

Coronal evolution modeling driven by AI generated synchronized magnetograms

1. Time evolving coronal simulation driven by AI generated magnetograms from H.-J. Jeong (with a cadence of 5 minutes a magnetogram).
2. CR 2283 and 2284 (Around May event 2024, lmax=25 without filter). From 2024-04-09 05:32 to 2024-06-02 16:44.

Planned research works based on COCONUT for the upcoming months

COCONUT+EUHFORIA: Magnetohydrodynamic Modeling of Time-Evolving Sun-to-Earth Solar Wind Background

CME propagation modeling in a time-evolving coronal channel

1. CME simulation triggered by RBSL flux rope, but in a time-evolving background corona.
2. The same case as Jinghan Guo did, or an observation-based CME case (If we can get detail observation information of a flux rope).

Looking forward to more good ideas and
comments

Thanks

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