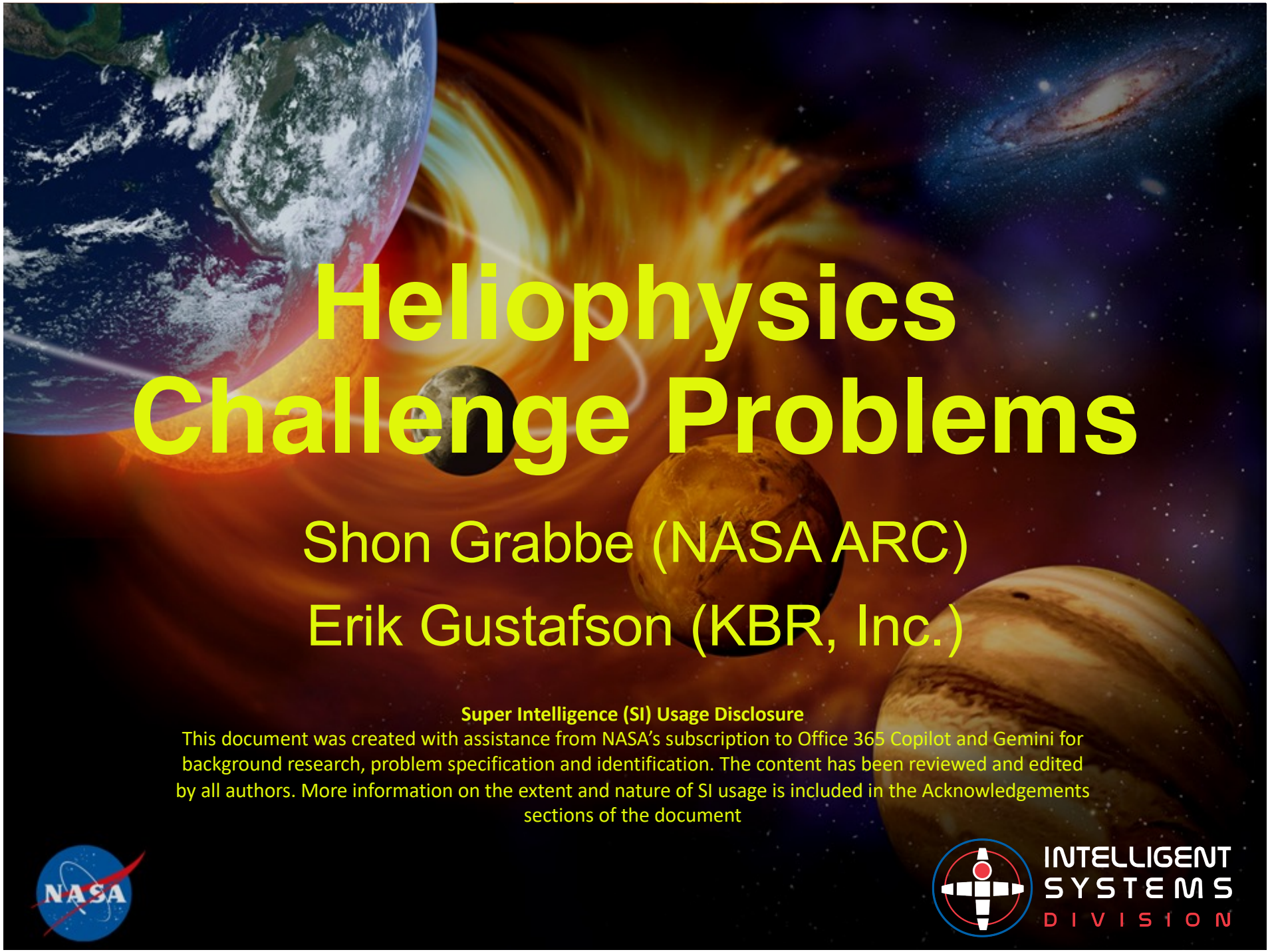


Heliophysics Challenge Problems

Shon Grabbe (NASA ARC)

Erik Gustafson (KBR, Inc.)

Super Intelligence (SI) Usage Disclosure

This document was created with assistance from NASA's subscription to Office 365 Copilot and Gemini for background research, problem specification and identification. The content has been reviewed and edited by all authors. More information on the extent and nature of SI usage is included in the Acknowledgements sections of the document



1. Photosphere and Corona Modelling

2. Solar Energetic Particle Forecasting



Photosphere and Corona Modelling

Heliophysics : Photosphere and Corona Modelling

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Application Details

- Identify outgoing characteristic of the solar wind and particles from ab initio eruptive dynamics based on data driven photosphere-to-corona simulations.
- Behavior of the sun for forecasting SEPs
- Protect astronauts from danger solar radiation

Problem Details

- Problem specification: Solve thin surface magnetohydrodynamics (i.e., at the photosphere-to-corona boundary)
- Solving partial differential equations
- Input: Data driven observations, initial solar atmosphere
- Output: plasma wave mode speeds

Current Approaches

- State-of-the-art:
  - PDE's with data driven / non reflecting boundary conditions
  - 512^2 x700 grid
- Can accurately describe the evolution of eruptive events.
- Very slow taking weeks or up to a month.

Impact of New/Better Solution

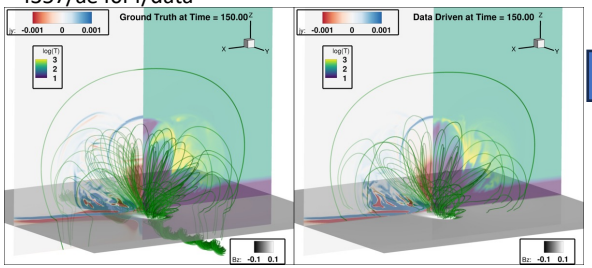
- Better solution would perform simulations in hours rather than weeks
- Enable forecasting for identification of speed and direction of solar wind
- What more will that enable in the application
- Protect health of personnel on moon-to-mars missions
- Identify deleterious solar flares well in advance to minimize impacts.

Application Goal

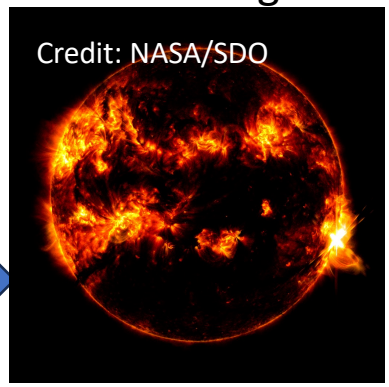
Goals:

1. Predict the Alfvén, slow, fast, and magnetic field speeds for the solar flare or coronal mass ejections
2. Highly accurate feed in information for predictions of Solar Energetic particles and solar wind to protect astronauts.
3. Reduce computational runtime by an order of magnitude or more

Image: Lucas A. Tarr *et al* 2026 Video, Figure 1. from: Simulating the Photospheric to Coronal Plasma Using Magnetohydrodynamic Characteristics. III. Validation Including Gravity, Flux Emergence, and an Eruption, American Astronomical Society, doi:10.3847/1538-4357/ae40f4/data

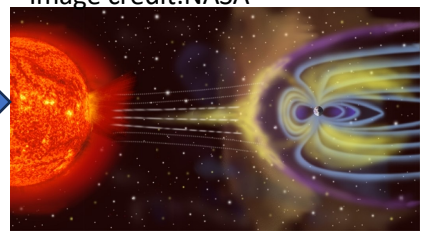


Magnetohydrodynamics simulation



Flare / coronal mass ejection

Image credit:NASA



Solar wind / Space weather

Computational Problem

Table of Problems

1. Toy Problems
    1. Linear Alfven Wave [Key25]
    2. Sod Shock Tube [Sod78]
    3. Brio-Wu Shock tube [Bri88]
2. Stepping-Stone Problems
    1. Initially unbalance spheromak that expands into a field-free homogeneous plasma [Tar23]
    2. Hot sphere in angle magnetic field [Key25]
    3. Advecting Spheromak (CME + Magnetic field ejection) [Key25]
3. Challenge Problem
    1. Data driven simulation of a coronal mass ejection modified from [Che2026]

Current Approaches

Photospheric to coronal plasma modeling approaches include [Tar23]:

Static Methods: Construct an estimate of the coronal state based on boundary observations at a single instance in time

Evolving Methods: Use a time series of observations at a boundary to iteratively modify the volume state

Fully Dynamic Methods: Numerically integrate the full MHD equations such that the state at one time is causally related to the state at the next time through the combination of Maxwell's equations and Newton's laws from which the MHD equations are derived

Data-driven simulation: Dynamically evolving simulation that directly incorporates estimates for the primitive variables (the elements of the MHD sate vector U) into the simulation boundary

State of the Art Methods

Data-driven simulation methods [Tar23]:

- Most hold some subset of the primitive variables constant in time while directly setting others (Bourdin et al. 2013; Galsgaard et al. 2015; Hayashi et al. 2018; Jiang & Toriumi 2020; Kaneko et al. 2021; Guo et al. 2021; Inoue et al. 2023)
- Typically, some subset of the velocity and magnetic field vectors are time-varying while the remaining velocity and magnetic field variables, the density, and the pressure are held constant
- In general, these approaches cannot and do not evolve the boundary in a way that is consistent with the MHD equations. The reason is that the evolution of the primitive variables are not independent from each other but instead are coupled together by the MHD equations (see for example, [Tor20] for shortcoming of methods)
- [Tar23] was the first to derive data-driven boundary conditions that optimally matches the state of the plasma inferred from a time series of observations of a boundary (e.g., the solar photosphere)

Current Avaliable Data

- Helioseismic and Magnetic Imager (HMI) instrument on NASA's Solar Dynamics Observatory (SDO)
  - Optimized for magnetic field and Doppler velocity measurements at moderate spatial resolution (~1 arcsecond) and temporal cadence (typically 12 minutes and 45 seconds for vector and line-of-sight magnetograms, respectively) [hmi.stanford.edu]
- SDO's predecessors include
  - SOHO/MDI and ground-based NSO/GONG network are similar but have lower temporal- and spatial resolution

Mathematical Formulation

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Model Details

1. Perform magnetohydrodynamics simulations of the stellar surface to describe eruptive dynamics

2. Eruptive dynamics that reach the boundary use novel boundary conditions to allow information to “leave the system”

3. Information that leave the PDE is coupled to out going physics informed models to predict location and type of energetic solar particles.

Mathematical Formulation

Equations of importance for ideal Magneto hydrodynamics are

$$\frac{\partial \rho}{\partial t} + \nabla(\rho\,\vec{v}) = 0$$

$$\frac{\partial \vec{v}}{\partial t} + \vec{v}\ \nabla\vec{v} + \frac{1}{\rho}\nabla P - \frac{1}{\rho}\,\vec{j}\times\vec{B} - \vec{g} = 0$$

$$\frac{\partial \epsilon}{\partial t} + \vec{v}\ \nabla\epsilon + \frac{P}{\rho}\nabla\ \vec{v} = 0$$

$$\frac{\partial \vec{B}}{\partial t} + (\vec{v}\ \nabla)\vec{B} - \left(\vec{B}\ \nabla\right)\vec{v} + \vec{B}(\nabla\ \vec{v}\,) = 0$$

Where ρ is the density of the plasma, $\vec{v}$ is the velocity vector, P is the pressure, ϵ is the internal energy, $\vec{j} = \nabla\times\vec{B}/\mu_0$ is the electric current density, μ_0 is the permeability of free space, and t is time. This system has a constrain equation relating the following quantities:

$$P = (\gamma - 1)\rho\epsilon$$

Use data driven / nonreflective boundary conditions

Data Driven boundary conditions: A Primer

- Data driven boundary conditions are a type of open boundary condition
  - Periodic Boundary conditions define continuity by having things leave on end of a system appear at the other end
  - Open Boundary conditions put constraints on what the derivative or value of the field is at the boundary

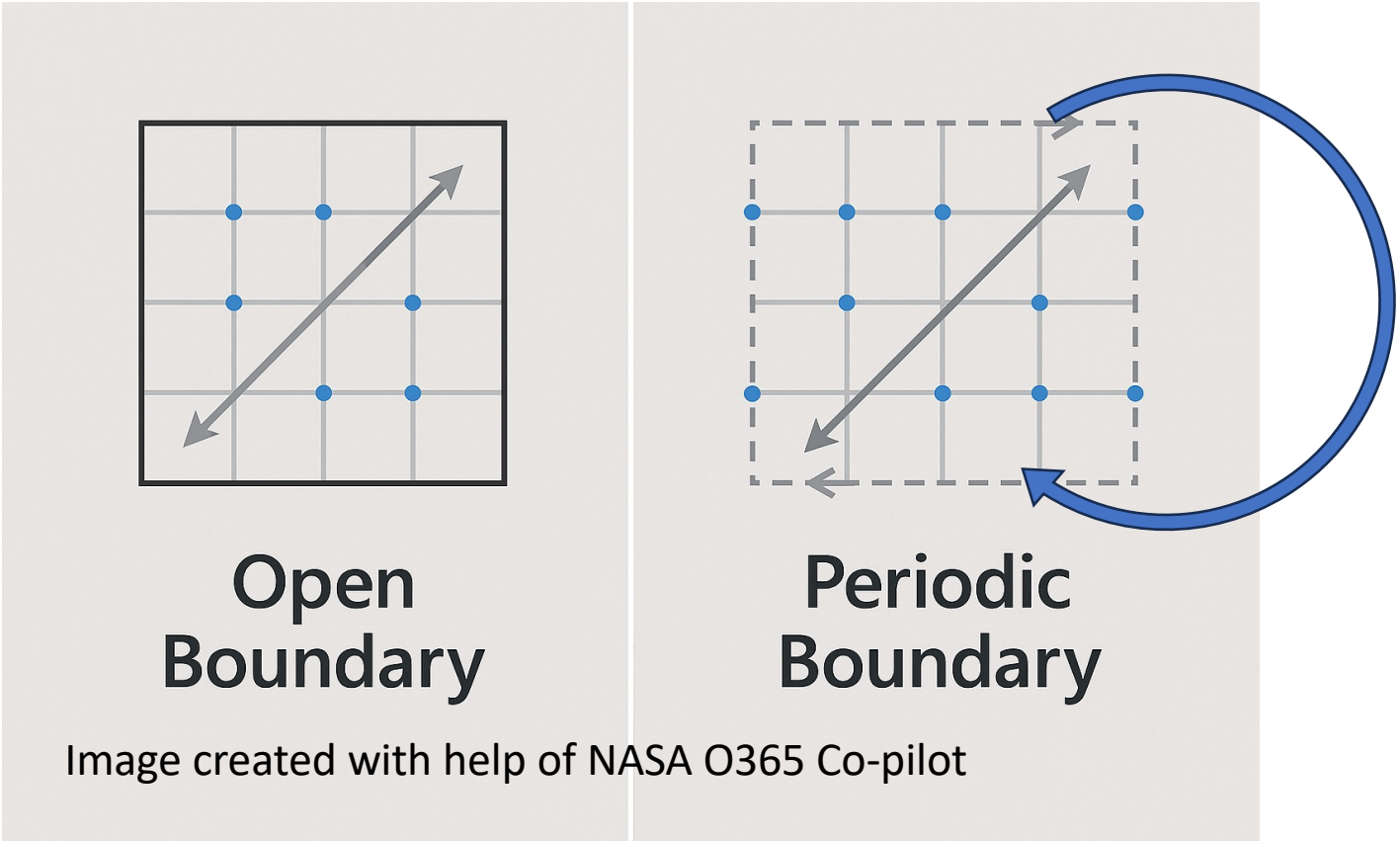


Image created with help of NASA O365 Co-pilot

Data Driven boundary conditions: A Primer

- Typical OBC fall in the class of Von Neuman or Dirichlet boundary conditions
  - Von Neuman Boundary conditions: impose constraint that $\frac{df}{dx}|_{x=x_{boundary}} = C$
  - Dirichlet Boundary conditions: impose the constraint that $f(x_{boundary}) = C$
  - Data driven boundary conditions impose dynamical constraints that either $\frac{df(x,t)}{dx}|_{x=x_{boundary}} = C(t)$ or $f(x_{boundary}, t) = D(t)$

- Data driven boundary conditions while simple in certain circumstance have problems in magnetohydrodynamics
- Data-driven informed modifications to the boundary conditions can allow for permeabl transmission of quantities ”back and forth”
- Changes are fixed by constraints for MHD equations.

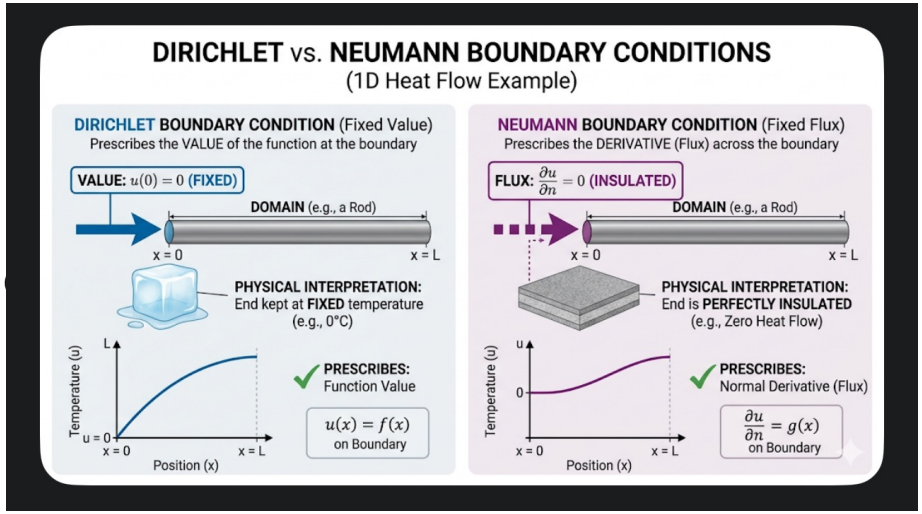


Image generated by Gemini

Impact of a New/Better Solution

- NASA Impacts
  - Reduction in compute time enables efficient usage of HPC resources
  - Safety of astronauts by better forecasting for solar energetic particles
- External Impacts
  - Effective simulations of Magnetohydrodynamics would have impacts for multiple other agencies including:
    - Department of Energy
    - Airforce, Navy, and Army Research Labs
    - Department of War
- Financial impact
  - Order of magnitude reduction in runtime could yield an order of magnitude reduction in financial burden from HPC resources.
  - Cost of astronaut training for replacements

What specifies and instance

What do we need for a problem instance?

- Volume for simulation
- Gridding resolution
- Data driven information for boundary conditions
- Magnetic field initializations $\vec{B}$
- Plasma density ρ
- Energy density ε
- Impurity input (Spheromak; plasma getting ejected)

What specifies and instance

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1 dimensional Toy Problems

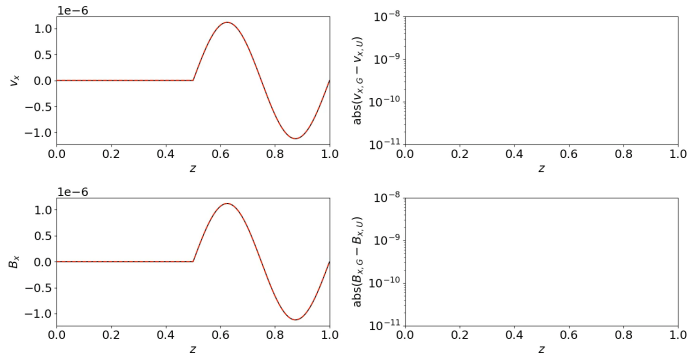


Image used under cc-by-4.0 created by Kee et al. W/o modification.

Increasing Computational Resource

3d examples stepping stones

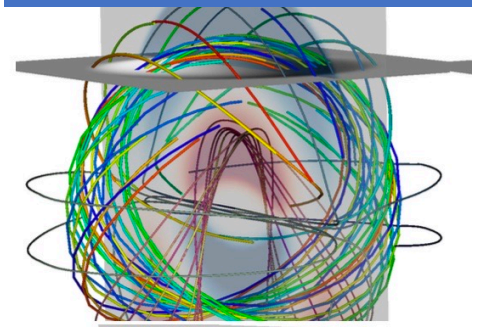
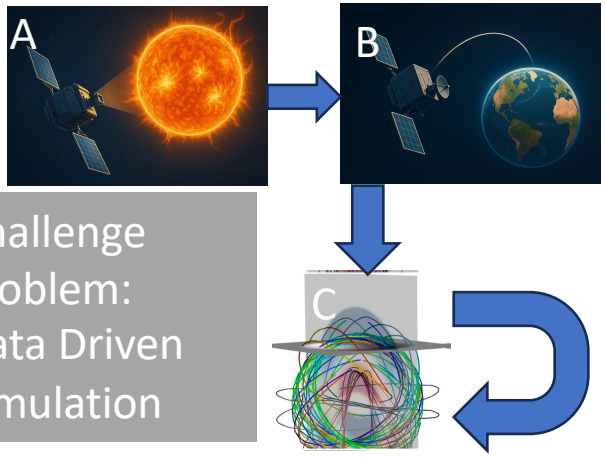


Image used under cc-by-4.0 created by Tarr et al. With minor Modifications



Challenge Problem: Data Driven Simulation

A and B were created with O365 Copilot. C: Image used under cc-by-4.0 created by Tarr et al. With minor Modifications

Increasing Time constraints with ”real world” data

Toy Problem (1/3): Linear Alfven Wave

Inputs

- $\rho = \epsilon = 1.0$
- $B_z = 1.0, B_x = B_y = 10^{-6}$
- $N_x \times N_y \times N_z$: $8 \times 8 \times 2048$
- $L_z = (0,2)$
- Linear Alfvén wave
- $f(z) = \begin{cases} 10^{-6}\sin(4\pi z) & 0.5 \le z \le 1 \\ 0 & otherwise \end{cases}$

Outputs

Full simulation quantities compared

Inputs

- $\rho = \epsilon = 1.0$
- $B_z = 1.0, B_x = B_y = 10^{-6}$
- $N_x \times N_y \times N_z$: $8 \times 8 \times 2048$
- $L_z = (0,2)$
- Linear Alfvén wave
- $f(z) = \begin{cases} 10^{-6}\sin(4\pi z) & 0.5 \le z \le 1 \\ 0 & otherwise \end{cases}$

Outputs

Full simulation quantities compared

Supplementary Video for Alfvén wave in Fig. 8 of Ref [Kee25]. Image used under cc-by-4.0 created by Kee et al.

Goals

Solve order of magnitude faster than standard PDE implementations.
Equivalent accuracy to [Kee25].

Toy Problem (2/3): Sod Shock Tube

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Inputs

Left state:

- $\rho = 1.0, \epsilon = 1/(\rho(\gamma - 1))$

Right state:

- $\rho = 1/8\ \epsilon = 0.1/(\rho(\gamma - 1))$

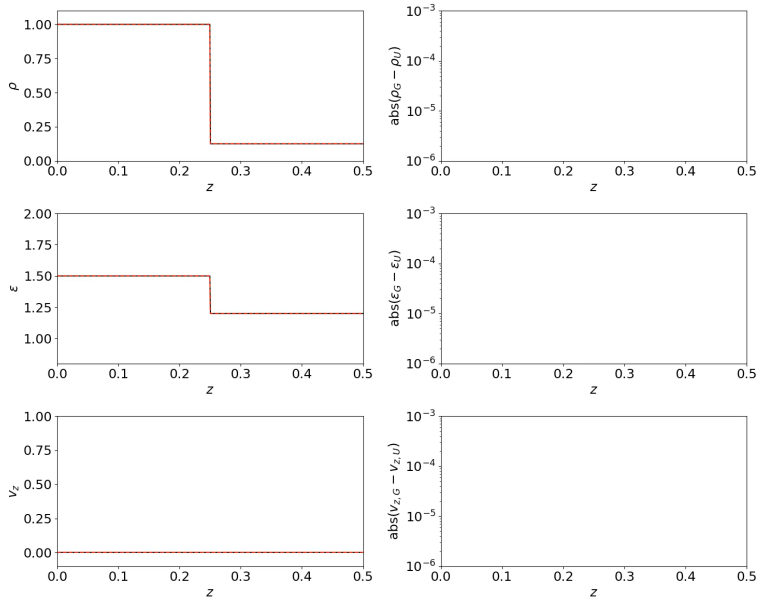
Discontinuities

$$z = 0.5$$

NRBCs: at $z = 0$

Volumes:

- $N_x \times N_y \times N_z = 8 \times 8 \times 2048$
- $l_x \times l_y \times l_z = \frac{1}{128} \times \frac{1}{128} \times 2$



Supplementary Video from [Kee25] showing the Sod Shock-tube evolution using NRBC. Image used under cc-by-4.0 created by Kee et al..

Outputs

Full simulation quantities compared

Goals

Order of magnitude faster than existing

Equivalent accuracy to current methods

Toy Problem (3/3): Brio-Wu Shock Tube

INTELLIGENT SYSTEMS DIVISION

Inputs

Left state:

- $\rho = 1.0, \epsilon = 1/\rho$
- $B_y = 1.0,\ B_z = 0.75$

Right state:

- $\rho = 1/8\ \epsilon = 0.1/(\rho(\gamma - 1))$
- $B_y = -1.0,\ B_z = 0.75$

Discontinutities

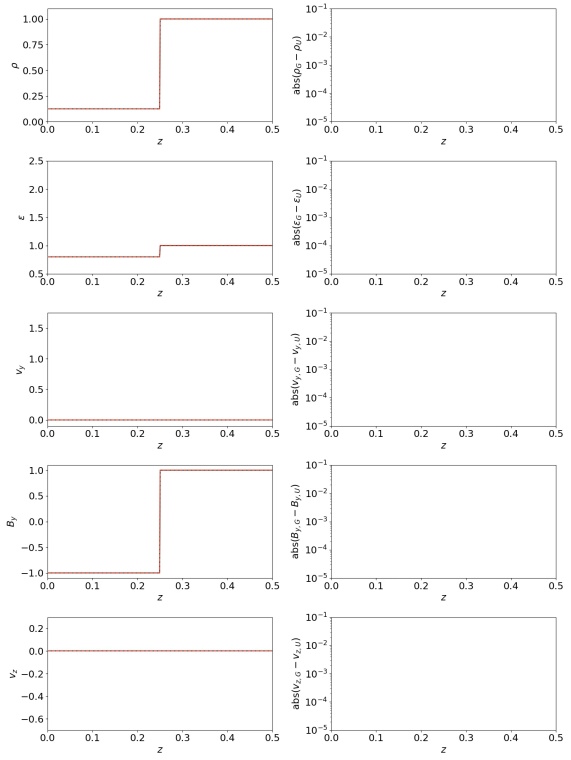
$$z = 0.5$$

NRBCs: at $z = 0$

Volumes:

- $N_x \times N_y \times N_z = 8 \times 8 \times 2048$
- $l_x \times l_y \times l_z = \frac{1}{128} \times \frac{1}{128} \times 2$

Supplementary video from [Kee25]. Showing the time evolution of the Brio-Wu shock tube simulation including the initial conditions. Image used under cc-by-4.0 created by Kee et al.



Outputs

Time dependent quantities for all simulation variables

Goals

Order of magnitude faster than existing
Equivalent accuracy to current methods

Stepping Stone Problem (1/3): Unbalanced Spheromak

INTELLIGENT SYSTEMS DIVISION

Inputs

- $N_x = N_y = 256, N_z = 192\ cells$
- $\mathrm{L}_x = \mathrm{L}_y = 8.0, \mathrm{L}_z = 6.0$
- $-4.0 \leq x, y \leq 4.0, -2.0 \leq z \leq 4.0$
- Initialized with ground state axisymmetric spheromak

$$\psi_1^0 = \mathrm{B_o} \mathrm{j}_1(\kappa \mathrm{r}) \mathrm{P}_1^0(\cos\theta)$$

- Field outside the r=1 flux surface set to 0 (forces spheromak to expand initially)
- Embedded spheromak in an initially non-uniform gas pressure to speed expansion
- Normalizations:
- $\mathrm{L_N} = 1m, \rho_\mathrm{N} = 1\ kg\ \mathrm{m}^{-3}$

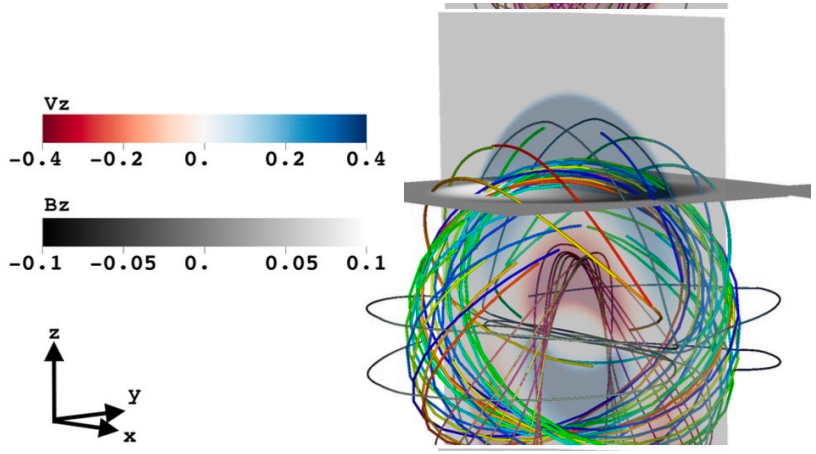
$$\mathrm{B_N} = \sqrt{4\pi \times 10^{-7}\mathrm{T}}$$

Outputs

Time dependent quantities for all simulation variables

Goals

Order of magnitude reduction in runtime. Equivalent accuracy to existing methods compared to ground truth



Intermediate time instance of an unbalanced spheromak in an angled magnetic field (shown by black lines). Modified from figure in [Tar23]. Image used under cc-by-4.0 created by Tarr et al. With minor Modifications

Stepping Stone Problem (2/3): Hot Spheromak in angled magnetic Field

INTELLIGENT SYSTEMS DIVISION

Inputs

- $\vec{D} = \vec{0},\ \rho = 1, \epsilon = 1$
- $v_x = v_y = v_z = 0$
- $\vec{B} = \vec{1}$
- $N_x \times N_y \times N_z = 128^3$
- $l_x \times l_y \times l_z = 1^3$

Sphere Location

- $z = 0.3$
- Radius = $0.1\sqrt{2}$

NRBCs

$L_{\sigma,\mathcal{J}} = 0$

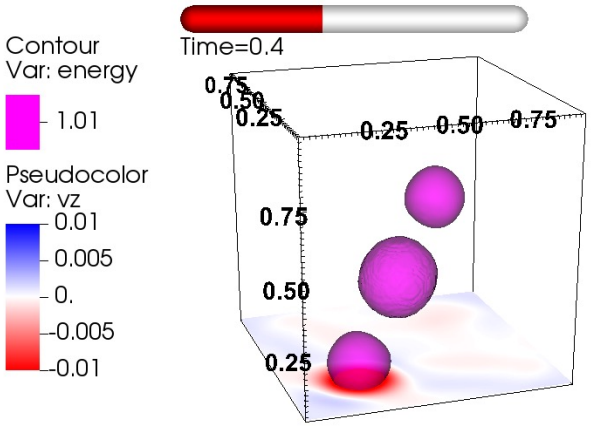
- Normalizations
- $L_N = 1\ m, \rho_N = 1\frac{kg}{m^3}$
- $|B| = \sqrt{4\pi 10^{-7}}$ T

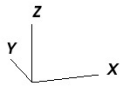
Outputs

Time dependent quantities for all simulation variables

Goals

Order of magnitude reduction in runtime
Equivalent accuracy to existing methods
Compared to ground truth





Intermediate time instance of the hot spheromak in an angled magnetic field (shown by black lines) Modified from figure in [Key25]. Image used under cc-by-4.0 created by Kee et al..

Stepping Stone Problem (2/3): Advecting Spheromak

INTELLIGENT SYSTEMS DIVISION

Inputs

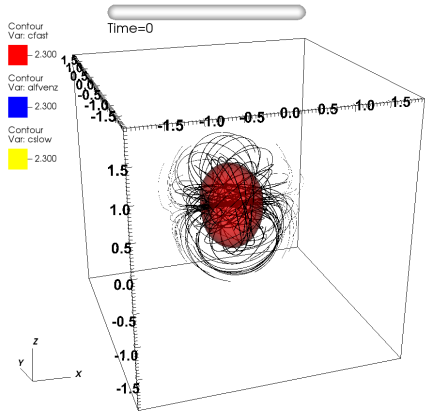
- Grid: 128^3
- Volume: 4^3
- Spheromak initial position:
  - (0, 0, 0)
- BCs: X, Y, Z (PBC, PBC, OBC)
- $v_x = v_y = v_z = 0$
- $\rho = 1, \epsilon = 1$
- B_x, B_y, B_z defined such that r=1 for spheromak
- $c_f = 2.3$
- $v_{ad} = -3.5$
- Normalized stable background thermalized with Spheromak
- Run until t=5/v

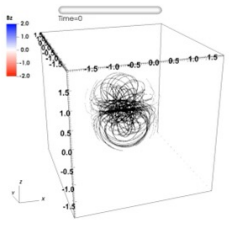
Outputs

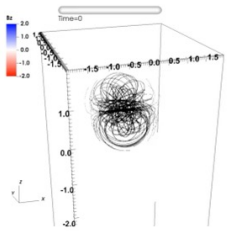
Contours of the characteristic velocities slow and fast magnetosonic speeds, c_f and c_s, and the c_a (Alfvén speed)

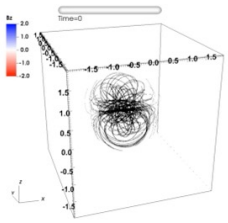
Goals

Order of magnitude reduction in runtime
Equivalent accuracy to existing methods
Compared to ground truth









Graphics: from Fig. 4 of Ref [Kee25] and the supplementary material video 4.
Image used under cc-by-4.0 created by Kee et al. No changes were made

Challenge Problem (Stage 1)

INTELLIGENT SYSTEMS DIVISION

Background

Three step problem for simulation:

1. formation of coronal structure
2. Onset of eruption
3. Propagation of eruption

These follow the computation from [Che25]

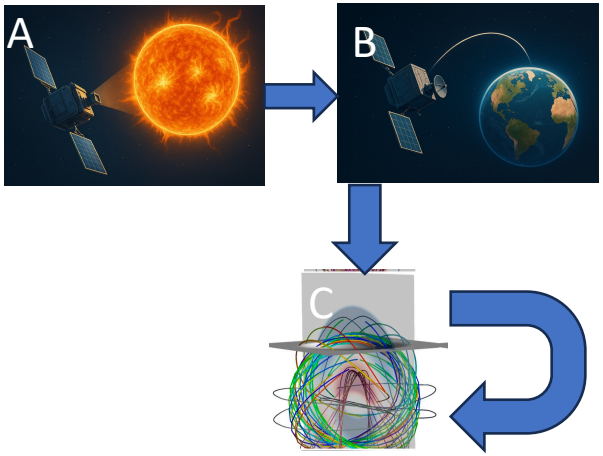
Stage 1 is a low cost simulation to provide background information about what the magnetic field of the sun looks like at accelerated to a given point in time.

Stage 2 and Stage 3 are iterative refinements that model the active regions using data driven boundary conditions from real-world data.

Goals

Timesteps faster than satellite data (12 minutes)

Equivalent accuracy or better to Chen (2025). https://arxiv.org/pdf/2512.01201



A and B were created with O365 Copilot. C: Image used under cc-by-4.0 created by Tarr et al. With minor Modifications

Challenge Problem (Stage 2)

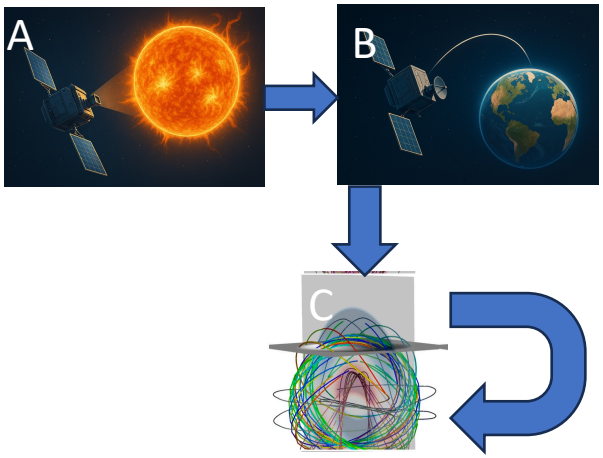
INTELLIGENT SYSTEMS DIVISION

Inputs (Stage 2)

- Grid: 512^2x1920
- Volume: 276.48Mm^2 x 122.88 Mm
- BCs: (PBC, PBC, DDBC)
- Initial conditions:
  - $B_{init} = B_{P-512} + B_{NP-512} + B_{QS}$ interpolated from Stage1
  - Other terms extrapolated similarly from Stage 1
  - $\Omega = 1.0 \times 10{-}5\ s{-}1$
- Utilize Active Region 11158 and the X2.2 Flare as input data for the DDBC
- Runtime: 3.2hrs simulation time.

Outputs

Contours of the characteristic velocities slow and fast magnetosonic speeds, c_f and c_s, and the c_a (Alfvén speed)



A and B were created with O365 Copilot. C: Image used under cc-by-4.0 created by Tarr et al. With minor Modifications

Challenge Problem (Stage 3)

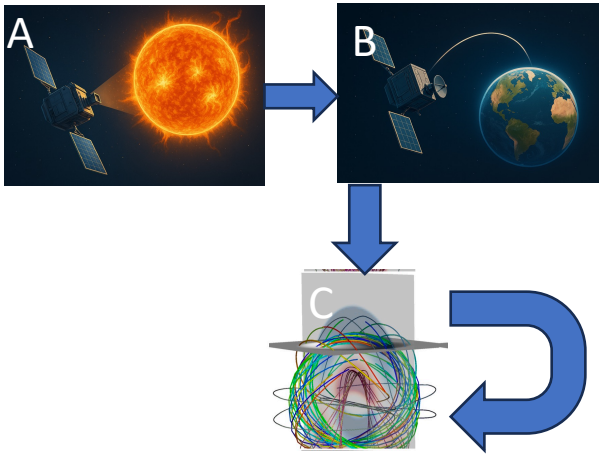
INTELLIGENT SYSTEMS DIVISION

Inputs (Stage 3)

- Grid: 512^2x3840
- Volume: 276.48Mm^2 x 245.76 Mm
- BCs: (PBC, PBC, DDBC)
- Initial conditions:
  - Snapped from stage 2 at ending
- Utilize Active Region 11158 and the X2.2 Flare as input data for the DDBC
- Runtime: 50 minutes simulation time

Outputs

Contours of the characteristic velocities slow and fast magnetosonic speeds, c_f and c_s, and the c_a (Alfvén speed)



A and B were created with O365 Copilot. C: Image used under cc-by-4.0 created by Tarr et al. With minor Modifications

Useful References

Data-driven simulation methods:

- [Tar23] L.A. Tarr, et al., simulating the photospheric to coronal plasma using magnetohydrodynamic characteristics I: data-driven boundary conditions, The Astrophysical Journal supplement series, 270:30, Feb. 2024. arXiv:2311.02281
- [Kee25] N.D. Kee, et al., Simulating the Photospheric to Coronal Plasma Using Magnetohydrodynamic Characteristics. II. Reflections on Non-reflecting Boundary Conditions, The Astrophysical Journal, 983;80, 2025 April 10.
- [Brio88] Brio, M., & Wu, C. C. 1988, Journal of Computational Physics, 75, 400, doi: 10.1016/0021-9991(88)90120-9
- [Sod78] Sod, G. A. 1978, Journal of Computational Physics, 27, 1, doi: 10.1016/0021-9991(78)90023-2
- [Che25] Chen, Feng. "Data-driven Radiative Magnetohydrodynamics Simulations with the MURaM Code: the Emergence of Active Region 11158 and the X2. 2 Flare." *arXiv preprint arXiv:2512.01201* (2025).
- [Tar23] L.A. Tarr, et al., Simulating the photospheric to coronal plasma using magnetodydrodyanamic characteristics I: data-drive boundary conditions, The Astrophysical Journal Supplement Series, 270:30, 2024. arXiv:2311.02281.



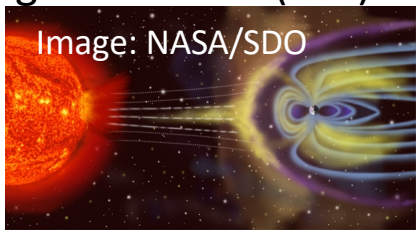
Solar Energetic Particle Forecasting

Solar Energetic Particle Event Forecasting

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Application Details

- Forecast Solar Energetic Particle (SEP) Events
- Particles pose a potential threat to astronauts and their habitats, satellites, comm., ozone levels, and air travel over the poles



Problem Details

- Solutions of the 3D time-dependent MHD equations are the starting point to SEP forecasting.
- Observational Inputs: Real-time solar wind data, coronal mass ejection (CME) parameters, and magnetic field models of the Sun.
- Outputs: Predicted SEP fluxes at target locations.

Current Approaches

- ML, empirical, and physics-based models are used for predicting SEP events.
- Physics-based Magnetohydrodynamics (MHD) solvers integrating observational data
- Need faster predictions < 2hrs to improve operational forecasting

Impact of New/Better Solution

- More timely forecasts will buy astronauts on the Moon or Mars critical time to shelter when performing maneuvers outside a spacecraft and for cancellation of planned extravehicular activities
- Unlike ML models, physics-based models have the ability to provide forecasts anywhere in the heliosphere

Application Details

Solar flares and coronal mass ejections (CMEs) launch bursts of high-energy charged particles (solar energetic particles, SEPs) into space. On a mission to the Moon or Mars, these particles can quickly reach astronauts and electronics, posing severe radiation hazards.

A high-fidelity physics-based simulation of SEP acceleration and propagation would let planners forecast when and how intense such particle storms
will be at the Moon or along spacecraft trajectories.

Current tools often run much slower than real time or make simplifying assumptions; an improved SEP simulation capability can potentially predict SEP events anywhere in the heliosphere.

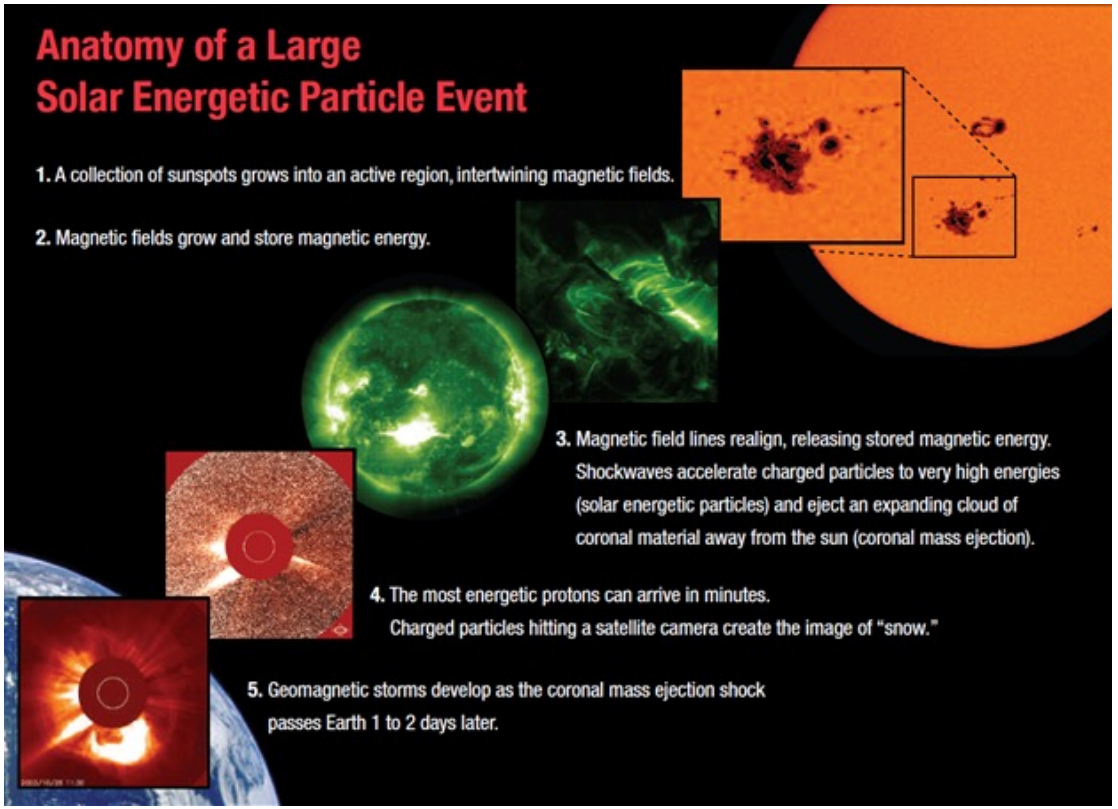


Diagram summarizing the steps of an SEP event. (Wings In Orbit, Scientific and Engineering Legacies of the Space Shuttle, 1971-2010 NASA/SP-2010-3409, Published 2010. Page 454.)

The goal is to predict the occurrence of SEP events with significantly increased lead time in the inner heliosphere. Early warning of SEP events enables preventive actions such as powering down sensitive instruments, re-orbiting satellites, scheduling spacewalks, well before harmful radiation arrives at Earth, on the Moon, or in-transit spacecraft.

Motivation Civil Space Shortfalls

#1603 Solar Particle Events (SPEs) remain difficult to forecast & “now”-cast, and they continue to pose a risk to astronauts, especially if caught away from a shelter on the lunar surface. They occur when Solar Energetic Particles are emitted from the Sun and are accelerated o high energies during a solar flare or in interplanetary space by a Coronal Mass Ejection (CME). Unlike the much more predictable Galactic Cosmic Radiation (GCR) which is slowly modulated by the Sun’s 11-year solar cycle, SPEs occur episodically and exhibit high variability in terms of intensity, duration, composition, and energy spectra. Their occurrence varies from several per week when the Sun is “active” to fewer than one per month when the Sun is quiet, following an 11-year cycle generally consisting of 4 inactive years (solar minimum) and seven active years (solar maximum).

In 2019, state-of-the-art probability of detection for a **20 minutes “now-cast was only 40%, with a false alarm rate of almost 60%.** Even with recent use of machine learning, success rate has not improved by a lot. More kinds of data are needed. Plans are underway to fly solar imagers at Sun-Earth L4 and L5 Lagrange points. Development of machine learning, foundation models, and other new modeling tools are needs to continue.

Metrics: Timeliness and time window for SPE forecasts/early warning. SPE probability of advanced detection. Low false alarm rate.

Nasa civil space shortfalls: https://www.nasa.gov/spacetechpriorities/ 2024.

Motivation: Executive Order: Ensuring American Space Superiority

- Sec 2.d.i “optimizing space research-and-development investments to achieve my Administration’s near-term space objectives, use emerging technologies and scientific discoveries to advance mission capabilities, and enable scientific discovery for America’s long-term science and technology leadership”
- Sec. 2.d.iii “improving high-value space and Earth weather forecasting and operations to meet needs on Earth and beyond, utilizing improved business approaches such as firm fixed-price contracts and as-a-service models for both space and ground-based segments;”



45 47

PRESIDENTIAL ACTIONS

ENSURING AMERICAN SPACE SUPERIORITY

Executive Orders | December 18, 2025

By the authority vested in me as President by the Constitution and the laws of the United States of America, it is hereby ordered:

Section 1. Purpose. Superiority in space is a measure of national vision and willpower, and the technologies Americans develop to achieve it contribute substantially to the Nation's strength, security, and prosperity. The United States must therefore pursue a space policy that will extend the reach of human discovery, secure the Nation's vital economic and security interests, unleash commercial development, and lay the foundation for a new space age.

Sec. 2. Policy. My Administration will focus its space policy on achieving the following priorities:

EO: https://www.whitehouse.gov/presidential-actions/2025/12/ensuring-american-space-superiority/ Dec. 18, 2025.

Inputs and Outputs

Inputs (see for example, [Liu25]):

- Magnetogram, which provides the photospheric radial magnetic field (B_r)
- Extreme-ultraviolet (EUV) and/or X-ray Images, typically used to provide the active region (AR) location
- Coronograph images, used to estimate the CME speed

Outputs:

- Predicted SEP intensity (e.g., particle count rate above 10 MeV and 100 MeV, for example) as functions of time and energy at target locations (e.g., the Earth, Moon surface, spacecraft trajectories).
- Can be used in conjunction with space craft information to compute radiation dose rates.

[Liu25] W. Liu, et al., Simulated Real-Time Testing of the Prototype Implementation of the SOFIE Model: The 2025 Space Weather Prediction Testbed Exercise, arXiv:2511.09716

Model Details

- The initial step to simulate, forecast, or nowcast space weather events involves solving for the time-dependent, steady state solar winds
  - Entails solving the time-dependent 3D magnetohydrodynamics (MHD) equations from a surface close to the Sun to $\gtrsim$ 1au
- Space weather disturbances (e.g., Coronal Mass Ejections, CMEs) propagate and shocks and disturbances are generated
- SEP transport, as well as the formation of their seed population, is mostly controlled by this back-ground solution as well [Sok22]

An example of a state-of-the-art physics-based SEP forecasting model includes the Solar-wind with Field-lines and Energetic-particles (SOFIE) model [Liu25]. This is a multi-physics model that includes:

- Alfvén Wave Solar atmosphere Model-Realtime (AWSoM-R), solves the stream-aligned MHD equations [Sok22] for simulating the ambient solar wind with reliable magnetic connectivity
- Eruptive event Generator with the Gibson-Low magnetic configuration (EEGLE), for CME generation and propagations
- Multiple Field-Line-Advection Model for Particle Acceleration (M-FLAMPA), for simulating particle acceleration and transport process

Mathematical Formulation

The starting point for global models of the solar atmosphere are generally based on the standard time-dependent magnetohydrodynamic (MHD) equations [Sok22]

$$\partial_t \rho + \nabla(\rho \mathrm{u}) = 0$$

$$\partial_t \mathrm{B} + \nabla(\mathrm{uB} - \mathrm{Bu}) = -\mathrm{u}(\nabla \cdot \mathrm{B})$$

$$\partial_t(\rho \mathrm{u}) + \nabla[\mathrm{puu} - (\mathrm{BB}/\mu_\mathrm{o}) + (\mathrm{P} + (\mathrm{B}^2/2\mu_\mathrm{o})\hat{\mathrm{I}}] = -(1/\mu_\mathrm{o})\mathrm{B}(\nabla \cdot \mathrm{B})$$

$$\partial_t((\rho \mathrm{t}^2/2) + (P/(\gamma - 1)) + (\mathrm{B}^2/2\mu_\mathrm{o}) + \nabla[((\rho \mathrm{u}^2/2) + (\gamma \mathrm{P}/(\gamma - 1))\mathrm{u}] + \nabla[(\mathrm{uB} - \mathrm{Bu}) \cdot \mathrm{B})/\mu_\mathrm{o} = -(\mathrm{u} \cdot \mathrm{B})/\mu_\mathrm{o}(\nabla \cdot \mathrm{B})$$

ρ: mass density $= \mathrm{m_p n_i}$, u: velocity

B: magnetic field

γ: polytropic index $= 5/3$

Current Physics Based Approaches

[Whi23] Provides a comprehensive review of solar energetic particle prediction models, including machine learning, empirical, and physics-based models

- Noted that, “most of these [physics-based] models are computationally intensive, and the ability to produce a prediction “in real time” may be limited by the resources available, so they may not be readily incorporated into a forecasting workflow”
- “fundamental parameters required by the model may be poorly characterized. However, these complex models hold the promise of modeling the complete distribution of SEP events with time in 2- or 3-dimensional space. “
- Solar-wind with Field-lines and Energetic-particles (SOFIE) model [Liu25]. Is an example of a state-of-the-art physics-based model
  - Developed by NASA’ CLEAR Space Weather Center of Excellence at the Univ. of Michigan
  - SOFIE was evaluated during the Space Weather Prediction Testbed exercise at NOAA’s Space Weather Prediction Center (SWPC) in May 2025
  - We talked to the SOFIE team as part of this activity
- SEPMOD (Solar Energetic Particle MODel] [Luh07] and iPath (improved Particle Acceleration and transport in the heliosphere) [Hu17] are additional examples

Impact of New / Better Solution

- **Astronauts**: More timely forecasts will buy astronauts on the Moon and Mars critical time to shelter when performing maneuvers outside a spacecraft and for cancellation of planned extravehicular activities
- **Aviation Industry**: Better protection for airline crews and passengers on high altitude polar routes
- **Satellite Industry**: satellite operators can "… switch their spacecraft to safe mode or safe hold." [NOAA26]
- Electric Power Providers: "Geomagnetic storms can induce currents in the electric power grid, damaging transformers and other components..Utility companies [use forecasts] to reinforce grid stability, preventing outages…" [NOAA26]

[NOAA26] Safeguarding Satellites; How NOAA Monitors Space Weather to Prevent Disruptions. https://www.nesdis.noaa.gov/news/safeguarding-satellites-how-noaa-monitors-space-weather-prevent-disruptions

Family of Solutions

Repeated, continuous forecasting. This problem is solved repeatedly (e.g. hourly) as new solar images arrive.

This is a family of problems:

SEP simulations must run whenever a major solar eruption is detected. Each forecast run uses the latest solar inputs to simulate a new event.

Problem Specification (1/5)

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Predict the > 10 MeV and > 100 MeV proton intensity profiles at Earth based on the solar radiation storm that took place on 4 Nov. 2001



Image used under cc-by-nc-sa-4.0 from [Liu25] changes made to middle figure

Background:

This is one of the two solar radiation storms that was modeled during the Space Weather Prediction Testbed (SWPT) exercise at NOAA's Space Weather Prediction Center (SWPC) in May 2025 [Liu25]

- At 16:09 UT on 4 Nov. 2001, an X-ray flare was first observed by SWPC forecasters, originating from NOAA AR 9684 at N05W24 as viewed from Earth
- The flare peaked at ~16:18 UT with an intensity corresponding to the X1.0 class intensity
- Shortly afterwards, at 16:35 UT, the associated CME was first detected by LASCO/C2

[Liu25] W. Liu, et al., Simulated Real-Time Testing of the Prototype Implementation of the SOFIE Model: The 2025 Space Weather Prediction Testbed Exercise, arXiv:2511.09716

Problem Specification (2/5)

Inputs:

- Magnetograms from GONG (Global Observation Network Group) and MDI (SOHO/Michelson Doppler Imager) from
  - https://gong.nso.edu/data/magmap/
  - http://jsoc.stanford.edu/MDI/MDI Magnetograms.html,
- Extreme Ultra Violet (EUV), X-Ray and H\alpha and Coronagraph Images:
  SOHO (Solar and Heliospheric Observatory) / LASCO (Large Angle and Spectrometric Coronagraph)
  white-light (WL) images
  - https://www.lmsal.com/solarsoft/
  - Used by SMEs to infer the CME speed (2650 km s^{-1}) and AR (active region) Location (S12W85) that are used as model inputs

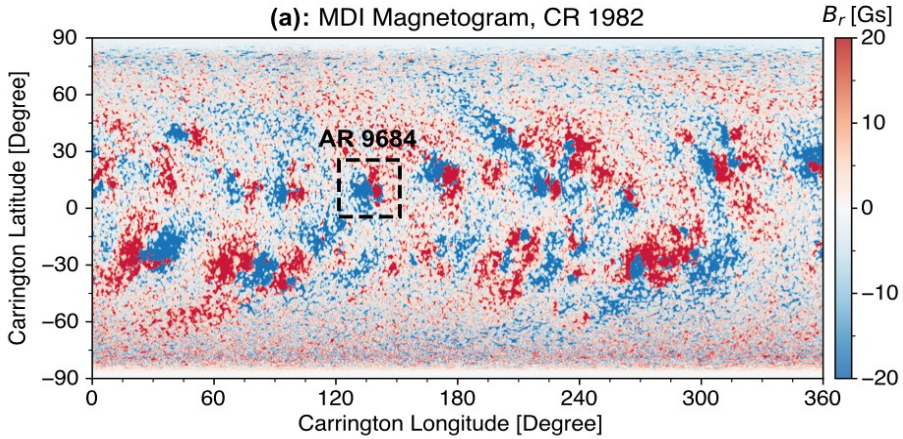


Image source: [Liu25] used under cc-by-nc-sa-4.0 from [Liu25] . No changes were made

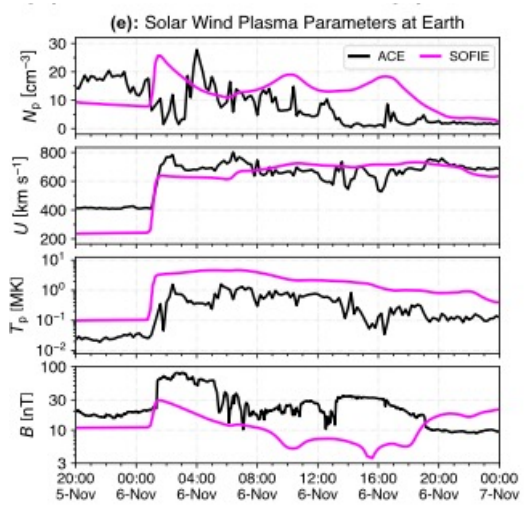
[Liu25] W. Liu, et al., Simulated Real-Time Testing of the Prototype Implementation of the SOFIE Model: The 2025 Space Weather Prediction Testbed Exercise, arXiv:2511.09716

Problem Specification (3/5)

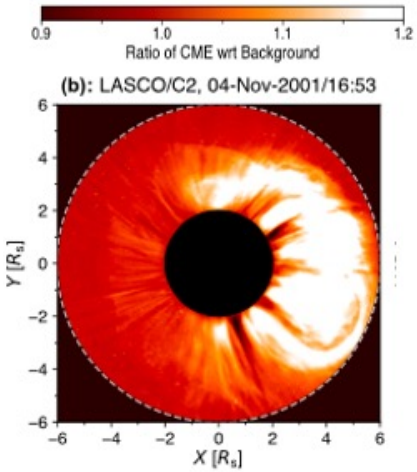
INTELLIGENT SYSTEMS DIVISION

Outputs:

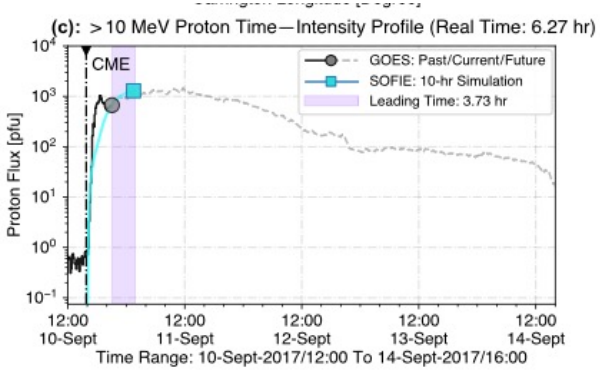
- Proton Fluxes
- Threshold Crossing Times
- Peak Time & Intensity
- LASCO/C2 observations of WL (for model verification)
- Advanced Composite Explorer (ACE) spacecraft Solar Wind Plasma Parameters at L1 (for model verification)

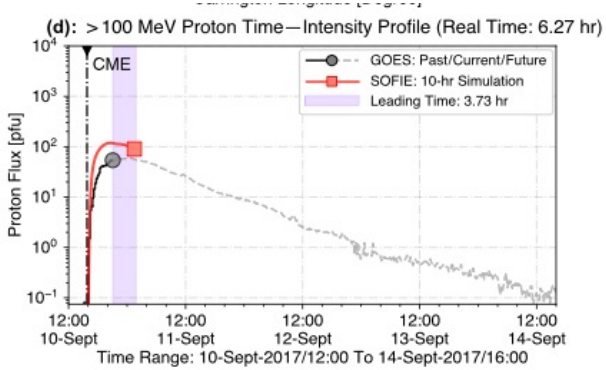


Black curve: solar wind plasma observations from from [Liu25]. Used under cc-by-nc-sa-4.0 from [Liu25] . No changes were made



LASCO/C2 WL Observations from [Liu25]. Used under cc-by-nc-sa-4.0 from [Liu25] . No changes were made





Black curve >10 MeV and > 100 MeV proton time intensity profile at Earth 6.27 real-time hours after the eruption. Image from from [Liu25]. Used under cc-by-nc-sa-4.0 from [Liu25] . No changes were made

[Liu25] W. Liu, et al., Simulated Real-Time Testing of the Prototype Implementation of the SOFIE Model: The 2025 Space Weather Prediction Testbed Exercise, arXiv:2511.09716

Problem Specification (4/5)

Runtime Requirements for real-time forecasting:

- 4-day simulation within **1-2 hours** while accounting for the ~1 delay in obtaining coronal mass ejection (CME) observations for the simulations associated with the 4 Nov 2001 event
- Predict the energetic storm particles (ESP) phase (i.e., the period when the CME-driven shock reaches the observing spacecraft, GOES, causing a sharp increase in particle intensity – see image) within a point-to-point Spearman correlation coefficient **> 0.9**
  - SOTA SOFIE model performed predictions in **~14.5 hrs** (including ~1h delay for CME observations) in simulated real-time testing a solar storm that took place on 4 Nov 2001 [Liu25]. Predictions are faster than elapsed time since flare onset.

Stepping-stone Problem Instance 1:

- Complete the 4-day simulation of the solar radiation storm that started on 4 Nov. 2001 in under **34 hours** and predict the energetic storm particles (ESP) phase (i.e., the period when the CME-driven shock reaches the GOES satellite, causing a sharp increase in particle intensity – see image to right) within a point-to-point Spearman correlatio **0.9.**
  - Elapsed time since flare onset was ~34 hrs, so this is roughly realtime and accuracy is consistent with SOFIE in the 'Setup 1' configuration.

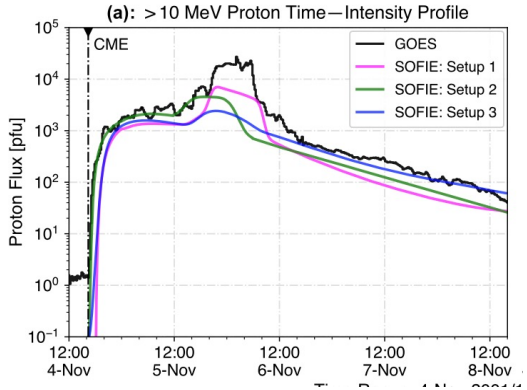


Image source: [Liu25] cc-by-nc-sa-4.0 from [Liu25] . No changes were made

[Liu25] W. Liu, et al., Simulated Real-Time Testing of the Prototype Implementation of the SOFIE Model: The 2025 Space Weather Prediction Testbed Exercise, arXiv:2511.09716

Problem Specification (5/5)

Stepping-stone Problem Instance 2:

- Complete the 4-day simulation of the solar radiation storm that started on 4 Nov. 2001 in under **24 hours** and predict the energetic storm particles (ESP) phase (i.e., the period when the CME-driven shock reaches the observing spacecraft, GOES, causing a sharp increase in particle intensity) within a point-to-point Spearman correlation coefficient **> 0.9.**
  - Time is slightly faster than real time (elapsed time since flare onset) and accuracy is consistent with what SOFIE achieved in the 'Setup 1' configuration (fine grid).

Stepping-stone Problem Instance 3:

- Complete the 4-day simulation of the solar radiation storm that started on 4 Nov. 2001 in under **~14.5 hours** and predict the energetic storm particles (ESP) phase (i.e., the period when the CME-driven shock reaches the observing spacecraft, GOES, causing a sharp increase in particle intensity) within a point-to-point Spearman correlation coefficient **> 0.9.**
  - Time is faster than real time and is the runtime achieved by the SOTA SOFIE model and accuracy is consistent with what SOFIE achieved in the 'Setup 1' configuration (fine grid).

Points of Contact

Who we have talked to so far:

- Kathryn Whitman, NASA JSC Space Radiation Analysis Group (SRAG)
- Lulu Zhao and Tamas Gombosi / Univ. Of Michigan, NASA CLEAR (Center for All-Clear Solar Energetic particle Forecast) Space Weather Center of Excellence and SOFIE model developers
  - Charles 'Nick' Arge/GSFC was in attendance at the meeting with Lulu and Tamas, and we are planning a follow-up discussion
- [Indirectly] Ricky Egeland, NASA JSC SRAG through monthly SEP ML meetings
- N. Dylan Kee, NASA/GSFC, James E. Leake, NASA/GSFC
- Charles 'Nick' Arge, Head of the Solar Physics Laboratory at GSFC

- Initial discussions conducted with Dylan, James and Nick on 2 Mar. 2026



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