Interactive Tool for Modeling Multiple Solar Eruptions from Sun to Earth

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INTRODUCTION

Coronal mass ejections (CMEs) are large explosions that eject plasma and magnetic field away from the Sun and are the primary cause of major geomagnetic storms. Predicting whether CMEs will hit the Earth and carry geo-effective magnetic fields is a key priority for space weather readiness. Due to their inherent complexity, the mechanisms that control CME properties are poorly understood and challenging to model empirically. Therefore, data-constrained magnetohydrodynamic (MHD) simulations of CMEs are a promising path forward for improving our understanding and advancing space weather prediction capabilities.

To facilitate such simulations for community use, we are developing an interactive modeling framework called **CORHEL-AMCG** that allows *non-expert users* to routinely model multiple CMEs in a realistic coronal and solar-wind environment and propagate them to 1 AU. The first component of the framework is a web-based interface called the Automated Multiple CME Generator (AMCG) used to design and set up low cost zero-beta MHD models of one or more flux ropes, quasi steady-state coronal MHD background models, and high-fidelity time-dependent CME simulations. All simulations are performed with the second framework component - a heavily updated version of the CORHEL modeling suite. CORHEL consists of a collection of tools and simulation codes (including the Magnetohydrodynamic Algorithm outside a Sphere (MAS) code) linked together through BASH scripts for ease of use. It also includes auto-generated web-based visualization reports for each stage of the CME design and simulation.

The **CORHEL-AMCG** framework is designed to run on high performance computing platforms as well as in-house multi-GPU servers. This is a step towards future operational model-based space-weather forecasting and rapid and inexpensive turn-around for research-focused CME simulations. The CME simulation data is also usable as input for the STAT solar energetic particle (SEP) model.

Here we demonstrate using **CORHEL-AMCG** to model the multiple CME event that occurred on 2012-01-23 from start to finish, highlighting key features of the framework.

CORHEL-AMCG

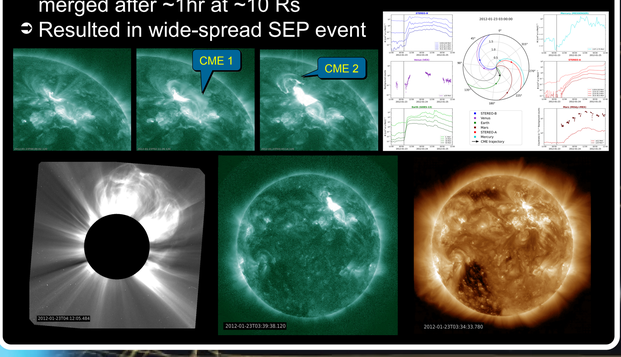
- Interactive web-based interface designed for non-expert users
- Flux rope designer with rapid turn-around zero-beta MHD simulations
- Computationally efficient global thermodynamic MHD CME simulations
- Automatic self-contained visualization reports for easy evaluation
- Will be available for runs on demand at NASA's CCMC
- CME simulations can be used as input to the STAT SEP model

Download example reports: `predsci.com/~caplanr/shine2022`

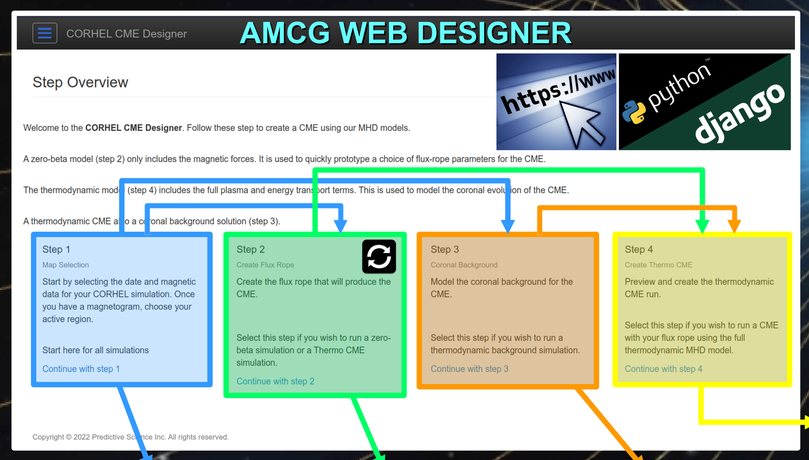
Community Coordinated Modeling Center

EXAMPLE CASE: THE DOUBLE CME EVENT OF 2012-01-23

- Two very fast CMEs from nearby ARs (NOAA 11401/2), merged after ~1hr at ~10 Rs
- Resulted in wide-spread SEP event



AMCG WEB DESIGNER

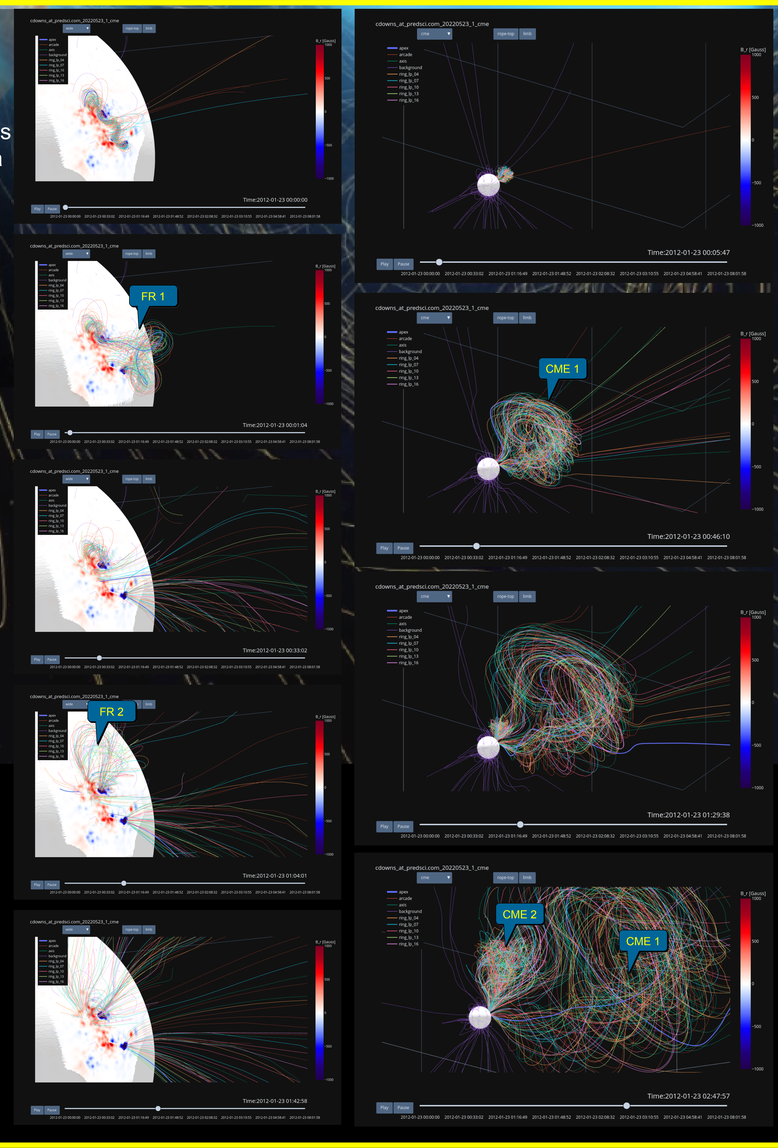


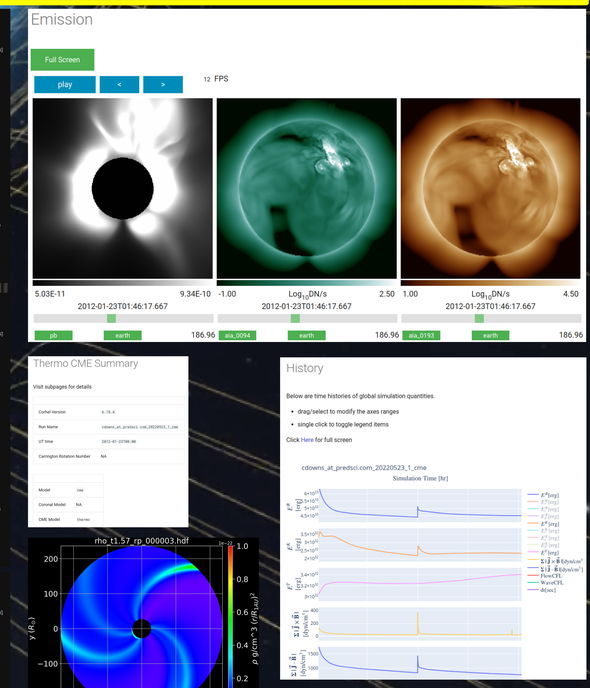
MAS — MHD CME ERUPTION AND PROPAGATION THROUGH CORONA AND HELIOSPHERE

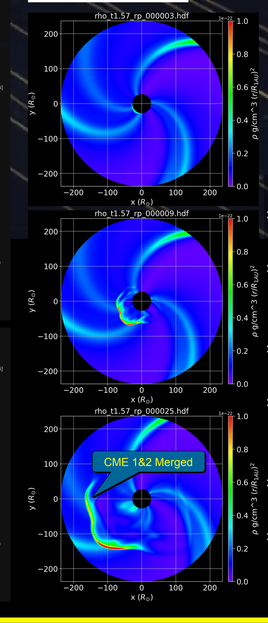
Coronal CME eruption
- Start with remesh of coronal background solution to high resolution
- Insert flux rope(s) at specified times
- Run until CME(s) leave low corona

Coronal CME(s) propagation
- Start with remesh of eruption run's last state to lower resolution
- Propagate CME(s) out of corona

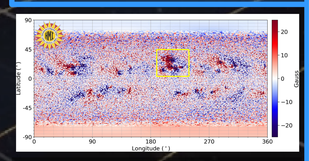
Helospheric propagation
- Initial condition remeshed from heliospheric background solution
- Driven by coronal boundary slices







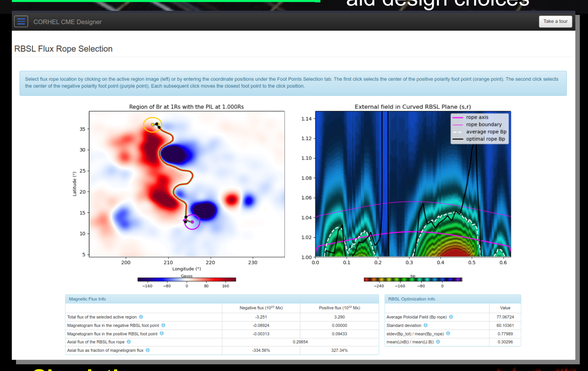
MAP SELECTION



- Download or provide Br map and process it for model input
- Select active region(s) to insert flux rope(s) into

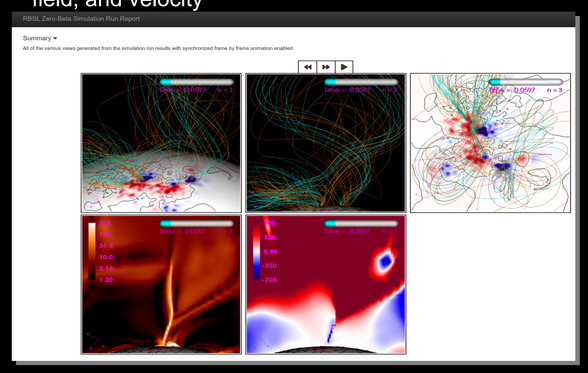
(MULTIPLE) FLUX ROPE DESIGN

Designer
- Web-based interface
- Designed for non-experts with tool tips to guide users
- Save states
- TdM & RBSL flux rope models
- Real-time diagnostics to aid design choices



Simulations (MAS)
- Potential field initial condition, then flux rope(s) inserted
- Zero-beta MHD simulation to evaluate stability properties and eruption(s) speed, direction, etc.

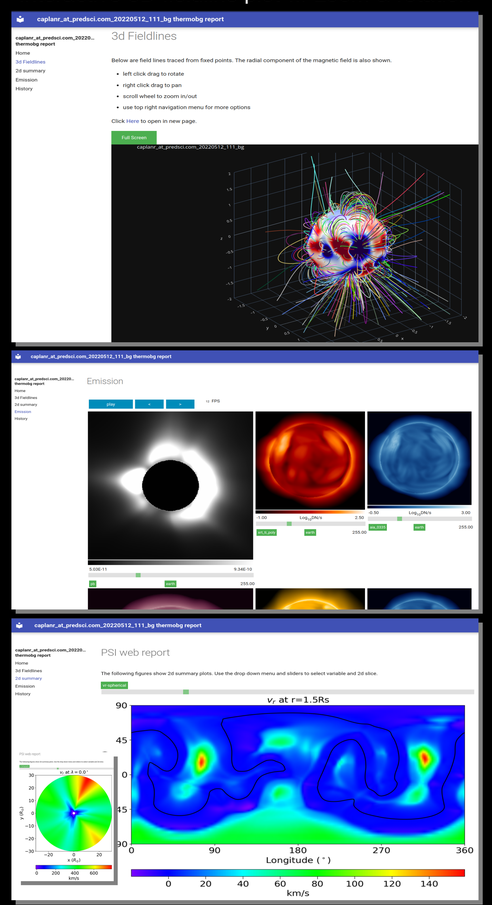
Report
- Stand-alone package, viewed in local web browser
- 3D views of field lines, cut-planes of current, magnetic field, and velocity



THERMODYNAMIC MHD QUASI-STEADY-STATE BACKGROUND

Simulation (MAS)
- Modest resolution coronal relaxation to quasi-steady state (choice of heating model)
- Heliospheric relaxation to quasi-steady state

Report
- Stand-alone package, viewed in local web browser
- Emission images of channels from AIA, EIT, XRT, and white light for all longitudes
- Interactive 3D fieldline plot w/ zoom & rotation



Report
- Stand-alone package, viewed from local web browser
- Emission images of channels from AIA, EIT, XRT, and white light for all times and 3 views
- Interactive history plots of derived quantities
- Interactive time animated 3D fieldline plots w/ zoom, rotation, and 3 preset views
- Heliospheric cut plane animations
- In-situ Earth comparisons under development

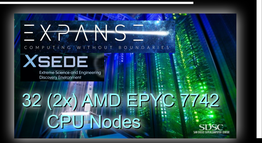
COMPUTATION DETAILS

- MAS written in Fortran and parallelized using MPI+OpenACC
- Can run on supercomputers or local multi-GPU workstations

Example wall clock times:

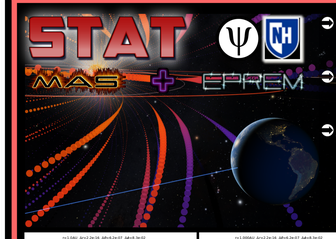
Coronal Zero-Beta MHD Flux Rope Eruption	01:15:00
Coronal Thermodynamic MHD Background	07:00:00
Heliospheric MHD Background	02:00:00
Heliospheric MHD CME Propagation	01:30:00
Coornal Thermodynamic MHD CME Eruption	06:00:00
Coronal Thermodynamic MHD CME Propagation	03:00:00

(4x) NVIDIA RTX 2080Ti GPUs



32 (2x) AMD EPYC 7742 CPU Nodes

SOLAR ENERGETIC PARTICLE SIMULATION



- CME simulation used as input
- Integrates focus transport model
- Stand-alone web page report