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Towards Inserting Magnetic Ejecta into a Space Weather Model

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14. ABSTRACT

This research project was part of a larger team effort toward predicting the intrinsic magnetic field within solar coronal mass ejections (CMEs). Our contribution included observation/analysis of CME structure and the development and
application of CME models, along with testing scenarios for CME evolution during propagation. We found a generic 3D morphology that, with perspective effects, accounts for ~85% of the variability in observed CME morphology. We
refined a novel, "fluxon" code for modeling CME onset and ejection from the corona, making major progress toward a data-driven space weather model capable of capturing CME onset in near real time and predicting space weather
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Contract PI: Craig DeForest, SwRI

Final Report, 30 April 2021

Introduction

This research project was part of a larger team effort toward measuring and predicting the intrinsic magnetic field within coronal mass ejections from the Sun. Our team's contribution included observation and analysis of CME substructures, including the flux rope cavity, and the application and improvement of models of CMEs at large distances from the Sun, along with the testing of various physical scenarios involving CME evolution through the solar wind. The work was motivated by the major objective of investigating and characterizing magnetic structures within CMEs from eruption at the Sun to impact with Earth's magnetosphere, using a combination of novel data-supported models and remote sensing data to connect solar and in-situ measurements.

The following report describes the contributions to this project by the contracting team at the Southwest Research Institute. The report describing the contributions by the entire team, including those in *this* report, will be submitted by the PI, Curt de Koning. The contribution by the team at SwRI has involved the analysis and reduction of particular CME datasets and the measurement of their substructure, and development of the fluxon code to be used in Y4 joint simulations.

In 2014, the Air Force Office of Scientific Research (AFOSR) awarded funding to the collaborative grant, ``*Towards Inserting Magnetic Ejecta Into A Space Weather Model*.'' Funding was awarded to research teams at two institutions: (i) University of Colorado at Boulder/Cooperative Institute for Research in Environmental Sciences (CIRES), consisting of Curt A de Koning (Grant PI), Dusan Odstrcil, and George Millward; and (ii) Southwest Research Institute (SWRI) – Boulder, consisting of Timothy Howard (Institutional PI) and Craig DeForest. AFOSR awarded five years of funding to both teams; however, the starting dates for the teams did not coincide — the University of Colorado start date was 9/30/2014, whereas the SWRI start date was 9/1/2014.

In November 2016, SwRI PI Timothy Howard left the field of solar/space physics and returned home to Australia. Howard's departure led to difficulty with the SwRI element of the grant, until the hire and training of Chris Lowder to operate and extend the fluxon code. Nevertheless, we produced several important science results and significantly advanced the technology of fluxon modeling – achieving a major milestone of carrying out meaningful global, data-driven 3D MHD modeling of the corona in the low-beta regime with several orders of magnitude less computer time than would be required for a comparable conventional code.

Accomplishments

In Y1 and Y2 we focused primarily on the analysis goals of the project, culminating in two important papers challenging current understanding of CME onset. In Y1, Howard & Pizzo (2016) made a strong case that blast waves driven by magnetic explosions play an important role in the most energetic CME onset events (Figure 1).

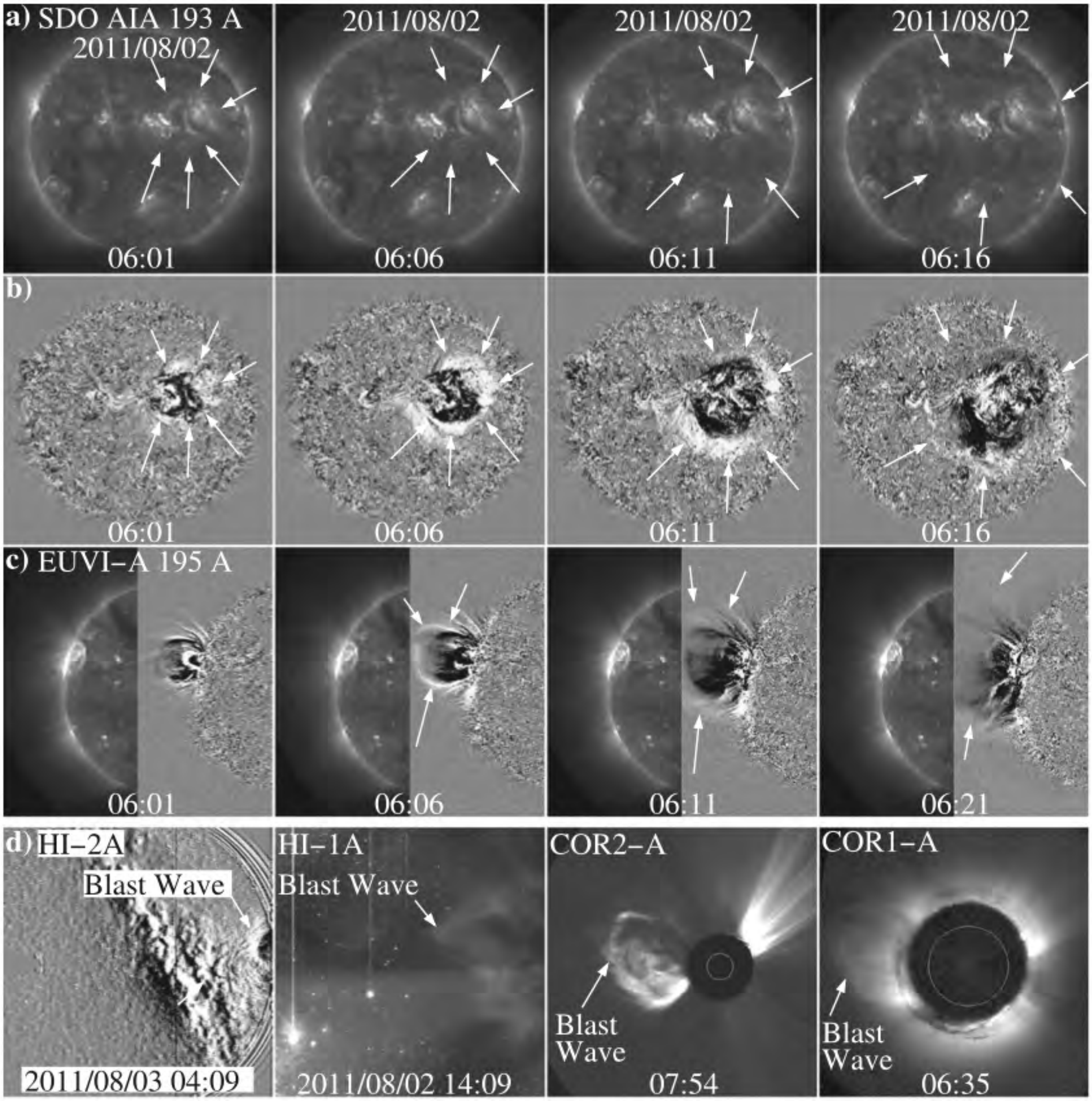

Figure 1 (Fig. 3 of Howard & Pizzo 2016): blast waves from magnetic explosions, despite being downplayed through the field, are important to the physics of the fastest, most energetic CME events.

In Y2, Howard, DeForest, Schneck & Alden (2017) demonstrated that many "filaments" observed in coronagraph movies of CME onset are consistent with optical illusions caused by perspective effects acting on writhed CME flux ropes in the corona (Figure 2). This insight may solve the "case of the missing filaments": cool filamentary material is occasionally observed *in situ* but at much lower rates than the typical three-part CME paradigm would imply. The result shows that filamentary material, whether it erupts in the low corona or not, need not survive to high altitudes to reproduce the appearance of most three-part CMEs in wide-field coronagraphs. The result indicates that filament "evaporation" through conductive heating may influence onset and early propagation more than previously thought, perturbing CME acceleration and affecting model extrapolations of halo CME arrival time.

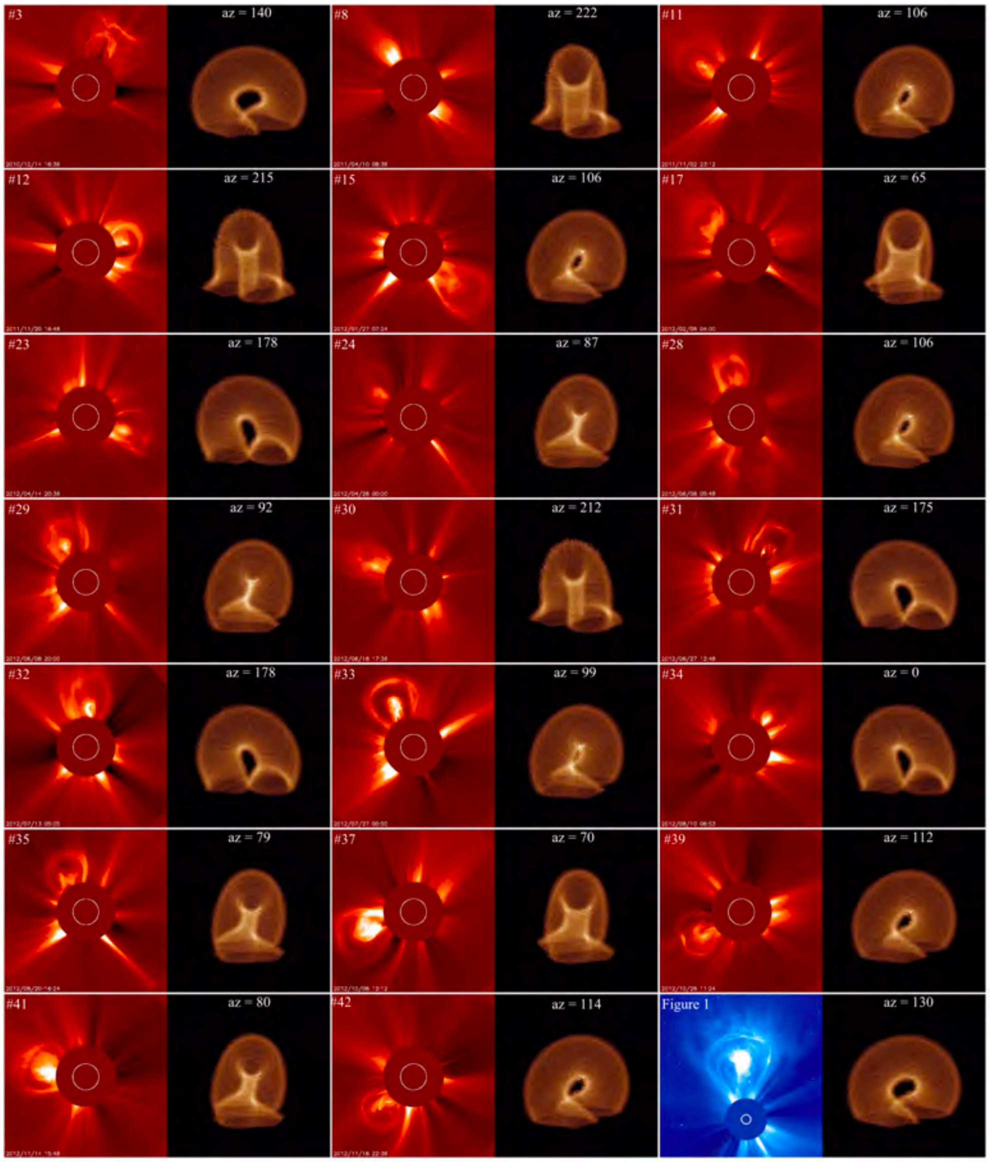

Figure 2 (Fig. 11 of Howard et al. 2017): a simple writhed-flux-rope model, viewed from different angles, substantially reproduces the appearance of many "three-part" CMEs. This implies that some or all "three-part" CMEs may be missing the central "part" (the filament core) in the LASCO C2 or C3 fields of view, potentially explaining the "missing filament" problem of in-situ CME observations.

In Y3 and Y4 we worked with PI De Koning to apply novel noise-reduction techniques to STEREO data and demonstrate the 3D chiral sense of a CME that later impacted SOHO (DeForest, DeKoning & Elliott 2017). This important result demonstrated, for the first time, that visible-light remote sensing of CMEs *as they propagate through interplanetary space*, can determine the chirality (rotational sense) of the flux rope in transit (Figure 3). This, in turn, provides a means to connect now-commonly-available magnetograph measurements of east/west field direction in the CME source region, with extremely important and currently-impossible-to-measure sign of Bz (the north/south component of the CME's entrained magnetic field), through direct measurement rather than modeling. Bz is a critical measurement because it is the single largest determinant of a CME's geoeffectiveness, but it is not currently measurable until the CME sweeps over an *in situ* probe such as ACE or SOHO.

Follow-up work (de Koning & DeForest 2018) revealed that STEREO-B, viewing the CME from the opposite side, placed the structures consistently with the STEREO-A and SOHO results.

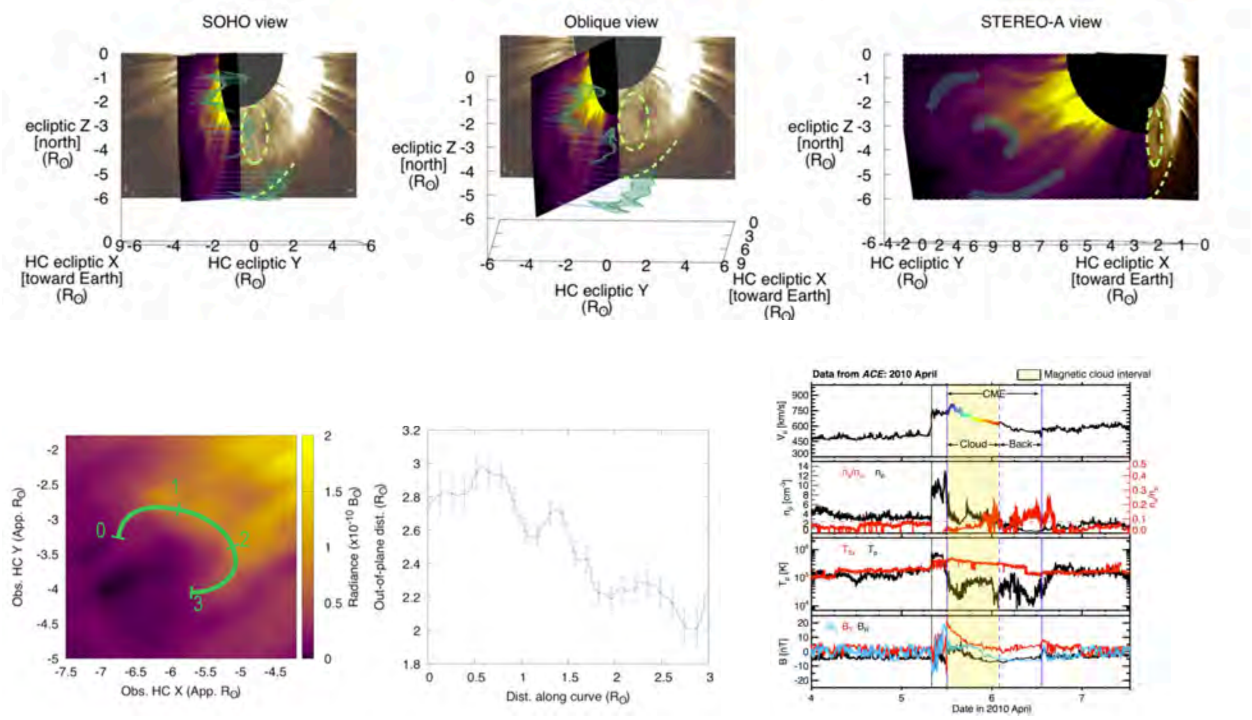

Figure 3: (Figures from DeForest, DeKoning, & Elliott 2017): polarization analysis of a CME demonstrates location of the CME and also determines its chirality. Counterclockwise from top right: (i) CME appears as a clean eastern-limb event from STEREO-A; (ii) oblique view shows green regions-of-interest outside the original image plane based on polarization; (iii) reprojecting to the SOHO point of view aligns the ROI features with SOHO-observed features; (iv) close-up of the core shows a path around the flux rope; (v) path is right-handed helical; (vi) ACE in-situ data confirm right-handed chirality.

In Y4 through Y6, we focused on improving the fluxon simulation code FLUX. FLUX is a quasi-Lagrangian 3D MHD model that is optimized for low-beta-parameter systems such as the lower corona. The model is constructed to use the magnetic field itself as a grid: the magnetic domains of the corona are modeled directly, with curvilinear fluxons (field lines that carry finite, rather than infinitesimal, magnetic flux) that interact via the familiar magnetohydrodynamic (MHD) magnetic pressure and curvature forces. Because magnetic domains are quantized, numerical reconnection is completely eliminated and it is not necessary to oversample the domain. This reduces the computational requirements for a full-corona model by a factor between 10^3 and 10^4 compared to an Eulerian MHD code of comparable resolution that is capable of capturing the pre-CME flux system.

Because FLUX is the first fluxon model intended to simulate the Sun, the simulation problem has proved more complex than anticipated and major development was needed. In Y4 we carried out programmer-interface improvements, allowing improved interaction with the model and 3D rendering and visualization of the entire corona via Python plot libraries (Figure 4). We also validated the simulation against WSA models of the coronal morphology during particular Carrington rotations.

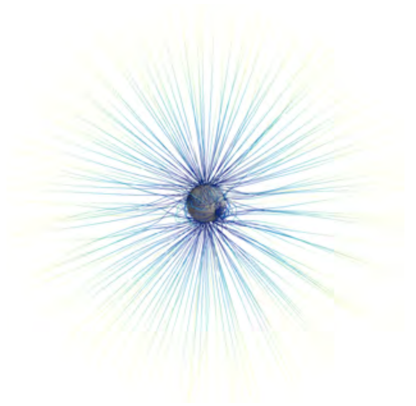

Figure 4: Improved rendering of a global fluxon model shows uniform outer field as expected; reveals connectivity of streamer boundaries and coronal holes to the heliosphere.

In Y5 we added mass flows to the model, in particular enabling simulation of the solar wind environment (Figure 5). We validated stationary flows against WSA and against analytic treatment of several typical open magnetic structures. By the end of Y5 we began to insert closed but unstable flux systems into the model to allow them to erupt – either from toroidal force or from explicit reconnection. We requested a one year No-Cost Extension to enable applying the FLUX code to the team-selected CME events.

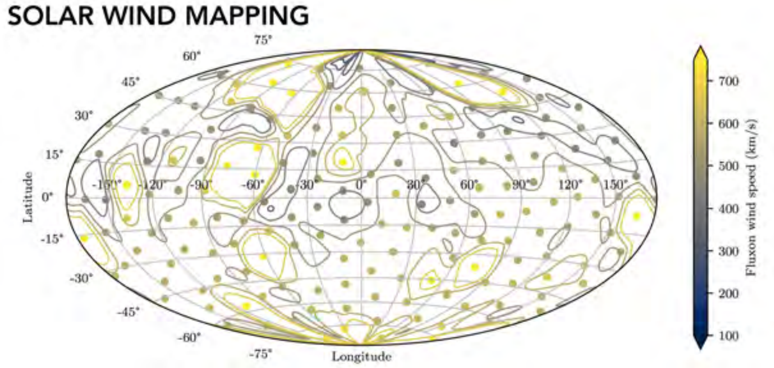

Figure 5: Addition of flow to individual fluxon domains allows prediction of solar wind speed over the entire outer stretch of the corona. This wind model uses a polytropic index and uniform basal temperature; cross sectional morphology of open field lines differentiates fast from slow flows.

In Y6, we encountered several novel numerical difficulties as we scaled up to full-resolution simulation codes. We found that certain models which converged well with 1,000 fluxons did not converge well (or at all) with 3x improved resolution (10,000 fluxons) – let alone with our target density of 100,000 fluxons. After several months of effort we tracked down two separate errors that prevented applying the model to the targeted CMEs at the required resolution. First, models and boundary conditions were being transferred between parallel processes with insufficient numerical precision, leading to occasional "sticky" infinities in the force calculation. This, in turn, froze portions of the model and prevented convergence with high fluxon counts but had no effect at low fluxon counts and therefore was difficult to reproduce under controlled circumstances. To identify and resolve this particular issue we had to develop an entirely new 3D visualization back-end for the code to allow us to trace and browse individual fluxons and their neighborhoods through the simulation. Second, certain aspects of the mass calculation led to new unanticipated numerical instabilities that involved interactions between the cross sectional area around each fluxon and the modeled flow characteristics. We refined the flow code by using a higher order interpolation of the flux tube cross section and also by imposing damping terms to the analytic 1-D treatment of the flow, to prevent the instability. These quasi-viscous terms smooth flow along each field line and help to find the correct solution -- but do not damp shear flows across field lines. The result of these efforts is that we can now automatically produce data-driven wind models at the anticipated resolution (Figure 6).

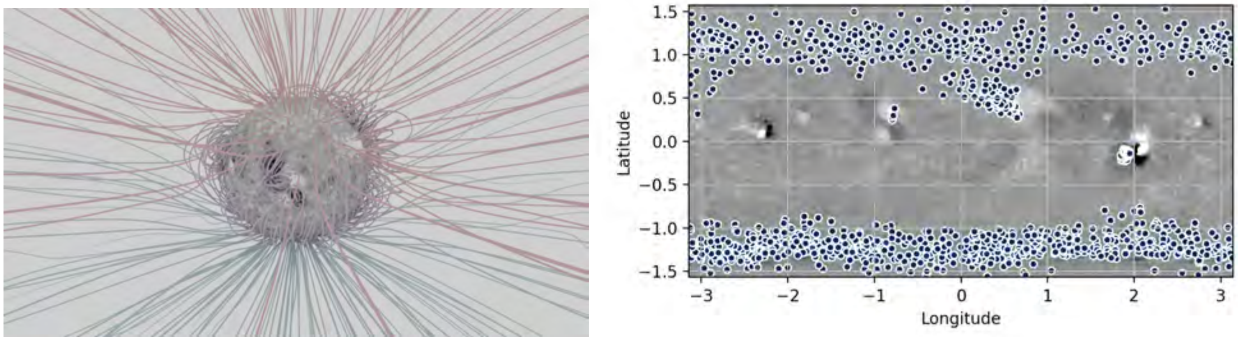

Figure 6: *morphology of a data-driven fluxon model of the Sun during Carrington Rotation 2193 shows high fluxon density (left) and appropriate open-field-line locations (right) after overcoming some difficulties with numerical scaling in Y6. The entire map is covered with fluxons at equal or higher density; only open fluxons are shown, to avoid completely obscuring the magnetogram.*

In the final months of the project, after the Y6 annual report was submitted, we identified and resolved an algorithmic issue that perturbed magnetic results. Because fluxon models in general (and FLUX in particular) treat the magnetic field as a collection of discrete field lines, local discrete geometry of the neighborhood of each fluxon is important. This importance is irreducible: adding more fluxons to a particular simulation refines the grid but retains the low-order polyhedral nature of the neighborhood around each fluxon. We found that the analytic field results could, under certain circumstances, change by a factor of up to 30% between hexagonal-neighborhood fluxons and pentagonal-neighborhood fluxons in force equilibrium in the same domain. The issue turned out to be in the treatment of gradients: while the magnetic field calculation was and remains sound, the treatment of spatial gradients implicitly assumed the same number of sides to each neighboring polygonal domain between fluxon. The issue appears resolved in current versions of the code.

The final result of the development effort is that FLUX is now ready to be used for MHD simulations of CMEs in a background solar wind, and has achieved meaningful data-driven, low-beta 3D MHD simulations of the entire corona with resolution sufficient to capture CME source region. These simulations can be run in a single workstation rather than a supercomputing cluster, and take hours rather than weeks to complete.

Although we were unable to complete the planned simulations of particular CMEs, we have indeed moved toward inserting magnetic ejecta into a space weather model. We will continue to advance FLUX development and deployment under separate funding.

The FLUX model is available from github: http://github.com/clowder.

References

DeForest, C.E., de Koning, C.A., and Elliott, H.A. 2017: “3D Polarized Imaging of Coronal Mass Ejections: Chirality of a CME”, Astrophys. J. 850, 130.

de Koning, C.A. and DeForest, C.E. 2018: “Using Polarized White Light Triplets Measured by STEREO to Isolate Internal Structure”, Proc. SHINE-2018.

Howard, T.A. and Pizzo, V.J. 2016: “Challenging Some Contemporary Views of Coronal Mass Ejections. I. The Case for Blast Waves”, Astrophys. J. 824, 92.

Howard, T.A., DeForest, C.E., Schneck, U.G., and Alden, C.R. 2017: “Challenging Some Contemporary Views of Coronal Mass Ejections. II. The Case for Absent Filaments”, Astrophys. J. 834, 86.