Modeling Coronal Mass Ejections with the Multi-Scale Fluid-Kinetic Simulation Suite

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Abstract. The solar eruptions and interacting solar wind streams are key drivers of geomagnetic storms and various related space weather disturbances that may have hazardous effects on the space-borne and ground-based technological systems as well as on human health. Coronal mass ejections (CMEs) and their interplanetary counterparts, interplanetary CMEs (ICMEs), belong to the strongest disturbances and therefore are of great importance for the space weather predictions. In this paper we show a few examples of how adaptive mesh refinement makes it possible to resolve the complex CME structure and its evolution in time while a CME propagates from the inner boundary to Earth. Simulations are performed with the Multi-Scale Fluid-Kinetic Simulation Suite (MS-FLUKSS).

1. Introduction
The solar wind (SW) emerging from the Sun is the main driving mechanism of solar events which may lead to geomagnetic storms that are the primary causes of space weather disturbances. Such disturbances affect the magnetic environment of Earth and may have hazardous effects on the space-borne and ground-based technological systems as well as on human health. For this reason, accurate modeling of the background SW is a necessary part of space weather forecasting. Geomagnetic storms are caused both by SW stream interactions and by the largest solar coronal disturbances called coronal mass ejections (CMEs) and their interplanetary counterparts, interplanetary CMEs (ICMEs). Therefore, modeling stream interaction background and ICME propagating through it on the basis of observational data is a key area of research in solar and heliospheric physics. Such modeling should necessarily be built on mathematically- and physically-consistent connections between eruptive events, magnetic phenomena on the Sun, and SW structures in the solar atmosphere and inner heliosphere (IHS). Substantial success has been achieved in global numerical modeling of the IHS, see, e.g., [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41]. The quest to create a nearly real-time model of the solar atmosphere and IHS not only requires appropriate codes, but also a
formulation of time-dependent boundary conditions (b.c.’s) that would incorporate remote and in situ observations of the Sun in a self-consistent way (see, e.g., [42, 38, 43, 44, 45, 46]).

Such boundary conditions are implemented in a Multi-Scale Fluid-Kinetic Simulation Suite (MS-FLUKSS) collaboratively developed by the UAH and LBNL teams [47, 48, 49, 50]. MS-FLUKSS is a collection of problem-oriented routines incorporated into the Chombo adaptive mesh refinement (AMR) framework [51]. We added the MHD, multi-fluid components, and kinetic Boltzmann components, and the possibility of using non-orthogonal meshes, while the parallelization, load balancing, and other data choreography of the AMR code remains the responsibility of Chombo. We also have implemented a hybrid parallelization for efficient use of the plasma data set in the kinetic module [49]. A new version of our AMR code allows us to perform simulations with the fourth order of accuracy in time and space and uses cubed spheres [52, 53, 54, 55, 56] to generate meshes around the Sun. MS-FLUKSS solves MHD equations with the volumetric heating source terms. It can also resolve the transport of neutral atoms kinetically, by solving the Boltzmann equation. Beyond the Alfvénic surface out into the interplanetary space, we also take into account the influence of interstellar neutral atoms, nonthermal pickup ions, and SW turbulence. In addition, we have implemented special algorithms to track exactly the surfaces that passively propagate with the SW (heliospheric current sheet, CME driving surface, etc) once their initial position is known. Combining these features with AMR, we are able to analyze transient heliospheric structures with high precision. MS-FLUKSS is a parallel (hybrid, MPI/OpenMP implementation) code which has been applied successfully to a number of heliospheric problems and SW interaction with the local interstellar medium [57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67].

In this paper, we present a few examples of our application of MS-FLUKSS to modeling CMEs. In all these simulations, the inner boundary conditions are specified on a sphere where the radial component of the SW velocity vector is greater than the fast magnetosonic speed and provided externally. This means that we do not use our own coronal model (see the paper of Yalim et al. in this volume). As such, we do not use these simulations to reproduce observations at Earth, but rather investigate the capacity of MS-FLUKSS to model discontinuities that

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**Figure 1.** *(Left panel.)* The initial distribution of the heliospheric magnetic field. *(Right panel.)* The CME “blob” structure in radial velocity at 10 $R_{\odot}$ as seen from Earth.
accompanied CME propagation through the interplanetary space.

2. Modeling results

Firstly, we show our solution for the CME event that occurred on Jan 23, 2012. The boundary conditions are designed at 10 \( R_\odot \). We use a simple Parker solution, which extends from 1 \( R_\odot \) to 1 AU, as the background SW in this simulation. This background solution is further modified by the insertion of a CME into it at 10 \( R_\odot \). It is assumed that the temperature and density at the coronal base is \( 1.85 \times 10^6 \) K and \( 3.35 \times 10^{-4} \) kg/km\(^3\), respectively. In this case, \( V_\odot = 8.16 \) km/s. This results in the critical sphere at 4.08 \( R_\odot \) and the corresponding velocity on it equal to 154 km/s. The initial distribution of magnetic field between the inner boundary and 1 AU is obtained with the PFSS method (see Fig. 1, left panel). Magnetic field in the solar corona is assumed to be potential and radial at some distance from the Sun (at the source surface). The distribution is approximated by associated Legendre functions. The coefficients in the expansion are derived from the line-of-sight magnetic field measurement through the Fe I \( \lambda 5250 \) line observations at the Wilcox Solar Observatory. The CME is inserted at 1.5 \( R_\odot \) in the direction N6W27 with respect to the Earth location using the “blob” approach [68, 69, 70, 71] (the blob radius is 0.33 \( R_\odot \)). The maximum velocity, density, and temperature in the blob are the following: 2241 km/s, \( 2 \times 10^{-3} \) kg/km\(^3\), and \( 8 \times 10^6 \) K. Such a blob of high density and pressure is created and launched with high velocity in the outward radial direction, being superimposed with the background SW flow. In Fig. 1 (right panel), we show this CME as seen on the surface of 10 \( R_\odot \) from Earth. To obtain the solution between the inner sphere and 1 AU, we use a spherical grid with the base level resolution 256\(^3\) and one AMR level (the refinement ratio is 4) around the CME. The computational mesh is adapted to the CME profile to capture fine features of its structure including the forward shock wave, compressed ambient SW, and tangential discontinuity that separates the ejected plasma from the compressed SW.
Figure 3. Plasma temperature (left panel) and density (right panel) distributions in the meridional and ecliptic planes for a Jan 23, 2012 CME 23 hours after eruption. The black line in both figures shows the surface driving the CME, which is identified by following the evolution of the “blob” surface with a level-set method.

Figure 2 shows the radial velocity distribution in the ecliptic plane (left panel) and in the plane formed by the Sun’s rotation axis (the $z$-axis) and the line defined by the CME axis (right panel) 23 hrs after its origin. In Fig. 3, we show the plasma temperature and density distributions for the same CME. To demonstrate the evolution of this CME in time, in Figs. 4 and 5, respectively, we show the distributions of plasma temperature in the ecliptic plane and in the plane formed by the $z$-axis and the Earth position 23 and 34 hrs after eruption. Additionally, in Fig. 6, we show the linear distributions of the radial velocity component (left panel) and density (right panel) as functions of time at Earth.

Since the initial shape of the blob is well defined as a tangential discontinuity and knowing that such discontinuities propagate at SW velocity, we can follow the evolution of this surface (the CME driver) as a function of time. It is seen from Fig. 3, that the “mushroom” shape of this CME resembles that of an astrophysical jet injected into the surrounding interstellar medium [72]. Since tangential discontinuities are typically unstable, one would expect that further increase of space resolution will reveal more instabilities.

Another simulation is related to a CME that occurred on 4 November, 1997. The boundary conditions at 10 $R_\odot$ are taken from [73] and are obtained with the Solar-Interplanetary Conservation Element/Solution Element (SIP-CESE) MHD model [46]. The boundary distributions on the inner sphere are shown in Fig. 7 (the density and the radial velocity component) and Fig. 8 (the radial and toroidal magnetic field components) at different moments of time: $t = 0$, $t = 90$ min, and $t = 150$ min. The physical time interval was placed around the CME injection time ($t = 0$) and covered 12 hours.

The boundary conditions were propagated to 0.45 AU with MS-FLUKSS and saved there. Afterwards, the latter were used to establish the solution to 12 AU. The evolution of the SW radial velocity component and density are shown in Figs. 9 and 10, respectively, for the same moments of time as above. It is seen that AMR allows us to resolve the discontinuities accompanying the CME with high accuracy. The solution presented here is in agreement with that obtained in [73]. Worth noticing is the latitudinal asymmetry in the CME propagation.

Finally, in Fig. 11, we show the radial velocity distribution to distance of 12 AU 4 and 23 days after the eruption. Our solution at 12 AU may be used to drive time-dependent interaction of the SW and LISM. Such simulations will be shown elsewhere.
Figure 4. Plasma temperature in the ecliptic plane (left panel) and the plane formed by the $z$-axis and the Earth location (right panel) for a Jan 23, 2012 CME 23 hours after eruption. Distances are given in astronomical units.

Figure 5. The same as in Fig. 4, but 34 hrs after eruption. Distances are given in astronomical units.
3. Conclusions

This paper is a brief summary of our efforts to model CME propagation with MS-FLUKSS. It shows our ability to resolve discontinuities in the SW flow sharply enough to have meaningful predictions at 1 AU and beyond. We did not take into account turbulence and separation between thermal and non-thermal ions in this paper. This clearly should be done at distances beyond 5–10 AU, when these processes become important. Such simulations are of importance for the New Horizons mission and for the future IMAP mission. Regardless of the system of equations to be used near the solar surface, one needs to formulate enough physical boundary conditions to ensure the consistency of the mathematical model of the solar corona. Such boundary conditions can be provided only by the SDO/HMI vector magnetograms. Paper [41] shows the application of characteristic boundary conditions when applying vector magnetograms to modeling active regions on the solar surface.

As shown in [74], the quality of SW predictions at Earth provided by existing first-principles models is improving, but still lags behind data assimilation approaches. On the other hand, it is hard to imagine a data-assimilation model that would be able to reproduce the plasma
Figure 8. Time-dependent boundary conditions at 10 $R_{\odot}$: the radial (top row) and toroidal (bottom panel) magnetic field components at $t = 0$, $t = 90$ min, and $t = 150$ min after the CME launch (from the left to the right) on 4 Nov 1997.

Figure 9. From the left to the right, the distribution of the radial SW velocity component 5, 10, and 20 hrs after the CME launch on 4 Nov 1997. Distances are given in units of $R_{\odot}$.

Figure 10. From the left to the right, the distribution of plasma density 5, 10, and 20 hrs after the CME launch on 4 Nov 1997. Distances are given in units of $R_{\odot}$. 
Figure 11. Distributions of the radial velocity component 4 days (left panel) and 23 days (right panel) after the CME launch on 4 Nov 1997.

and magnetic field properties at Solar Orbiter and Solar Probe Plus, Earth, and other planets at once [59, 75]. The heliospheric community is seeking for an MHD simulation model that is largely data-driven and utilizes characteristic boundary conditions. Given the current and future observational capabilities offered through spacecraft missions around the world, it is possible to apply such models to study the problems of CME origination, propagation and interaction central to heliophysics science, utilizing all available and critical observations. These quantitative measurements range from the photospheric magnetograms to in-situ measurements of plasma and magnetic field properties, which provide the inner boundary conditions, constraints and validations to models. A completely data-driven approach might enable physics-based simulation to improve numerical solutions by making them more realistic and improving our understanding of the underlying physical processes that lead to CME formation, eruption, and dynamic and morphological changes.

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