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Modeling interplanetary coronal mass ejections

Pete Riley [a,*], J.A. Linker [a], Z. Mikic [a], Dusan Odstrcil [b]

[a] Science Applications International Corporation, 10260 Campus Point, Dr. San Diego, CA 92121, USA
[b] NOAA, Space Environment Center, 325 Broadway Boulder, CO 80305, USA

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Abstract

Heliospheric models of Coronal Mass Ejection (CME) propagation and evolution provide an important insight into the dynamics of CMEs and are a valuable tool for interpreting interplanetary in situ observations. Moreover, they represent a virtual laboratory for exploring conditions and regions of space that are not conveniently or currently accessible by spacecraft. In this report, we summarize our recent advances in modeling the properties and evolution of CMEs in the solar wind. We describe our current state of research with three examples: (1) interpreting the global context of in situ observations; (2) identifying new phenomena in the simulations; and (3) differentiating between CME initiation models. We conclude by discussing what topics will likely be important for models to address in the future.

Keywords: Coronal mass ejections; Magnetohydrodynamics; Solar wind; Sun

1. Introduction

The disruption of magnetically closed regions in the solar corona often leads to the eruption of large quantities of material into interplanetary space. During these events, known as coronal mass ejections (CMEs), 10^{12}–10^{13} kg of material are typically released. CMEs play a crucial role in the large-scale evolution of the solar corona (e.g., Hundhausen (1987)) and are the leading cause of large, non-recurrent geomagnetic storms (e.g., Gosling et al. (1993)). Fast CMEs, in particular, have been identified as the leading cause of non-recurrent geomagnetic storms (Gosling, 1997) and can also enhance the geoeffectiveness of recurrent storms (Crooker and Cliver, 1994), making their study of practical importance.

While the coronal magnetic field is undoubtedly the source of energy for the eruption of a CME at the Sun, the basic pre-eruption configuration and the topological changes in the magnetic field that result in the conversion of a large fraction of the magnetic energy into kinetic energy are not well known. By necessity, modeling efforts must be idealized and as such tend to focus on reproducing a particular aspect of the eruption process at the expense of others. While analytic and numerical models have been successful in two dimensions, we are only now beginning to explore the additional richness and complexity that the third dimension brings. Given the inherent complexity of CMEs, it is hardly surprising that theoretical models tend to be idealized. Nevertheless, if we are to make progress in understanding such phenomena, it is important to make connections between models and observations.

Simulations of CME evolution in the inner heliosphere have typically started at 20–30 solar radii (R_S) from which point it is both computationally and physically a much simpler problem to solve. Unfortunately, there are little to no observable parameters at these distances to constrain the boundary conditions, which can lead to a game of "tweaking", where you modify your boundary conditions to improve fits to the observations;

* Corresponding author. Tel.: +1 858 826 9550; fax: +1 858 826 6261.
E-mail addresses: Pete.Riley@saic.com (P. Riley), Jon.Linker@saic.com (J.A. Linker), Zoran.Mikic@saic.com (Z. Mikic).

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all without fear of contradicting any observable parameter (Riley et al., 1997; Riley and Gosling, 1998; Riley, 1999; Odstrcil and Pizzo, 1999a,b). More recently, modelers have extended the lower radial boundary to $1R_S$, but have included ad hoc eruptions, such as velocity pulses (?), superimposed density enhancements (Groth et al., 2000), analytic flux rope representations (Manchester et al., 2004a,b), or an increase in the axial current in a streamer belt configuration (Wu et al., 1999). In these cases, a CME is driven by the resulting force imbalance. In contrast, the approach we have taken is to model the entire process from CME initiation using a mechanism that is consistent with observations, although not necessarily correct through its evolution in the inner heliosphere. Our lower boundary is the photosphere, which is a readily observable region. We use either idealized magnetic field configurations or observed line of sight observations of the photospheric magnetic field.

Using a global resistive MHD model, we have been able to reproduce many of the observed features of coronal mass ejections in the corona and solar wind. Moreover, the simulation results have predicted features that we believe have been subsequently identified in the observations. While these simulations are currently research tools, we expect that in the near future, they will be capable of predicting potentially geo-effective phenomena in the near-Earth environment.

In this report, we summarize our recent advances in modeling the properties and evolution of CMEs in the solar wind. We focus on the physics described by our models rather than the models themselves. We summarize our current state of research with three applications of the models, and we suggest what topics will likely be important for models to address in the future.

2. Description of the model

In this section, we briefly describe the basic features of the coronal and heliospheric models and discuss their integration. A more detailed description is provided elsewhere (Odstrcil et al., 2002). We solve the basic set of time dependent, magnetohydrodynamic (MHD) equations that describe many aspects of the large-scale behavior of the solar corona and inner heliosphere. We separate space into two parts, distinguishing between the "coronal" region, which spans the photosphere up to $20R_S$, and the "heliospheric" region, which spans $20R_S$ to 5 AU. The SAIC coronal MHD model (Mikić and Linker, 1994) is used to solve for the coronal region and the NOAA/SEC heliospheric MHD model (Odstrcil and Pizzo, 1999a) is used to solve for the heliospheric region, being driven directly by output from the coronal solution. This approach has a number of practical and scientific advantages. In particular, each code has been designed specifically for its respective environment. Moreover decoupling these regions in this way allows the heliospheric portion to run at significantly larger time steps than are required by the coronal algorithm.

The details of the algorithm used to advance the equations of the SAIC coronal model are given elsewhere (Mikić and Linker, 1994; Lionello et al., 1998; Mikić et al., 1999). Here, we make a few brief remarks. The equations are solved on a spherical (r, θ, ϕ) grid, which permits non-uniform spacing of mesh points in both r and θ, thus providing better resolution of narrow structures, such as current sheets. In the radial (r) and meridional (θ) directions we use a finite difference approach. In azimuth (ϕ), the derivatives are calculated pseudospectrally, i.e., in the Fourier domain. We impose staggered meshes in r and θ, which has the effect of preserving $\nabla \cdot \mathbf{B} = \mathbf{0}$ to within round-off errors for the duration of the simulation.

The NOAA/SEC heliospheric model solves the time-dependent MHD equations in a spherical geometry using either the Flux-Corrected-Transport or Total-Variation-Diminishing schemes (e.g., Odstrcil (1994); Toth and Odstrcil (1996)). These high-resolution schemes produce second-order accuracy away from discontinuities, while simultaneously providing the stability that ensures non-oscillatory solutions.

The SAIC coronal model, as implemented here, uses a polytropic index of $\gamma = 1.05$ to mimic the near isothermal nature of the solar corona, and thus produces plasma parameters that agree with observed values. On the other hand, the NOAA/SEC code uses $\gamma = 5/3$ in agreement with the observed near adiabatic nature of the solar wind. Ideally one would like to implement a coronal model incorporating conduction, coronal heating, radiation loss, and Alfvén wave acceleration, together with $\gamma = 3/2$ to provide a seamless boundary between the two models. Unfortunately, practically speaking, such an approach is only now becoming feasible in two dimensions (Lionello et al., 1999). We have examined solutions in the vicinity of the boundary between the two models to estimate what artifacts may have been introduced by allowing γ to vary discontinuously across the boundary. Remarkably, with the exception of temperature (and hence thermal pressure), the magnetofluid parameters remain continuous. The radial profile of the plasma temperature obviously changes abruptly at the boundary since $T \propto r^{2(\gamma-1)}$. Thus, in the coronal model, $T \propto r^{-1/10}$, whereas in the heliospheric model, $T \propto r^{-4/3}$. We are currently exploring improvements to the solar model to remove this artifact. Nevertheless, our analysis suggests that the results are qualitatively correct.

For the two-dimensional results presented here, the coronal solution was computed on a non-uniform grid of 200×300 points. The radial spacing ranged from $0.005R_S$ at the inner boundary ($1R_S$) to $0.6R_S$ at the