Three-dimensional global simulation of interplanetary coronal mass ejection propagation from the Sun to the heliosphere: Solar event of 12 May 1997

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[1] A newly developed hybrid code, HAFv.2+3DMHD, that combines two simulation codes, Hakamada-Akasofu-Fry code version 2 (HAFv.2) and a fully three-dimensional (3-D), time-dependent MHD simulation code, is used to study the global interplanetary coronal mass ejection (ICME) from the 12 May 1997 solar event. The solar wind structure is first simulated from the photosphere (1 solar radius, Rs) out to 2.5 Rs. The first step is derived from daily solar magnetograms. The HAFv.2 code is then used from 2.5 Rs to provide input at 18 Rs (0.08 AU) for the three-dimensional MHD code that calculates the evolution of solar wind plasma and interplanetary magnetic field beyond this distance into the heliosphere. A dynamic disturbance, mimicking the flare’s energy output from the 12 May 1997 solar event, is then delivered to this quiescent nonuniform heliospheric structure to model the evolution and interplanetary propagation of the ICME (including its shock). We compare the derived ICME velocity and number density with the Wind spacecraft observations near Earth. We integrate the line-of-sight density in the plane of sky to compare with the white light brightness data observed by the Large-Angle Spectrometric Coronograph (LASCO) instrument on SOHO. This simulation will provide a tool to link the general cases of ICME at 1 AU to their solar sources, as well as to identify the possible origins of shock formation due to CMEs and CME/corotating interaction region interactions. In the case of complex or interacting ejecta, model interpretation is often required to accurately determine the solar sources of the ejecta at 1 AU. Because this newly developed model is performed using 3-D MHD, its results can be extended to simulate coronal and heliospheric observations, including the ambient medium’s nonuniformity provided by the HAFv.2 model, from the recently launched Solar Terrestrial Relations Observatory (STEREO) mission.


1. Introduction

[2] Interactions of interplanetary shock waves and identification of their subsequent products are fundamentally important scientific and space weather topics. From a space weather perspective, it is important to track a specific solar event’s plasma and interplanetary magnetic field (IMF) output as it propagates into interplanetary space with a possible geoeffective consequence. This latter objective is especially important for forecasting purposes when some solar events take place. An interplanetary shock can also accelerate highly energetic particles in interplanetary space. There are many kinds of solar sources, e.g., solar flare, coronal mass ejection (CME), solar filament, or corotating interaction region (CIR) that might produce interplanetary shocks. The CME occurrence rate varies with solar activity. ICMEs occurred every other day during solar minimum (e.g., 196 CMEs occurred in 1996) and four times per day during solar maximum (e.g., 1535 CMEs occurred in 2000) [e.g., Wu et al., 2003].

[3] An interplanetary CME (ICME) is what a solar-generated CME is called as it propagates from the Sun through the heliosphere and is measured by magnetic field and solar wind plasma instruments. It is now believed that magnetic clouds (MCs) constitute an important subset of ICMEs, although Richardson and Cane [2005] indicate that only 15% of CMEs measured at Earth during Cycle 23 were in this category. A magnetic cloud is characterized by above average magnetic field magnitude, low field variance with the field’s slow rotation (many hours), low plasma beta (ratio of thermal to magnetic pressure), unusual alpha/
The electrodynamic connection between the Sun and the Earth-Moon system, or other heliospheric location, is enabled by the solar wind plasma's interaction with the IMF. ICMEs, carrying unusually high strength in the embedded IMF, propagate through dense, high-speed shocked solar wind plasma. These shocks are often accompanied by, and, in fact, accelerate and send ahead energetic ions along the upstream IMF to locations of interest (Earth, Mars, etc.) as discussed, for example, by McKenna-Lawlor et al. [2005] and Aran et al. [2007]. These energized ions penetrate spacecraft, instrument shielding, and, potentially, astronauts with elevated radiation doses. Then, ICMEs, carrying unusually high IMF magnitudes, interact with the magnetosphere or plasmasphere of a planet, causing ionospheric currents with the potential to affect instruments above the surface of the planet. Our interest is to understand better the common trigger of these disturbances, the shocks and MC structures which constitute a large subset of all ICMEs. Often (but not always), the embedded structure in the solar wind is complex, i.e., composed of a magnetic cloud, with an upstream shock wave. The mass and thermodynamics of such structures (ICMEs or magnetic clouds) are important to understand their evolution in the heliosphere. We have therefore explored these structures from both a parametric and explicit event approach for more than 20 years.

The first time-dependent 3-D simulations of interplanetary shock propagation were performed by Han et al. [1988]. Using this model, some parametric studies utilized 3-D MHD simulations of interplanetary magnetic field changes at 1 AU as a consequence of an interaction with a flat heliospheric current/plasma sheet (HCS/HP) [Wu et al., 1996] and also with a tilted HCS/HP [Wu and Dryer, 1997]. In addition, Dryer et al. [1997] used the code to simulate the 14 April 1994 interplanetary CME and its propagation to Earth and Ulysses (in the southern hemisphere at ~4 AU). Wu et al. [2005] recently performed a parametric study, via 3-D MHD simulations, of the shock time of arrival at Earth. They found that the background nonuniformity of the solar wind plasma and IMF is of negligible consequence provided the energy output of the solar disturbance is unusually large, e.g., $10^{34}$ ergs or higher.

All of these studies, however, were limited by having a lower boundary at 18 Rs (where Rs = solar radius = $6.95 \times 10^8$ km) and with an ideal steady state solar wind condition. This motivated us to relax this restriction and to perform a global three-dimensional (3-D) numerical simulation from the Sun to the Earth. Therefore we linked the space weather-validated 3-D Hakamada-Akasofu-Fry version 2 (HAFv.2) model [c.f., Hakamada and Akasofu, 1982; Fry et al., 2001; Dryer et al., 2004] to the full 3-D MHD model of Han et al. [1988]. Thus solar surface magnetograph observations can now drive, continuously, the HAFv.2 model and, then, the Han et al. model throughout the heliosphere. We will refer to this hybrid model, henceforth, as “HAFv.2+3DMHD.”

In this study, we use this newly developed global 3-D simulation model to simulate a famous solar event of 12 May 1997 which is described observationally by Thompson et al. [1998, 1999] and simulated by Wu et al. [2001]. This is an “ideal” event from two points of view: (1) the solar flare, “EIT wave,” and full halo CME took place during solar minimum with no other significant disk activity; and (2) the HCS/HPS was nearly “flat,” i.e., gently waving.

The interplanetary portion of this event has been studied previously with the use of a 3-D MHD model [Odstrcil et al., 2004, 2005]. These authors concluded that “it is always an advantage to use different models for the same problem. Not only can one obtain higher confidence in predicted features and effects, but also the differences in results are very helpful in estimating their accuracy, in understanding the physics, and in learning what should be improved in the future.” The present work is presented in this spirit.

Odstrcil et al. [2004, 2005] were concerned with the interplanetary differences caused by various coronal outflow models (c.f. Arge and Pizzo [2000], Arge et al. [2002, 2004], and subsequent variations thereof) for small-scale structures in the pre-event background solar wind. On the other hand, we will use only one of the Arge and Pizzo [2000] approaches but with a different assumption for mimicking the launch and solar origin of the ICME. As in the Odstrcil et al. [2005] work, we will also be concerned with the comparison of the observed Wind velocity profile with our simulated one. In addition to offering a “Model A–Model B” validation in the spirit noted above, we offer another motivation. As noted above, the HAFv.2+3DMHD model can be driven continuously and therefore can be used as a second generation operational tool, the first one being the HAFv.2 model [Fry et al., 2001]. The numerical simulation model is described in section 2; observations are described in section 3; simulation results are described in section 4. Discussion and conclusions are given in sections 5 and 6, respectively.

2. Simulation Model

The nonuniform background conditions of the solar wind plasma and IMF are essential for the model coupling of the corona to the solar wind modeling codes. We use this hybrid model to simulate CME/ICME/Shocks propagating
from the Sun to the Earth and beyond with a realistic solar wind background condition.

Several fully 3-D MHD simulations exist for studying solar eruptions from the Sun to Earth. However, each model has its own limitation. For example, Han et al. [1988] first used a 3-D, MHD, time-dependent numerical model to study supersonic and super-Alfvénic MHD flow from 18 Rs to 1 AU. Their code can study solar phenomena outward from 0.08 AU because it was designed only for supersonic/super-Alfvénic flow. In order to study the physics of the flow from the subsonic/sub-Alfvénic region to the supersonic/super-Alfvénic regime, the entire solution requires special mathematical treatment of time-dependent lower boundary conditions as discussed extensively by Wu and Wang [1987]. These boundary conditions were unavailable to Han et al. [1988]. Thus an alternative hybrid solution that combines the latter code with the empirical data-based source surface code (see section 2.1) is adopted for this paper.

Another 3-D MHD numerical model used to investigate the temporal and spatial evolution of large-scale solar wind structures was developed by Odstrcil and Pizzo [1999a, 1999b]. These workers studied the evolution of coronal mass ejections launched at several heliographic positions into a tilted-dipole ambient solar wind flow which is appropriate around solar activity minimum and declining phase [Odstrcil and Pizzo, 1999b]. However, the 3-D model used by Odstrcil and Pizzo [1999a, 1999b] can only simulate solar wind structures beyond 21.5 Rs. It has the same limitation as the 3-D model developed by Han et al. [1988], although its numerical diffusion is decreased when similar grid sizes are used as discussed in section 2.2.

As noted in section 1, HAFv.2+3DMHD combines two simulation codes, Hakamada-Akasofu-Fry code (HAFv.2) [see also Fry et al., 2001, and references therein] and a fully 3-D, time-dependent MHD simulation code [Han et al., 1988; Detman et al., 1991, 2006]. We briefly summarize below two basic steps: (1) from the Sun to 2.5 Rs, thence to 0.08 AU (18 Rs); and (2) from 0.08 AU to the Earth and beyond.

2.1. Model for Simulating CME/ICME/Shock From 2.5 Rs to 0.08 AU (18 Rs)

This physics-based code is a kinematic model, HAFv.2 [Fry et al., 2001]. The model uses a modified kinematic approach to simulate the solar wind conditions out to 18 Rs with data from Carrington Rotation maps (2.5 Rs), provided by NOAA’s Space Environment Center (http://sec.boulder.noaa.gov), as the input. The output of HAFv.2 at 18 Rs (0.08 AU) provides inputs for the time-dependent 3-D MHD solar wind model. The system is driven by a time series of photospheric magnetic maps composed from daily solar photospheric magnetograms (http://wso.stanford.edu). Use of these data to provide solar wind velocity and radial IMF at 2.5 Rs is described by Arge and Pizzo [2000].

2.2. Model for Simulating CME/ICME/Shock From 0.08 AU to the Earth and Beyond

The numerical 3-D MHD scheme used in this analysis is an extension of the two-step Lax-Wendroff finite difference method [Lax and Wendroff, 1960]. We found that using the Lax-Wendroff (L-W) method is still a valid approach (see next paragraph). The details of the computational procedures can be found in the work of Han et al. [1988] and Detman et al. [1991]. When using the two-step Lax-Wendroff finite difference method, the governing equations are required to be written in conservation form. A complete description of this conversion can be found in the work of Han [1977]. The governing equations, for an ideal, single fluid, perfect gas, include conservation of mass, equation of motion, conservation of energy, and induction equation.

It is appropriate to ask: why are we using the early L-W computational method, known for high numerical diffusion (hence nonsharp shocks), when newer techniques [c.f., Odstrcil et al., 2002; Manchester et al., 2004] are now in use? This is indeed an appropriate question from readers interested in “Model-Model” validation. The answer is twofold: first, the L-W method is an explicit, second-order scheme which means that numerical diffusion is proportional to the square of the grid size. Thus reducing the grid cell size by one-half will reduce the diffusion by one-fourth. Vandas and Odstrcil [2000] performed a comparison study (on a complex 3-D MHD flux rope problem in the solar wind) with both the Han et al. [1988] model and the Odstrcil and Pizzo [1999a, 1999b] model; the latter is based on the more modern TVD (total variation diminishing) scheme. They demonstrated that equivalent results are obtained provided the L-W grid size is sufficiently small. Second (noting this accuracy), from a practical viewpoint, the L-W approach, running on a desktop personal computer, runs much faster than real time (depending on boundary conditions.)

The computational domain for the 3-D MHD simulation is a Sun-centered spherical coordinate system (r, θ, φ) with the r-axis in the ecliptic plane. Earth is located at r = 215 Rs, θ = 0°, and φ = 0°. The domain covers −87.5° ≤ θ ≤ 87.5°; 0° ≤ φ ≤ 360°; 18 Rs ≤ r ≤ 285 Rs. An open boundary condition at both θ = 87.5° and θ = −87.5° is used so that there are no reflective disturbances. A constant grid size of Δr = 3 Rs, Δθ = 5° and Δφ = 5° is used. The two angular grid sizes are chosen to be equal to those provided by the photospheric magnetic maps described by Arge and Pizzo [2000]. The radial grid size, at this time, is chosen to be also large but still sufficient to provide insight for global structures such as shocks. (The Odstrcil et al. [2005] study used a smaller set of grid sizes (~0.67 Rs, 2°, and 2°, respectively) for their specialized study (on a supercomputer) as discussed above.) Future work will consider smaller grid sizes for further physical exploration after basic physical features are examined.

3. Observations

In this study, we investigate a famous full halo CME event (first seen by SOHO Large-Angle Spectrometric Coronograph’s (LASCO) C2 coronagraph at 0530 UT) that occurred after a flare, starting at about 0516 UT and located at N21W08, on 12 May 1997. More details on the solar observations are provided by Thompson et al. [1998, 1999].

Figure 1a shows the solar wind plasma and magnetic field observations from the Wind spacecraft. The dashed vertical line represents the fiducial shock arrival time at Wind at about 0115 UT on 15 May 1997. A magnetic cloud
(noting the high field magnitude, low field variance, low temperature, low beta, and Bz rotation) is also observed following the shock. We will discuss, in section 4, the simulation results at Earth (i.e., at Wind) and elsewhere in the heliosphere out to 285 Rs. Our emphasis will be on the latter 3-D global ICME propagation that started on the date and time mentioned above.

4. Simulation Results

4.1. Initialization “Tuning”

[20] The reader is reminded that the HAFv.2+3DMHD code, in the “event mode,” is initialized by an input solar wind velocity pulse of 600 km/s that is used (at the center of an expanding quasi-spherical disturbance) to mimic the energy released by the flare. This velocity pulse rises exponentially for 45 min to reach the peak, remains constant for 170 min, and then decays to the original value after a total of 260 min. The 3-D MHD near-Sun study by Wu et al. [2001, Figure 10] showed that a weak shock had developed at 1.2 Rs following a small pressure pulse. In the present study, we “tuned” our shock to arrive at the observed time at Earth. It should be noted that our initialization differs from that used by Odstrcil et al. [2005] who used a density pulse of 4 times the background value for 5.6 hours as well as a speed of 650 km/s. In both studies, then, these transient disturbances are assumed to be the “ICME” without further consideration of, for example, a flux rope or other IMF configuration. Another difference between the two approaches is that our “ICME” is initially centered at N21W08 (i.e., above the flare site), whereas the Odstrcil et al. [2005] study considers the initial central axis to point...
4.2. Validation at Wind

[21] We first draw attention to the simulation comparison with the Wind observations at Earth in Figure 1b. The red dotted lines for the simulated solar wind plasma speed and density shows, first, that the ambient solar wind speed was overpredicted (by about 100 km/s). Also, the ambient density was underpredicted. We believe these discrepancies are due to uncertainty errors in the Wang-Sheeley-Arge approximations used in the HAFv.2 model as well as in the coarse gridding (5° × 5°) of the observation’s source surface computation, the same as that required, thereby, for the HAFv.2 grid size. Nevertheless, by appropriate tuning, as noted above, for the “flare input” procedure, the shock arrival time and its subsequent temporal speed and density profiles are excellent for several days thereafter.

4.3. General Outline of Global Presentation

[22] Figure 2 shows the simulated global view of the solar wind velocity, V. Figure 3 shows a related global view of the solar wind density, N. We discuss Figures 2 and 3 below in more detail. These two figures indicate an effort to present snapshots in the spatial sense of a medical MRI (magnetic resonance imager) but with the added temporal presentation for our interplanetary propagation requirement. Verification of such “MRIs,” of course, will require “ground truth” from many more spacecraft in addition to ACE’s L1 location. The spatial and temporal snapshots are described in the next three paragraphs.

[23] First, the first three columns show the solar wind speed (Figures 2a–2o) and density (Figures 3a–3o) on surfaces of angular cones that are centered at the Sun’s center. These conical angles are at 22.5° north, close to the actual flare’s latitude; 25° north, close to Earth’s latitude in the solar equatorial coordinate system; and 22.5° south, representative of a response in the southern heliosphere. Second, the three top rows of Figures 2 and 3 show V and N simulated data within 100 Rs from the Sun’s center. The solid circle in the lower two rows is at 1 AU (215 Rs). Earth is located at heliolongitude, φ = 0°; thus the east limb (relative to Earth) is at the top, 90° east; and the west limb is at the bottom, 90° west. The outer boundary for the two bottom rows of both Figures 2 and 3 (with V and N color bars) is at 285 Rs.

[24] Third, the two rightmost columns (Figures 2p–2y and 3p–3y) are meridional views of V and N, respectively. One column is in the plane perpendicular to the solar equatorial plane and through the Sun-Earth axis (i.e., at φ = 0°). The other column is a view from φ = 20°E. Lack of space, obviously, precludes views in other conical and meridional “slices” of our “MRI” presentation. (Movies of these “slices” are available on request.)

4.4. Figures 2 and 3 Global Presentations

[25] The time period in Figure 2’s top three rows is the short time within 100 Rs, from 1100 UT to 1500 UT on 12 May 1997; i.e., within 10 hours after flare initiation. The first three columns, as noted above, show the velocity on three conical surfaces: 22.5° north (Figures 2a–2e); 2.5° north (Figures 2f–2j); and 22.5° south (Figures 2k–2o). The last two columns, as also noted above, show the velocity within two meridional planes: 0° (i.e., including the Earth), (Figures 2p–2t); and 20° east of Earth (Figures 2u–2y). The lower two rows in Figure 2 show zoom-out views, to 285 Rs, of the simulated outer heliosphere’s disturbed solar wind velocity about 2 days later, i.e., 1400 UT to 2000 UT on 14 May 1997, just prior to the shock and ICME impacts at Earth.

[26] The time period in Figure 3’s top three rows is extended to the day after the flare, again within 100 Rs: from 1100 UT on 12 May to 0900 UT on 13 May 1997. The conical views in the first three columns are the same as in Figure 2, and the meridional views in the last two columns are the same, also, as in Figure 2. The lower two rows in Figure 3 show the zoom-out view (to 285 Rs) of the compressed, followed by rarefying, density process of the shock and ICME from 1600 UT on 14 May to 0100 UT on 15 May 1997 when the shock arrives at Earth. Note that our present 3-D MHD simulation does not include an embedded flux rope that apparently is indicated in the Wind data shown in Figure 1.

[27] Asymmetry of the Shock/ICME is clearly seen in heliolongitude and heliolatitude as the global structure passes through the 18 Rs sphere and into the nonuniform ambient solar wind medium that prevailed during solar minimum. This structural nonuniformity is especially notable within the inner heliosphere as seen in the first rows of Figure 2. Also, the limited latitudinal extent of the reverse shock in the northern hemisphere (see the trailing red trace in Figures 2f, 2g, 2h, and 2y) precludes its penetration to the Earth at between θ ~ −2.8° and θ ~ −2.3° south during 13–18 May.

[28] It is clear that the CME/Shock arrived at 18 Rs in the north (see Figures 2a–2c) earlier than at the solar equator (see Figures 2f–2h) and in the southern hemisphere (see Figures 2k–2l). Figures 2p–2r and 2u–2w also show clearly that CME/Shock arrived at 18 Rs in the north earlier than in the other places. However, they were overtaken (radially) by their propagation into a high-speed stream at 20° east close to the HCS/HPS.

[29] Figures 2d–2e, 2i–2j, 2n–2o, 2s–2t, and 2x–2y and Figures 3d–3e, 3i–3j, 3n–3o, 3s–3t, and 3x–3y also show that the shock arrived at 1 AU in the general direction of the original ejection direction of the CME (~22.5°N) as anticipated. Yet such an assumption cannot be made under solar maximum conditions when the ambient medium has a contorted HPS/HCS’ highly nonuniform flow. In the present case of solar minimum, it is obvious that the ICME/Shock arrived to the north much earlier than in the other directions (i.e., in the solar equatorial plane or southern hemisphere). Again, we emphasize the fact that although this result was expected because of the flare’s location, one can expect contrary effects under conditions of strong background nonuniformities. Figures 2–3 also show (c.f., Figure 2c) the ICME/Shock deformation effect of the so-called solar minimum bimodal background solar wind on the propagation speed of the shock.

4.5. Simulated White Light Views in Plane of Sky

[30] We also integrated the density along lines of sight from the Earth (as well as, not shown, from a Solar
Terrestrial Relations Observatory (STEREO)-like vantage at 90° west of Earth. We subtracted the steady-state solar wind plasma data from this integration in order to approximate the resultant, combined CME/ICME/Shock brightness difference images as viewed, hypothetically, by the coronagraphs on STEREO/SECCHI from Earth’s vicinity. Figure 4 shows this plane of sight, simulated coronagraph view after the “pre-event” brightness is removed. Note the higher

**Figure 2.** The simulated profiles of velocity using the HAFv.2+3DMHD model (see text in sections 4.3 and 4.4).
density in the Eastern sky, relative to the western sky, that is due to a CIR development in the eastern hemisphere (c.f. Figure 2a and Figures 3r and 3w). Similar results were described by Odstrcil et al. [2005] thus confirming general features of, in essence, a “Model A–Model B” validation. Figure 5 shows a comparison of the actual SOHO/LASCO image at 1739 UT, 12 May 1997, with the simulation: (1) zoomed-out image shown in Figure 2a; and (2) the
zoomed-in image, Figure 2b, from 18 to 100 Rs. The latter figure includes the LASCO C3 field of view out to 32 Rs.

5. Discussion

[32] Odstrcil et al. [2002] recently combined a portion of a 3-D model [Mikic and Linker, 1994], the latter being capable for simulation of the solar wind from the Sun (1 Rs) to 21.5 Rs, with the 3-D MHD model of Odstrcil and Pizzo [1999a]. It is not clear, however, if the inner portion of this combined code used lower boundary conditions as noted by Wu and Wang [1987]. This hybrid model was then capable of simulating the solar wind beyond the matching position (21.5 Rs) to interpret the global context of a coronal mass ejection observed by two spacecraft. In another 3-D approach, a parallel adaptive mesh refinement (AMR) finite-volume scheme for specifying ideal MHD flows was used to simulate the initiation, structure, and evolution of a coronal mass ejection observed by two spacecraft. In another 3-D approach, a parallel adaptive mesh refinement (AMR) finite-volume scheme for specifying ideal MHD flows was used to simulate the initiation, structure, and evolution of a coronal mass ejection observed by two spacecraft. In another 3-D approach, a parallel adaptive mesh refinement (AMR) finite-volume scheme for specifying ideal MHD flows was used to simulate the initiation, structure, and evolution of a coronal mass ejection observed by two spacecraft. In another 3-D approach, a parallel adaptive mesh refinement (AMR) finite-volume scheme for specifying ideal MHD flows was used to simulate the initiation, structure, and evolution of a coronal mass ejection observed by two spacecraft. In another 3-D approach, a parallel adaptive mesh refinement (AMR) finite-volume scheme for specifying ideal MHD flows was used to simulate the initiation, structure, and evolution of a coronal mass ejection observed by two spacecraft. In another 3-D approach, a parallel adaptive mesh refinement (AMR) finite-volume scheme for specifying ideal MHD flows was used to simulate the initiation, structure, and evolution of a coronal mass ejection observed by two spacecraft. In another 3-D approach, a parallel adaptive mesh refinement (AMR) finite-volume scheme for specifying ideal MHD flows was used to simulate the initiation, structure, and evolution of a coronal mass ejection observed by two spacecraft. In another 3-D approach, a parallel adaptive mesh refinement (AMR) finite-volume scheme for specifying ideal MHD flows was used to simulate the initiation, structure, and evolution of a coronal mass ejection observed by two spacecraft. In another 3-D approach, a parallel adaptive mesh refinement (AMR) finite-volume scheme for specifying ideal MHD flows was used to simulate the initiation, structure, and evolution of a coronal mass ejection observed by two spacecraft. In another 3-D approach, a parallel adaptive mesh refinement (AMR) finite-volume scheme for specifying ideal MHD flows was used to simulate the initiation, structure, and evolution of a coronal mass ejection observed by two spacecraft. In another 3-D approach, a parallel adaptive mesh refinement (AMR) finite-volume scheme for specifying ideal MHD flows was used to simulate the initiation, structure, and evolution of a coronal mass ejection observed by two spacecraft. In another 3-D approach, a parallel adaptive mesh refinement (AMR) finite-volume scheme for specifying ideal MHD flows was used to simulate the initiation, structure, and evolution of a coronal mass ejection observed by two spacecraft. In another 3-D approach, a parallel adaptive mesh refinement (AMR) finite-volume scheme for specifying ideal MHD flows was used to simulate the initiation, structure, and evolution of a coronal mass ejection observed by two spacecraft. In another 3-D approach, a parallel adaptive mesh refinement (AMR) finite-volume scheme for specifying ideal MHD flows was used to simulate the initiation, structure, and evolution of a coronal mass ejection observed by two spacecraft. In another 3-D approach, a parallel adaptive mesh refinement (AMR) finite-volume scheme for specifying ideal MHD flows was used to simulate the initiation, structure, and evolution of a coronal mass ejection observed by two spacecraft. In another 3-D approach, a parallel adaptive mesh refinement (AMR) finite-volume scheme for specifying ideal MHD flows was used to simulate the initiation, structure, and evolution of a coronal mass ejection observed by two spacecraft. In another 3-D approach, a parallel adaptive mesh refinement (AMR) finite-volume scheme for specifying ideal MHD flows was used to simulate the initiation, structure, and evolution of a coronal mass ejection observed by two spacecraft. In another 3-D approach, a parallel adaptive mesh refinement (AMR) finite-volume scheme for specifying ideal MHD flows was used to simulate the initiation, structure, and evolution of a coronal mass ejection observed by two spacecraft.

[33] The goal of this latter work was to generate the well-known flux rope and shock ICME at Earth. Although this is an important step in 3-D MHD studies, this work is limited to the mimicking of single solar events, not to the study of multiple events and their shock interactions. Alternatively, while the latter physical processes are studied by Dryer et al. [2004], their approach is a kinematic one that conserves mass, momentum, and magnetic flux but is not fully MHD because the energy equation is not considered.

[34] In the present study, we were motivated by a flare observed at 0516 UT on 12 May 1997 which was located at N21W08. A full halo CME was first observed by SOHO/LASCO at 0530:05 UT on that day. The estimated speed of the leading edge from 2 to 32 Rs is about 600 km/s. In this study, we added a solar disturbance at N21W08 with a solar wind input speed pulse, \( V = 600 \) km/s. This value was guided by the 3-D MHD theoretical calculation of Wu et al. [2001] as well as by the “tuning” objective for a correct shock arrival time. The simulated shock’s arrival (about 0115 UT, 15 May 1997) is close to the observation at 1 AU at 0100 UT on May 15 (see Figure 1 and also inferred from Figures 3j and 3t).

[35] Using a 3-D MHD model with TVD Lax-Friedrichs scheme, Odstrcil et al. [2004, 2005] studied the 12 May...
1997 solar event. They used the following procedures, different from ours, to simulate the propagation of the ICME. (1) They launched a plasma cloud with a pressure pulse of 4 times the ambient value and a uniform velocity of 650 km/s at 30 Rs [Odstrcil et al., 2004] and revised to 21.5 Rs [Odstrcil et al., 2005]. (2) They applied an empirical cone model with its central axis of the CME cone pointing to N3.0 and W1.0 with an angular width of 50 degrees. This empirical model assumes the CME to be confined within this angle from the Sun to the distances mentioned above. (3) They estimated the leading edge of the CME to have reached a radial height of 30 Rs at 1530 UT with a speed of 700 km/s [Odstrcil et al., 2004]. In their newer work [Odstrcil et al., 2005], these estimates were 21.5 Rs, 1400 UT, and 650 km/s, respectively. (4) They estimated that the CME took about 8 hours (with the anticipated diameter of 50 degrees) to pass through that 30 Rs position [Odstrcil et al., 2004]. In the newer work, their estimate is 5.6 hours at 21.5 Rs. (5) The simulation domain is 120° and 360° in latitude and longitude direction, respectively. Thus they assumed that the CME does not expand in latitude or longitude in the lower corona. Our temporal result, initiated at 2.5 Rs, was not artificially confined by any empirical “model” as in their case. Instead, its latitudinal and longitudinal expansion was governed by first principles within our 175° (heliolatitudinal) and 360° (heliolongitudinal) domain. For some unknown reasons, their simulated CME does not expand significantly in the longitude direction at 1 AU. For example, Figure 9 of Odstrcil et al. [2005] shows clearly that the width in longitude of the ICME in the solar equatorial plane is about 60°, slightly greater than the empirically imposed 50° cone angle’s requirement.

[36] In this study, we simulate solar wind features by adapting observation data near the surface of the Sun (2.5 Rs). We use observed daily solar photospheric magnetograms to provide data at 2.5 Rs by using the Arge and Pizzo [2000] inverse flux divergence and speed calculation procedure to provide inputs to the HAFv.2 model at that location. Then we use the output data at 18 Rs from the HAFv.2 model as the input for the 3-D MHD model. Our approach differs from Odstrcil et al. [2005] who added a plasma cloud at 0.1 AU instead of near the Sun. On the basis of the observations of a solar disturbance, e.g., a solar flare within an active region, we added the disturbance at the flare’s location, at N21W02, but Odstrcil et al. [2004, 2005] used N03W01 as suggested by their empirical cone model. We consider the latter to be unnecessary as part of a self-consistent 3-D MHD simulation. Our results not only show the expansion of the ICME at 1 AU but also demonstrate its propagation asymmetry in both latitude and longitude directions which are due to (1) the location of the solar disturbance source, and (2) nonuniform background solar wind media (see Figures 2 and 3 and the description in section 4). In addition, this study also shows the density profiles along with the plane of sky brightness plots that were compared with the SOHO/LASCO observation of the CME (see Figures 4 and 5). The reports of Odstrcil et al. [2004, 2005] did not show these features.

[37] We believe that this simulation code, HAFv.2+3DMHD, will provide a tool to link general cases of ICMEs at 1 AU to their solar sources, as well as to identify the possible origins of shock formation due to CMEs and CME/CIR interactions. In the case of complex or interacting ejecta, model interpretation is often required to accurately determine the solar sources of the ejecta at 1 AU. The results of the present simulation show the asymmetry of the CME/ICME/Shock in longitude and latitude as the structure passes through the 18 Rs sphere into the nonuniform solar medium during solar minimum. The CME/ICME/Shock arrived at 1 AU earlier in the northern flare axis direction of the disturbance, as anticipated, than at the other directions (see the left three columns of Figures 2–3).

[38] In addition, this model is also capable to integrate the density along lines of sight from any direction. The results, simulated from Earth’s position, are similar to the SOHO/LASCO image (see Figure 5). Since this is a fully 3-D MHD simulation, we are also able to integrate the density from lines of sight positions such as 90° west or east from the Earth [see, also, Odstrcil et al., 2005]. This kind of work will provide simulation results that may be compared with future observations from the upcoming STEREO mission. Finally, it is important to emphasize the fact that HAFv.2+3DMHD results, following appropriate validations, can provide simulated benchmarks, including continuously running ambient heliospheric background approximations, for a variety of 3-D coronal and heliospheric observations.

6. Conclusions

[39] This study performs a simulation example of coronal mass ejection and shock propagation as a realistic 3-D solar wind structure from the Sun to the Earth. The famous solar event of 12 May 1997, described observationally by Thompson et al. [1998, 1999] and theoretically by Wu et al. [2001], is used as motivation for this simulation. The newly developed code, HAFv.2+3DMHD, combines two simulation codes: Hakamada-Akasofu-Fry code version 2 (HAFv.2) [Fry et al., 2001] and a fully three-dimensional, time-dependent MHD simulation code [Han et al., 1988]. The solar wind structure is simulated out to 2.5 Rs from source surface maps derived from daily-provided solar magnetograms using procedures given by Arge and Pizzo [2000] and the HAFv.2 code. The latter code is then used to provide input for the lower boundary of the 3-D MHD code to calculate the evolution of solar wind plasma beyond 18 solar radii (0.08 AU). A dynamic disturbance (velocity pulse in the present case) is delivered to this nonuniform structure to model the evolution and interplanetary propagation of a coronal mass ejection (ICME, including its shock but without a flux rope). We felt it unnecessary to parameterize the input pulse (c.f. magnetic flux emergence, pressure pulse, etc.) for this study. We also integrated the line of sight density changes to compare with data observed by the LASCO instrument on SOHO. In particular, we offer this procedure to provide insight to the global structure of the derived ICME (including the shock, of course) structure at 1 AU via comparison to Wind solar wind data and IMF for this 12–15 May 1997 event during a reasonably ideal period of solar minimum.

[40] We believe that this simulation procedure can provide a tool to link the general cases of ICMEs at 1 AU to their solar sources, as well as to identify the possible
origins of shock formation due to CME and CME/CIR interactions. In the case of complex or interacting ejecta, model interpretation is often required to accurately determine the solar sources of the ejecta at 1 AU. Because this newly developed model, HAFv.2+3DMHD, is performed using 3-D MHD, its results can be extended to simulate a variety of coronal and heliospheric observations, including the essential ambient medium’s nonuniformity provided by the HAFv.2 model in a continuous temporal mode.

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