MHD SIMULATIONS OF SOLAR AND INTERPLANETARY PHENOMENA

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Abstract. Workers in the field of magnetohydrodynamics (MHD) have been interested in the hypothesis that observed solar activities can be utilized in a deterministic way to predict the bulk flow consequences of these activities in the three-dimensional heliosphere. Exploration of this hypothesis, using the conventional/classic initial boundary value approach, will be reviewed against the background of basic, ideal (except for shocks) one-fluid approximations. This work has been divided into two parts: near-Sun simulations in two dimensions of coronal mass ejections (CMEs) as well as interplanetary simulations in 2D and 3D of propagating shocks. In the latter case, the flows behind the shocks should be thought of as interplanetary "ICMEs", i.e., the interplanetary, evolutionary consequences of the near-Sun simulations.

Initialization of these simulations has been based on observations (optical, soft X-ray, radio) from both ground- and space-based instruments. Simulation outputs have been compared with *in situ* plasma and field observations and interplanetary scintillations (IPS). Improvements in the initialization procedures – spatial/temporal variations of solar plasma and field parameters at the coronal base – are expected from YOHKOH, SOHO, CORONAS-I, and TRACE experiments. "Ground truth" observations from WIND, SOHO, ACE, and INTERBALL experiments should then be compared with three-dimensional MHD outputs in tests of the fluid hypothesis noted above.

Key words: Solar-Interplanetary – Corona – Solar Wind MHD Simulation – Coronal Mass Ejections

1. Introduction

The MHD modeler in the field of solar/interplanetary physics is faced with a truly "grand challenge". He or she is given the fundamental fluid conservation laws of mass, momentum, and energy as well as the magnetic induction equation (subject to the solenoidality condition) and a plasma constituative equation. The modeler then chooses restrictions such as an ideal plasma (or a resistive, viscous, and/or thermal conductive plasma) and a single (or, perhaps, a two-fluid) gas in the solar corona and/or the solar wind. Dimensionality (one-dimensional, two-dimensional, or three-dimensional) is the next choice. The modeler will sometimes choose a variant, in order to study additional wave modes by considering, say, two or three components of the velocity and magnetic field vectors in conjunction with the simplest one-dimensional (1D) or the more complicated two-dimensional (2D) geometries. In the former case, only partial derivatives of the dependent variables are computed with respect to time and one spatial coordinate; in the latter

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case, they are computed with respect to time and two coordinates. Hence the "jargon" for such models is often called one and one-half dimensional, one and three-fourths dimensional, or two and one-half dimensions if partial derivatives with respect to additional spatial coordinates are taken into account. Analytic solutions for physically realistic problems generally are beyond reach for all but the 1D problems. The grand challenge, when confronted with the necessity of comparison with observations, is clearly to obtain meaningful three-dimensional (3D) solutions in the numerical context.

This review is concerned with the following two parts: (a) near-Sun simulations in 2D of coronal mass ejections in Section 2; and (b) interplanetary simulations in 2D and 3D of propagating fast mode waves or shocks, in Section 3. I will also discuss some issues of solar "drivers", used in these examples for initialization of these codes, and their output comparisons with *in situ* plasma and interplanetary magnetic field (IMF) as well as with remotely sensed interplanetary scintillations (IPS). Some concluding remarks will be given in Section 4.

2. Near-Sun Simulations

A topic of intensive research is associated with the question: what is the cause (or, more appropriately phrased, what **are** the "causes") of coronal mass ejections (CMEs)? A recent proposal (Gosling, 1993; Hundhausen, 1993) is that large, nonrecurrent geomagnetic storms are caused by "CMEs", measured in interplanetary space, that come exclusively from de-stabilized coronal helmet streamers, i.e., from large-scale solar magnetic structures. These workers maintain that solar flares (i.e., from smaller-scale magnetic structures) play no fundamental role in the generation of well-known, coronagraph-observed white-light CMEs near the Sun. Another proposal (Dryer, 1994) is that both small **and** large-scale magnetic structures, depending on the details of the driving mechanism, play fundamental roles in the generation of CMEs and their interplanetary, evolutionary counterparts (ICMEs).

The "causes" of CMEs have been, and continue to be, of great interest to the observational and modeling communities. Reviews from differing perspectives have been written, for example, by Low (1982); Dryer (1982, 1994); and Hundhausen (1993). One approach to the study of the physical processes of one class of CMEs is to consider the quasi-static evolution of force-free coronal magnetic fields as they respond to photospheric perturbations. At some critical point in this large-scale field evolution, either loss of equilibrium (Low, 1981) or instability (Klimchuk and Sturrock, 1989) causes the structure to disrupt, thereby releasing its free energy, propelling a "CME", and shifting thereafter to a lower energy state.

A second, more rigorous approach has been chosen by a separate group of workers, who chose to use the full set of 2D, time-dependent, MHD equations as noted in the Introduction. For example: (1) Wu *et al.* (1983) first examined the magnetic field evolution that follows photospheric footpoint shearing in a dissipationless plasma; (2) Forbes and Priest (1982) studied 2D reconnection that followed emerging magnetic flux from below the photosphere; and (3) Mikic *et al.* (1988) also used a resistive plasma but in the "driver-forcing" case of footpoint shearing motion.

The question of stability was studied in both the linear framework (Hood and Priest, 1980) as well as in the nonlinear framework (Wu *et al*, 1991). Also, using proper time-dependent boundary conditions (Hu and Wu, 1984), both the globally ideal and locally resistive models were studied by Wu *et al.* (1995a) and Zhang *et al.* (1994) in the context of emerging magnetic flux as the "driver"; by Linker and Mikic (1995) in the context of helmet-streamer footpoint shearing; and by Guo *et al.* (1992), who studied various kinds of "drivers". The latter compared previous thermally-driven models (Dryer *et al.*, 1978; Steinolfson and Hundhausen, 1988) with results from a magnetically- and mass-driven model (Hu, 1990). To obtain loop-shaped CMEs, such as those observed by Sime *et al.* (1984), Guo *et al.* (1992) found that:

1. both pre-event coronal configurations and driving mechanisms are important;
2. introduction of an arbitrary heating function in the corona is not necessary; and
3. magnetic flux emergence, footpoint shearing, and momentum increases are *all* likely "driver" candidates to propel *non-flare-associated* CMEs. The thermal pulse, explicitly suggested by various light curve observations of density and temperature increases (Dryer *et al*, 1978, and more recently by YOHKOH soft and hard X-ray imagery), is still considered to be a likely "driver" candidate for *flare-associated* CMEs.

At the present time, most attention from the modeling community has been directed to the case of non-flare-related CMEs, possibly as a result of the apparent popularity of the "solar flare myth" hypothesis proposed by Gosling (1993). Nonetheless, recent 3D resistive modeling of the reconnection process and coalescence of two current loops (Fushiki and Sakai, 1995; Sakai and Fushiki, 1995) suggests very strongly that the subsequent large pressure increases, as well as plasmoid and magnetosonic wave formation, support the pioneering use of the 2D pressure-pulse driver for flare-associated CMEs. The pressure increases and plasmoid formation in these simulations have been confirmed by Yohkoh observations; unfortunately, wave propagation is impossible to detect by soft X-ray imagery (L. Acton, private communication, 1995) and, therefore, must be accepted on the basis of first principles of physics (Dryer *et al*, 1978; Wu *et al*, 1982, 1995b; Sun *et al.*, 1995) as well as by the microwave and metric Type II radio bursts (Karlicky and Odstrcil, 1994) that are fast MHD shock signatures that follow flare initiations.

A third approach in the study of CMEs is the 1D, kinematic use of the momentum equation under various assumptions of magnetic flux and thermal pressure drivers (Chen and Garren, 1993; Stepanova and Kosovichev, 1994). This approach (and the first one discussed above) may provide some insight; however the second approach, regardless of the choice one makes for the "driver", is essential for the more comprehensive physical understanding that may be derived from comparison of the physical parameters with observations.

The near-Sun launch of CMEs, then, is best represented by the 2D and 2 1/2D methodology discussed in extensive detail by Wu *et al.* (1995b, and references therein), who have considered both the physical energy requirements and the mathematical and computational time-dependent boundary condition requirements (Sun *et al.*, 1995).

The 3D extension of this work and, by implication, its linkage to the work of Fushiki and Sakai (1995) and Sakai and Fushiki (1995) for the flare situation has not been done, nor has the 3D extension to the non-flare situation been done. The 2-1/2D approach has been taken by Linker and Mikic (1995) for the latter case; these workers have made a significant advance by incorporating the time-dependent boundary conditions proposed by Hu and Wu (1984). They found that the acceleration of the plasmoid to the local solar wind speed is consistent with observations of "slow CMEs," which travel at the background solar wind speed, rather than with the "fast CMEs" that generate shock waves. The Linker and Mikic (1995) work, however, utilized a pre-event (i.e., pre-shearing motion) helmet-streamer configuration that (like earlier models) assumed constant boundary conditions at the coronal base and a polytropic gas with $\gamma = 1.05$. Wang *et al* (1995), however, demonstrated (via the similar numerical relaxation technique) that a more realistic pre-event corona (both closed and open field regions) is found when latitudinally-dependent boundary conditions and $\gamma = 1.67$ are assumed. Their pre-event corona and solar wind are shown in Figure 1. It should be pointed out that this result is an excellent approximation to the more mathematically-rigorous helmet-streamer solution found by Cuperman *et al.* (1995). These workers consider the classical zero pressure condition at infinity, the exact cusp configuration that divides closed from open field lines, as well as the latitudinally-dependent boundary conditions at the coronal base for the 2-1/2D steady-state case.

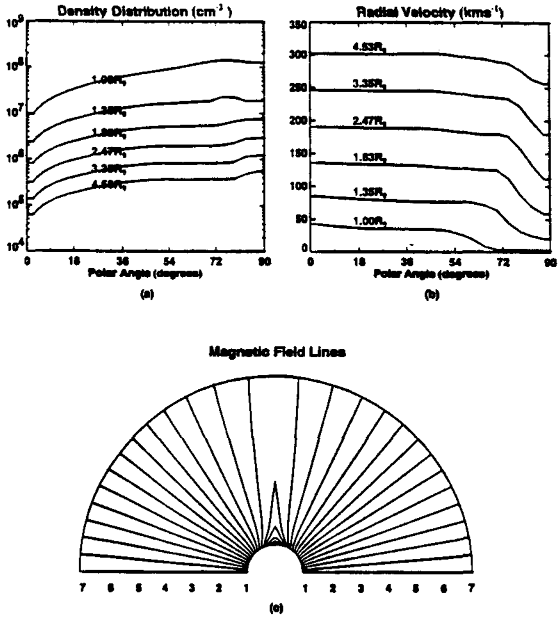

Figure 1. Pre-event corona found by the relaxation technique of Wang *et al.* (1995). Latitudinally dependent boundary conditions at the coronal base are assumed with $\gamma = 5/3$ and a volumetric heating term. (a) Latitudional dependence of density as a function of polar angle (equatorial plane $= 90^o$) and helioradial distance. (b) Latitudinal dependence of solar wind velocity. (c) Magnetic field lines; note the realistic sharp cusp that was not found with $\gamma = 1.05$ (constant or latitude dependent boundary conditions) or with $\gamma = 5/3$ (constant boundary conditions and volumetric energy source). Note, however, that the closed helmet structure, as a result of the relaxation procedure, still has a small, but finite, velocity at $\theta = 90^o$. Wang *et al.* (1995) pointed out that no steady state solution can be obtained whenever an *ad hoc* heating term is added to the energy equation. However, there is a steady state solution (in this procedure) if no heating term is added. However, YOHKOH images indicate that the corona is evolving continuously.

3. Interplanetary Disturbances Simulations

In the previous section, it was my intention to give the reader a sense of the progress that has been made in the simulation of the genesis of interplanetary disturbances at, and near, the Sun. The propagation of 2, 2-1/2, and 3D shocks in the solar wind outside (i.e., anti-sunward of) the steady-state critical points has recently been summarized by Dryer (1994). Recent 3D work by Usmanov and Dryer (1995) has directed attention to a fairly complete simulation of the multiple events (eight major flares) that took place during

June 1991, together with a comparison of plasma and IMF parameters with extremely limited IMP-8 observations. This simulation was initialized, and followed by additional "flare" simulations, by the real-time optical, radio and X-ray observations by the USAF/NOAA ground- and space-based observatories together with the background measurements of the photospheric line-of-sight magnetic field observations made by the Wilcox Observatory at Stanford University. There are some limitations to this first simulation of the temporally complete, 4π sr, Sun-Heliosphere response to this complex series of solar flares: (i) time dependent lower boundary conditions were not taken into account; (ii) the spatial domains were divided into two parts, $1 < R/R_s < 10$ and $R/R_s > 10$, rather than being continuous; and (iii) polytropic exponents of $\gamma = 1.05$ and 1.17 were assumed in these two domains, respectively.

Zeroth-order comparison of "ground truth" L_1 spacecraft data with 3D model outputs is an obvious requirement for checking the validity of the model's physical assumptions, mathematical methodologies, and degree of observational inputs. It would, of course, be desirable to have an armada of additional heliospheric spacecraft to complement the L_1 position; needless to say, this capability is financially and politically untenable in the forseeable future. Additional "ground truth" can be obtained by the interplanetary scintillation (IPS) technique. Manoharan *et al.* (1995) and Janardhan *et al.* (1995) have demonstrated the use of IPS "g", together with "V" (for velocity), all-sky maps to confirm the use of a simple shock-prediction model that is based on a 2D MHD model. Following a series of solar flares, the simple (basically kinematic) model was used, in real-time, to alert the radio astronomers at Ooty, Cambridge, and Toyokawa. Their observations of plasma velocity increases at (approximately) the appropriate times and parts of the sky confirmed the shock-propagation methodology.

Finally, the 2D and 3D MHD modeling approach has been extended in four additional directions:

1. self-consistent interaction of the solar wind with magnetic clouds (Detman *et al.* 1991; Vandas *et al.* 1995).
2. shock energization of particles and prediction of $< 1.6\ MeV$ particle flux and anisotopies along the IMF lines that connect the observer to the constantly changing connection point along the expanding shock (Heras *et al.*, 1992).
3. prediction of the IMF-turning direction (northward, southward) at 1 AU following disturbances at various locations on the Sun (Wu *et al.*, 1992; McAllister *et al.*, 1994).
4. interaction of solar-generated shocks with the heliospheric plasma sheet-current sheet system (D. Odstrcil, private communication, 1994).

Item (1) above has demonstrated the deformation and kinematics of expanding segments of magnetic flux ropes and plasmoids; in addition, it has revealed zones of magnetic traps where particles may experience bi-directional streaming *outside* of the clouds.

Item (2) has the potential of enabling flux predictions of particle energies as high as 20 MeV (D. Lario, private communication, 1994) from flare-generated and eruptive prominence-generated shocks. Item (3) has demonstrated the global IMF deformation (following arbitrary solar disturbances) and, in principle, the prediction of geomagnetic storm onset, duration, and severity. Item (4) has shown the drastic distortion of, and possible reconnection of, the HCS/HPS system as a result of shock interaction as well as the shock's attenuation on the side of the HCS/HPS opposite to that from which it originated.

4. Concluding Remarks

Validations of any MHD simulations are ultimately dependent on the quality of the models, of the solar observations that must be relied upon to provide inputs, and of the *in situ* and remotely observed physical parameters of the solar wind and the IMF. It is now recognized that the models must be fully 3D and time-dependent before further progress can be made in the prediction of the basic parameters: density, temperature and velocity, and magnetic field vectors. A set of physical "drivers" at the Sun is now available (for flare and non-flare situations) to the modelers for generating interplanetary disturbances. Also, new ground-based radio astronomical observatories are gradually coming "on-line" at various longitudes that can monitor the global density and velocity via the interplanetary scintilliations technique. The libration point, L_1, is also being populated, gradually, by spacecraft that can, together with the IPS technique, provide "ground truth" for the model outputs. The "grand challenge", then, will be the task of putting all of these numerical and observational outputs together in a classical demonstration of the scientific method.

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References

1. Chen, J. and Garren, D. A.: 1993, *Geophys. Res. Lett.*, **20**, 2319

2. Cuperman, S., Bruma, C., Dryer, M. and Semel, M.: 1995, *Astron. Astrophys., in press*
3. Detman, T. R., Dryer, M., Yeh, T., Han, S. M., Wu, S. T. and McComas, D. J.: 1991, *J. Geophys. Res.* **96,** 9531
4. Dryer, M., Wu, S. T., Steinolfson, R. S. and Wilson, R. M.: 1978, *Astrophys. J.* **227,** 1059
5. Dryer, M.: 1982, *Space Sci. Rev.*, **33,** 233
6. Dryer, M.: 1994, *Space Sci. Rev.*, **67,** 363
7. Forbes, T. G. and Priest, E. R.: 1982, *Solar Phys.*, **81,** 303
8. Fushiki, T. and Sakai, J.-I.: 1995, *Solar Phys.* **156,** 265
9. Gosling, J. T.: 1993, *J. Geophys. Res.* **98,** 18937
10. Guo, W. P., Wang, J. F., Liang, B. X. and Wu, S. T.: 1992, *Eruptive Solar Flares (Z. Svestka, B. V. Jackson and M. E. Machado, eds.) IAU Colloq. 133, Springer-Verlag, Berlin, pp. 381-384,*
11. Heras, A. M., Sanahuja, B., Smith, Z. K., Detman, T. R. and Dryer, M.: 1992, *Astrophys. J.* **391,** 359
12. Hood, A. W. and Priest, E. R.: 1980, *Solar Phys.*, **66,** 113
13. Hu, Y. Q. and Wu, S. T.: *1984, J. Comp. Phys,* **55,** *33*
14. Hu, Y. Q.: 1990, *Chinese J. of Space Sci.*, **10,** 163
15. Hundhausen, A. J.: 1993, *J. Geophys. Res.*, **98,** 13177
16. Janardhan, P., Balasubramanian, V., Ananthakrishnan, S., Dryer, M., Bhatnagar, A. and McIntosh, P. S.: 1995, *Solar Phys., submitted*
17. Karlicky, M. and Odstrcil, D.: 1994, *Solar Phys.* **155,** 171
18. Klimchuk, J. A. and Sturrock, P. A.: 1989, *Astrophys. J.*, **345,** 1034
19. Linker, J. A. and Mikic, Z.: 1995, *Astrophys. J.*, **438,** L45
20. Low, B. C.: 1981, *Astrophys. J.*, **251,** 352
21. Low, B. C.: 1982, *Rev. Geophys. Space Phys.*, **20,** 145
22. Manoharan, P. K., Ananthakrishnan, S., Dryer, M., Detman, T. R. , Leinbach, H., Kojima, T., Watanabe, T. and Khan, J.: 1995, *Solar Phys.* **156,** 377
23. McAllister, A. H., Dryer, M., McIntosh, P., Singer, H. and Weiss, L.: 1994, *Proc. SOHO III Workshop, ESA SP-373, Paris, pp. 315-318,*
24. Mikic, Z., Barnes, D. C. and Schnack, D. D.: 1988, *Astrophys. J.*, **328,** 830
25. Sakai, J.-I. and Fushiki, T.: 1995, *Solar Phys.* **156,** 281
26. Sime, D. G., MacQueen, R. M. and Hundhausen, A. J.: 1984, *J. Geophys. Res.* **89,** 2113
27. Steinolfson, R. S. and Hundhausen, A. J.: 1988, *J. Geophys. Res.* **93,** 14269
28. Stepanova, T. V. and Kosovichev, A. G.: 1994, *Space Sci. Rev.*, **70,** 176
29. Sun, M. T., Wu, S. T. and Dryer, M.: 1995, *J. Computational Phys.* **116,** 330
30. Usmanov, A. V. and Dryer, M.: 1995, *Solar Phys., in press*
31. Vandas, M., Fischer, S., Dryer, M., Smith, Z. and Detman, T. R. : 1995, *J. Geophys. Res., in press*
32. Wang, A. H., Wu, S. T., Suess, S. T. and Poletto, G.1995, *Solar Phys.,* in press
33. Wu, S. T., Dryer, M., Nakagawa, Y. and Han, S. M.: 1982, *Astrophys. J.* **262,** 369
34. Wu, S. T., Hu, Y. Q., Nakagawa, Y. and Tandberg-Hanssen, E.: 1983, *Astrophys. J.*, **266,** 866
35. Wu, S. T., Song, M. T., Martens, P. C. H. and Dryer, M.: 1991, *Solar Phys.*, **134,** 353
36. Wu, S. T., Dryer, M. and Wu, C.-C.:: 1992, *Proc. of 26th ESLAB Symposium, ESA SP-346, Paris, pp. 333-336,*
37. Wu, S. T., Wang, A. H. and Guo, W. P.: 1995a, *IAU Colloq. 154, in press*,this Proceedings
38. Wu, S. T., Guo, W. P. and Wang, J. F.: 1995b, *Solar Phys., in press*
39. Zhang, J. H., Wu, S. T., Dryer, M. and Wei, F. S.: 1994, *Solar Coronal Structures:(V. Rusin, P. Heinzel and J. C. Vial, Eds.), IAU Colloq. 144, VEDA Publ. Co., Bratislava, pp.91-95,*