ON THE DYNAMICS OF THE SOLAR CORONA: FIRST RESULTS OBTAINED WITH A NEW 3D MHD MODEL

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ABSTRACT

A newly developed self-consistent 3D MHD code (see poster by Kleimann et al., this conference) is applied to the problem of the dynamics of the solar corona. First, we present the basic system of equations for a two-fluid description of the solar wind plasma and point out possible numerical difficulties arising from an improper choice of variables. Second, we perform a study of the solar wind expansion during phases of minimum solar activity, serving mainly as a first "real world" test case. Third, we discuss first results of the application of the model to propagating disturbances, such as coronal mass ejections and/or shocks.

Key words: solar wind; MHD; numerical simulation; two-fluid modeling; CWENO.

1. MOTIVATION

For many decades space scientists have been attracted to the solar wind and its delicate interaction with the highly variable solar magnetic field. A recent wide-spread increase in interest was spawned not only by many stimulating inputs due to groundbreaking space-based observations but also by the fact that the impact of space weather phenomena on the Earth’s environment is becoming more obvious every year. Thus, detailed and realistic models of solar wind dynamics have in fact become mandatory for space weather forecasting and data analysis of forthcoming spacecraft missions to the inner heliosphere.

Fortunately, these urgently needed advances have also become possible in the first place by recent progress in computing speed and sophisticated algorithms. Clearly, such a huge and complex topic has room for many investigators, and a number of groups have indeed achieved impressive results in this field. It therefore seems appropriate to begin by pointing out why we felt that the community might benefit from yet another modeling approach.

2. WHY ANOTHER MODEL?

The new aspects by which our approach differs from various other works can be grouped into two fields: physics and numerics.

2.1. New aspects – physics

The novel aspects on the physics side are mainly three-fold:

- Contrary to previous assumptions, the SOHO mission has revealed that the electrons and protons which largely constitute the solar wind plasma are indeed far away from thermal equilibrium, with the proton temperature being about five times larger than the electron temperature. For this reason, it seems appropriate to abandon the single-fluid model approach and instead consider these species as two separate fluids interacting via collisions.

- The process of restructuring of magnetic field lines known as magnetic reconnection has been identified to play a major role in both coronal heating and the dynamic evolution of "disturbances", such as coronal mass ejections. Since this process cannot occur in an ideally conducting medium, a finite resistivity is explicitly included into our system of equations. As a side effect, this will also help to improve the code’s numerical stability.


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Finally, we will try to abandon the concept of both ad-hoc heating functions (which do help to generate reasonable wind speeds but completely lack any physical mechanism) and consistent heating rates according to Hollweg (1986) in favor of true Alfvénic wave heating. The fluctuations of the interplanetary magnetic field (mainly Alfvén waves) make up a considerable fraction of the magnetic field energy in the inner heliosphere, and they could well be partly responsible for heating the corona to its temperature of some $10^6 \, K$.

2.2. New aspects — numerics

Since our object of study, the solar corona at full maximum, is clearly void of any potentially simplifying symmetry, one major point in favor of spherical or cylindrical coordinates is lost. We therefore decided to use a plain Cartesian grid, which does make the treatment of the photospheric boundary slightly more complicated but is much simpler to implement, and also advantageous in terms of numerical stability.

To advance the equations in this box-shaped computational domain, we have implemented a newly developed CWENO (Central Weighted Essentially Non-Oscillatory) algorithm. (Nessyahu & Tadmor, 1990 and Kurganov & Levy, 2000) Since its details are given in our poster contribution On the dynamics of the solar corona: the numerics behind a self-consistent 3D MHD model by Kleinmann et al. (this conference), we only note here that CWENO is a

- third-order, (almost) non-oscillatory
- flux-conserving
- shock-capturing

scheme, and that all these characteristics make it of course a very appealing tool for our purpose.

This algorithm is then combined with two powerful numerical features which have recently received increased attention within the computational fluid dynamics community:

1. Adaptive mesh refinement (AMR). High spatial grid resolution, while being not only desirable but indeed necessary for our envisaged simulations, is crucially limited by the available resources in terms of both computational memory and CPU speed. We have therefore chosen to implement a powerful adaptive mesh refinement technique, which dynamically adapts the local spatial resolution according to the presence or absence of strong gradients. Details of this procedure are described by Friedel, Grauer, and Marliani (1997).

2. An implementation of a recent divergence cleaning algorithm by Dedner et al. (2002) ensures that the solenoidality condition $\nabla \cdot \mathbf{B} = 0$ stays valid throughout the simulation, thus preventing the rise of increasingly unphysical field line configurations which would otherwise be created by the accumulation of round-off errors.

3. BASIC EQUATIONS

In dimensionless form, the equations governing the evolution of our magnetized two-fluid system (characterized by densities $\rho_\alpha$, velocities $\mathbf{v}_\alpha$ and gas pressures $p_\alpha$, resistivity $\eta$, magnetic induction $\mathbf{B}$ and associated current density $\mathbf{j} = \nabla \times \mathbf{B}$) is given by

$$
\partial_t \rho = -\nabla \cdot (\rho \mathbf{v}) \tag{1}
$$

$$
\partial_t (\rho \mathbf{v}) = -\nabla \cdot (\rho \mathbf{v} \mathbf{v}) - \nabla (p_\alpha + p_\beta + p_w) \tag{2}
$$

$$
-\rho \frac{\Phi_{\text{grav}}}{\eta} \mathbf{j} \times \mathbf{B} \tag{3}
$$

$$
\partial_t \mathbf{B} = -\nabla \cdot (\mathbf{v} \mathbf{B} - \mathbf{B} \mathbf{v}) - \nabla \Psi \tag{4}
$$

$$
\gamma - 1 \rho \mathbf{v} \cdot \nabla \rho + Q_\alpha \tag{5}
$$

$$
\partial_t p_\alpha = -\nabla \cdot (p_\alpha \mathbf{v}_\alpha) - \nu_\text{ep} (p_\alpha - p_\beta) \tag{6}
$$

$$
\gamma - 1 \rho \mathbf{v} \cdot \nabla p_\alpha + Q_\alpha \tag{7}
$$

where $\alpha$ and $\beta \neq \alpha$ indicate the different species (e for electrons, p for protons). The equation of state $p_\alpha = \rho_\alpha T_\alpha$ of a mono-atomic ideal gas is adopted, along with an adiabatic exponent $\gamma = 5/3$. We also introduced the mean density $\rho := \rho_0 + \rho_e$ (assuming quasi-neutrality, i.e. $\rho_e/m_e = \rho_0/m_p$) and the mean velocity

$$
\mathbf{v} := \frac{(\rho_0 \mathbf{v}_0 + \rho_e \mathbf{v}_e)}{\rho}, \tag{8}
$$

from which the expressions for the individual velocities may be obtained by

$$
\mathbf{v}_e = \mathbf{v} + \frac{\mathbf{j}}{\rho} \quad \text{and} \quad \mathbf{v}_p = \mathbf{v} - \frac{m_e}{m_p} \frac{\mathbf{j}}{\rho} \approx \mathbf{v}. \tag{9}
$$

As can be seen on the rhs. of the momentum balance equation, plasma elements are accelerated by gradients of both gas and wave pressures, as well as magnetic induction and the Sun’s gravitational potential $\Phi_{\text{grav}} = -GM_S/r$. The induction equation (3) not only accounts for spatial variation of $\eta$ via the $\nabla \eta \times \mathbf{j}$ term but is furthermore supplemented with a new term $-\nabla \Psi$ accounting for said divergence cleaning, $\Psi$ itself being an non-physical quantity which carries away any non-vanishing $\nabla \cdot \mathbf{B}$. For further details of $\Psi$ and its equation (6) see Dedner et al. (2002).

The gas pressures are advanced in time using Eqs. (4), with $\nu_\text{ep}$ denoting the frequency at which elastic collisions occur. Electrons are heated by standard Ohmic dissipation

$$
Q_\text{e} = \eta \mathbf{j}^2, \tag{10}
$$

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