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FIRST RESULTS ON MHD SIMULATION OF MAGNETIC CLOUDS USING A ROE-TYPE APPROXIMATE RIEMANN SOLVER

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Abstract. The magnetoplasma associated with magnetic clouds inside the solar wind is analyzed. Especially, the behaviour of magnetoplasma in the sheath region between the cloud and its shock front will be simulated using a Godunov scheme for solving the system of governing equations for ideal magnetohydrodynamics. A Roe-type Riemann solver is applied on a two-dimensional semi-geodetic grid reflecting the idealized cylindrical structure of magnetic clouds. Two case studies are presented to test the validity of the numerical algorithm. First, the magnetic cloud is modelled as a solid obstacle and the flow of the solar wind plasma around this obstacle is simulated. Second, the boundary of the magnetic cloud is provided with a magnetic field causing magnetic reconnection to appear on the front side of the magnetic cloud and leading to an expansion of the cloud's diameter.

1. Introduction

Magnetic clouds (MCs) can be considered as a subset of interplanetary coronal mass ejections (ICMEs) exhibiting a special plasma and magnetic field configuration. The characteristics of MCs are: a low plasma-β, low mass density and low ion temperature if compared to the ambient solar wind. Furthermore, the strong magnetic field of MCs (approximately 15 - 30 nT) executes a smooth rotation. So, magnetic clouds can be visualized as large scale magnetic flux ropes with their feet still attached to the sun's atmosphere while propagating into interplanetary space (Bame et al., 1981; Farrugia et al., 1993). Furthermore, MCs are expanding while propagating thereby reaching a diameter of 0.2 - 0.4 AU at a distance of 1 AU from the sun (see Fig. 1). About 30% - 40% of all ICMEs can be associated with the special type of such magnetic clouds (Gosling, 1990). Magnetic clouds are often modelled on the basis of a force-free magnetic field model (Lundquist, 1950) in combination with cylindrical symmetry for the cloud structure (Burlaga, 1988; Lepping et al., 1990). Several authors (see e.g., Hu and Sonnerup, 2002; Riley and Crooker, 2004) together with various data from in-situ observations have shown that approximating locally the MC structure by a cylinder with circular cross section may be highly idealized. This study reinvestigates the major problems with regard to magnetic clouds on the basis of a fully self-consistent numerical model.

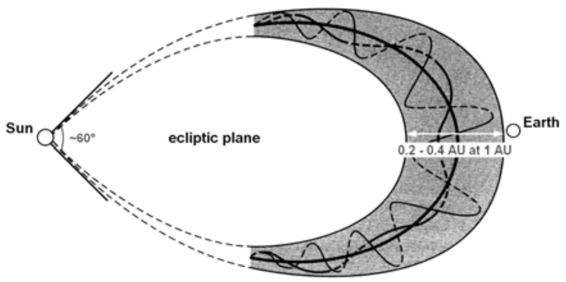

Fig. 1: Sketch of a magnetic cloud propagating parallel to the ecliptic plane from the sun towards Earth. Three selected magnetic field lines are highlighted. Near the cloud's axis, the magnetic field is oriented mainly along the axis. Towards the cloud's boundary, magnetic field lines become more and more helical. (after Burlaga et al., 1990)

2. The system of ideal MHD governing equations

The model applied to magnetic clouds and the ambient solar wind is based on the equations of magnetohydrodynamics. In the frame of magneto-hydrodynamics, a plasma is treated with the laws of fluid mechanics including also electromagnetic forces. For a simple approach, we consider a solar wind plasma composed of two fluids, one for the electrons and one for the protons (H^+). The macroscopic fluid equations for the transport of mass, momentum, magnetic induction and energy can be inferred from kinetic theory. Considering only adiabatic motions, i.e., the heat flux vector vanishes, they constitute a complete set of MHD governing equations. This set of equations can be further simplified by assuming a non-viscous and quasi-neutral plasma in thermal equilibrium. Furthermore, the plasma is considered as a highly conducting fluid and collisions between plasma particles are neglected.
If the equations of ideal MHD are analyzed numerically, the initial condition $\nabla \cdot \vec{B} = 0$ is usually not fulfilled throughout the evolution due to

numerical diffusion. Powell (1994) proposed to treat this difficulty by introducing an additional source term leading to a more numerically stable solution. Thus, the system of governing equations to be solved reads as follows (weakly non-conservative form):

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho\\ \rho\vec{u}\\ \vec{B}\\ E\end{pmatrix}+\nabla\cdot\begin{pmatrix}\rho\vec{u}\\ \rho\vec{u}\vec{u}+\mathbf{I}(p+\frac{B^2}{2})-\vec{B}\vec{B}\\ \vec{u}\vec{B}-\vec{B}\vec{u}\\ (E+p+\frac{B^2}{2})\vec{u}-\vec{B}(\vec{u}\cdot\vec{B})\end{pmatrix}=-\begin{pmatrix}0\\ \vec{B}\\ \vec{u}\\ \vec{u}\cdot\vec{B}\end{pmatrix}\nabla\cdot\vec{B} \tag{1}$$

with the total energy E (thermal + kinetic + magnetic energy) given as

$$E=\frac{p}{\gamma-1}+\frac{\rho u^2}{2}+\frac{B^2}{2} \tag{2}$$

The used symbols have the following meanings: ρ = mass density, $\vec{u}$ = bulk velocity, $\vec{B}$ = magnetic induction, p = plasma pressure, γ = ratio of specific heats and $\mathbf{I}$ = unity tensor.

3. Numerical solution: a Roe-type approximate Riemann solver

A numerical solution for the quasi-linear system of eight partial differential equations (1) is derived using a Roe-type approximate Riemann solver as proposed by Powell (1994). Calculations are performed on a semi-geodetic grid given in cylindrical coordinates. The space of analysis is divided into cells and a global solution is a composition of constant solutions found for each cell with discontinuities at the cell interfaces. According to Godunov (1959) the discretization of the general system of governing equations

$$\frac{\partial\vec{U}}{\partial t}+\nabla\cdot\mathbf{F}=\vec{S} \tag{3}$$

($\vec{U}$ … parameter vector, $\mathbf{F}$ … flux matrix, $\vec{S}$ … source term vector) is defined for the simplified one-dimensional case as

$$\frac{\vec{U}_i^{n+1}-\vec{U}_i^n}{\Delta t}+\frac{\vec{F}_{i+1/2}-\vec{F}_{i-1/2}}{\Delta x}=\vec{S}_i^n \tag{4}$$

Index i denotes the cell-index in x-direction and index n is the time index. The fluxes at the cell interfaces, which are indicated by $\vec{F}_{i\pm1/2}$, are calculated by inserting the parameters given at the cell interfaces into the flux matrices ($\vec{F}_{i\pm1/2}=\vec{F}(\vec{U}_{i\pm1/2})$).

The parameters at the cell interfaces are found from the eigenvalues and the left and right eigenvectors of the linearized Riemann problem (one-dimensional case)

$$\frac{\partial\vec{W}}{\partial t}+\mathbf{A}\frac{\partial\vec{W}}{\partial x}=\vec{S} \tag{5}$$

The matrix $\mathbf{A}$ is the matrix of coefficients and $\vec{W}=(\rho,u_x,u_y,u_z,B_x,B_y,B_z,p)$ is the vector composed of the primitive variables. The eigenvalues and the left and right eigenvectors of $\mathbf{A}$ belong to eight characteristic waves: one entropy wave, two Alfvén waves, two slow and two fast magneto-acoustic waves and one divergence wave. The divergence wave results from the $\nabla\cdot\vec{B}=0$ constraint and ensures that any $\nabla\cdot\vec{B}\neq0$ created locally is convected away.

The eigenvalues and left and right eigenvectors of $\mathbf{A}$ at a certain cell interface are calculated from the mean of the primitive variables $\vec{W}$ with regard to the cells left and right from the interface. These mean eigenvalues and eigenvectors are then used to propagate $\vec{W}$ to the cell interfaces and furthermore, to derive the fluxes at the cell interfaces. By knowing $\vec{F}_{i\pm1/2}$ and $\vec{S}_i^n$, the $\vec{U}_i^{n+1}$ are computed according to equ. (4) in an iterative process.

4. Results

The Roe-type approximate Riemann problem for the ideal MHD governing equations has been solved on a two-dimensional semi-geodetic grid. Even so, we shall not ignore the third component of the velocity and magnetic field vectors. Thus, such kind of analysis is often referred to as a 2.5-dimensional approach. The grid consists of 180 cells in azimuthal direction and 201 cells in radial direction. Furthermore, all parameters are normalized to solar wind quantities at infinity (index ∞) as follows: $\tilde{u}=u/u_\infty$, $\tilde{\rho}=\rho/\rho_\infty$, $\tilde{p}=p/(\rho_\infty u_\infty^2)$ and $\tilde{B}=B/(\sqrt{4\pi\rho_\infty u_\infty^2})$.

At first, the magnetic cloud is modelled as a solid obstacle exhibiting a circular cross section and the flow of solar wind plasma around such kind of solid obstacle is studied. The results for density, velocity, pressure and the magnetic field are displayed in Fig. 2. The origin of the cylindrical coordinate frame is fixed with the centre of the MC's circular cross section. The solar wind plasma is streaming from the right to the left and the interplanetary magnetic field is oriented perpendicular to the cloud's axis (from bottom to top). As can be seen, a bow shock develops upstream, i.e., ahead of the cloud, at a distance of ~2 R_{MC} to the MC-axis. Inside the sheath region, i.e., between the bow shock and the MC boundary, the solar wind plasma is decelerating and ρ, p and B are increasing.

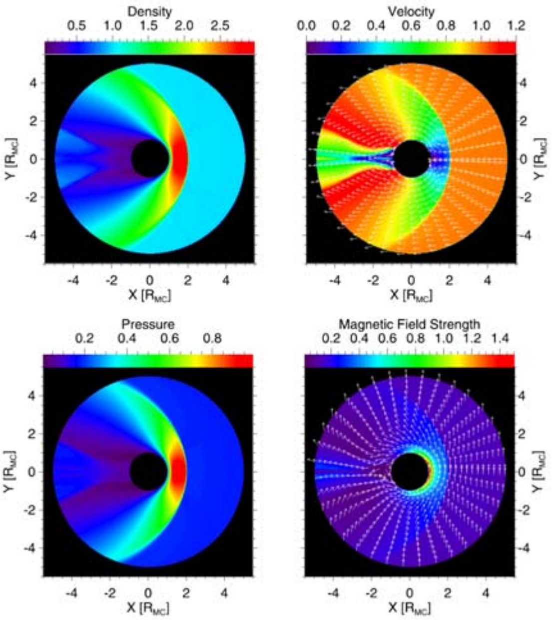

Fig. 2: Simulation results for the parameters density (top left), velocity (top right), plasma pressure (bottom left) and magnetic field strength (bottom right) around a magnetic cloud embedded in the ambient solar wind flow. The cloud is modelled as a solid obstacle (circular cross section). The solar wind streams from right to left. The bow shock upstream of the cloud and the formation of a magnetic barrier (enhanced *B*) directly in front of the cloud are clearly visible.

The draping of magnetic field lines around the obstacle causes a so-called "magnetic barrier" to appear on the front side of the cloud (Biernat et al., 1995; Erkaev et al., 1995) and a neutral line is formed on the back side. The magnetic barrier acts as a mechanism for acceleration of plasma, thereby producing a plasma depleted region, the so-called "depletion layer" (Zwan and Wolf, 1976; Erkaev, 1981, 1988; Farrugia et al., 1997; Biernat et al., 2005).

As a next step, the possibility of magnetic reconnection between the interplanetary magnetic field and the magnetic field of the MC is introduced (Cargill et al., 1996; McComas et al., 1994). This is managed by using appropriate boundary conditions for $\vec{B}$ on the cloud's surface. In Fig. 3 a situation is presented with an anti-parallel orientation of magnetic field lines given at the front side of the magnetic cloud. This generates a plasma cavity around the cloud containing a low-β plasma, i.e., the magnetic pressure is much higher than the thermal pressure. This affects the evolution of the bow shock on the front side and additionally causes a reverse shock as the cavity expands.

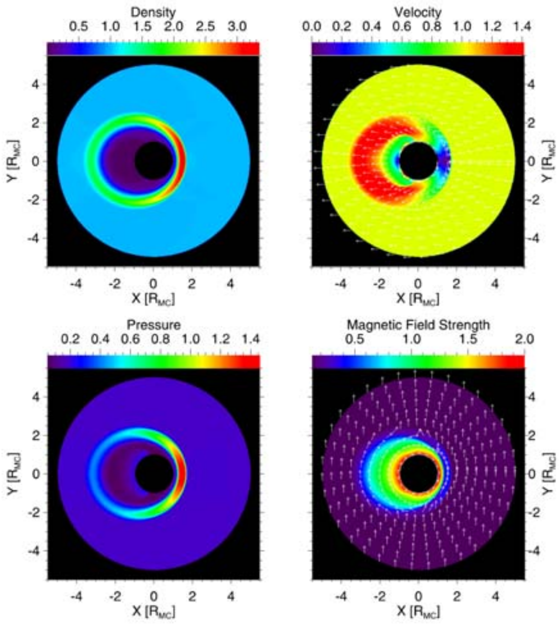

Fig. 3: Simulation results for density, velocity, plasma pressure and the magnetic field on the basis of a magnetized obstacle for the magnetic cloud. Due to magnetic reconnection, the magnetic cloud is expanding thereby deforming its circular cross section.

5. Conclusions

The system of magnetohydrodynamic governing equations is applied to the solar wind plasma for modelling a special type of interplanetary coronal mass ejections called magnetic clouds. A numerical solution is achieved by constructing a Roe-type approximate Riemann solver as proposed by Powell (1994). In order to test the validity of the algorithm, two special configurations for magnetic clouds have been processed. First, the MC is modelled as a solid obstacle. Already such kind of simple approach reveals characteristic structures like formation of a bow shock, formation of a magnetic barrier and mechanisms for acceleration of plasma (depletion layer). Furthermore, the MC is provided with a magnetic field. This causes magnetic reconnection between the cloud’s magnetic field and the interplanetary magnetic field and has significant influences on the shape of the MC boundary.
More detailed studies like the dependence of the stand-off distance of the bow shock on the configuration of the interplanetary magnetic field or the evolution of MCs in a highly structured solar wind will be performed in the near future. Finally, simulation results will be compared to observational data from several spacecraft (WIND, ULYSSES, STEREO).

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References

Bame, S. J., J. R. Asbridge, W. C. Feldman, J. T. Gosling, and R. D. Zwick, Bi-directional streaming of solar wind electrons > 80 eV; ISEE evidence for a closed field structure within the driver gas of an interplanetary shock, Geophys. Res. Lett., 8, 173 – 176, 1981.

Biernat, H. K., G. A. Bachmaier, T. M. Kiendl, N. V. Erkaev, A. V. Mezentsev, C. J. Farrugia, V. S. Semenov, and R. P. Rijnbeek, Magnetosheath parameters and reconnection: a case study for the near-cusp region and the equatorial flank, Planet. Space Sci., 43, 1105 – 1120, 1995.

Biernat, H. K., H. Lammer, D. F. Vogl, and S. Mühlbachler (Editors), Solar-planetary relations, Research Signpost, 2005.

Burlaga, L. F., Magnetic clouds and force-free fields with constant alpha, J. Geophys. Res., 93, A7, 7217 – 7224, 1988.

Burlaga, L. F., R. P. Lepping, and J. A. Jones, Global configuration of a magnetic cloud, in: Physics of magnetic flux ropes, AGU, Washington DC, 373-377, 1990.

Cargill, P. J., J. Chen, D. S. Spicer, and S. T. Zalesak, MHD simulations of the motion of magnetic flux tubes through a magnetized plasma, J. Geophys. Res., 101, 4855, 1996.

Erkaev, N. V., Effect of magnetic barrier in non-dissipative magnetohydrodynamics (in Russian), Rep. 3253-81, 55 pp., All Russ. Sci. and Tech. Inf. Inst., Moscow, 1981.

Erkaev, N. V., Results of the investigation of MHD flow around the magnetosphere, Geomagn. Aeron., 28, 455, 1988.

Erkaev, N. V., C. J. Farrugia, H. K. Biernat, L. F. Burlaga, and G. A. Bachmaier, Ideal MHD flow behind interplanetary shocks driven by magnetic clouds, J. Geophys. Res., 100, A10, 19919-19931, 1995.

Farrugia, C. J., I. G. Richardson, L. F. Burlaga, R. P. Lepping, and V. A. Osherovich, Simultaneous observations of solar MeV particles in a magnetic cloud and in the Earth’s northern tail lobe: implications for the global field line topology of magnetic clouds and for the entry of solar particles into the magnetosphere during cloud passage, J. Geophys. Res., 98, 15497 – 15507, 1993.

Farrugia, C. J., N. V. Erkaev, H. K. Biernat, L. F. Burlaga, R. P. Lepping, and V. A. Osherovich, Possible plasma depletion layer ahead of an interplanetary ejecta, J. Geophys. Res., 102, A4, 7087 – 7094, 1997.

Godunov, S. K., A finite difference method for the computation of discontinuous solutions of the equations of fluid dynamics (in Russian), Mat. Sbornik, 47 (89), No. 3, 271 – 306, 1959.

Gosling, J. T., Coronal mass ejections and magnetic flux ropes in interplanetary space, in C. T. Russell et al., (Eds), Physics of magnetic flux ropes, AGU Monograph 58, AGU (Washington D. C.), 343, 1990.

Hu, Q., and B. U. Ö. Sonnerup, Reconstruction of magnetic clouds in the solar wind: Orientation and configuration, J. Geophys. Res., 107, doi:10.1029/2001JA000293, 2002.

Lepping, R. P., J. A. Jones, and L. F. Burlaga, Magnetic field structure of interplanetary magnetic clouds at 1 AU, J. Geophys. Res., 95, A8, 11957 – 11965, 1990.

Lundquist, S., Magneto-hydrostatic fields, Arkiv för fysik, 2, 361 – 365, 1950.

McComas, D. J., J. T. Gosling, C. M. Hammond, M. B. Moldwin, J. L. Phillips, and R. J. Forsyth, Magnetic reconnection ahead of a coronal mass ejection, Geophys. Res. Lett., 21, 1751, 1994.

Powell, K.G., An approximate Riemann solver (that works in more than one dimension), ICASE report no. 94-24, NASA Langley Research Center, 1994.

Riley, P., and N. U. Crooker, Kinematic treatment of coronal mass ejection evolution in the solar wind, Astrophys. J., 600, 1035 – 1042, 2004.

Zwan, B. J., and R. A. Wolf, Depletion of solar wind near a planetary boundary, J. Geophys. Res., 81, 1636, 1976.