Large scale hybrid simulations of interacting plasmas in space

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Abstract. Solar wind interaction with artificial atmospheres is studied through the use of a three dimensional particle-in-cell (PIC) hybrid code. This code has been used to successfully model the AMPTE release experiments and its extension now allows the study of other systems such as the Mini-Magnetosphere Plasma Propulsion (M2P2) system. Simulation results regarding these systems are presented.

1 INTRODUCTION

The interaction of the solar wind with planetary/cometary objects and satellites is of paramount importance in space plasma physics. Problems are highly nonlinear, involve intricate physics and full scale simulations are only now starting to be possible due to the qualitative advances in available computing power. Examples of problems falling in this category are the solar wind interaction with unmagnetized planets (e.g. Mars) or the plasma sail concept[1].

The temporal and spatial scales of these problems require the use of hybrid codes, in which ions are treated as kinetic particles and electrons as a fluid. On one hand, magnetohydrodynamic (MHD) codes cannot capture all the physics in these problems, (e.g. finite Larmor radius effects). On the other hand, full particle–in–cell (PIC) codes are computationally demanding and it is not possible now to simulate such large scale phenomena in three dimensions.

We have developed a new hybrid code, which has evolved from the code dcomet previously used to study the AMPTE releases[2]. In this 3D code, the ions are kinetic and pushed by a two step leap–frog technique, while the electrons are assumed massless and treated as a fluid. The fields are solved on a spatial grid using a Lax–Wendroff method. There is also the possibility to use it as a particle MHD code[3]. The present version allows for arbitrary field configurations, and advanced visualization with the OSIRIS analysis package[4].

As example of applications of this code, we have modeled the AMPTE releases, and we observed some of the expected features (e.g. the magnetic field compression, the formation of an diamagnetic bubble and the cloud recoil in the $\vec{v} \times \vec{B}$ direction).

Furthermore, we show that the study of the M2P2 concept can also be conducted with hybrid codes: magnetic field configurations, force exerted on the plasma sail and other issues can be easily addressed.

2 THE HYBRID MODEL

The hybrid model follows the work of R. Bollens et al[2] and F. Kazeminezhad et al[5] and its deduction is presented here for the sake of completeness. The hybrid set of push equations can be derived from the Vlasov and Maxwell equations. As a consequence of the electrons being treated as a massless fluid, both the electric field and the electrons can be ruled out of the problem – only a push equation for the ions and a field advance equation for the magnetic field have to be found. Considering only electromagnetic forces applied to all plasma species (i.e. neglecting the electron and the ion pressure tensors), and considering the Vlasov equation for the massless electrons, one gets:

$$\vec{E} = -\vec{V}_e \times \vec{B} \tag{1}$$

Faraday's law, used together with the total current density and Ampere's law without the displacement current allow for the substitution of the electron velocity in (1):

$$\vec{V}_e = \vec{V}_f - \frac{1}{ne\mu_0}\nabla\times\vec{B} \tag{2}$$

in which $\vec{V}_f$ is the ion fluid velocity and where quasi-neutrality is assumed (i.e. $n \approx n_e \approx n_i$). The magnetic field time advance equation and the ion push equation can then be written as

$$\frac{\partial\vec{B}}{\partial t} = \nabla\times(\vec{V}_f\times\vec{B} - \frac{1}{ne\mu_0}(\nabla\times\vec{B})\times\vec{B}) \tag{3}$$

$$\frac{d\vec{V}}{dt} = \frac{e}{M}\left[(\vec{V}-\vec{V}_f)\times\vec{B} + \frac{1}{ne\mu_0}\nabla\times\vec{B}\times\vec{B}\right] \tag{4}$$

Equation (4) differs from its MHD counterpart by the the first term that accounts for finite Larmor radius effects.

As equation (3) cannot be cast straightforwardly in a time-centered finite difference form, a Lax-Wendroff method is employed to obtain second-order accuracy in the time step. Given $\vec{B}_n$ and $\vec{V}_{fn}$ the algorithm states

$$\vec{B}_{n+1/2} = \{\vec{B}_n\} + \nabla\times(\vec{V}_{fn}\times\vec{B}_n)\frac{\Delta t}{2} + \nabla\times(\vec{B}_n\times(\nabla\times\vec{B}_n))\frac{\Delta t}{2} \tag{5}$$

$$\vec{B}_{n+1} = \vec{B}_n + \nabla\times(\vec{V}_{fn+1/2}\times\vec{B}_{n+1/2})\Delta t + \nabla\times(\vec{B}_{n+1/2}\times(\nabla\times\vec{B}_{n+1/2}))\Delta t \tag{6}$$

A two step leap-frog technique is implemented to push the ions. The velocities are defined, as usual, on half time step boundaries, whereas the positions are defined on full time step boundaries. A Gaussian spatial frequency filter is also implemented through the use of Fourier transformations. This is needed in order to eliminate the numerical noise with wavelength on the order of the grid size, due to the grid and finite size particles.

3 THE AMPTE RELEASE EXPERIMENTS

In the AMPTE release experiments[2,6], Barium and Lithium were released from an orbiting satellite into the solar wind. As the gas cloud expanded, a plasma is formed by sunlight UV photo ionization. When the solar wind plasma collides with the Barium/Lithium plasma a shock front is formed, and a diamagnetic cavity centered in the core of the cloud was measured. These features are clear in our simulation results (Fig. 1). Simulations also reveal effects not theoretically expected, but which naturally occurred in these experiments. The plasma cloud does not drift with the solar wind, and instead a $\vec{v}\times\vec{B}$ drift is observed. This is a rocket effect induced by a jet of outflowing cometary ions in the opposite direction[2]. This is clearly observed in our three-dimensional simulations. Benchmark with two dimensional hybrid simulations also confirms our findings[5].

The anomalous deflection of the bulk of the comet can be seen in figure 2. In these simulations the solar wind is flowing in the $+\,x$ direction and the background magnetic field B_0 is on the $+\,z$ direction. Magnetic field compression in the shock front and a diamagnetic cavity can be observed in figure 2.

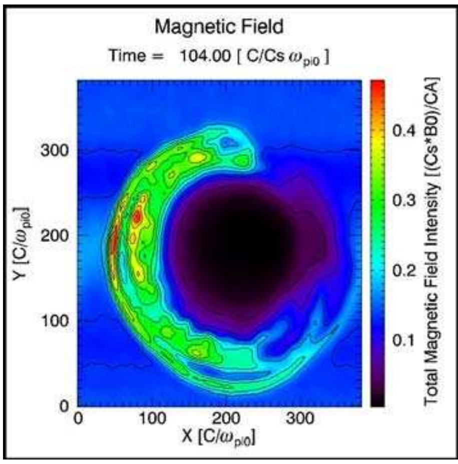

Fig. 1: Magnetic field intensity

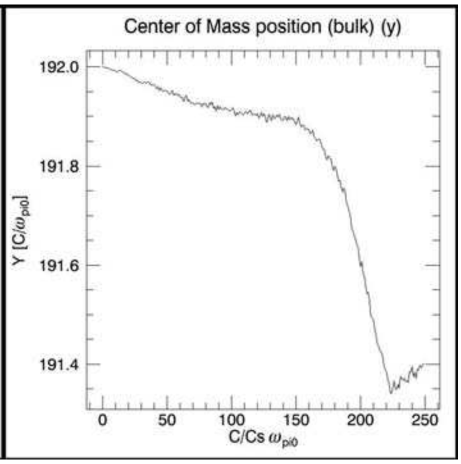

Fig. 2: Center of mass position

4 MINI-MAGNETOSPHERIC PROPULSION

Our code has been extended to incorporate arbitrary external magnetic fields. This is an important feature that allows the study of atmospheres with a global magnetic field, such as the M2P2 concept which requires the presence of an externally applied dipole field.

The M2P2 system consists of an expanding plasma, whose expansion is coupled with the dipole field. The solar wind transfers momentum to the plasma cloud and this momentum is transferred by the expanded magnetic field lines to the spacecraft. In figure 3 we show the plasma sail unfolding and the asymmetry introduced by the solar wind. In the same way as in the comet scenario, a shock front is formed, but now a clear asymmetry is observed in the dipole field (which has already expanded with the cloud). The B-field dragged by the plasma cloud, and compressed by the solar wind, decays much slower than a dipole field configuration and it is asymmetric thus indicating that a significant force will be exerted on the spacecraft. Detailed estimates will be presented elsewhere.

Feasibility studies about this system include assessment about the magnitude of the force exerted on the spacecraft and the magnetic field intensity decrease with distance.

Results from our simulation code show the magnetic bubble being formed – magnetic field configuration of the early stage development of the cloud can also be seen in figure 3.

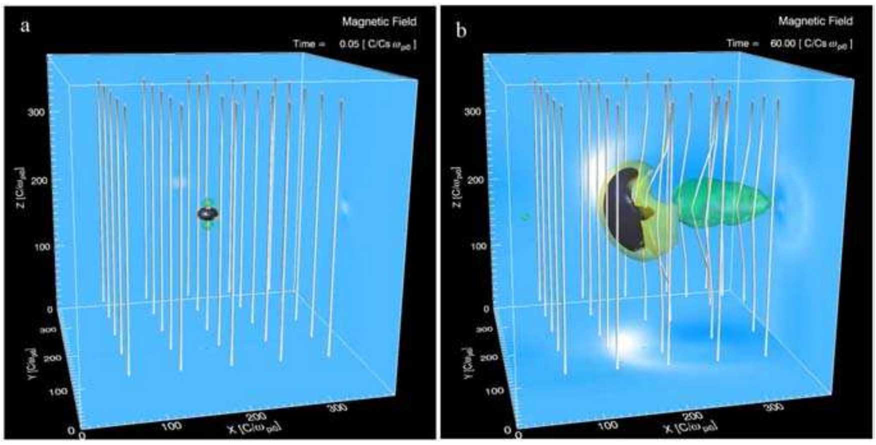

Fig.3: Magnetic field configuration at t=0.05 (a), and at t=60 (b). The magnetic field expansion is evident.

REFERENCES

[1] R. M. Winglee et al, J. Geophys. Res. **105**, 21067 (2000)

[2] R. Bollens, UCLA PhD thesis (1993)

[3] J. N. Leboeuf, T. Tajima, J. M. Dawson, J. Comp. Phys. **31**, 379 (1979)

[4] R. A. Fonseca et al, LNCS **2331**, 342 (Springer, Heidelberg, 2002)

[5] F. Kazeminezhad et al, J. Geophys. Res. **98**, 9493 (1993)

[6] R. Bingham et al, Comp. Phys. Commun. 49, 257 (1988)