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Four-fluid MHD Simulations of the Plasma and Neutral Gas Environment of Comet Churyumov-Gerasimenko Near Perihelion

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Abstract

We develop a 3-D four fluid model to study the plasma environment of comet Churyumov-Gerasimenko (CG), which is the target of the Rosetta mission. Our model is based on BATS-R-US within the SWMF (Space Weather Modeling Framework) that solves the governing multifluid MHD equations and and the Euler equations for the neutral gas fluid. These equations describe the behavior and interactions of the cometary heavy ions, the solar wind protons, the electrons, and the neutrals. This model incorporates mass loading processes, including photo and electron impact ionization, furthermore taken into account are charge exchange, dissociative ion-electron recombination, as well as collisional interactions between different fluids. We simulate the near nucleus plasma and neutral gas environment with a realistic shape model of CG near perihelion and compare our simulation results with Rosetta observations.

1 Introduction

The neutral and plasma environment is critical in understanding comet CG. Rubin et al. (2014) developed a multi-fluid plasma model and compared their simulation results with a hybrid simulation and showed that the multi-fluid plasma code can represent some distinct features from the hybrid simulation. However, their code applies a spherically symmetric neutral background from the analytical Haser model, which is only a crude approximation. Moreover, recent observations showed that comet CG has an irregular shape, which will likely influence the near body neutral and plasma distribution.

To understand the neutral gas and plasma interactions along with the irregular shape, we develop the first 3D multi-fluid neutral gas + plasma code, based on BATS-R-US within SWMF, with arbitrary shape.

2 Model Philosophy

Hydrodynamic equations for cometary neutral gas are provided in Equation 1:

$$\begin{aligned}
&\frac{\partial \rho_n}{\partial t} + \nabla \cdot (\rho_n \mathbf{u_n}) = \frac{\delta \rho_n}{\delta t}\\
&\frac{\partial \rho_n \mathbf{u_n}}{\partial t} + \nabla \cdot (\rho_n \mathbf{u_n} \mathbf{u_n} + p_n \mathrm{I}) = \frac{\delta \rho_n \mathbf{u_n}}{\delta t}\\
&\frac{\partial p_n}{\partial t} + \nabla \cdot (p_n \mathbf{u_n}) + (\gamma - 1) p_n (\nabla \cdot \mathbf{u_n}) = \frac{\delta p_n}{\delta t}
\end{aligned} \tag{1}$$

while MHD equations for cometary heavy ions (subscript s), solar wind protons (subscript s) and electrons (subscript e) are shown in Equation 2:

$$\begin{aligned}
&\frac{\partial \rho_s}{\partial t} + \nabla \cdot (\rho_s \mathbf{u_s}) = \frac{\delta \rho_s}{\delta t}\\
&\frac{\partial \rho_s \mathbf{u_s}}{\partial t} + \nabla \cdot (\rho_s \mathbf{u_s} \mathbf{u_s} + p_s \mathrm{I})\\
&\qquad - Z_s e \frac{\rho_s}{m_s} (\mathbf{E} + \mathbf{u_s} \times \mathbf{B}) = \frac{\delta \rho_s \mathbf{u_s}}{\delta t}\\
&\frac{\partial p_s}{\partial t} + \nabla \cdot (p_s \mathbf{u_s}) + (\gamma - 1) p_s (\nabla \cdot \mathbf{u_s}) = \frac{\delta p_s}{\delta t}\\
&\frac{\partial p_e}{\partial t} + \nabla \cdot (p_e \mathbf{u_s}) + (\gamma - 1) p_e (\nabla \cdot \mathbf{u_e}) = \frac{\delta p_e}{\delta t}\\
&\frac{\partial B}{\partial t} = -\nabla \times \mathbf{E}\\
&\mathbf{E} = -\mathbf{u}_+ \times \mathbf{B} - \frac{1}{n_e e} \nabla p_e
\end{aligned} \tag{2}$$

u_+ in Equation 2 is the charge averaged ion velocity and it can be expressed as $u_+ = \frac{\sum_{s=ions} Z_s n_s \mathbf{u_s}}{n_e}$. All the source terms for neutral gas and plasma fluids are incorporated in the right hand side of both Equation 1 and 2. The neutral gas fluid and the plasma fluids are coupled together. We specify the inner boundary at the comet surface and the outer boundary at the edge of the simulation domain.

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References

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