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Modeling comet 1P/Halley's plasma environment using multifluid MHD

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Abstract

Observations by ESA's Giotto spacecraft at comet 1P/Halley on March 14, 1986, allowed a detailed glance into the interaction between the neutral gas coma and the solar wind. For a highly productive comet such as 1P/Halley the plasma environment is remarkably diverse when probed at various cometocentric distances. We apply a global scale multifluid magnetohydrodynamics (MHD) approach in which the individual plasma components are treated as a set of coupled magnetized fluids ([1], [2]). This is a continuation of our previous work using a single species model ([3], [4]) and provides insight on some of the involved dynamical processes that might otherwise only be accessible by Monte Carlo Hybrid-type models.

1. Introduction

Given the minimal gravity of the comet, the neutral gas sublimating from the surface forms an extended coma orders of magnitude larger than the comet itself. In turn these neutral gas particles are ionized by solar UV photons and as such then subject to the magnetic and electric fields of the encompassing solar wind. As the solar wind approaches the comet it is mass-loaded and gradually slowed down due to its complex interaction with the plasma and neutral gas of cometary origin.

2. Model description

Our MHD model BATS-R-US (Block Adaptive Tree Solarwind Roe Upwind Scheme) is able to resolve the required disparate length scales through a tree-based mesh and parallel implementation for execution on computer clusters. We solve the multifluid MHD equations with point implicit source terms in a steady state approach applying the Rusanov scheme [5] with local time stepping.

In our model the neutral gas environment is precomputed. For the parent species (mostly H_2O and CO/CO_2) we use the model by Haser [6] and the distribution of the light neutrals (mostly atomic hydrogen from dissociation) we use a fit to the model results by [7].

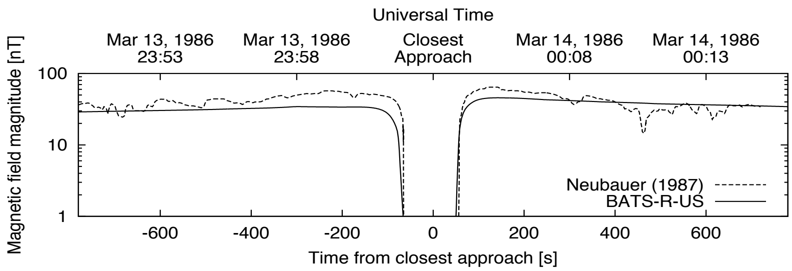
Table 1: Modeled species, dominant production and loss processes vary with location.

Plasma groups	Major production process	Major loss process
Solar wind protons	Sun	H^+_{SW} & $H_2O \rightarrow H_2O^+$ & H
Cometary light ions	H_2O & hν $\rightarrow H^+_{CL}$ & OH & e^-	H^+_{CL} & $H_2O \rightarrow H_2O^+$ & H
Cometary heavy ions	H_2O & hν $\rightarrow H_2O^+$ & e^-	H_2O^+ & $e^- \rightarrow H_2O$
Electrons	H_2O & hν $\rightarrow H_2O^+$ & e^-	H_2O^+ & $e^- \rightarrow H_2O$

The plasma species are consolidated into four major fluids (Table 1). First the solar wind is introduced at the upstream boundary of the simulation. Its composition is dominated by protons (H^+_{SW}). The second fluid contains the cometary light ions (H^+_{CL}: H^+ and H_2^+) and the third group the cometary heavy ions (H_2O^+, H_3O^+, CO^+, …). For each of these three groups we solve the coupled continuity, momentum, and pressure equations. The fourth group, the electrons, is derived from the ion species groups assuming charge-neutrality but furthermore includes a separate equation for the pressure to more self-consistently calculate the temperature of the thermal electron population.

The model treats the involved physical processes as source terms for the governing MHD equations. Included are photo- and electron impact ionization, (dissociative) ion-electron recombination, ion-neutral charge exchange, (in)elastic ion-neutral, ion-ion, and ion-electron collisions.

Figure 1: Modeled magnetic field strength along the Giotto trajectory compared to [8].



3. Summary of our results

We compare the results of our model to the observations obtained by the instruments on board Giotto, including the measured magnetic field as well as densities, bulk speeds, and temperatures of the individual ion groups. Our results indicate:

- The plasma bulk speeds and temperatures of the individual ion species stay coupled inside the ion pile-up region (~20,000 km).
- Farther away from the comet the fluids clearly interact with each other through the Lorentz force. Solar wind protons and cometary heavy ions are deflected in opposite directions.
- There the temperature of the pick-up ions reaches ~ 10^8 K and is thus much hotter than the solar wind temperature (~100,000 K).
- The model is capable of qualitatively reproducing the sharp increase of the electron temperature in the ion pile-up region responsible for the reduction in the ion-electron recombination rate. Inside the cavity the electrons are efficiently cooled by inelastic electron-H_2O collisions.
- The model reproduces the magnetic cavity, as shown in Fig. 1, and the associated inner shock.
- Solar wind protons vanish in the vicinity of the comet, i.e. inside the ion pile-up.

Of course, while getting a satisfactory match to the observations, the results have to be understood in the limitations of the chosen fluid approach.

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