INPE – National Institute for Space Research
São José dos Campos – SP – Brazil – May 16-20, 2016

SIMULATING THE INTERACTION OF A COMET WITH THE SOLAR WIND USING A MAGNETOHYDRODYNAMIC MODEL

Edgard de F. D. Evangelista[1], *Margarete O. Domingues*[2], *Odim Mendes*[3], *Oswaldo D. Miranda*[4]

[1]Laboratório Associado de Computação e Matemática Aplicada (LAC), INPE-PCI, São José dos Campos, Brazil, edgard.evangelista@inpe.br
[2]Laboratório Associado de Computação e Matemática Aplicada (LAC), INPE, São José dos Campos, Brazil, margarete.domingues@inpe.br
[3]Divisão de Geofísica (DGE), INPE, São José dos Campos, Brazil, odim.mendes@inpe.br
[4]Divisão de Astrofísica (DAS), INPE, São José dos Campos, Brazil, oswaldo.miranda@inpe.br

Abstract: We present the simulation of a comet interacting with the solar wind. The simulations are treated in the framework of the ideal magnetohydrodynamics (MHD), using the FLASH code in order to solve the equations of such a formalism. In our simulations the comet is treated as a spherically symmetric source of ions. Our aim is to study the influence of the solar wind on the characteristics of the comet.

keywords: Fluidodynamics, Plasma and Turbulence; Modeling, Numerical Simulation and Optimization; Geophysical Nonlinear Dynamics; FLASH code; magnetohydrodynamics.

1. INTRODUCTION

A comet may be defined as a object formed by rock, dust and water ice and which undergoes the action of the gravitational field of the Sun. In such objects it is usual the presence of gases such as ammonia, methane and carbon oxides[1].

Concerning the physical models, it is common to figure a comet as a ball of “dirty ice”, which undergoes sublimation when it reachs the regions close to the perihelion of its orbit. The sublimation causes the ejection of gases and dust, forming the characteristic coma and tail of the comet.

The simulation of the interaction between the coma and tail with the solar wind are important once it provides physical insights of the processes characteristic of cometary atmospheres. Besides, such simulations may yield information about the physical and chemical processes in the coma. Further, the interaction of the comet with the plasma of the solar wind may be used as a tool for tracing the behaviour of the space environment.

The aim of this extended abstract is to show the work to be presented at the NSC conference. This work consists on the numerical simulation of a comet interacting with the solar wind. Particularly, the comet is modelled as a spherically isotropic source of ions. The simulation are performed with the FLASH Code of the University of Chicago[2], using the formalism of the ideal, two dimensional magnetohydrodynamics (MHD).

In Section 2 we present the basic formalism of the MHD, with the terms representing the comet included in the equations; in Section 3 we show the numerical aspects of the problem and one subsidiary result; in Section 4 we present the results of the simulations.

2. THE MHD MODEL

The MHD formalism describes the interaction between compressible plasma and magnetic fields. This model is built when one combines the equations governing the fluid dynamics with the Maxwell equations of the electromagnetism resulting, in a 3D domain, in a systems of eight equations describing the conservation of mass and momentum, Faraday’s

Law and the conservation of energy[3]. In the present work we are considering the ideal MHD, that is, the case where dissipative terms such as resistivity and viscosity are neglected. Besides, we restrict ourselves to the non-relativistic case, that is, all the velocitites considered are small when compared to the speed of light in vacuum. The system of equations of the MHD is given by[4]:

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho \\ \rho\mathbf{v} \\ \mathbf{B} \\ \rho E\end{pmatrix} + \nabla\cdot\mathbb{F} = \begin{pmatrix} A \\ -\mathbf{v}A \\ \mathbf{0} \\ \frac{Au_n^2}{2}\end{pmatrix}, \qquad (1)$$

where

$$\mathbb{F} = \begin{pmatrix} \rho\mathbf{v} \\ \rho\mathbf{v}\mathbf{v} - \mathbf{B}\mathbf{B} + \left(p + \frac{B^2}{2}\right)\mathbf{I} \\ \mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v} \\ \mathbf{v}\left(\rho E + p + \frac{B^2}{2}\right) - \mathbf{B}(\mathbf{v}\mathbf{B})\end{pmatrix}. \qquad (2)$$

In Eq. 1 and 2, ρ is the mass density, p is the thermal pressure, $\mathbf{v}$ is the velocity, $\mathbf{B}$ is the magnetic field, $\mathbf{I}$ is the 3x3 identity matrix, u_n is the radial velocity in which the gas is ejected from the comet and E is the total energy. On the other hand, A is the source term representing the comet, which has the form[4]:

$$A = A(r) = \frac{Q}{4\pi\lambda r^2} e^{-r/\lambda}\,\mathrm{kg\ m^{-3}\ s^{-1}}, \qquad (3)$$

in which r is the radial distance from the center of the comet, Q is the gas production rate and $\lambda = \tau u_n$, where $\tau = 3.03\times 10^5$ s is the typical ionisation time.

3. NUMERICAL METHODS

The simulations are performed with the FLASH Code distributed by the Center for Astrophysical Thermonuclear Flashes at the University of Chicago[2]. This code permits the user to choose several parameters of the problem being simulated, such as initial and boundary conditions and the schemes for the calculation of the numerical fluxes, for example.

In the present simulations it is used the Roe flux and a second order Godunov method called piecewise-parabolic (PPM) algorithm. Besides, it is used the adaptive refinement scheme known as PARAMESH.

As a subsidiary result, we show the simulation of a comet with $Q = 1.0\times 10^{30}\,\mathrm{s^{-1}}$, adiabatic index $\gamma = 5/3$, in a box domain of size $x \in [-2.8, 1.6]\times 10^9\,\mathrm{m}$ and $y \in [-2.2, 2.2]\times 10^9\,\mathrm{m}$ and with a CFL parameter of 0.8. The physical parameters of the solar wind are shown in Table 1.

The simulation starts with a block of 8×8 cells and evolves up to six levels of refinement. Each level of refinement quadruplicates the number of blocks such that at the end of the process the domain would have 32×32 blocks if it would be entirely refined. This case correspond to a mesh of 256×256 cells. Figures 1 and 2 show the density profiles at the instant $t = 1.0\times 10^5\,\mathrm{s}$. Figure 2 shows the configuration of blocks and cells generated by the adaptive mesh refinement.

Table 1 – Parameters of the solar wind.

ρ kg m^{-3}	T 10^5 K	(B_x, B_y, B_z) nT	(v_x, v_y, v_z) 10^5 m s^{-1}
6.5×10^{-21}	2.4×10^4	$(0, 0, 6.0)$	$(-5.0, 0, 0)$

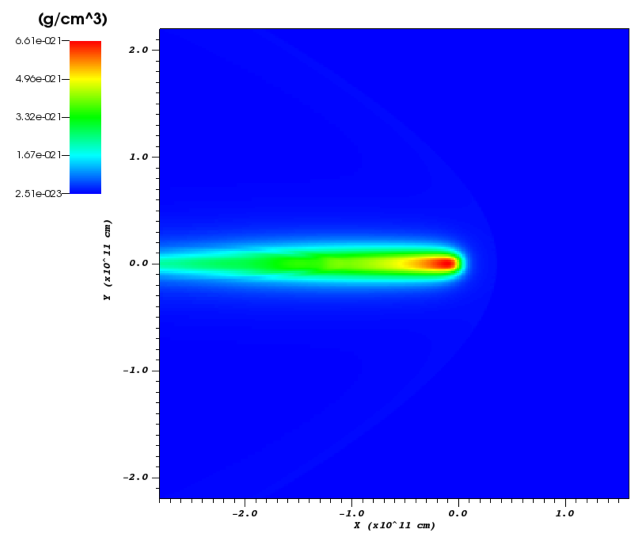

Figure 1 – Density profile at $t = 1.0\times 10^5\,\mathrm{s}$ for the scenario given in Table 1.

4. RESULTS

We address to the case where the comet has a gas production rate Q which is not constant. In fact, such a rate generally depends on the physical properties of the solar wind and of the heliocentric distance. In our case, we take four scenarios, where the physical properties of the solar wind and of the comet itself assume different values in each case. We follow [5] and take the four scenarios shown in Table 2.

Table 2 – Parameters of the comet and the solar wind for the four cases being considered.

	Case 1	Case 2	Case 3	Case 4
Q $10^{24}\,\mathrm{s^{-1}}$	1.000	80.00	800.0	5000
λ 10^9 m	11	7.3	4.0	1.7
ρ 10^{-21} kg m^{-3}	1.50	2.34	4.18	10.0
B_z nT	1.6	2.0	2.8	4.9
$\mathbf{v}$ 10^5 m s^{-1}	$(4, 0, 0)$	$(4, 0, 0)$	$(4, 0, 0)$	$(4, 0, 0)$

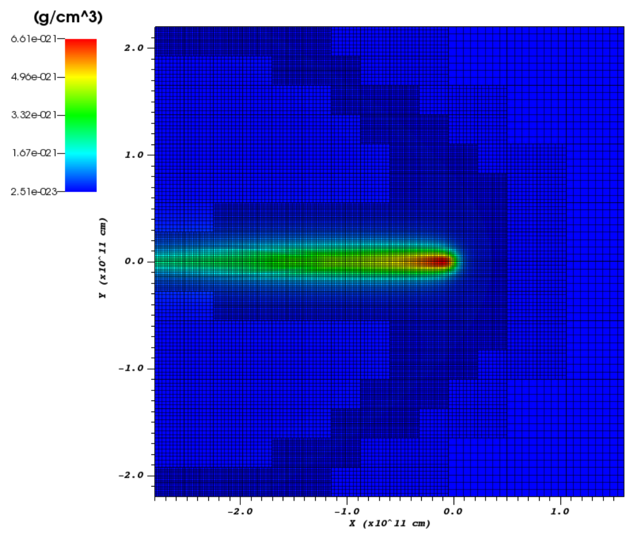

Figure 2 – Same as in Fig. 1 but showing the configuration of blocks and cells generated by the adaptive mesh refinement.

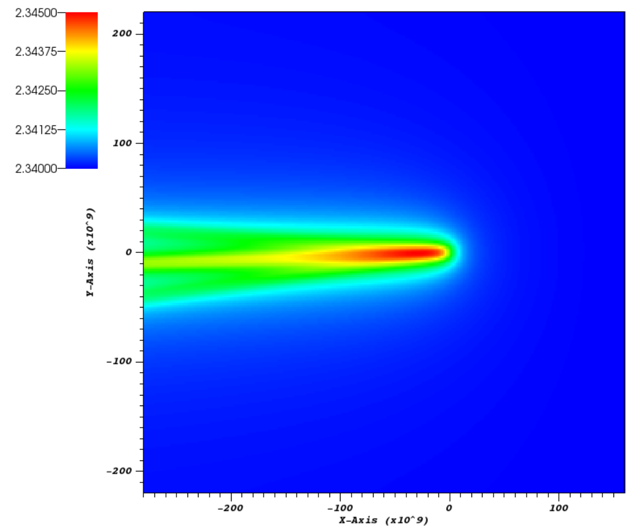

Figure 4 – Same as in Fig. 3 for the Case 2.

Figures 3–6 show the density profiles for the four cases considered, taken at the instant $t = 1.0 \times 10^5$ s. Observing the figures, we may note that the choice of the parameters in the range determined by the four scenarios has small effect on the resulting simulation. However, we observe that the tail of the comet for the scenario 4 is wider than in the other cases. This behaviour can be explained by the action of the rate Q: with effect, in the scenario 4, such a rate is three orders of magnitude greater than the one in the scenario 1.

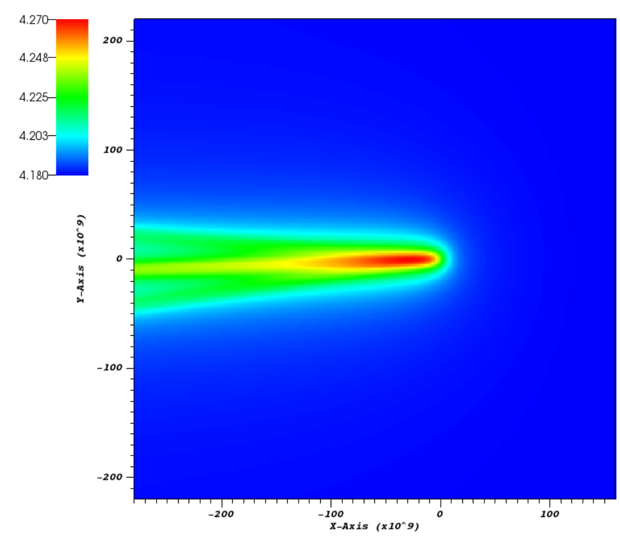

Figure 5 – Same as in Fig. 3 for the Case 3.

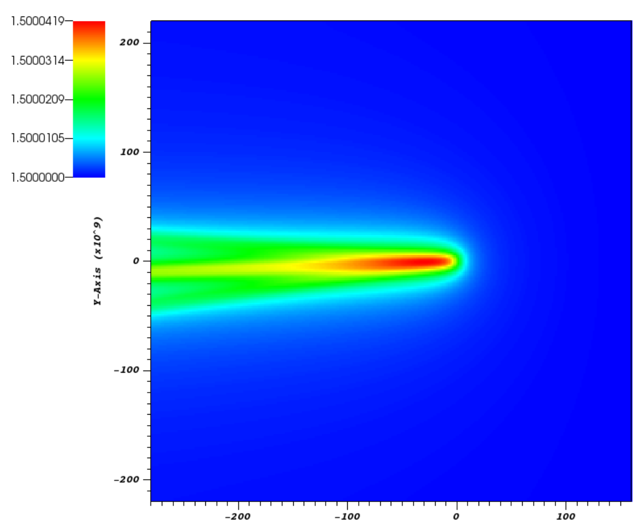

Figure 3 – Density profile (given in $\times 10^{-21}$ kg m^{-3}) at $t = 1.0 \times 10^5$ s for the Case 1 given in Table 2.

Note that in the case of Fig. 3 we have the smallest variations in the density, where the density in the inner regions of the cometary atmosphere has a value which is $\sim 0.003\%$ greater than the ones observed in the environment. Again, such a behaviour may be justified by the values of the rate Q: scenario 1 has the Q with the smallest value. Besides, note that the tail of the comet forms a small angle with the horizontal, though the initial conditions and the values of the parameters are symmetric in the domain. This fact can be explained by the action of the magnetic field present in the simulations.

The scheme treated here are a very versatile tool for the understanding of the mechanisms of interaction of a comet with the plasma of the solar wind. Particularly, it is possible analise the influence of the several parameters on the characteristics of the coma and tail of the comet.

Further, in order to provide a validation for our scheme, its results can be compared to the others found in the literature. For example, the present simulations show a good

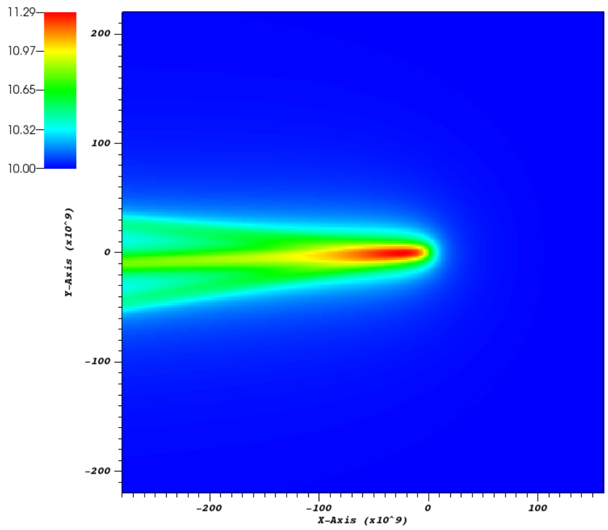

Figure 6 – Same as in Fig. 3 for the Case 4.

agreement with the ones found in [4], where the solar wind flow around the comet is simulated using a MHD model developed by the authors.

5. CONCLUSIONS

We presented the simulations of a comet interacting with the solar wind. We considered four different scenarios, with different parameters for the solar wind and for the comet itself. For the range of values considered, the choice of a particular scenario did not have a strong impact on the results, though we could observe a small effect in the width of the tail of the comet. Such a difference was related to the increase in the Q rate.

The present model is a useful tool in the study of the processes involving comets and the plasma in the space environment. The model is versatile once the parameters of a given simulation can be easily changed and their effects on the results can be readily analysed. This characteristic may be specially interesting in the study of the instabilities which may occur in this type of interaction.

In subsequent works we will study the formation of hydrodynamic instabilities in the coma and tail of comets when interacting with the plasma of the solar wind. We will focus on the search for Kelvin-Helmholtz instabilities.

ACKNOWLEDGMENTS

EFD Evangelista acknowledges the Brazilian agency CNPq, grant 300089/2016-3 (PCI INPE). O Mendes, MO Domingues and OD Miranda acknowledge MCTI/FINEP/INFRINPE-1 (grant 01.12.0527.00), the Brazilian agencies CNPq (grants 306038/2015-3; 312246/2013-7), FAPESP (grant 2015/25624-2), CAPES for financial support. Solar wind data were provided by GSFC/SPDF with the OMNIWeb interface. FLASH was in part developed by the DOE NNSA-ASC OASCR Flash Center at the University of Chicago.

References

[1] J. M. Greenberg, “Making a comet nucleus”, Astron. Astrophys., Vol. 330, No. 1, pp. 375-380, February 1998.

[2] B. Fryxell *et al.*, “FLASH: an adaptive mesh hydrodynamics code for modeling astrophysical thermonuclear flashes”, Astrophys. J. Suppl. S., Vol. 131, pp. 273-334, November 2000.

[3] K. G. Powell, P. L. Roe, T. J. Linde, T. I. Gombosi, and D. L. De Zeeuw, “A solution-adaptive upwind scheme for ideal magnetohydrodynamics”, J. Comp. Phys., Vol. 154, pp. 284-309, 1999.

[4] A. Ekenbäck, M. Holmström, S. Barabash, and H. Gunell, “energetic neutral atom imaging of comets”, Geophys. Res. Lett., Vol. 35, No. 5, pp. L05103, March 2008.

[5] M. G. Lebedev, V. B. Baranov, and D. B. Alexashov, “Interaction of low-activity comets with the solar wind”, Earth Moon Planets, Vol. 116, No. 3, pp. 159-179, December 2015.