Proceeding Series of the Brazilian Society of Applied and Computational Mathematics, Vol. 5, N. 1, 2017.

Trabalho apresentado no CNMAC, Gramado - RS, 2016.

Proceeding Series of the Brazilian Society of Computational and Applied Mathematics

Simulating the interaction of a comet with the solar wind using a magnetohydrodynamic model

Edgard de F. D. Evangelista[1]
Laboratório Associado de Computação e Matemática Aplicada (LAC), INPE-PCI, São José dos Campos, SP, Brazil
Margarete O. Domingues[2]
Laboratório Associado de Computação e Matemática Aplicada (LAC), INPE, São José dos Campos, SP, Brazil
Odim Mendes[3]
Divisão de Geofísica (DGE), INPE, São José dos Campos, SP, Brazil
Oswaldo D. Miranda[4]
Divisão de Astrofísica (DAS), INPE, São José dos Campos, SP, Brazil

Abstract. This paper presents the simulation of the interaction of a comet with the solar wind. It is used the formalism of the ideal magnetohydrodynamics (MHD) in order to simulate the behaviour of such a system. The comet itself is inserted in the equations as a spherically symmetric source of ions. Specifically, this source term represents the process of mass-loading, that is, the phenomenon where the heavy cometary ions are picked up by the solar wind. From the numerical viewpoint, it is used the FLASH code to solve the system of equations of the MHD and to generate the output files. It is investigated the influence of the physical characteristics of the solar wind, such as velocity and magnetic field, on the coma and tail of the comet. This issue is addressed by performing simulations considering, for sake of comparison, three regimes of solar activity, namely: low activity, "mean" or typical activity and intense activity.

Keywords. Magnetohydrodynamics, FLASH Code, Solar Wind, Comet

1 Introduction

A comet is a small Solar System body formed basically by a amalgamation of rock, dust and water ice. Besides, one can find gases such as ammonia, methane and carbon oxides [4] in its composition. Roughly speaking, it is common to figure a comet as a ball of "dirty ice" and when an of such objects approaches the perihelion of its orbit, that is, when it come close to the sun, the sublimation causes the ejection of its gas and dust [5].

[1]edgard.evangelista@inpe.br
[2]margarete.domingues@inpe.br
[3]odim.mendes@inpe.br
[4]oswaldo.miranda@inpe.br

 © 2017 SBMAC

Firstly, the simulations of the interaction of the solar wind with comets are important once they help us to understand the physical processes characteristic of comet atmospheres [7]. Secondly, such simulations can provide information about the physical and chemical phenomena taking place in the coma[5]. As a third aspect, comets interacting with the plasmas of the solar wind can be potentially used as visible tracer for the space environment behaviour.

It is worth mentioning that in such interactions several interesting plasma processes can occur [6], giving special attention to the MHD instabilities such as the Kelvin-Helmholtz instability [5]. These facts reinforce the importance of studying such interactions.

There are in the literature many examples of the study of comets interacting with solar wind. For example, in [10] the authors address to the interaction of solar wind with Comet 19P/Borrelly; in [6] it is analysed the cometary ion instabilities during the interaction; the paper [1] treats Comet Halley, comparing a theoretical model with observational data taken during its apparition in 1986. Besides, the reader may find studies such as [9], where the authors focus on the study of comet tails and the processes characteristic of them. Last, the reference [7] shows the MHD simulation of Comet Halley, comparing the results to observational data.

The aim of this paper is to present numerical simulations of a comet interacting with the solar wind, where the comet is modelled as a spherically isotropic source of ions. These simulations are performed with the FLASH Code [3] of the University of Chicago and in the framework of the ideal, two-dimensional magnetohydrodynamics (MHD). Particularly, it is analysed the influence of the physical parameters of the solar wind on the behaviour of the comet.

This paper is organised in the following form: the basic formalism of the MHD with the source terms representing the comet are discussed in Section 2; Section 3 addresses to the numerical aspects of the simulation, such as physical parameters and computational methods; the results and discussions are shown in Section 4, while the conclusions are presented in Section 5.

2 The MHD model

Basically, the formalism of the MHD describes the interaction between a magnetic field and a compressible fluid. Such a model is built through the combination of the equations governing the fluid dynamics with the Maxwell equations of the electromagnetism, which, in a 3D domain, results in a system of eight equations, namely: conservation of mass (1 equation); conservation of momentum (3 equations); Faraday's Law (3 equations) and conservation of energy (1 equation) [8].

In this case one considers the ideal MHD, in which the viscosity and the resistivity of the fluid can be neglected, that is, there are no dissipative terms in the equations. Besides, the fluid has a non-relativistic behaviour at all points of the domain, that is, all the velocities being considered are small when compared to the speed of light in vacuum.

[5] *Coma* is the envelope around the nucleus of comets. It is formed by ice, dust and gases.

DOI: 10.5540/03.2017.005.01.0328 © 2017 SBMAC

On the other hand, the comet is inserted in the simulation as a spherically symmetric source of photo-ions, which results in a process of mass-loading between the solar wind and such photo-ions. Quantitatively, the comet is modelled as the ion source term

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

where $r(x,y) = \sqrt{(x-x_0)^2 + (y-y_0)^2}$ is the distance from the centre of the comet (x_0, y_0), Q is the gas production rate and $\lambda = \tau u_n$ is the typical ionisation distance (τ is the ionisation time). Typically, Q=$1.0\times10^{30}\,\text{s}^{-1}$; τ=3.03×10^5 s and u_n=1.0×10^5 cm s^{-1}.

The system given in equation (2) shows the equations of the ideal MHD adapted for the present problem, with the source terms representing the comet at the right hand [2]. It is used the non-dimensional form, that is, without the constants 4π and μ_0.

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho\\ \rho\mathbf{v}\\ \mathbf{B}\\ \rho E\end{pmatrix} + \nabla\cdot\begin{pmatrix}\rho\mathbf{v}\\ \rho\mathbf{v}\mathbf{v} - \mathbf{B}\mathbf{B} + \left(p + \frac{B^2}{2}\right)\mathbf{I}\\ \mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v}\\ \mathbf{v}\left(\rho E + p + \frac{B^2}{2}\right) - \mathbf{B}(\mathbf{v}\mathbf{B})\end{pmatrix}^T = \begin{pmatrix}A\\ -\mathbf{v}A\\ \mathbf{0}\\ \frac{Au_n^2}{2}\end{pmatrix}, \tag{2}$$

where 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 3×3 identity matrix , u_n is the radial velocity in which the gas is ejected from the comet and E is the total energy given by

$$E = \epsilon + \frac{\rho v^2}{2} + \frac{B^2}{2}. \tag{3}$$

Besides, in this case it is considered the equation of state of an ideal gas, relating the pressure p to the internal energy ϵ in the form $p = (\gamma-1)\rho\epsilon$ or $p = \rho k_B T/M$, where γ is the adiabatic index, M is the mean atomic mass and $k_B = 1.38\times10^{-23}$ J/K is the Boltzmann's constant.

3 Numerical aspects

FLASH code, which was originally created for handling general compressible flow problems found in many astrophysical environments, has been developed and is distributed by the Center for Astrophysical Thermonuclear Flashes, or FLASH Center, at the University of Chicago[6]. This code has a modular architecture and has been developed for adaptive-mesh and parallel simulations. Besides, it permits the users to choose initial and boundary conditions for a given simulation, permits the customisation of the codes in order to simulate particular cases and, thanks to its modular architecture, allows changes in the algorithms and the creation of new physics modules.

Further, it is worth mentioning that the FLASH code uses the PARAMESH library to manage the block-structured adaptive refinement scheme and uses the Message-Passing

[6] http://flash.uchicago.edu/site/flashcode

 © 2017 SBMAC

Interface (MPI) library to allow portability on a variety of computers when dealing with parallel computation.

In the present simulations it is used the Roe flux and the split piecewise-parabolic (PPM) algorithm, which is a second-order Godunov method. Generally speaking, the Godunov method uses a spatial discretisation with finite volumes to solve the Euler equations. On the other hand, the time advancement of the equations is handled by means of the second-order Strang splitting and it uses the constrained transport for keeping the solenoidal constraint on the magnetic field.

In this particular case, the simulation is started with a block of 8×8 cells and evolves up to six levels of refinement. Each level of refinement quadruplicates the number of blocks, in such a manner that if the whole domain would be refined, the domain would have 32×32 blocks at the end of the process. Such a case correspond to a mesh of 256×256 cells. Further, it is worth bearing in mind that the PARAMESH uses a refinement criteria adapted from Löhner's error estimator with threshold 10^{-2} in order to trigger the mesh refinement process.

The simulation box domain is $x \in [-2.8, 1.6] \times 10^{11}$ cm and $y \in [-2.2, 2.2] \times 10^{11}$ cm, with the boundary condition *outflow* at $\mathrm{x_{left}}$, *user defined* at $\mathrm{x_{right}}$ and *periodic* at $\mathrm{y_{left}}$ and $\mathrm{y_{right}}$. The *outflow* boundary condition stands for a null gradient at the border, that is, it means that the shocks can leave the domain; on the other hand, the *periodic* condition can be figured as a "wrap-around" of the domain. Last, the *user defined* condition is the one defined by the user and here, particularly, represents the solar wind emerging from $\mathrm{x_{right}}$ and flowing in the negative x-direction. All simulations used a CFL parameter of 0.8, an adiabatic index $\gamma = 5/3$ and are computed to a final time 1.0×10^5 s.

Table 1 shows the parameters of the solar wind for the three cases being considered: low solar activity, typical solar activity and intense solar activity. The parameters for the low and intense cases were extracted from the GSFC/SPDF OMNIWeb interface[7], which provides data collected by the ACE, Wind, IMP 8 and Geotail spacecrafts. The parameters for the low and intense cases were collected, respectively, in 12/05/2009 and 24/10/2003 and are given in Geocentric Solar Ecliptic (GSE) coordinates. It is worth mentioning that such data were collected at the distance of ~1 AU from the Sun[8]. On the other hand, the data for the typical case are given in [2].

Table 1: Initial conditions of the environment

	ρ $\times 10^{-23}$ g cm^{-3}	T $\times 10^5$ K	(B_x, By, Bz) $\times 10^{-9}$ T	(v_x, v_y, v_z) $\times 10^7$ cm s^{-1}
Calm	0.65	0.24	$(-1.31, -1.88, 0.97)$	$(-3.52, -0.14, -0.01)$
Typical	2.51	2.00	$(0.00, 0.00, 6.00)$	$(-5.00, 0.00, 0.00)$
Intense	9.23	2.62	$(-8.38, 18.70, 12.38)$	$(-6.03, -0.54, 0.26)$

[7] `http://omniweb.gsfc.nasa.gov/form/omni_min.html`

[8] AU stands for astronomical unit and corresponds to the mean distance between the Earth and the Sun, that is, ≈150 million kilometers.

 © 2017 SBMAC

4 Results

Figures 1-3 show the simulation of the comet for the three scenarios, respectively: calm, typical and intense. Besides, note that it is shown the resulting configuration of blocks and cells generated by the adaptive mesh refinement.

One may note the effect of the solar wind on the tail of the comet. For example, for the *calm* scenario, the tail is smaller ($\sim 2 \times 10^{11}$ cm) and less developed when compared to the other cases. A similar behaviour may be seen in the coma, which becomes more exuberant as the solar wind becomes more intense. The tail is thinner in the *intense* case, which can be explained by the action of the magnetosphere around the comet. Such a magnetosphere is created by the plasma being carried away by the solar wind. Therefore, one can imagine the magnetic field lines being "wrapped" around the comet and modelling the tail by means of the magnetic force.

It is interesting to observe the bow shock, that is, the region where occurs the shock of the solar wind with the "obstacle" represented by the comet. Note that such a region is too tenuous to appear in the *calm* and *typical* cases shown in Figures 1 and 2 but it can be observed from the mesh configuration. In the shock, the density of cometary ions increases as the regime become more intense.

Comparing to the *typical* case, the *calm* scenario has the shock which is farther from the coma and exhibits a wider angle ($\theta \sim 130°$, versus $\theta \sim 100°$of the *typical* case). On the other hand, for the *intense* case the shock is attached to the coma and has the smallest opening angle among the three scenarios ($\theta \sim 54°$). Particularly, in Figure 3 one can note that the bow shock has its form similar to a Mach wave. This fact suggests the supersonic behaviour of the comet relative to the solar wind.

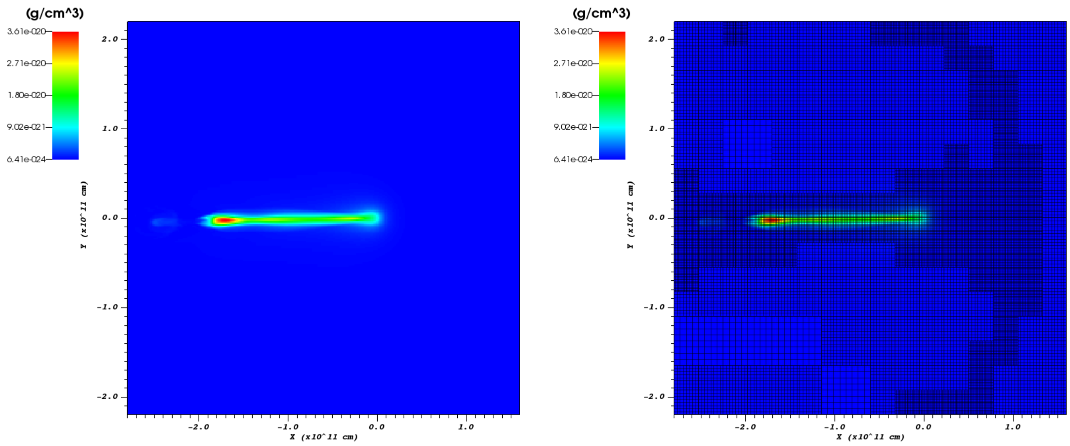

Figure 1: Density profiles at $t = 1.0 \times 10^5$ s for the *calm* scenario. The right side shows the resulting configuration of blocks and cells generated by the adaptive mesh refinement.

DOI: 10.5540/03.2017.005.01.0328 © 2017 SBMAC

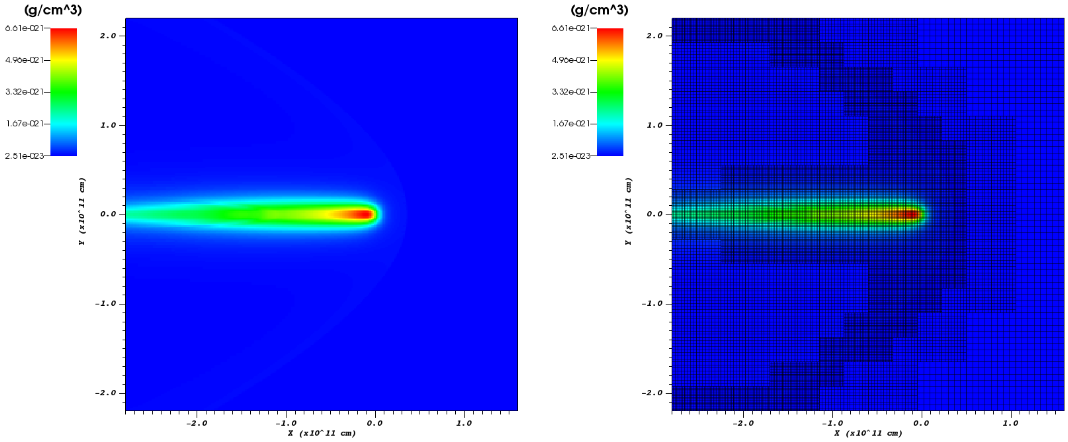

Figure 2: Same as in Figure 1 for the *typical* scenario.

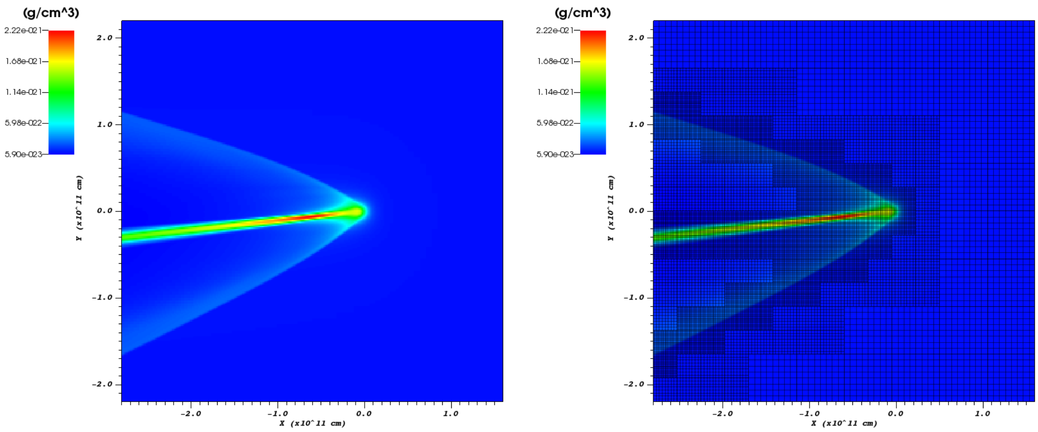

Figure 3: Same as in Figure 1 for the *intense* scenario.

5 Conclusions

Simulations of a comet interacting with the solar wind were shown. The comet was treated as a source of ions, which are carried away by the solar wind in a process of mass-loading. In order to study the influence of the solar wind on the comet, the simulation were performed for three different space environment scenarios: with solar plasmas under calm, typical and intense regimes. It was observed that the scenario affect the characteristics of the comet, such as its tail and coma. Particularly, the more intense the solar wind is, the more exuberant the coma and the more developed the tail is. Besides, it was analysed the behaviour of the bow shock. For more intense regimes, such a shock tends to exhibits smaller opening angles and lie closer to the coma. For the *intense* scenario considered in

 © 2017 SBMAC

this paper, the shock is attached to the coma and has its shape similar to a Mach wave.

Upcoming papers will address to the case where the comet has a gas production rate Q which is not constant, or more specifically, where such a rate depends on the physical properties of the solar wind and of the heliocentric distance.

Acknowledgements

EFD Evangelista acknowledges the Brazilian agency CNPq, grants 158967/2014-3, 300089/2016-3 (PCI INPE). O Mendes, MO Domingues and OD Miranda thankfully 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. We thank to Eng. Varlei Menconi (MCTI/INPE-PCI 455097/2013-5) for computational assistance. 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] V. B. Baranov and M. G. Lebedev. The interaction between the solar wind and the comet P/Halley atmosphere: observations versus theoretical predictions, *Astron. Astrophys.*, 273:695–706, 1993.

[2] A. Ekenbäck, M. Holmström, S. Barabash and H. Gunell. Energetic neutral atom imaging of comets, *Geophys. Res. Lett.*, 35:L05103, 2008.

[3] B. Fryxell *et al.* FLASH: an adaptative mesh hydrodynamics code for modeling astrophysical thermonuclear flashes, *Astrophys. J. Suppl. S.*, 131:273–334, 2000.

[4] J. M. Greenberg. Making a comet nucleus, *Astron. Astrophys.*, 330:375–380, 1998.

[5] H. Gunnel *et al.* Acceleration of ions and nano dust at a comet in the solar wind, *Planet. Space Sci.*, 119:13–23, 2015.

[6] L. Matteini, S. J. Schwartz and P. Hellinger. Cometary ion instabilities in the solar wind, *Planet. Space Sci.*, 119:3–12, 2015.

[7] K. Murawski. Two-dimensional MHD simulations of the solar wind interaction with Comet Halley, *Acta Astronom.*, 48:803–817, 1998.

[8] K. G. Powell *et al.* A Solution-Adaptive Upwind Scheme for Ideal Magnetohydrodynamics, *J. Comp. Phys.*, 154:284–309, 1999.

[9] R. Wegmann. The effect of some solar wind disturbances on the plasma tail of a comet: models and observations, *Astron. Astrophys.*, 358:759–775, 2000.

[10] D. T. Young *et al.* Solar wind interaction with Comet 19P/Borrolly, *Icarus*, 167:80–88, 2004.

 © 2017 SBMAC