*SF2A 2011*
*G. Alecian, K. Belkacem, R. Samadi and D. Valls-Gabaud (eds)*

# NUMERICAL MODELLING OF THE ACCRETION COLUMN IN MAGNETIC CATACLYSMIC VARIABLES

C. Busschaert[1, 2], C. Michaut[1], E. Falize[1,2], B. Loupias[2], A. Ravasio[3], A. Dizière[3], H. C. Nguyen[1] and M. Koenig[3]

**Abstract.** Numerical simulations of the accretion column in magnetic cataclymic variables are presented along with the experimental principle of laboratory experiment from the POLAR project. The main focus of the project is to design and diagnose an exact scaled accretion column using powerful lasers. These measurements allow the testing of the astrophysical models of accretion processes present in magnetic cataclysmic variables.

Keywords: laboratory astrophysics, magnetic cataclysmic variables, radiative shocks, accretion, scaling laws

## 1 Introduction

Modern high-energy density facilities allow to bring up matter, reproducibly, to extreme states of density, temperature and velocity which are relevant to astrophysical environments (Remington et al. 2006). In the context of the POLAR project (Falize et al. 2011b) new similarity experiments are realized in order to study the formation and the dynamics of accretion shocks in magnetic cataclysmic variables (mCVs).
The mCVs are semi-detached binary systems containing an accreting magnetic white dwarf which accretes matter from a late type Roche-lobe filling secondary star (Warner 1995). They are divided into two main sub-classes according to the magnetic field intensity (Cropper et al. 2002): the intermediate polar or DQ Her star which has 1 MG $<$ B $<$ 10 MG and the polar or AM Her star with B $>$ 10 MG. In polar stars, the magnetic field is so strong that it prevents the formation of an accretion disc. The accreted gas is confined to stream flowing along the magnetic field line onto the pole of white dwarf (Wu 2000).
We developed a theoretical model of radiative optically thin shocks which can be easily confronted with observations from polars since the radiation of those objects comes mainly from an area near the white dwarf surface: the base of the accretion column where many spectroscopic clues indicate the presence of radiating shocks. However the size scales associated with the accreted shock are smaller than the white dwarf radius. Consequently it is impossible for now to resolve this zone by direct observations (Hoogerwerf et al. 2006). In order to explore more precisely what happens in the column, we can use an adapted scaling law which allows to reproduce with powerful laser a diagnosable accretion column.
At first, we will detail the model and numerical results obtained with the code HYDRO-COOL for the accretion column at the astrophysical scale and then we will detail how to build a model of those objects in the laboratory.

## 2 Analytical model of the accretion column and numerical study

During the accretion process in polars, the matter is directed along the magnetic field lines toward the magnetic pole(s) of the white dwarf. When the flow hits the surface of the star at supersonic velocity, a reverse shock is created and propagates upward in the accretion column until a position on the order of 100-1000 km above the surface (see Fig. 1).

The shock's height, $x_s$, is determined by radiative processes which occur in the post-shock region. Indeed,

[1] LUTH, Observatoire de Paris, CNRS, Université Paris-Diderot, 92190 Meudon, France
[2] CEA-DAM-DIF, F-91297 Arpajon, France
[3] LULI Ecole Polytechnique, CNRS, UPMC, Route de Saclay, 91128 Palaiseau, France

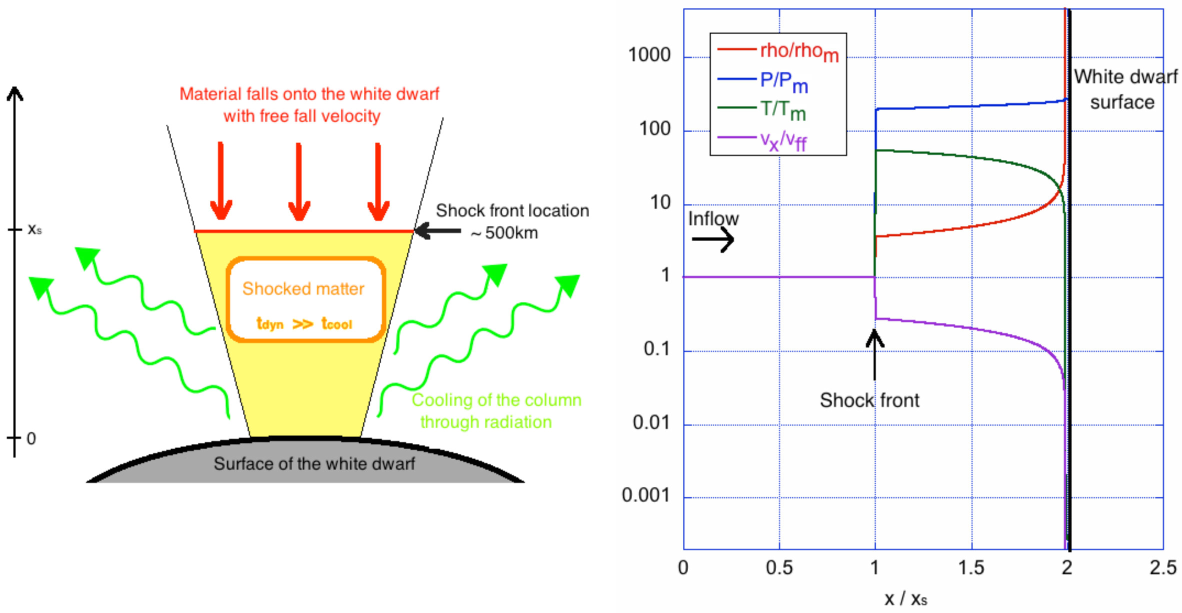


**Fig. 1. Left**: the model of accretion column in polars: free-falling material hits the surface of the white dwarf. A shock is created and propagates upward in the accretion column until a position on the order of 100 km above the surface. **Right**: typical normalized profil for temperature, density, pressure and velocity in the column.

the loss of energy implies a decrease of temperature toward the white dwarf, accompanied by a densification and a decrease of velocity (see Fig. 1). The shock position is then settled given that the fluid needs enough time to cool and slow down before reaching the surface. We describe this post-shock region by considering 1D hydrodynamical equations with a source term in the energy conservation equation $\Lambda(\rho, T) = \Lambda_0 \rho^\alpha T^\beta$, where $\rho, T, \Lambda_0, \alpha, \beta$ are respectively the density, temperature and three constants (Chevalier & Imamura 1982; Falize et al. 2009b):

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho\, v) = 0 \tag{2.1}$$

$$\frac{\partial}{\partial t}(\rho\, v) + \frac{\partial}{\partial x}(\rho v^2 + P) = 0 \tag{2.2}$$

$$\frac{\partial E}{\partial t} + \frac{\partial}{\partial x}[v(E+P)] = -\Lambda(\rho, T) \tag{2.3}$$

where $t$, $x$, $v$ and $E$ are respectively time, position, velocity and total energy of the fluid with $E = \rho e + 1/2 \rho v^2$, $e$ being the internal energy of the fluid. We then assumed that the plasma is optically thin which is a good approximation since considering typical parameters for the system we found that the horizontal optical depth is approxively of $\tau = 8.10^{-2}$ (Frank et al. 2002). As long as the magnetic field is lower than 50 MG and the accretion rate higher than 1 $g.cm^{-2}.s^{-1}$ the main cooling process is bremsstrahlung and its exact cooling function corresponds to $\alpha = 2$, $\beta = 0,5$ (Rybicki & Lightman 1979). For higher magnetic field and/or lower accretion rate, we need to take into account the cyclotron cooling whose cooling function can also be approximated as a power law (Chanmugam et al. 1985; Saxton et al. 1998).
For such power law form cooling function, complete analytical solution exists in the stationnary regime (Chevalier & Imamura 1982; Falize et al. 2009b). In particular, we use them as one of our initial conditions in our time-dependant simulations. Otherwise, as initial conditions, we launch the fluid in our simulation box to observe the appearance of the shock and its evolution. Similar results are obtained with those two different initial conditions at long time.

Numerical simulations are made thanks to HYDRO-COOL which is a 2D hydrodynamical code developed at LUTH (Michaut et al. 2010). The code is based on a MUSCL-Hancock scheme; the Riemann problem is computed by a HLLC or a HLLE solver depending on the conditions of the simulation case; the source term is included in the scheme using the Strang splitting method and calculated thanks to a Runge-Kutta method. Assuming that cooling is mainly due to bremsstrahlung, we found similar results as Imamura et al. (1984) and Strickland & Blondin (1995) using similar boundary conditions: the position of the shock front is unstable and oscillates with a characteristic timescale of the order of the cooling timescale right behind the shock (see Fig. 2). Thus the origin of the oscillations seems to be a cooling instability which occurs in the shocked region: if the shock front is displaced toward (resp. away from) the white dwarf, the fluid has too little time (resp. too much) to cool down, there is too much (resp. not enough) thermal energy in the shocked region, pressure increases (resp. decreases) and drives the shock away from (resp. toward) the white dwarf. This oscillation induces a variation in luminosity of those objects which could correspond to optical quasi periodical oscillations observed in some polars (Larsson 1989).

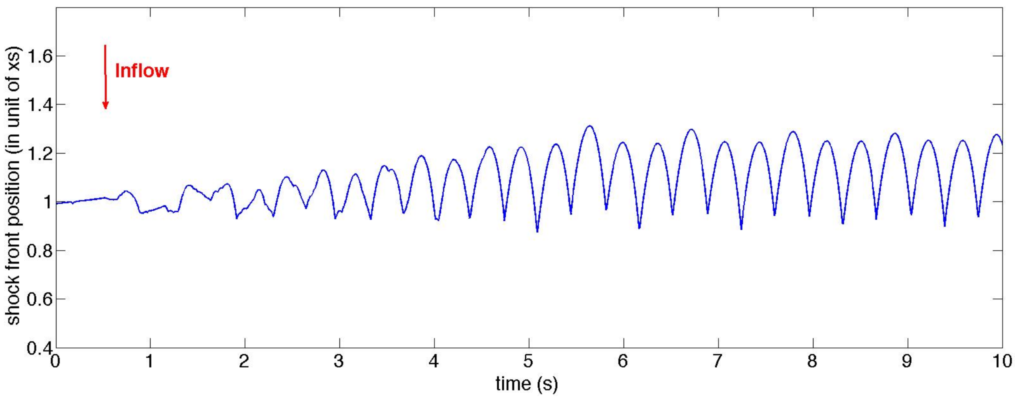


**Fig. 2.** Variation of the position of the shock front in unit of the stationnary position $x_s$ with time for an accretion column cooled by bremsstrahlung. The sytem is in an overstable regime and the oscillations rapidly reach a saturated amplitude.

## 3 Similarity and scaling laws

The distance between the shock front and the surface of the white dwarf is very small (on the order of 100 km) compared to the radius of the white dwarf (on the order of $10^4$ km), thus it is impossible to observe directly the structure of the accretion column. A new point of view is to create a model of the column in the laboratory thanks to powerful lasers in order to test our model.

It was proved that exact scaling laws exist for different accretion column regimes -one temperature with bremsstrahlung and/or cyclotron cooling (Falize et al. 2009a, 2011c) and two temperatures (Falize et al. 2011a) ; the number of free parameters depending on the degree of similarity we choose. For example, following the Aizu model (Aizu 1973), in the case of an accretion column dominated by bremsstrahlung cooling considering the absolute similarity – leaving the equations invariant and allowing a rescaling of all physical quantities – the scalability properties of the column are the following:

$$x/\tilde{x} = B/A^2\,;\; t/\tilde{t} = \sqrt{B/A^3}\,;\; v/\tilde{v} = \sqrt{B/A}\,;\; \rho/\tilde{\rho} = A\,;\; P/\tilde{P} = B\,;\; T/\tilde{T} = B/A\,,$$

where $A$ and $B$ are two free parameters linking the physical quantities of the astrophysical and laboratory systems respectively with and without tilde.

According to this scaling law, it is possible to reproduce the accretion column phenomenon in the laboratory since the needed regime is achievable (see Table 1). Moreover, one can notice that the typical length of the post-shock region, $10^{-3}$ cm, is large enough to be well diagnosed in the laboratory.

Based on this scaling law, an experimental principle was designed and is described in Fig. 3 (Falize et al. 2011a). The laser impacts on a pusher, creating a plasma which propagates into the tube toward an obstacle. The parallele with the astrophysical case is immediate: the expanding plasma corresponds to the material falling on the white dwarf which is itself modeled by the obstacle, and the collimation role of the magnetic field is played by the tube.

**Table 1.** Typical scale of the two systems of interest: the astrophysical and laboratory accretion columns

| | $x$ (cm) | $t$ (s) | $v$ (cm/s) | $\rho$ (g/cm$^3$) | $T$ (K) |
|---|---|---|---|---|---|
| Astrophysical system | $10^7$ | 1 | $5.10^8$ | $10^{-8}$ | $10^8$ |
| Laboratory system | 0.1 | $10^{-7}$ | $5.10^7$ | $10^{-2}$ | $10^6$ |

For now, one experiment has taken place using the laser LULI2000 (Ecole Polytechnique - LULI) with different compositions of the target pusher in order to test the experimental principle. We did observe the flow propagating into the tube until the collision against the obstacle, and we observed the reverse shock (Falize et al. 2012).

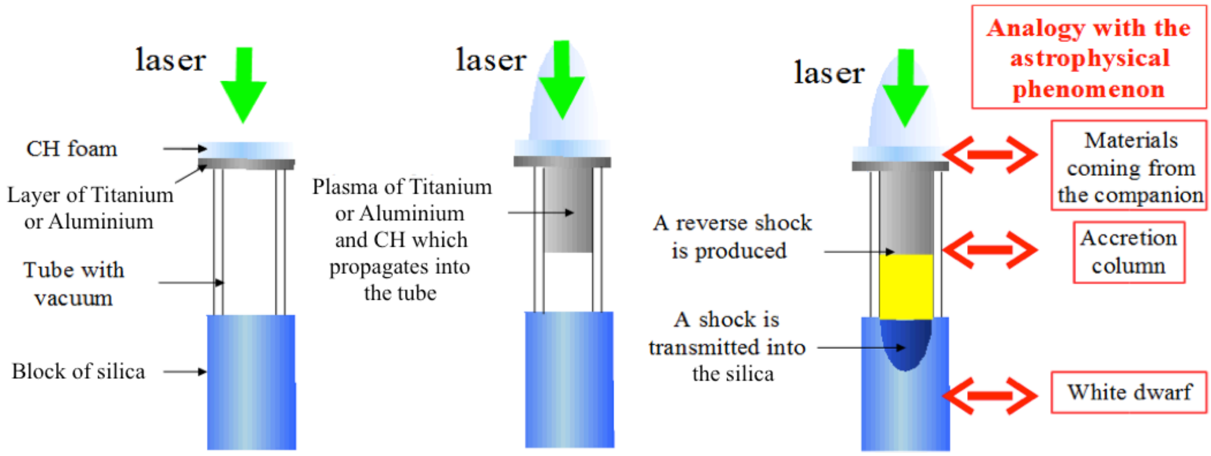


**Fig. 3.** Experimental principle

## 4 Conclusions and Perspectives

In this work, we showed our preliminary numerical simulations at the astrophysical scale. In order to test our code HYDRO-COOL, we retrieved former results using differents initial conditions and boundary conditions. We are currently improving the code in order to take into account more ingredients in our model such as multiple cooling processes or being able to modify the geometry of the column.

We also presented the theoretical bases of the experimental setup which aims at producing a model of the accretion column in the laboratory. The first experiment allowed us to test our target design and to diagnose the plasma flow propagation through the tube. In future work, we plan to improve the target design in order to reach more relevant regimes and improve similarity with astrophysical scaled phenomenon.

## References

Aizu, K. 1973, Progress of Theoretical Physics, 50, 344
Chanmugam, G., Langer, S. H., & Shaviv, G. 1985, ApJ, 299, L87
Chevalier, R. A. & Imamura, J. N. 1982, ApJ, 261, 543
Cropper, M., Ramsay, G., Hellier, C., et al. 2002, RSPTA, 360, 1951
Falize, E., Bouquet, S., & Michaut, C. 2009a, Ap&SS, 322, 107
Falize, E., Dizière, A., & Loupias, B. 2011a, Ap&SS, 138
Falize, E., Loupias, B., Ravasio, A., et al. 2011b, Ap&SS, 80
Falize, É., Michaut, C., & Bouquet, S. 2011c, ApJ, 730, 96
Falize, E., Michaut, C., Cavet, C., et al. 2009b, Ap&SS, 322, 71

Falize, E., Ravasio, A., Loupias, B., et al. 2012, High Energy Density Physics, 8, 1
Frank, J., King, A., & Raine, D. J. 2002, Accretion Power in Astrophysics: Third Edition
Hoogerwerf, R., Brickhouse, N. S., & Mauche, C. W. 2006, ApJ, 643, L45
Imamura, J. N., Wolff, M. T., & Durisen, R. H. 1984, ApJ, 276, 667
Larsson, S. 1989, A&A, 217, 146
Michaut, C., Nguyen, H. C., & di Menza, L. 2010, Ap&SS, 320
Remington, B. A., Drake, R. P., & Ryutov, D. D. 2006, Review of Modern Physics, 78, 755
Rybicki, G. B. & Lightman, A. P. 1979, Radiative processes in astrophysics, 393
Saxton, C. J., Wu, K., Pongracic, H., & Shaviv, G. 1998, MNRAS, 299, 862
Strickland, R. & Blondin, J. M. 1995, ApJ, 449, 727
Warner, B. 1995, Cambridge Astrophysics Series, 28
Wu, K. 2000, Space Sci. Rev., 93, 611