Mem. S.A.It. Vol. 83, 665
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Accretion shock in polars

Numerical and experimental simulations

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Abstract. Two years ago, our group has elaborated an experimental and numerical program of simulation of the accretion column in polars, taking into account the strong accretion shock. The experimental study, planned on several years, is based on the use of high-power lasers in order to design and diagnose an exact scaled accretion column. This paper summarizes in what consists an experiment in terms of design, set-up, diagnostics and shows that we have succeeded the three first steps demonstrating the feasibility of an accretion flow driven by laser. With appropriated targets and adapted diagnostics, the dynamics and the main physical properties of laboratory accreting plasma are well characterized, including the formation of a reverse shock. The next goal is the access to the largest laser facilities in order to achieve the complete similarity with astrophysical accretion columns.

Key words. Stars: Magnetic Cataclysmic Variables, Radiative Shocks, Accretion – Theory: Scaling Laws – Experiment: Laboratory Astrophysics, High-Power lasers

1. Introduction

This paper deals with a work having for goal the numerical and experimental simulations of the accretion shock in magnetic cataclysmic variables (mCVs), named also polars. This project is provided in a multi-disciplinary collaboration, composed by theoreticians, astronomers and experimentalists. Below we describe our main objectives constituting the experimental POLAR project (Falize, et al. 2011b) and some preliminary results. We remind that in mCVs the companion star matter goes directly toward the white dwarf (WD) photosphere, *i.e.* without the formation of an accretion disk. The main goal is the understanding of the physics occurring in the accretion column, which undergoes a strong shock emitting consequently radiation in the X-rays and optical ranges. Observationally some questions remain open in particular to explain the optical quasi-periodic oscillations (Larsson 1992) and an over-intensity some-

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times recorded in the soft X-ray spectrum (Ramsay, et al. 1994).

In this context, we propose to develop an accurate astrophysical model of the accretion. This part is superficially approached in this issue (Sec. 2) so as to leave more place for the description of experiments (Sec. 3). Effectively, we aim to lead an experimental program on large laser facilities, since laboratory experiments present a good way for validating numerical codes and examining involved physical processes.

2. Accretion shock description

From a theoretical point of view, the description of the accretion process in a polar consists in a cold supersonic flow coming from the companion star Roche lobe and falling toward the WD photosphere, as illustrated in Fig. 1. The matter flow is supposed to be channeled by the strong magnetic field (B>10^3 T), forming an accretion column. As the free-fall velocity is high (~1000 km.s^{-1}), a strong shock forms at the collision surface and goes up to the column. Due to strong temperatures, the post-shock region emits a lot of radiation and some energy is lost. Therefore the reverse shock brakes until more or less a steady-state position (x_s). The strong accretion shock modifies drastically the hydrodynamic parameters between the shock and the WD photosphere surface, as shown schematically in Fig. 1.

We develop a numerical model, based on our 2D code HYDRO-COOL (Michaut et al. 2011) which contains numerical schemes adapted for high-Mach number flows and also managing high contrasts in hydrodynamic parameters. Preliminary results (Busschaert, et al. 2011) exhibit the same oscillations in the luminosity curve than in Imamura, Wolff, & Durisen (1984); Strickland & Blondin (1995); Mignone (2005).

3. Experimental principle

Laboratory astrophysics is one of the applications of high-power lasers, especially for the new facilities such as National Ignition Facility (NIF) in USA or Laser Megajoule (LMJ) in France. Using lasers, in the so-called HEDP (High Energy Density Physics) regime, one can produce matter in extreme states (high temperature, high density). Consequently performing relevant astrophysical experiments represents a very exciting way to test, validate or even complete the astronomical observations. Among these extreme phenomena, the accretion processes are probably the most common ones, occurring on a wide range of astrophysical scales, and they constitute the main radiation source of accreting compact objects. Here we present an original work devoted to the study of accretion column dynamics in mCV's.

Based on recent analytical works (Falize, Michaut, & Bouquet 2011) on the scalability of radiation hydrodynamic flows (Falize, et al. 2011b), we have established the exact scaling laws for different accretion column regimes (Falize, Dizière, & Loupias 2011) and especially for the bremsstrahlung-dominated case. Therefore, we can study this specific radiation accretion column regime in laboratory.

3.1. Experimental preparation: scaling

The astrophysical relevance of experiments is determined by a comparison of the key dimensionless numbers of the laboratory and astrophysical plasmas. A radiation hydrodynamic flow is determined by different dimensionless numbers which allow to quantify the coupling between radiation and matter. But their evaluation is not easy in our experiment, as explained in Falize, et al. (2011a), due to the density and temperature high-spatial gradients. In spite of this difficulty the radiation regimes are characterized by a cooling parameter $\chi = t_{cool}/t_{dyn}$ where t_{cool} and t_{dyn} are respectively the characteristic cooling and dynamical times. The exact scaling law is given in Falize, et al. (2011a).

3.2. Experimental preparation: targets and numerical simulations

When the scaling is done, numerical simulations help us for the design of the targets for

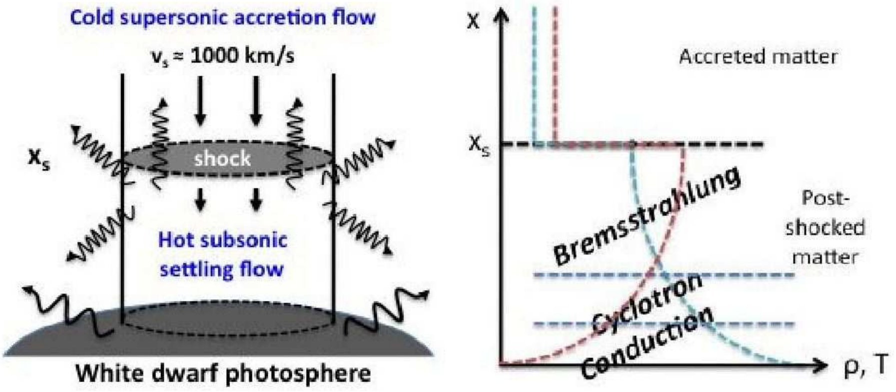

Fig. 1. Schematically the inflow has a cold temperature, a small density and high velocity. It goes through the shock front, then both the temperature and the density increase whereas the velocity slows down. Due to energy losses by bremsstrahlung, or cyclotron and conduction, the temperature (red curve) decreases toward the surface leading to an increasing density (blue curve).

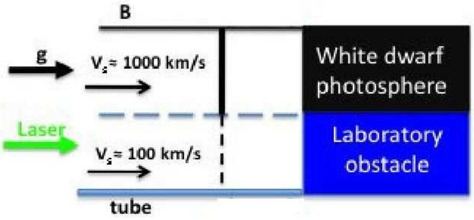

Fig. 2. Analogy between the polar accretion column and the laser target where 10^5 m corresponds to 10^{-3} m in laboratory.

the laser interaction and the diagnostics. In this work, the used code is FCI2 (Schurtz, Nicolai, & Busquet 2000), dedicated to laser/matter interaction. Taking into account the intensity (10^{14} W.cm^{-2}) and the pulse (1.5 ns) of the LULI2000 laser (Ecole Polytechnique, France), the target design has been elaborated. The similarity with the astrophysical situation is given by a transparent solid tube which channels the matter instead of the WD magnetic field and the WD photosphere is replaced by a solid piece of material (quartz) in order to block the flow and to create the reverse shock, as illustrated in Fig. 2. Actually the target is composed of three parts: a pusher, used to generate a supersonic plasma, the tube and the obstacle. The role of the pusher is to generate the accreting plasma flow by converting the laser energy in mechanical energy. This process generates a high-velocity plasma flow (~100 km.s^{-1}). The impact of supersonic plasma flow with the obstacle leads to the formation of both a transmitted shock and a reverse shock which travels back to the plasma, heating and ionizing it.

3.3. Experiments

The fundamental difficulty is to generate plasma conditions (dynamical and thermodynamical conditions and geometry) relevant to astrophysical environments. Therefore at the beginning of this experimental program, preparing the access on very energetic facilities, the objective is to realize three main steps demonstrating the experimental feasibility. They are first the realization of a plasma expansion in a tube (2 mm plexiglas), second the collision with an obstacle and third the production of a reverse shock, taking into account the capability to diagnose all these three stages.

Two sets of diagnostics have been implemented. These include a time resolved optical self-emission *i.e.* Self-Optical Pyrometry (rear SOP), which gives the impact time and the propagation path of the shock transmitted in the quartz. A second ensemble of transverse diagnostics involves time resolved 1D and 2D self-emission snapshots obtained by a streak camera and a fast gated optical imager (GOI) respectively. From streaked transverse emission, the flow propagation through the tube is diagnosed and the mean velocity and the impact time are inferred. A low-energy probe laser beam coupled to two GOIs provides both shadowgraphy and interferometry snapshots diagnosing the plasma propagation and the tube behavior. From transverse self-emission diagnostic we could infer the position of the radiating plasma front as a function of time and thus its velocity. The ensemble of diagnostics insures the coherence of the results and the characterization of the accreting plasma. We found that the plasma propagates at a mean velocity of ~80 km.s^{-1}colliding the quartz at t~23 ns and leading to a strong radiation emission. Then the estimated temperature in the post-shock region reaches 2 eV (Falize, et al. 2011a). Figure 3 summarizes the shock positions versus time obtained both experimentally and numerically, demonstrating a very good agreement.

4. Conclusion

Experimentally, the first three steps have been realized exhibiting that our target design generates a supersonic inflow colliding with an obstacle and then producing the reverse shock. This is the demonstration that the accretion column is reproducible in HEDP laboratory astrophysics. The positions of the accretion shock are well recorded and are in agreement with numerically expected ones. Nevertheless, at this stage of the scientific program, the comparison between the astrophysical situation in polars and the laboratory leads to some remarks on the similarity. Firstly, the Mach number reached in experiment is around 3 instead of more than 10 in astrophysics. Secondly, in laboratory the post-shock region does not emit enough radiation compared to accretion process in polars. Actually, the calculated cooling parameter χ~1 is too large. The radiative losses play an important role in the evolution of the plasma but do not dominate the dynamics as in the astrophysical regime. This is due to the low-temperature in the post-shock medium which is a consequence of the low-Mach number (M~3) of the observed reverse shock. Although such environments are completely new in laboratory, it is necessary to reduce χ to create more relevant astrophysical situations. These extreme regimes can only be produced by NIF or LMJ facilities.

5. Discussion

ELENA PAVLENKO: The first recognized magnetic nova is V1500 Cyg. What is the second one?

MARTINE MOUCHET's Comment: Concerning polars, except V1500 Cyg, the other nova is V4633 Sgr. Both would be systems of polar type slightly desynchronized. The optical flux of V1500 Cyg is well polarized with a determination of B~25 MG, but there is no "direct" detection of B for V4633 Sgr. Nevertheless it is classified as typical asynchronous AM Her, in the catalog of Ritter & Kolb (see Lipkin & Leibowitz, 2008). Concerning intermediate polars (IPs), it exists well established novae (as DQ Her and GK Per) and several candidates.

ŞÖLEN BALMAN: Will the reverse shock in your model heat up the pre-shock flow as it propagates up the column?

CLAIRE MICHAUT: No, it does not. As the radiative shock is supposed in an optically thin regime, all radiation escapes and does not interact with the matter in the pre-shock flow.

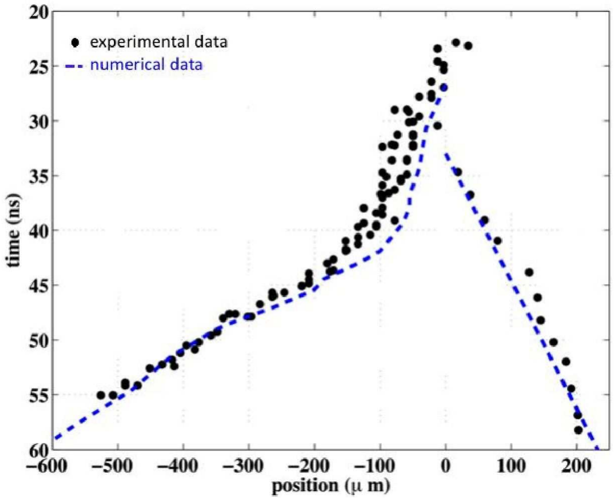

Fig. 3. Comparison between both experimental and numerical data of the reverse shock position (<0) versus time and its transmitted part (>0) in the obstacle (Falize, et al. 2011a).

DMITRY BISIKALO: Is it possible to get a second shock below the first one in your numerical model? Did you see it in your results?

CLAIRE MICHAUT: Yes, it does. We see the formation of the second shock in our simulations which depends on the initial conditions.

GIORA SHAVIV's Comment: The discovery of the oscillations were made by Langer, Chanmugam & Shaviv (1981) four years before Imamura et al. There it was already shown that the shock is unstable against corrugation.

The idea of the experiment is really beautiful, but it has a different lateral behavior and hence the interpretation must be carefully carried out.

CLAIRE MICHAUT: We know there is a different lateral behavior in experiment due to the presence of a tube instead of the magnetic field. But, we plan to implement a magnetic field in experiments, but it is particularly difficult.

Acknowledgements. For the financial support of the GdR-PCHE and the Scientific Council of the Paris Observatory (France).

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