Options of applying of numerical codes for the study of transient processes in a binary star with a white dwarf

Daniela Boneva[1], Dmitry Kononov[2]
[1] Space and Solar-Terrestrial Research Institute, Bulgarian Academy of Sciences, Sofia
[2] Institute of Astronomy, Russian Academy of Sciences, Moscow
danvasan@space.bas.bg[1] , dkononov@inasan.ru[2]
(Submitted on 28.01.2012 Accepted on 08.02.2012)

Abstract. In this paper we present the idea of applying of numerical codes, particularly of the ZEUS, for the study of transient processes in the close binary stars during the interaction. As a transient processes they could be long- and short-lived and we take into consideration both of them in our survey, as we explained their behavior and connection with tidal influence in the binary configuration. Basic features of the code are revealed. Using the hydrodynamical possibilities of ZEUS 2D and applying our hydrodynamical system of examination, we show what kind of possible results we can derive. This solution gives the initial distribution of the wave after tidally flow of the matter through the contact point of the binary. It is compared to the results obtained with recently employed codes, the ability of working with ZEUS and other numerical codes capabilities to find out the most suitable code or their combination and to make the problem solvable.

Key words: Accretion, accretion disks; Hydrodynamics; Waves; Methods: numerical; (Stars:) binaries: close;

Introduction

In the context of transient processes in stars, they can be defined as a short-lived and long-lived. And they both exist in the binary configuration. It is important to study the behavior of these patterns, because of their role for the stability of the existence of the whole structure of the disc around accretor star. Short-lived processes are not new as a definition. It has been used in different areas of astronomy research. Short-lived is usually associated with the bursts in CV binaries and they cause a significant variability in the system. In the context of long-lived we include the structures like: spirals, spiral's waves, density formations, vortices, which are well studied in the literature.

J. A. Sellwood (2011) gives complete analysis of the lifetimes of spiral patterns in disc galaxies. In his paper he presented some theoretical and observational evidence for short- and long-lived behavior of spirals in the discs. The software with numerical codes, which we have been using are not efficient any more for the discussed processes. That is why it is necessary to include in our research additional codes and methods. One of the possibilities we present in this paper is using the ZEUS 2D (as we are using here only this version, further we refer to it as ZEUS) code in the gas-dynamical processes of formation of the above patterns.

Although ZEUS is an old code, several features make it particularly well suited for astrophysical fluid dynamics (Stone & Norman 1992). This code is time-explicit, based on the method of finite-differences. The first code formally named ZEUS was developed by David Clarke (Clarke 1988; Clarke et al. 1986) for MHD simulations of radio jets. ZEUS solves the gas dynamic equations on a staggered mesh using high-order upwind methods to solve the advection terms, and an artificial viscosity to capture shocks. Covariant differencing forms are used to allow computation on any orthogonal coordinate system (Monchmeyer & Muller 1989). Both two- and three-dimensional versions are available, and the code has been implemented on architectures ranging from desktop workstations to distributed memory parallel supercomputers.

The code is widely used, well documented in the literature (Stone & Norman 1992a), (Stone & Norman 1992b), extensively tested (Stone et all. 1992), Fromang and Papaloizou (2007) have derived and solved a simple ODE, as they applied finite difference codes such as ZEUS, which describes the structure of nonlinear density waves propagating in accretion disks. Such an analysis is important for understanding the properties, stability and dissipation of waves that propagate in discs in many situations: tidal excitation by a companion, waves generated by the disk self-gravity when it is massive enough or even waves generated by MHD turbulence resulting from the MRI. Using these simulations, they could study the nonlinear evolution of the instability. In the paper of Fernandez (2010), the non-axisymmetric modes were studied by combining linear stability analysis and three-dimensional, time-dependent hydrodynamic simulations with Zeus-MP, focusing on characterizing their spatial structure and angular momentum content. In this paper they have studied the spiral modes of the Standing Accretion Shock Instability in the linear and nonlinear regime. Bate et al. (2002) analysed the non-linear propagation and dissipation of axisymmetric waves in accretion discs using the ZEUS-2D hydrodynamics code.

Johnson and Gammie (2005) applied ZEUS code on the study of vortices in thin, compressible, unmagnetized discs. They considered the formation and evolution of vortices in a hydrodynamic shearing-sheet model. The evolution was done numerically using a version of the ZEUS code and this showed that the presence of long-lived vortices in weakly ionized disks may be an integral part of the angular momentum transport mechanism in these systems. Like many schemes for numerical hydrodynamics, ZEUS can tolerate only a limited dynamic range in density. The numerical method of McKinney and Gammie (McKinney and Gammie 2002) is based on ZEUS-2D (Stone & Norman 1992) with the addition of an explicit scheme for the viscosity. ZEUS is an operator-split, finite-difference algorithm on a staggered mesh that uses an artificial viscosity to capture shocks. This algorithm guarantees that momentum and mass are conserved to machine precision. Total energy is conserved only to truncation error, so total energy conservation is useful in assessing the accuracy of the evolution.

Up to now The gas-dynamical analysis of the flow structure in the close binary star system has revealed tidal interaction between the out-flowing matter from donor through the point of libration and the flow around the accretor. Bisikalo et al. (2001) have shown that even a small variation in mass transfer rate of the binary system, could disturb the equilibrium state of the hot accretion disc. This may cause the appearance of an area with increased density, called "blob". On the other hand, the tidal interaction between the incoming flow and circumdisc area causes shock wave density formation and the so called "hot line" in the area.

Our recent results on transient processes were pointed to long-lived patterns, which come rising by the tidal interaction in close binaries: We have analyzed the flow structures during the outbursts, which could be considered as short-lived processes. Actually, we analyzed how the short-lived outbursts have affected the long-lived patterns. We applied gas-dynamical numerical method and Maximum entropy method (Boneva et all. 2009, Kononov et all. 2008) to reveal the elements of the flow.

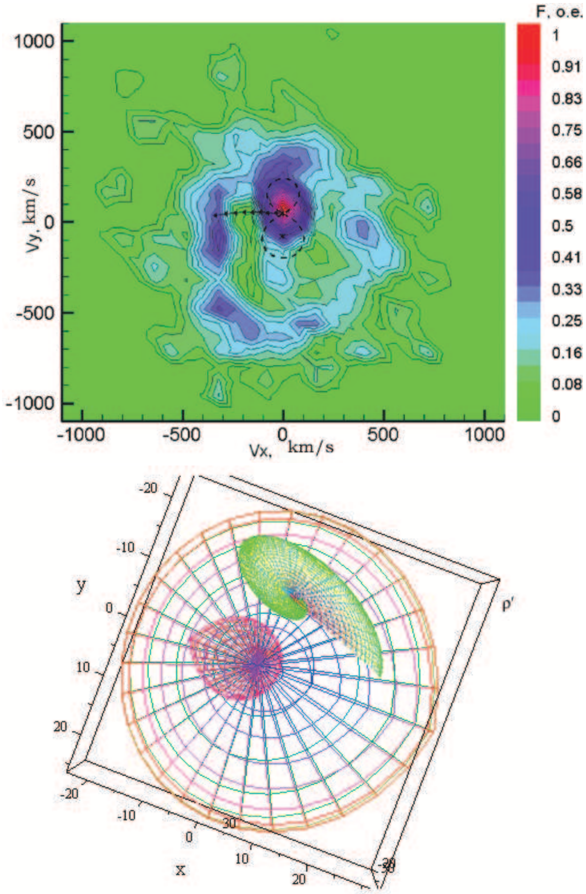

Fig. 1. Hγ tomogram of SS Syg during the outburst, Fig. 1a (up). The analysis shows significant changes in the flow's structure and in the form of accretion disc. The numerical simulations on the disc flow reveal the existence of patterns, known as periodically stable formations, Fig. 1b (down).

We have examined the interacting flows properties by using different from ZEUS numerical schemes and codes (Boneva 2010, Boneva 2009). This study revealed that during the transient processes the long-lived patterns: spiral density wave (green) and tick density formation (purple) have been formed (figure 1b). The figure seen is made with superposition of two different images, received from the calculations.

1 Employing of the ZEUS code

We paid a lot of attention to ZEUS in previous section and here we point to the basic features. Several features of the ZEUS code make it particularly well suited for astrophysical fluid dynamics. In its first form, the code is time-explicit, two-dimensional Eulerian hydrocode based on the method of finite-differences, characterized by a high degree of simplicity, robustness and speed. According to the schematic flow chart of the ZEUS-2D code with hydrodynamical algorithms (Stone and Norman 1992), we could simplify this consequence as follows. As usually, it consists of problem setup box; sources step with 3 substeps; transport steps; setting of new grid; interrupted checker with data output and graphics; new timestep; final data output and graphics.

1.1 Abilities and first results.

Since we consider flow dynamic and accretion processes by macroscopic quantities, it is most suitable to work with the familiar equations of hydrodynamics for compressible flows: mass conservation, equation of motion, energy conservation equation and equation of state. A splitting operator can break the solution of PDEs into parts and each part consists of different term in the equations. This step is called the "operation split solution procedure" (Stone & Norman1992).

Further, the already mentioned, source and transport steps are turning on. The first one is related to the finite-difference approximation solution, while in the second step finite-difference approximation is solved to the integral equations. In Zeus 2D, it is possible to assign several different conditions and to apply variables for each different boundary. They can be applied independently for every zone of the computational zone. The kind of boundaries could be listed as: Reflecting boundary conditions; Axis of Symmetry boundary conditions; Inflow boundary conditions; Outflow boundary conditions; Periodic boundary conditions. All they are explained in (Stone & Norman1992).

As we use in our study box-schemes to define the boundaries, so we are free to change their values. Now, in a similar way as Stone (1999), Johnson & Gammie (2006)) did, we have to define the numerical grid. The most basic property of any grid-based numerical algorithm is the representation of the dependent variables on the numerical mesh. We have a finite area $(Nx; Ny; Nz)$, with the corresponding grid in our case (Nr, Nz). Then, the zones with grid sizes are Δr and Δz. Our computational domain then is containing $Nr \times Nz$ grid cells. After applying the above methods and conditions over the system of equation, we could receive the type of solutions, showed at Figure 2 down:

The Figure 2 top shows and confirms the previous result of our study that after the tidal interaction of the streams in the close binary star system, the parameters (density and velocity) have changed their values. This causes again structure transformation in the flows, expressed by the appearance of long-lived vortical like formations and waves. The snapshot is taken in the moment of time close to the first tidal interaction of the flows. The errors in these images are not eliminated, but they were not eligible enough to change the final view.

ZEUS code is suitable for many astrophysical problems, which require multiple time and length scales. The nonuniform grid and the adaptive mesh method, involved in the code, are functional for studying of the accretion disc dynamics and especially accretion onto compact objects. Some of the astrophysical problems are complicated enough and need to be solved by applying of more than one numerical code. We present in the next section the basic structure and capabilities of such code.

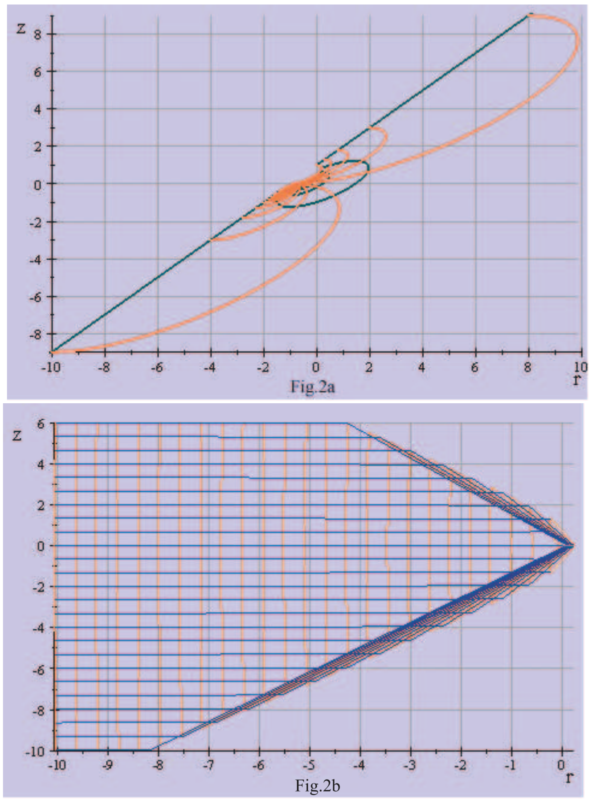

Fig. 2. Calculations with ZEUS 2D, based on the hydrodynamical compressible flow's systems. Fig. 2a (up) shows the initial development of wave of vortices. The distribution of this wave can be seen in the Fig. 2b (down). The grid measure is [25 × 25] in r, z computational area.

2 Comparison with PLUTO code

This is a multi-physics, multi-algorithm high resolution code (Mignone et al. 2007). The code is particularly suitable for time-dependent, explicit computations of highly supersonic flows in presence of strong discontinuities and it can be employed under different regimes, i.e., classical, relativistic unmagnetized and magnetized flows.

The code has already been successfully employed in the context of stellar and extragalactic jets (Bodo et al. 2003; Mignone et al. 2004, 2005), radiative shocks (Mignone 2005; Massaglia et al. 2005), accretion disks (Bodo et al. 2005), magneto-rotational instability, relativistic Kelvin-Helmholtz instability and so forth.

PLUTO is distributed with four independent physics modules for the explicit numerical integration of the fluid equations under different regimes and conditions. The hydrodynamics (HD), magnetohydrodynamics (MHD), relativistic (RHD), and relativistic MHD (RMHD) modules solve, respectively, the Euler equations of gas dynamics, the ideal/resistive MHD equations the energy-momentum conservation laws of a special relativistic perfect gas.

We use the paper of (Mignone 2005, Mignone 2007) and summarize the most important characteristics of the code.

PLUTO has a modular structure: the possibility to easily code and combine different algorithms to process different physics. It offers a number of features which can be combined together. Besides four physical modules (incl. Newtonian/relativistic hydrodynamics with or without magnetic fields), gravity, radiative cooling, resistivity, multidimensional geometries, equations of state may be included where required.

This code can provide the user with a number of numerical schemes and several algorithms (Riemann solvers, interpolations, choice of boundary conditions and so on). PLUTO possesses portability in different Unix-based systems. In addition the code can run in either serial, single-processor or parallel machines.

Grid adaptivity: the ability to resolve flow features with different spatial and temporal scales on the same computational domain. The code provides one-dimensional AMR (Adaptive Mesh Refinement) integrator and multidimensional extensions. A simple user-interface based on the Python scripting language is available to setup a physical problem in a quick and self-explanatory way.

One useful advantage is that PLUTO is entirely written in the C programming language and can run on either single processor or parallel machines. The hydrodynamics module of the code allows implementation of fluid dynamics equations. It has been designed for the solution of nonlinear systems of conservative partial differential equations of parabolic (and hyperbolic) type. This feature makes this code applicable in the study of our astrophysical problems, related to patterns formation in close binary stars. We are still not fully familiar with PLUTO and applying it to solve the astrophysical problems, related to structures formation in close binary accretion disc, is a task for the future paper.

Conclusion

Vortices and wave patterns in the discs of close binary stars undoubtedly exist. Our aim is to examine their structures and behaviour, origin and life-time. For this reason, on the bases of ZEUS capabilities we present the possible results in the study of interacting stars flow and following processes. We made comparison of numerical codes, which are appropriate to examine the astrophysical problems, related to hydrodynamics behavior of the stars matter, particularly the task of long-lived patterns in white dwarf accretion disc. Depending on the essence of the submitted conditions, studying objects or the type of astrophysical processes, we could choose the right one for solving the problems or use them in combination. We came to the conclusion that it was important to study the structures and possibilities of the codes above, so now we have clearer view on the applicability of the methods.

All these numerical codes are created to study and solve the systems of conservation laws of hydrodynamics and magneto-hydrodynamics. In the further studies, we intent to complete our calculations with ZEUS 2D and continue the research of pattern's formation by employment of the later version of ZEUS 3D, worked out by Clarke in (Clarke 2010).

Acknowledgments

Use of ZEUS-3D, developed by D. Clarke at the ICA (http://www.ica.smu.ca) with support from NSERC, is acknowledged.

References

Bisikalo, D. V., Boyarchuk A. A., Kilpio A.A.. Kuznetsov O. A., 2001, Astron. Rep., 45, 676
Bodo, G., Chagelishvili, G., Murante, G., et al. 2005, A&A, 437, 9
Bodo, G., Rossi, P., Mignone, A., Massaglia, S., & Ferrari, A. 2003, New Astr. Rev., 47, 557
Boneva, D., 2010, AIP Conference Proceedings, 1273, 324
Boneva, D.V., 2010, BgAJ, 13, pp. 3-11, ISSN 1313-2709
Boneva, D.V., P. V. Kaigorodov, D. V. Bisikalo, and D. A. Kononov, 2009, Astron. Rep., 2009, Vol. 53, No. 11, pp. 1004–1012, Pleiades Publishing, Ltd., ISSN 1063-7729
Clarke, D. A. 1988, Ph.D. Thesis
Clarke, D. A., Norman, M. L., & Burns, J. O. 1986, ApJ, 311, L63
Clarke, D. A., 2010, ApJS, 187, 119
Fernandez, R., 2010 ApJ **725** 1563
Fromang, S., Papaloizou J., 2007, A&A, 468, 1, pp. 11-18
Johnson, B. M., Gammie Ch.F., 2005, ApJ, 635:149–156
Johnson, B. M., & Gammie, 2006, ApJ, 636, 63
Kononov,D. A., P. V .Kaigorodov, D. V. Bisikalo, A. A. Boyarchuk, M. I. Agafonov, O. I. Sharova, A.Yu.Sytov, and D. V. Boneva, Astron. Rep., 2008, vol. 85, No. 10, pp. 927-939
McKinney J. C., Gammie Ch. F.,2002, ApJ,573, 728
Mignone, A., Massaglia, S., Bodo, G. 2004, ApJSS, 293, 199
Mignone, A. 2005, ApJ, 626, 373
Mignone, A., Plewa, T., Bodo, G. 2005, ApJS, 160, 199
Mignone, A., Bodo G., Massaglia S., Matsakos T., Tesileanu O., Zanni C., Ferrari A., 2007, ApJSS, 170, 1, pp. 228-242
Monchmeyer, R., Muller E., 1989, A&A., 217, 351–367.
Sellwood, J. A.,2011, MNRAS, v.410, 3, pp 1637–1646
Stone, J.M., Hawley J.F, Evans C.R., Norman M., 1992, ApJ., 388, 415.
Stone, J.M., Norman M.L., 1992, ZEUS-2D: A radiation magnetohydrodynamics code for astrophysical flows in two space dimensions:
I. The hydrodynamic algorithms and tests, ApJS., 80, 753–790.
Stone, J.M., Norman M.L., 1992, ZEUS-2D: A radiation magnetohydrodynamicscode for astrophysical flows in two space dimensions:
II. The magnetohydrodynamic algorithms and tests, ApJS., 80, 791–818. http://www.nordita.org/software/pencil-code/.