



Effects of compressibility, turbulent viscosity and mass-transfer-rate on accretion discs in close binaries: timescales of outburst events

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Abstract. In this work, the role of both inflow kinematics at the inner Lagrangian point L1 as an initial boundary condition, gas compressibility and the physical turbulent viscosity, on accretion disc's dynamics and structure in a close binary, are investigated via 3D SPH simulations of stationary accretion disc models. Such investigation is here carried out in both high and low compressibility regimes, with the aim of evaluating, in a compressibility-viscosity graph, the most suitable domains where physical conditions allow a well-bound disc development as a function of mass transfer kinematic conditions. Results show that domains exist where physical turbulent viscosity supports the accretion disc formation. In such domains, the lower is the gas compressibility, the higher is the physical viscosity requested. A role played by the injection kinematics at the inner Lagrangian point L1 is also found. Conclusions about dwarf novae outbursts, induced by mass transfer rate variation, and considerations on periodicities in accretion discs are also reported.

Key words. Accretion: Accretion Discs – Methods: Numerical – Stars: Close Binaries – Stars: Dwarf Novae

1. Introduction

The investigation carried out in this paper is a consequence of the idea that physical viscosity supports accretion disc development inside the primary gravitational potential well in close binaries (CB), even for low compressibility modelling (Lanzafame et al. 2006). High compressibility viscous gas dynamics in accretion discs was investigated in Lanzafame

(2003), paying attention to the roles of physical turbulent viscosity and the kinematic of injection, by adopting $\alpha = 1$ and a high injection velocity at L1. In fact, in such a high compressibility modelling, accretion discs would form anyway even in physically inviscid conditions. In low compressibility viscid SPH simulations (Lanzafame et al. 2006) the Shakura-Sunyaev parameter $\alpha = 1$ (Shakura 1972; Shakura & Sunyaev 1973) was also adopted.

Physical viscosity works where the particle mutual velocity (and separation) changes in time, namely when a mutual acceleration exists, contrasting gas dynamics (rarefaction or compression), where particle velocity gradients are significant. This means that physical viscosity plays a relevant role mainly in the radial transport, while it has little influence on the tangential dynamics. It converts mechanical energy into thermal energy (heating the disc), supporting the development of well-bound accretion discs inside the primary potential well, even in spite of a hypothetical low compressibility (Lanzafame et al. 2006). It reduces the disc thickness and increases the accretion rate onto the accreting star, but, and this is the most important thing, it hampers the repulsive pressure forces among contiguous fluid elements, supporting the accretion disc in developing a well-bound consistency.

In this work, a grid of SPH disc models is produced, with the aim of detecting, in the compressibility-viscosity space, boundaries separating domains, where the disc development is supported, from domains where it is not. The injection velocity at L1 also plays a role. Therefore, in order to develop this idea, in this paper, after assuming a fixed kinematic injection at the L1 point as an initial boundary condition, several polytropic indexes γ have been adopted, identifying, for each of them, the boundary lower limit of the Shakura-Sunyaev parameter α able to provide a sufficient particle concentration to define a well-bound accretion disc within the primary's gravitational potential well. The polytropic index γ , introduced in the state equation, $p = (\gamma - 1)\rho\epsilon$, where ϵ is the thermal energy per mass unit, has the meaning of a numerical parameter whose value lies in the range between 1 and 5/3.

In order to build up a "well-bound" accretion disc, the ejection rate at the disc's outer edge must be at least two or three times lower than the accretion rate at the disc's inner edge. Whenever this condition is fulfilled, the disc's outer edge, as well as the whole disc, does not "evaporate" because of high pressure forces which are also dependent on the gas compressibility: $-\nabla p/\rho = -(\gamma - 1)\nabla(\rho\epsilon)/\rho$. Therefore, low compressibility gases are more

easily sensitive to evaporative effects of blobs of gas at the disc's outer edge itself, towards the empty external space, if the gravitational field is not able to keep the disc gas in the gravitational potential well, at the disc's outer edge. Such effects are enhanced and strongly evident in inviscid conditions (Molteni et al. 1991; Lanzafame et al. 1992).

In this paper, the viscous force contribution is represented by the divergence of the symmetric viscous stress tensor in the Navier-Stokes equation. A symmetric combination of the symmetric shear tensor multiplied by the particle velocity has been added to the energy equation as a viscous heating contribution. The SPH formulation of viscous contributions in Navier-Stokes and energy equations has been developed by Flebbe et al. (1992, 1994).

Results show that the role of a full viscous fluid dynamics is still far from any conclusion and that physical assumptions, as well as numerical hypotheses and boundary conditions are also determinant. Conclusions as far as timescales of outburst events are concerned, are also discussed, whenever disc thermodynamics or kinetic conditions at L1 allow transitional phases from a well-bound disc structure to a less-bound one and vice-versa.

2. Results and discussion

We carried out our simulations until we achieved full stationary configurations. This means that particles injected into the primary's gravitational potential well are statistically balanced by particles accreted onto the primary and by particles ejected from the disc's outer edge. Critical boundary conditions for the development of a well-defined accretion disc, for each pairs of (γ, α) values, were pursued, ensuring a minimum number of particle neighbours of the order of 15 for each SPH particle.

In CB where the two stellar components equal $1M_{\odot}$ each, and whose separation is $d_{12} \simeq 10^6$ Km, the mass accretion rates \dot{M}_{acc} for the injection velocity $v_{inj} = 13$ Km/s, and $v_{inj} = 130$ Km/s at the L1 point are of the order of 10^{16} g s⁻¹ and 10^{17} g s⁻¹, respectively. The higher α , the lower the ejection rate (the higher the accretion rate). Instead, the lower the gas

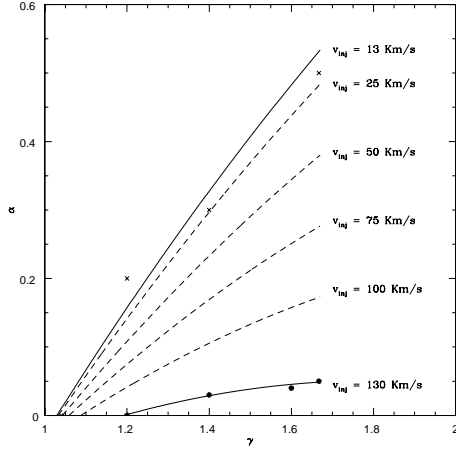


Fig. 1. Plot showing boundaries of stability in the (γ, α) diagram. Values of the injection velocity v_{inj} at L1 are also reported. Dashed lines refer to linearly interpolated boundaries. Crosses and asterisks refer to (γ, α) pairs used to define the outermost boundaries.

compressibility (the higher γ), the higher the ejection rate (the lower the accretion rate), although the main parameter, governing both accretion and the ejection rates, is the injection rate at L1.

Fig. 1 shows a (γ, α) diagram (compressibility versus physical turbulent viscosity) where boundaries, separating domains where the disc development is supported (the domain above each boundary) from domains where it is not (the domain below each boundary), are reported, performing parabolic best fits. For $v_{inj} = 130 \text{ Km/s}$ all disc models whose $\gamma < 1.2$ develop a well-bound disc, whatever the turbulent viscosity adopted is. The higher v_{inj} at L1, the higher the disc total particle number and the particle resolution, as a natural consequence of the fact that a higher particle kinetic energy involves a higher particle spatial concentration in order to get a counterbalance between the gas compressibility and the particle thrust.

For disc models whose viscosity is greater than the boundary limit ($\alpha > \alpha_b$), the physical, turbulent viscosity is able to develop a well-bound accretion disc in the primary's gravita-

tional potential well, while disc models whose $\alpha < \alpha_b$ do not.

These results show that not only the pair of (γ, α) values is important in the development of a well-bound accretion disc modelling in the primary star gravitational potential well, but also that the injection velocity at the L1 point plays a relevant role.

These results have a direct consequence on dwarf novae outburst modelling. In fact, according to these conclusions, as an example, we can consider the temporal evolution of an accretion disc when the fixed pair (γ, α) is periodically located *above* and *below* the boundary pertaining to a fixed injection kinematic conditions at L1. Fig. 2 shows XY plots regarding the disc structure during the transition between opposite stationary configurations from $v_{inj} = 130 \text{ Km/s}$ to $v_{inj} = 13 \text{ Km/s}$ at L1 and vice-versa, for $\gamma = 7/5$ and $\alpha = 0.1$. According to these results, in high compressibility regimes, dwarf novae outbursts temporarily represent phases of a well-bound accretion disc whose radius increases as a consequence of the higher mass transfer rate from L1. Alternatively they could represent phases where a low compressibility disc achieves a consistency when $\dot{M}_{acc} \sim 10^{17} \text{ g s}^{-1}$. Instead, in high compressibility regimes, quiescent phases represent low rate mass transfer phases where the accretion disc reaches its minimum radial extension as a consequence of the reduced mass transfer rate from L1. Alternatively, in low compressibility regimes, they could represent even vanishing disc phases when the disc radius not only decreases, but also vanishes when $\dot{M}_{acc} \sim 10^{16} \text{ g s}^{-1}$. A higher accretion rate onto the primary star involves a higher emission flux (especially in the X-rays, close to the primary compact star) by conversion of mechanical energy into heat.

The transitional length between opposite stationary disc configurations (bottom to top of the figure) is ~ 10 and ~ 5 orbital periods, respectively. Such values agree, in order of magnitude, with the outburst duration, as shown in Honey et al. (1988), where, among several hypotheses, a periodical modulation of the mass transfer rate is also taken into account as responsible, in SU UMa, OY Car, Z Cha and

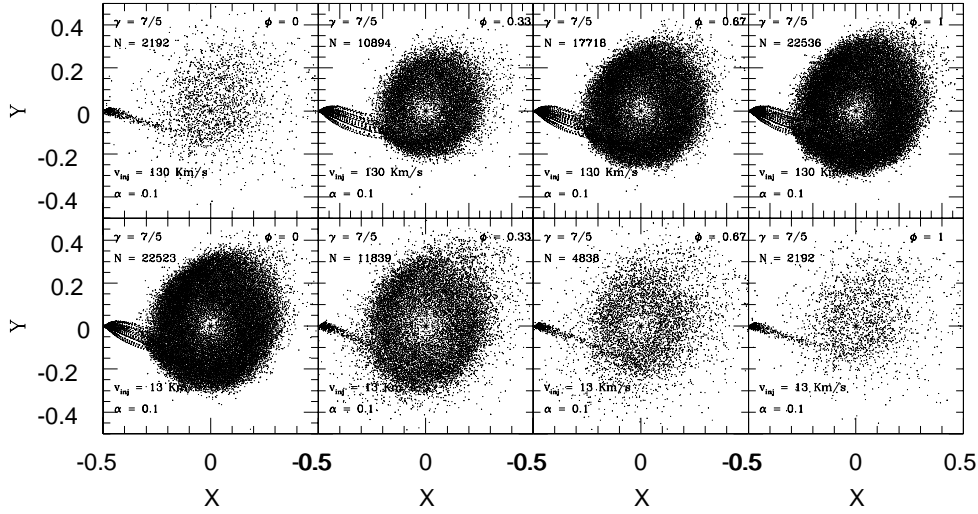


Fig. 2. XY plots of transitional phase active-to-quiet (top 4 plots) and vice-versa (bottom 4 plots) of accretion disc. The (γ, α) pair, the v_{inj} , as well as the phase ϕ are also reported.

SS Cyg-like systems, for periodical variation of systemic velocity both of outburst and of superoutburst phenomena according to the "Mass Transfer Burst Model" (Bath 1973) or according to the "Periodic Mass Transfer Modulation" (Bath 1973; Papaloizou & Pringle 1979). A similar periodical outburst modelling could be realized by modifying, for the same v_{inj} , the adiabatic index γ (compressibility) and/or the physical turbulent viscosity parameter α . Conclusions of this work do not preclude, according to Fig. 1, theoretical evaluations of α from agreeing with those deduced from observations if the adopted α is chosen significantly higher than α_b in low compressibility regime, in agreement with the adopted v_{inj} at L1. Results in this paper agree with observational evidence concerning outbursts and show the role of compressibility, physical turbulent viscosity and mass transfer kinematics on accretion disc structure, dynamics and energetics.

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