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Influence of the stellar-mass-ratio and local thermodynamics on accretion disc in close binaries

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The role of physical turbulent viscosity is to hamper flow dynamics. Such effect, in an accretion disc involves an enhanced radial mass and angular momentum transport in high compressibility conditions. A sticking effect throughout the disc also affects low compressibility disc's dynamics. Pairs of compressibility-viscosity values, together with initial kinematic conditions at the inner Lagrangian point, can define a well-bound accretion disc, whilst other pairs cannot produce such well-bound structures. In this work, the role of the stellar mass ratio M1/M2 between the compact primary and the companion in a close binary (CB) is also taken into account. Results show that such role is essential in modifying domains where parameters compressibility-viscosity-injection velocity in L1 allow a well defined disc consistency. The hygher the M1/M2 mass ratio, the wider is the domain where the accretion disc shows a well-bound consistent structure.

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1. Introduction

The role of compressibility, physical turbulent viscosity and injection velocity in L1 is yet investigated in [5, 6] for a CB, whose SMR $= 1/1$. SMR is however a fundamental parameter. Therefore, we investigate its role both in accretion disc structure - as far as its binding and consistency into the primary's potential well are concerned - to determine how it influences the quiescent-to-active (and vice-versa) phases as for the outburst duration of SU Uma, OY Car, Z Cha, SS Cyg-like objects and, in general for CBs whose SMR is beyond its restrict limits for dwarf novae. Results of this paper, together with those of [5, 6], could help us in better understanding the accretion disc phenomenology and instabilities.

In this work, a grid of disc models is produced in SPH [10], to detect, in a compressibility-viscosity space, boundaries separating domains where the disc development is supported from domains where it is not, for each assigned value of the SMR. The injection velocity in L1 also have a role. Therefore, according to fixed kinematic injection conditions at the L1 point as initial boundary conditions, several polytropic indexes γ have been adopted - where γ characterizes the ideal gases state equation: $p = (\gamma - 1)\rho\varepsilon$ - identifying, for each of them, the boundary lower limit of the Shakura-Sunyaev α parameter [11, 12], able to provide a sufficient particle concentration to get a well-bound accretion disc into the primary's gravitational potential well. In all simulations we got a stationary final configuration where the rate of injected particles is balanced by the rates of accreted and ejected particles, so that the number of disc particles is statistically conserved.

In order to build up a "well-bound" accretion disc in inviscid conditions, the ejection rate at the disc's outer edge is at least two or three times lower than the accretion rate at the disc's inner edge. Whenever this condition is fulfilled, the accretion disc does not consistently loose mass from its outer edge, as well as from its surfaces, due to pressure forces which are dependent on gas compressibility: $-\nabla p/\rho = -(\gamma - 1)\nabla(\rho\varepsilon)/\rho$. Low compressibility gases are more easily sensitive to evaporative effects of blobs of gas from the disc's outer edge, towards the empty external space. Such effects are enhanced and strongly evident in inviscid conditions [7, 9]. This work shows that the physical turbulent viscosity contributes to the gas binding within the gravitational potential well, starting from a lower threshold, to be defined, as a function of gas compressibility (γ), kinematic conditions in L1 and (scope of this work) the SMR.

In this paper, the viscous force contribution is represented by the divergence of the symmetric viscous stress tensor in the Navier-Stokes equation. The SPH formulation of viscous contributions in the Navier-Stokes equations has been developed by [1, 2].

2. Results

The characteristics of the binary system are determined by the masses of the two stars and their separation. The mass of the primary compact star $M_1 = 1 M_\odot$, while the mass of the secondary normal (or subgiant) star $M_2 = 1, 2, 3 M_\odot$, and $M_1 = 2 M_\odot$ and $M_2 = 1 M_\odot$. Stellar separation is $d_{12} = 10^6\ Km$ for a SMR $M_1/M_2 = 1$. Instead, $d_{12} = 2 \cdot 10^6\ Km$ for other values of the SMR. The injection gas velocity in L1 is fixed at $v_{inj} \simeq 13\ Km\ s^{-1}$, at $v_{inj} \simeq 50 Km\ s^{-1}$ and at $v_{inj} \simeq 130\ Km\ s^{-1}$, the three groups of models for each SMR assumed value, while the injection gas temperature in L1 is fixed at $T_\circ = 10^4\ K$, taking into account of some radiative heating of the secondary surface due to the disc enlightening. Gas compressibility is fixed by the adiabatic index γ. In our models the unknowns are: pressure, density, temperature, velocity, so we solve the continuity, momentum, energy and state (perfect gas) equations.

The formulation adopted for the 3D SPH accretion disc model including physical viscosity is the well-known [11, 12] α parametrization: $\nu = \alpha c_s H$, where $0 \leq \alpha \leq 1$ is the Shakura-Sunyaev parameter and $H = r_{xy} c_s / (M_1/r_{xy})^{1/2}$ is a dimensionless estimate of the standard disc thickness, where $r_{xy} = (X_i^2 + Y_i^2)^{1/2}$ is the cylindrical radial coordinate of the ith particle.

Physical turbulent viscosity hampers particle outflow from the disc outer edge, playing a role in both the disc radial extension and its thickness (also discussed in [3, 8]). The higher α, the thinner and radially more extended the disc. Therefore, it is obvious that there is not a significant difference in the total number of disc particles among disc models with the same injection velocity in L1. For each assigned value of the SMR, each boundary, determined by the adopted v_{inj}, determines a lower inviscid threshold $(\gamma_{thr}, 0)$ delimiting the γ value separating well-bound inviscid disc models by disc's models in which the physical turbulent viscosity plays a fundamental role in the disc binding, and where inviscid models produce unbound discs. Such a threshold point (γ_{thr}, 0), is a function of both v_{inj} and SMR values, as shown in Fig. 1 showing plots for 4 assigned valued of the SMR. In such 4 plots, compressibility versus physical turbulent viscosity (γ, α) diagrams show boundaries delimiting domains supporting the disc development (domain above each boundary) from domains where it is not (domain below each boundary). Boundaries are determined performing parabolic best fits. Each plot refers to an assigned value of the SMR. All disc models whose $\gamma < \gamma_{thr}$ develop a well-bound disc, whatever is the turbulent viscosity adopted. However, significantly lower α values, compared to the boundary lower limit in α: α_b, do not allow the disc structure in order to get a well-bound structure, as discussed in [5, 6]. The disc's total particle number and the particle resolution increase with v_{inj} in L1, as a natural consequence of the fact that a higher particle kinetic energy involves a higher particle concentration in order to get a counterbalance between the gas compressibility and the particle thrust.

Only in disc's models whose $\alpha > \alpha_b$, the physical turbulent viscosity is able to develop a well-bound accretion disc in the primary's gravitational potential well.

3. Discussion

Conclusions of this work, together with [5, 6] results deal with the dwarf novae outburst modelling. A well-bound accretion disc in the primary's gravitational potential well is fulfilled whenever the (γ, α) pair in the compressibility-viscosity diagram lies *above* the parabolic boundary determined for an assigned value of v_{inj} for an assigned values of the SMR (Lanzafame 2008ab). An instability in the disc is induced by a sharp reduction of the mass transfer rate through the reduction of v_{inj}, producing a decrease in disc radius, density, accretion rate, etc.. As a consequence, the same (γ, α) pair stays *below* the "new" boundary. As in [5, 6], $\gamma = 7/5$, $\alpha = 0.1$ and $13 Kms^{-1} \leftarrow v_{inj} \rightarrow 130 Kms^{-1}$. Our aim is to quantify the duration of the transitional phases as a function also of the SMR. While in high compressibility regimes, dwarf novae outbursts temporarily represent phases of a well-bound accretion disc, when its radius increases as a consequence of the higher mass transfer rate from L1 point, instead they represent phases where a low compressibility disc achieves a consistency when $\dot{M}_{acc} \sim 10^{17} gs^{-1}$. Quiescent phases represent, in high

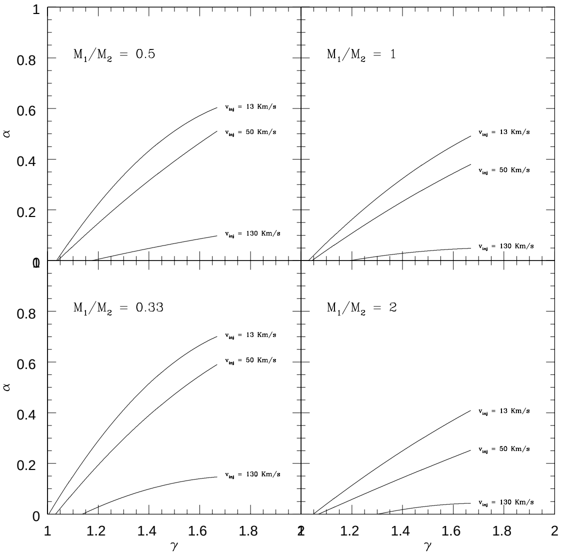

Figure 1: (γ, α) plots of boundaries separating domains where physical turbulent viscosity allows the development of a statistically defined accretion disc (above each boundary) from domains where it is not (below each boundary). Each plot refers to an assigned SMR value. Injection velocities v_{inj} at the inner Lagrangian point L1, are also reported for each boundary.

compressibility regimes, 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 point. In low compressibility regimes, they could represent even vanishing disc phases when the disc radius not only decreases, but also dissolves when $\dot{M}_{acc} \sim 10^{16} gs^{-1}$. A higher accretion rate onto the primary star involves a higher emission flux (especially in the X-ray close to the primary compact star) by conversion of mechanical energy into heat. A relevant difference between the two opposite stationary structures (quiescent - outburst) exists, in particular regarding the disc's radial extension and the disc's local densities when $\gamma \geq 1.1$. Gas densities in a stationary condition differs by a factor up to ~ 10 between the two opposite mass transfer conditions considered when $\gamma \geq 1.1$. This implies that in low compressibility regimes not only does the disc's radial extension effectively vary, but also the disc's local opacity and the accretion rate on the primary star. Therefore, while in high compressibility the transitional phase between quiescence and outburst (and vice-versa) seems more gradual, it is much more violent in a low compressibility regime. Of course, this does not preclude accretion discs in close binaries from effectively being in a high compressibility condition. When the transitional phase begins from a higher injection rate, from L1 to a lower injection rate or vice-versa, the disc bulk gradually evolves, adjusting its structure to the modified outer edge injection conditions at the L1 point. Injection conditions at the disc's outer edge involve not only the mass transfer rate itself, but also the angular momentum transport from L1. As a consequence, the higher the injection velocity, the higher the disc radius when a steady state is fulfilled. This behaviour compares to dwarf novae photometric periodical evolution, when evidences of a disc enlargement are reported. The transitional length between the opposite stationary disc configurations (bottom to top of the figure) is ~ 9 and ~ 4.5, ~ 9.5 and ~ 4.7, ~ 10 and ~ 5 and ~ 23.5 and ~ 5 orbital periods for SMR's $M_1/M_2 = 1/3, 1/2, 1/1$ and $2/1$, respectively. For values of the SMR comparable with those of SU UMa, OY Car, Z Cha and SS-Cyg-like systems, such values compare, as an order of magnitude, with the outburst duration, as shown in [3], where, among several hypotheses, a periodical modulation of the mass transfer rate is also taken into account as responsible for periodical variation of systemic velocity of outburst phenomena. Such time-scales show that characteristic filling time-scale t_{act} of the primary's gravitational potential well during active phases, and the characteristic depletion time (time of decay) during quiet phases t_{quiet} are, of course, functions of the mass transfer kinematics. However, t_{act} is not very sensitive to the SMR M_1/M_2 value as, instead, is t_{quiet}. Therefore, t_{quiet} is strictly linked to the viscous dissipation time $t_{diss} = t_\nu \simeq D^2/\nu$ (where D is the linear dimension of the primary's potential well) because, during the decaying quiet phases, the viscous transport effects characterize and rule out evolutionary times. As a secondary result, during the quiet phases, the injection rate from L1 is not the main element affecting the disc structure.

Conclusions are not so evident if γ is permanently < 1.1. In this case, in permanent high compressibility conditions, the previous phenomenology, explaining dwarf novae outbursts, is not be so stressed, although periodical quiescent-active phases are still significant.

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