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Model dependence of the multi-transonic behaviour, stability properties and the corresponding acoustic geometry for accretion onto rotating black holes

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HIGHLIGHTS

- Study on axisymmetric accretion onto a Kerr black hole for three disc geometries.
- The study is under generalised post Newtonian pseudo-Kerr black hole potential.
- Effect of black hole spin on shock is studied under different equation of states.
- Stationary solutions are found to be stable in astrophysically relevant time scale.
- Emergence of analogue gravity effects is a natural consequence in such analysis.

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ABSTRACT

Stationary, multi-transonic, integral solutions of hydrodynamic axisymmetric accretion onto a rotating black hole have been compared for different geometrical configurations of the associated accretion disc structures described using the polytropic as well as the isothermal equations of state. Such analysis is performed for accretion under the influence of generalised post Newtonian pseudo Kerr black hole potential. The variations of the stationary shock characteristics with black hole spin have been studied in details for all the disc models and are compared for the flow characterised by the two aforementioned equations of state. Using a novel linear perturbation technique it has been demonstrated that the aforementioned stationary solutions are stable, at least upto an astrophysically relevant time scale. It has been demonstrated that the emergence of the horizon related gravity like phenomena (the analogue gravity effects) is a natural consequence of such stability analysis, and the corresponding acoustic geometry embedded within the transonic accretion can be constructed for the propagation of the linear acoustic perturbation of the mass accretion rate. The analytical expression for the associated sonic surface gravity κ has been obtained self consistently. The variations of κ with the black hole spin parameter for all different geometric configurations of matter and for various thermodynamic equations of state have been demonstrated.

1. Introduction

The inner boundary condition imposed by the event horizon requires that accretion onto astrophysical black holes may manifest the transonic behaviour in general (Frank et al., 2002; Kato et al., 1998; Liang and Thomson, 1980). For low angular momentum inviscid axisymmetric flow under the influence of the post-Newtonian pseudo-Schwarzschild black hole potentials, multi-transonicity may be realised in the phase-portrait of the stationary accretion solutions. Such observations lead to the possibility of the formation of steady standing shock at certain location in between the saddle type outer sonic point and the centre type middle critical point Abramowicz and Chakrabarti (1990); Abramowicz and Kato (1989); Abramowicz and Zurek (1981); Blaes (1987); Chakrabarti (1989); Das (2002); Das et al. (2003); Liang and Thomson (1980); Muchotrzeb (1983); Muchotrzeb and Paczynski (1982); Muchotrzeb-Czerny (1986).

The inviscid flow assumption, however, requires that the accretion flow is characterised by reasonably low angular momentum. Such angular momentum distribution should necessarily be sub-Keplerian.

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Also, such flow is expected to possess ab-initio non-zero value of the advective velocity along the equatorial plane of the flow. Such a configuration may perhaps be better described by a quasi-spherical flow rather than a standard thin disc structure with radius dependent flow thickness. A conical wedge shaped configuration may be considered as a more appropriate description for the axisymmetric flow profile under consideration and such geometry may be a better alternative of the flow under hydrostatic equilibrium in the vertical direction (hereafter 'flow in vertical equilibrium', in brief). Conclusions drawn so far in the literature for the dynamical properties of the inviscid axisymmetric black hole accretion in vertical equilibrium are, thus, to be compared with the results obtained using a more general theoretical set up capable of studying various features of the low angular momentum inviscid axisymmetric accretion in all three different flow geometries usually considered in the relevant literature, viz., accretion flow with constant thickness, conical wedge shaped flow, and accretion in vertical equilibrium (see, e.g., Nag et al. (2012) and references therein).

Most of the works dealing with the multi-transonic accretion flow deal with the stationary integral flow solutions. Transient phenomena are, however, not quite rare in large scale astrophysical set up. Hence, it is important to establish that the information obtained from the stationary solutions is reliable by ensuring that the steady states are stable for black hole accretion – at least for astrophysically relevant time scales. Such a task may be accomplished by perturbing the set of equations describing the steady state accretion flow and by demonstrating that such perturbations do not diverge with time. For the pseudo-Schwarzschild black hole accretion, it has recently been argued in Nag et al. (2012) that the stationary inviscid flow described by a barotropic equation of state, is stable under linear perturbation of the mass accretion rate. Such observations remain valid for all three geometrical flow configurations described in previous paragraphs.

Equivalance between the stationary transonic astrophysical flows subjected to the gravitational attraction and certain aspects of the analogue gravity[1] has recently been established for pseudo-Schwarzschild axisymmetric accretion onto a non-rotating black hole for different geometric profiles of the accreting matter (Bilić et al., 2014). The corresponding acoustic geometry for each case was realised by studying the transonic properties of the stationary accretion solutions, and the numerical value of the associated acoustic surface gravity κ was estimated.

The conjecture that most (if not all) of the astrophysical black holes possess non-zero values of the spin angular momentum ($a \neq 0$, where a is the Kerr parameter) has gained widespread acceptance in recent years (Brenneman, 2013; Buliga et al., 2011; Daly, 2011; Dauser et al., 2010; Dotti et al., 2013; Fabian et al., 2014; Garofalo, 2013; Healy et al., 2014; Jiang et al., 2014; Kato et al., 2010; Martìnez-Sansigre and Rawlings, 2011; McClintock et al., 2011; McKinney et al., 2013; Miller et al., 2009; Nemmen and Tchekhovskoy, 2014; Nixon et al., 2011; Reynolds et al., 2012; Sesana et al., 2014; Tchekhovskoy and McKinney, 2012; Tchekhovskoy et al., 2010; Ziolkowski, 2010). It is thus imperative to understand how the black hole spin influences the salient features of the multi-transonic stationary integral flow solutions as well as to check whether the linear perturbation scheme gets affected by the variation of a. Which, in turn, would highlight how the space-time structure of the associated acoustic geometry depends on the rotation of the black hole. Complete general relativistic treatment to address such an issue is indeed non-trivial. Although the stationary multi-transonic solutions are possible to obtain for flows in the Kerr metric (Das and Czerny, 2012), full space-time dependent stability analysis of the transonic solutions does not seem to be amenable within the framework of the general relativity, especially when attempts are made to provide a complete analytical solution.

[1] See, e.g., (Barceló et al., 2011; Novello et al., 2002; Schützhold and Unruh, 2007) for a comprehensive discussion about the analogue gravity phenomena in general.

Motivated by the aforementioned arguments, in the present work we study low angular momentum inviscid axisymmetric hydrodynamic accretion onto a spinning black hole using post-Newtonian pseudo-Kerr potentials. Several such potentials are available in the literature (Artemova et al., 1996; Chakrabarti and Khanna, 1992; Chakrabarti and Mondal, 2006; Ghosh and Mukhopadhyay, 2007; Ghosh et al., 2014; Karas and Abramowicz, 2014; Lovas, 1998; Mukhopadhyay, 2002; SemerÃąk and Karas, 1999). Among the existing potentials, we however, pick up the one introduced by Artemova et al. (1996) for some of the explicit calculations which we present in our work. The potential proposed by Artemova et al. (1996) has a very simple algebraic form. The primary aim behind the introduction of a pseudo-Schwarzschild/Kerr black hole potential is to compromise between the convenience of handling of a Newtonian description of gravity and the space time structure described by complicated general relativistic calculations. Introduction of such potentials should allow one to investigate the basic physical process which occur during the accretion phenomena within the framework of a Newtonian construct, hereby avoiding the formal general relativistic description of the dynamics of the inflowing matter. The intrinsic simplicity of the algebraic presentation of a pseudo-potential is of paramount importance to let that potential qualify as the useful one. Among *all* such potentials proposed in the literature, no particular pseudo-potential stands alone as a significantly superior one (compared to the rest of such potentials) to mimic all the properties of the full general relativistic Kerr metric. This is especially true in connection to the description of the dynamics of the multi-transonic flow. We are chiefly interested to study such flows. Hence the potential with the simplest algebraic form will be of significant interest for our purpose.

The viscous transport of angular momentum is not taken into account in the present work. Forty two years after the introduction of the Standard Disc model (Novikov and Thorne, 1973; Shakura and Sunyaev, 1973), exact modelling of viscous transonic accretion flow incorporating proper heating and cooling effects is still an arduous task. Also, as will be demonstrated later in this work, construction of acoustic geometry becomes practically impossible for dissipative flow since the viscous effect may destroy the Lorentz invariance (Barceló et al., 2011). Large radial (advective) velocity close to the horizon ensures that the viscous time is larger than the dynamical infall time scale. Large radial velocity even at the larger distance is due to the fact that the rotational energy of the axisymmetric flow remains relatively low (Beloborodov and Illarionov, 2001; Igumenshchev and Beloborodov, 1997; Proga and Begelman, 2003). Aforementioned arguments indicate that the assumption of inviscid flow is not unjustified for low angular momentum flow with initial non-vanishing advective velocity profile.

For large scale relativistic astrophysical flows, however, the effect of the viscosity and magnetic field may not always be neglected. As a consequence, dissipative mechanism (through comptonisation, bremsstrahlung or synchrotron processes) may become significant to influence the overall flow dynamics and hence turbulent instabilities may develop. Non-linear perturbation may also be of considerable importance to determine the stability criteria of the flow. Chandrasekhar (1960) and Balbus and Hawley (1998) type magneto-rotational instabilities may be observed close to the black hole event horizon. These additional complexities clearly bring the system to the risk of complete destruction of the Lorentz symmetries. As a result, the analytical modelling of the flow profile, as well as of the sonic geometry embedded into it, becomes impossible. One has to take recourse to the large scale numerical simulation to handle such flow profiles, analysis of which is clearly beyond the scope of this work. Also to mention that the axisymmetric configuration of the flow is assumed a-priori and no misaligned flow structure may be handled using the formalism presented in this paper.