SONIC POINTS AND SHOCKS IN ISOTHERMAL ACCRETION AND WINDS IN KERR GEOMETRY

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Abstract. This paper is devoted to the study of sonic points and shocks in stationary, axially symmetric, isothermal flows around a Kerr black hole. We first show the dependence of the location of the sonic point with the flow’s angular momentum for different isothermal sound speeds. With our selected shock jump conditions, we then discuss the properties of the shock, including the location and the strength. The ambiguity regarding the shock locations is removed by stability analysis. We also find some differences between the shock in isothermal flows and that in adiabatic flows.


1. Introduction

Accretion flows onto a black hole must be transonic. Due to the general relativistic effect, there can exist more than one sonic points for the flow. The shock-free global solution only passes through one sonic point (Lu and Abramowicz, 1988). However, shocks may form when a supersonic flow is obstructed. In the case of black hole accretion, the flow is obstructed by the gravitational and centrifugal potential barrier. While for outflows (winds), the formations of shocks may be due to other perturbations, such as turbulence. Numerical simulations confirm this existence (Chakrabarti and Molteni, 1993; Sponholz and Molteni, 1994). The presence of shocks may change the temperature structure of accretion disks and may be responsible for a large number of astrophysical phenomena, such as soft X-ray radiation production and time variability.

Previously, shocks in accretion flows (or winds) were only studied on a case by case basis and a global understanding was lacking (e.g., Ferrari et al., 1985; Fukue, 1987). Using the Paczyński-Wiita (1980) potential to mimic the geometry around a Schwarzschild black hole, Chakrabarti (1989a,b) worked on shocks in isothermal and adiabatic flows and gave a full set of shock solutions. The models he used were all based upon that proposed by Matsumoto et al. (1984) which employed vertical averaging. He found that shocks can be produced only for some range of the parameter space, and that for a given set of initial parameters the shock could formally locate itself at one of the four positions, but he couldn’t remove the ambiguity of the shock locations by his stability analysis. Using the smoothed particle hydrodynamics (SPH) technique, Sponholz and Molteni (1994) presented a plenty of numerical results on shocks in adiabatic flows around a Kerr black hole.
hole, but in terms of another pseudo-Newtonian potential proposed by Chakrabarti and Khanna (1992). Chakrabarti (1990) dealt analytically with standing shocks in adiabatic flows in Kerr geometry, but the work is rather initial, in the sense that only a few examples of the shock solutions were presented. More recently, Chakrabarti (1996) presented fully general relativistic equations governing viscous transonic flows in vertical equilibrium in Kerr geometry and got the complete set of global solutions under adiabatic flow approximation. Under isothermal flow approximation, Yang and Kafatos (1995) investigated the shocks in accretion flows around a Schwarzschild black hole. However, astrophysically realistic black holes are generally believed to possess considerable angular momentum, it is therefore necessary to investigate shocks in Kerr geometry.

In the present paper, we study sonic points and shocks in isothermal accretion flows and winds in the equatorial plane of Kerr geometry. We neglect the viscosity, so that the specific angular momentum of flows is a constant of motion. But we think that the specific energy must not be constant, which is different from previous works. So it's not suitable to call any constant quantity as 'the specific energy' (e.g., Chakrabarti, 1989a) or to regard a constant as a quantity determined by 'the specific energy' (Yang and Kafatos, 1995). Instead, we find a constant of motion and name it the specific quasi-energy.

The plan of this paper is the following. In the next section, we give the radial motion equation, and show the variation of the sonic radius with the angular momentum for different sound speeds. Utilizing a constraint condition, we find that there exists a lower limit to the sonic radius. In addition to the mass and momentum flux conservations, the choice of the third shock jump condition has some degree of arbitrariness due to the variety of the assumed radiative efficiency at the shock. Following the same alternative as that in previous works (e.g., Chakrabarti, 1989a; Yang and Kafatos, 1995), we present the parameter space of possible shock formation and investigate the location and the strength of the shock in accretion flows and winds in Section 3. In Section 4 we make a short discussion.

We use the Boyer-Lindquist coordinates together with $G = c = 1$ units and $- + ++$ signature.

2. Basic Equations and the Critical Point

2.1. THE RADIAL MOTION EQUATION AND THE CRITICAL POINT CONDITIONS

We consider a stationary, axisymmetrical, inviscid isothermal flow in the equatorial plane of Kerr geometry. The relativistic hydrodynamic equations include the rest-mass conservation and the Euler equation. Note that the energy conservation equation does not hold now, it should be replaced by the temperature invariability, $T = \text{const}$.

The isothermal sound speed $b$ is defined as