New Astronomy 67 (2019) 103–115

Contents lists available at ScienceDirect

New Astronomy

journal homepage: www.elsevier.com/locate/newast

Effects of external magnetic field on the outflows of an accretion disc

Mahmoud Gholipour

Research Institute for Astronomy and Astrophysics of Maragha (RIAAM), P. O. Box: 55134-441, Maragha, Iran

ARTICLE INFO

Keywords:
Accretion
Accretion discs - magnetohydrodynamics (MHD) - stars: neutron

ABSTRACT

The aim of this work is to study the effects of an external magnetic field generated by a magnetized compact star on the outflows of its accretion disc. For this purpose, we solve a set of magneto-hydrodynamic (MHD) equations for an accretion disc in spherical coordinates to consider the disc structure along the θ-direction. We also consider the magnetic field of a compact star beyond its surface as a dipolar field, producing a toroidal magnetic field inside the disc. We convert the equations to a set of ordinary differential equations (ODEs) as a function of the θ only by applying self-similar assumptions in the radial direction. Then, this set of equations is solved under symmetrical boundary conditions in the equatorial plane to obtain the velocity field. The results are considered in the gas-pressure-dominated (GPD) region and radiation-pressure-dominated (RPD) region as well. The dipolar field of the compact stars can significantly enhance the speed of outflows. It also can change the structure of the disc. The results of this work would be useful in the study of X-ray binaries, the origin of ultra-relativistic outflows, and jet formation around the compact stars.

1. Introduction

An accretion disc is known as a structure formed by a diffuse material in orbital motion around a massive central object. This central object would be a newborn star or a compact star. Since the angular momentum is conserved, frictional forces are needed for orbiting materials in the disc to spiral inward towards the central object. The temperature of the material is increased by the gravitational and frictional forces leading to the emission of radiation from the disc. The frequency range of this radiation depends on the mass of the central object. The detected radiation from the accretion discs of young stars and protostars is in the range of infrared region, whereas the radiation from the discs around the neutron star and black hole is in the range of X-ray region. X-ray binaries belong to a class of binary stars luminous in the X-ray region. X-rays binaries consist of a donor and an accretor component (Tauris and van den Heuvel, 2006). The donor transfers the matter towards the accretor, and therefore, x-rays are produced. Generally, the donor is an ordinary star, whereas the accretor is a very compact star such as a neutron star or a black hole. The popular classification of X-ray binaries distinguished classes based on mass (high, intermediate, low) referring to the optically visible donor not to the compact X-ray emitting accretor. This classification includes the low-mass X-ray binaries (LMXB), intermediate-mass X-ray binaries (IMXB), high-mass X-ray binaries (HMXB) (e.g. Bhattacharya and van den, 1991; Tauris and van den Heuvel, 2006; Chen and Podsiadlowski, 2016). For instance, a low-mass X-ray binary (LMXB) is a binary star which its accretor is a compact star (black hole, neutron star or white dwarf), and its donor transfers mass to the accretor when its Roche lobe is filled (Liu et al., 2007). Also, this component (the donor) is less massive than the compact star (the accretor) and can be on the main sequence as well as an evolved star (red giant).

Many observations reveal that the strength of the magnetic field on the surface of the compact stars is very high. For instance, the field strength on the surface of a neutron star has been estimated to be in the range of 10^4 to 10^{11} tesla. This strong magnetic field can affect the structure of a disc orbiting around the neutron star. The magnetic field of a compact star beyond its surface can be estimated as a dipolar field. The original question here is how this field acts on the material inside the disc. One of the works addressing this question is the work of Banerjee et al. (1995) who argued that the dipolar magnetic field with the azimuthal motion of the gas disc can induce a toroidal magnetic field inside the disc. Somewhat later, regarding this work, Ghanbari and Abbassi (2004) studied the impact of self-gravity in a rotating accretion disc in the presence of a dipolar magnetic field. Using the self-similar solution, they showed that the thickness and shape of the disc can be changed by the self-gravity and the magnetism of the compact star. Also, they showed that the higher the self-gravity the thinner the discs. They neglected the effect of outflows in their study so that only toroidal component of the velocity is present in the disc. Also, for simplicity, they assumed that this component of velocity has a form similar to that of the magnetic field inside the disc.

Nowadays, the important effects of outflows on the structure and

E-mail address: gholipour@riaam.ac.ir.

https://doi.org/10.1016/j.newast.2018.09.010
Received 28 May 2018; Received in revised form 16 September 2018; Accepted 22 September 2018
Available online 24 September 2018
1384-1076/

evolution of accretion discs are obvious. In this regard, there is a lot of observational surveys and simulation works carried out for both optically thick and thin accretion discs. Furthermore, many theoretical studies have been done with numerical solution for the case of hot and cold accretions which show that the existence of the outflows during accretion is necessary (e.g. Gholipour, 2018; Samadi and Abbassi, 2016; Khesali et al., 2015; Mosallanezhad et al., 2014; Shadmehri, 2014; Khajenabi and Shadmehri, 2013; Khesali and Motamedi Koochaksarayi, 2013; Jiao and Wu, 2011). For instance, Gholipour (2018) considered the effect of a magnetic Prandtl number on the structure of an accretion flow with a bipolar outflow by focusing on the density structure. For this purpose, he followed the comprehensive work of Jiao and Wu (2011; hereafter JW11) who considered outflows in accretion discs by solving the set of hydrodynamic equations in spherical coordinates using the self-similar assumptions in the radial direction. He found that the outflows were essential in both cold and hot accretion flows. He showed that the existence of a suitable magnetic Prandtl number may lead to bump formation in hot accretion flows. By applying the same formalism in this study, we will consider the effects of a toroidal magnetic field produced by a compact star on the structure of an accretion disc with a particular focus on the outflows of the disc. This paper is organized as follows. In Section 2, we consider the effect of a dipolar field of the compact objects on the disc and the formulation of the governing equations. By using self-similar solutions, we obtain a set of ordinary differential equations (ODEs) in Section 3. The results and astrophysical implications are considered in Section 4. Finally, Section 5 is assigned to conclusions and discussion.

2. General formulation

In this section, we consider the magneto-hydrodynamics equations in a thick accretion disc in the presence of an induced magnetic field from the compact object. It is better to start by considering the magnetic field of the compact object as well as the magnetic field of the disc orbiting around this object. The magnetic field of compact object beyond its surface can be assumed as a dipolar. This magnetic field can induce a magnetic field through the disc that strongly coupled to component of dipolar magnetic field. The dipolar in a spherical coordinate system can be written as

$$B_r = 2B_*(\frac{R}{r})^3\cos\theta, \quad B_\theta = B_*(\frac{R}{r})^3\sin\theta, \tag{1}$$

where B_* and R are the strength of magnetic field on the surface of the compact object and the radius of the compact object, respectively. To obtain the magnetic field through the disc, we follow the work of Banerjee et al. (1995). They argued that the dipolar magnetic field with the azimuthal motion of the gas disc could induce a toroidal magnetic field inside the disc as follows (see also Ghanbari and Abbassi, 2004)

$$B_\phi = B_l(\frac{r}{R})^{n-3/2}\sin^{-2n}\theta, \tag{2}$$

where $n \le 3/2$ is a real constant, B_l is a constant having the dimension of magnetic field strength. Therefore, we assume this configuration (i.e. toroidal field) is dominant through the disc. Below we continue the problem with writing the set of MHD-equations which respectively are: the equation of continuity, the equations of motion and the energy equation:

$$\frac{\partial\rho}{\partial t} + \nabla.(\rho\mathbf{V}) = 0, \tag{3}$$

$$\frac{\partial\mathbf{V}}{\partial t} + (\mathbf{V}.\nabla)\mathbf{V} = -\frac{1}{\rho}\nabla P - \nabla\Phi + \frac{1}{\rho}\nabla.\mathbf{T} + \frac{1}{4\pi\rho}[(\nabla\times\mathbf{B})\times\mathbf{B}], \tag{4}$$

$$\rho\left(\frac{\partial e}{\partial t} - \frac{P}{\rho^2}\frac{\partial\rho}{\partial t}\right) + \rho\left(\mathbf{V}.\nabla e - \frac{P}{\rho^2}\mathbf{V}.\nabla\rho\right) = f\nabla\mathbf{V}:\mathbf{T}, \tag{5}$$

where ρ, P, $\mathbf{V}$, Φ, $\mathbf{T}$, $\mathbf{B}$ and e are the density of gas, the total pressure, the velocity vector, the gravitational potential, the viscous tensor, the magnetic field vector and the internal energy per unit volume, respectively. In addition, f is the advection parameter which describes the fraction of viscous heat that does not leave the system and is stored in the gas and transported with the flow (i.e. $f \equiv (Q_{vis} - Q_{rad})/Q_{vis}$ where Q_{vis} is the dissipation rate by viscosity and Q_{rad} represents the energy loss through radiative cooling).

In the following, we consider a thick accretion disc in the spherical coordinates (r, θ, ϕ) to be in equilibrium state ($\partial/\partial t \equiv 0$) and axisymmetric ($\partial/\partial\phi \equiv 0$). The other standard assumption are as follows: I) We assume that the $r\phi$-component of the viscous tensor is only dominant on the disc. II) The α-model is used for the viscosity, i.e. $T_{r\phi} = -\alpha P$ where α is the viscosity coefficient (Shakura and Sunyaev, 1973). III) The gravitational force is assumed as the Newtonian gravitational potential, $\Phi = GM/r$. IV) The effects of magnetic energy dissipation inside the disc as well as general relativistic effects are neglected in this work.

Under these assumptions, the set of equations converts to a simple form as follows. The continuity equation and three components of momentum equation can be respectively written as:

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\rho v_r) + \frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}(\sin\theta\rho v_\theta) = 0, \tag{6}$$

$$\frac{v_\theta}{r}(v_\theta - \frac{\partial v_r}{\partial\theta}) - v_r\frac{\partial v_r}{\partial r} + \frac{v_\phi^2}{r} - \frac{1}{\rho}\frac{\partial P}{\partial r} - \frac{GM}{r^2} - \frac{1}{4\pi\rho}\frac{B_\phi}{r}\frac{\partial}{\partial r}(rB_\phi) = 0, \tag{7}$$

$$v_\phi^2\cot\theta - v_\theta(v_r + \frac{\partial v_\theta}{\partial\theta}) - rv_r\frac{\partial v_\theta}{\partial r} - \frac{1}{\rho}\frac{\partial P}{\partial\theta} - \frac{1}{4\pi\rho}\frac{B_\phi}{\sin\theta}\frac{\partial}{\partial\theta}(B_\phi\sin\theta) = 0, \tag{8}$$

$$\frac{v_\phi}{r}(v_r + v_\theta\cot\theta) + v_r\frac{\partial v_\phi}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_\phi}{\partial\theta} - \frac{1}{\rho r^3}\frac{\partial}{\partial r}(r^3T_{r\phi}) = 0, \tag{9}$$

where v_r, v_θ and v_ϕ are the three velocity components, B_ϕ is the toroidal magnetic field which is induced by the dipolar field. In addition, the energy equation becomes

$$\rho\left(v_r\frac{\partial e}{\partial r} + \frac{v_\theta}{r}\frac{\partial e}{\partial\theta}\right) - \frac{P}{\rho}\left(v_r\frac{\partial\rho}{\partial r} + \frac{v_\theta}{r}\frac{\partial\rho}{\partial\theta}\right) = fT_{r\phi}r\frac{\partial}{\partial r}\left(\frac{v_\phi}{r}\right). \tag{10}$$

The relationship between the internal energy and the gas pressure and the radiation pressure is

$$e = \frac{1}{\rho}\left(\frac{P_{gas}}{\gamma_0 - 1} + 3P_{rad}\right), \tag{11}$$

where γ_0 is the adiabatic coefficient. In terms of the total pressure, this equation can be rewritten as follows

$$e = \frac{P}{\rho(\gamma - 1)}, \tag{12}$$

where γ replaces γ_0 and is defined as

$$\frac{1}{\gamma - 1} = \left(\frac{\beta}{\gamma_0 - 1} + 3(1-\beta)\right), \quad \beta = \frac{P_{gas}}{P_{gas} + P_{rad}}. \tag{13}$$

This definition is useful to transit the Gas Pressure Dominated (abbreviated here as GPD) region ($\beta = 1$ or $\gamma = 5/3$) to the Radiation Pressure Dominated (abbreviated as RPD) region ($\beta = 0$ or $\gamma = 4/3$).

3. Self-similar solution

Eqs. (6)–(10) are a set of coupled differential equations which should be solved numerically. In other words, this set of equations is partial differential equations (PDEs). In this regard, the self-similar method is a powerful technique as a common tool in astrophysical fluid mechanics which make us able to convert PDEs to ODEs. The radial and latitudinal dependence of the variables can be separated by assuming the radial part as a power-law function of the radius (e.g. JW11;