The launching condition of a jet driven by the magnetic field and radiation pressure of an accretion disc

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ABSTRACT

We find that cold gas can be magnetically launched from the surface of a disc with the help of the radiation pressure, if the angular velocity of the radiation-pressure-dominated accretion disc is greater than a critical value, which decreases when increasing the disc thickness \(H_d/R\) (radiation pressure). This indicates that the force exerted by the radiation from the disc does help to launch the outflow. The rotational velocity of the gas in the disc depends on the strength of the magnetic field threading the disc and the inclination \(\kappa_0\) (\(\kappa_0 = B_i/B_r\)) of the field line at the disc’s surface. The launching condition for cold gas at the disc’s surface sets an upper limit on the magnetic field strength, which is a function of the field-line inclination \(\kappa_0\) and the disc thickness \(H_d/R\). This implies that a more strict constraint on the maximal jet power can be extracted from a radiation-pressure-dominated accretion disc than that derived conventionally on the equipartition assumption.

Key words: accretion, accretion discs – black hole physics – magnetic fields – galaxies: jets – quasars: general.

1 INTRODUCTION

The winds that are driven from an accretion disc through the magnetic field lines threading the disc are considered to be promising explanations for jets/outflows observed in different types of sources, such as active galactic nuclei (AGNs), X-ray binaries and young stellar objects (see reviews in Spruit 1996; Konigl & Pudritz 2000; Pudritz et al. 2007; Spruit 2010). In this model, the ordered magnetic field corotates with the gases in the disc, and a small fraction of the gases are driven along the field line by the centrifugal force (Blandford & Payne 1982). The jets are powered by the rotational kinetic energy of the disc through the ordered field threading the accretion disc in this scenario. A crucial ingredient of this model is that the angle of the field line inclined to the mid-plane of the disc is less than \(\sim 60^\circ\), which is required for launching jets from the mid-plane of the Keplerian cold disc (Blandford & Payne 1982). This critical angle could be larger than \(60^\circ\) for an accretion disc surrounding a rapidly spinning black hole (Cao 1997). This indicates that the spin of black hole might help to launch jets centrifugally by cold magnetized discs (Cao 1997; Sadowski & Sikora 2010). Such analyses have been carried out based on two assumptions: the gas is cold (i.e. without considering its internal energy) and the gas is initially launched from the mid-plane of a Keplerian accretion disc. Strictly speaking, the circular motion of the gases in the accretion disc always deviates from Keplerian motion in the presence of a large-scale magnetic field, which usually exerts a radial force against the gravitation of the central object. Therefore, the accretion disc threaded by ordered magnetic field lines is always sub-Keplerian (Ogilvie & Livio 1998, 2001; Cao & Spruit 2002; Cao 2011). The gases are dominantly accelerated by the centrifugal force, which is proportional to \(R\Omega(R)\), where \(R\) is the radius of the magnetic field-line footpoint and \(\Omega\) is the angular velocity of the accretion disc. A strong magnetic field is helpful for launching the gases, while a stronger field leads to a lower circular velocity of the gas in the disc, which decreases the mass-loss rate in the outflow or even suppresses the outflow. Such effects on the launch of the outflow have been extensively explored previously (e.g. Ogilvie & Livio 1998, 2001; Cao & Spruit 2002).

It has also been suggested that the outflow can be accelerated by the radiation pressure of the disc (e.g. Shlosman, Vitello & Shaviv 1985; Murray et al. 1995). Proga (2000) has performed numerical simulations on the radiation-driven winds from a luminous Keplerian accretion disc threaded by a strong large-scale ordered magnetic field. It has been found that the radiation force is essential for producing winds from the disc if the thermal energy of the gas is low or if the field lines make an angle greater than \(60^\circ\) with respect to the disc mid-plane. The numerical simulations carried out in Proga (2000) are limited to Keplerian accretion discs. Recently, the global structure of accretion discs and outflows around black holes has been investigated using radiation-magnetohydrodynamics (MHD) simulations (e.g. Takeuchi, Ohsuga & Mineshige 2010; Ohsuga &...
Mineshige 2011). Vaidya et al. (2011) have carried out similar investigations for massive young stars. It has been found that the magnetic force, together with the radiation force exerted by accretion discs, can efficiently drive outflows from luminous accretion discs.

It is believed that black holes are accreting at high rates in narrow-line Seyfert I galaxies (NLS1s), some young radio galaxies and microquasars (e.g. Sulentic et al. 2000; Fender, Belloni & Gallo 2004; Czerny et al. 2009; Wu 2009). Most NLS1s are radio-quiet, while a fraction of them are radio-loud and some of them might possess relativistic jets (e.g. Zhou et al. 2003; Doi et al. 2006; Yuan et al. 2008; Gu & Chen 2010). For microquasars (e.g. GRs 1915+105), relativistic jets are present in their high-luminosity states (e.g. Fender et al. 2004). The outflows/jets in these sources accreting at high rates can probably be magnetically launched from the radiation-pressure-dominated accretion discs.

In this paper, we explore the condition for cold gas driven by the magnetic force and the radiation force from the surface of a radiation-pressure-dominated accretion disc. The disc structure, especially the circular motion velocity of the gases in the disc, is altered in the presence of a strong large-scale ordered magnetic field. The situation becomes complicated for the gas driven from the surface of a real disc with finite thickness. It has not been altered much by the field. The situation becomes complicated for the gas driven from the surface of a real disc with finite thickness. It has not been altered much by the field. The situation becomes complicated for the gas driven from the surface of a real disc with finite thickness. It has not been altered much by the field. The situation becomes complicated for the gas driven from the surface of a real disc with finite thickness. It has not been altered much by the field.

2 STRUCTURE OF A RADIATION-PRESSURE-DOMINATED ACCRETION DISC

The accretion disc is assumed to be in hydrodynamical equilibrium in the vertical direction. For the gas-pressure-dominated accretion disc, the gradient of the gas pressure is balanced with the gravity and magnetic force because of the curvature of the field in the vertical direction (Ogilvie & Livio 1998, 2001; Cao & Spruit 2002; Cao 2011). However, the situation is slightly different for the radiation-pressure-dominated accretion disc. The vertical component of the gravitational force of the black hole is balanced with the radiation pressure of the disc and the vertical component of the magnetic force at the disc surface \( z = H_{\Delta} \) (Laor & Netzer 1989). The curvature of the field line at the disc surface is usually very small, and the vertical component of the magnetic force can be neglected in the estimate of the disc scaleheight.

The scaleheight of the disc can be estimated with

\[
\frac{G M H_{\Delta}}{\left( R_{i}^{2} + H_{\Delta}^{2} \right)^{3/2}} = \frac{f_{\text{rad}} k_{\text{T}}}{c},
\]

which can be rewritten as

\[
\frac{\tilde{H}_{\Delta}}{\left( 1 + H_{\Delta}^{2} \right)^{3/2}} = \frac{f_{\text{rad}} k_{\text{T}}}{R_{i} \Omega_{k} c}.
\]

Here, \( f_{\text{rad}} \) is the flux from the unit surface area of the disc, \( \tilde{H}_{\Delta} = H_{\Delta}/R_{i} \) and \( \Omega_{k} = (G M/R_{i}^{3})^{1/2} \) is the Keplerian angular velocity at \( R_{i} \).

In a geometrically thin accretion disc, the circular velocity is almost Keplerian without magnetic fields. The circular motion of the disc becomes sub-Keplerian in the presence of magnetic fields, and the angular velocity \( \Omega \) of the disc can be calculated with

\[
R_{i} \Omega_{k} - R_{i} \tilde{\Omega} = \frac{B_{i}^{2} R_{i}}{2 \pi \Sigma_{z} R_{i}} = \frac{B_{i}^{2}}{2 \pi \Sigma_{z} R_{i} \kappa_{0}}.
\]

Here, \( \Sigma_{z} \) is the surface density of the disc, \( B_{i}^{2} \) and \( B_{i} \) are the radial and vertical components of the field at the disc surface \( z = H_{\Delta} \), respectively, and \( \kappa_{0} = B_{i}/B_{\parallel} \). The radial gradient of radiation pressure in the disc is not included in equation (3), which is negligible compared with the magnetic force in the thin accretion disc if the magnetic field is sufficient strong.

The pressure of a radiation-pressure-dominated accretion disc at the mid-plane is

\[
p_{\text{d}} = \frac{4 \sigma}{3 c} T_{c}^{4},
\]

where \( T_{c} \) is the central temperature of the disc. The flux radiated from the unit area of the disc surface is given by

\[
f_{\text{rad}} = \frac{8 \sigma T_{c}^{4}}{3 \Sigma_{z} k_{\text{T}}},
\]

Thus, equation (4) can be rewritten as

\[
p_{\text{d}} = \frac{\Sigma_{z} k_{\text{T}} f_{\text{rad}}}{2 c}.
\]

Substituting equations (2), (4), and (5) into equation (3), we have

\[
1 - \tilde{\Omega}^{2} = \frac{2 \beta \tilde{H}_{\Delta}}{\kappa_{0} (1 + H_{\Delta}^{2})^{3/2}},
\]

where the dimensionless quantities \( \tilde{\Omega} \) and \( \beta \) are defined as

\[
\tilde{\Omega} = \frac{\Omega}{\Omega_{k}}; \quad \beta = \frac{B_{i}^{2}/8 \pi}{p_{\text{d}}}.\n\]

3 LAUNCHING CONDITION FOR COLD GAS FROM THE DISC SURFACE

The condition for cold gas to be launched from the mid-plane of a Keplerian accretion disc has been given by Blandford & Payne (1982), and it is a good approximation for geometrically thin accretion discs with weak magnetic fields (i.e. the rotation of the discs has not been altered much by the field). The situation becomes complicated for the gas driven from the surface of a real disc with finite thickness in the presence of a strong magnetic field. In this case, the rotation of the gas in the disc deviates significantly from the Keplerian value (see the discussion in Section 2).

The effective potential along the field line threading the accretion disc with angular velocity \( \Omega \) at radius \( R_{i} \) is

\[
\Psi_{\text{eff}}(R, z) = -\frac{G M}{(R^{2} + z^{2})^{1/2}} - \frac{1}{2} \Omega (R_{i})^{2} R^{2},
\]

without considering the radiation force exerted on the gas in the outflow. It becomes

\[
\Psi_{\text{eff}}(R, z) = -\frac{G M}{(R^{2} + z^{2})^{1/2}} - \frac{1}{2} \Omega (R_{i})^{2} R^{2} - \frac{f_{\text{rad}} k_{\text{T}} z}{c},
\]

when the radiation pressure is considered. Here, \( f_{\text{rad}} \) is the flux emitted from the unit surface area of the disc and the Thompson scattering cross-section \( k_{\text{T}} = 0.4 \, \text{g cm}^{-2} \). For the outflow from the inner region of the disc, the gases are almost completely ionized and the Thompson scattering cross-section is therefore a good approximation. The analysis carried out in this paper can be applied to the outflow driven by the radiation pressure because of the line absorption if the Thompson scattering cross-section is replaced by the line opacity, although line-driven outflows are usually from the outer region of the disc (e.g. Silosman et al. 1985; Murray et al. 1995; Proga, Stone & Kallman 2000).

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Substituting equation (2) into equation (10), the effective potential along the field line threading the accretion disc with angular velocity $\Omega$ at radius $R_i$ can be rewritten in dimensionless form as

$$\Psi_{\text{eff}}(r, \tilde{z}) = \frac{\Psi_{\text{eff}}(R_i, \tilde{z})}{R_i^2 \Omega_K^3} = \frac{1}{2} \frac{\tilde{z}}{\Omega^2}^2 - \frac{\tilde{z}}{\Omega^2} \tilde{H}_d - \frac{\tilde{z}^2}{1 + \tilde{H}_d^2} \frac{1}{2} \Omega^2 r^2$$

where $r = R/R_i$ and $\tilde{z} = z/R_i$. Differentiating equation (11), we have

$$\frac{d\Psi_{\text{eff}}(r, \tilde{z})}{dr} = \frac{r + \tilde{z} \kappa_0}{(r^2 + \tilde{z}^2)^{3/2}} - r \frac{\tilde{H}_d \kappa_0}{(1 + \tilde{H}_d^2)^{3/2}}$$

which reduces to

$$\frac{d\Psi_{\text{eff}}(r, \tilde{z})}{dr} \bigg|_{r=1, \tilde{z}=\tilde{H}_d} = \frac{1}{(1 + \tilde{H}_d^2)^{3/2}} - \tilde{\Omega}^2$$

at the disc surface, $r = 1$ and $\tilde{z} = \tilde{H}_d$. This means that the cold gas can be magnetically launched from the disc surface with the help of radiation pressure only if the condition

$$\frac{d\Psi_{\text{eff}}(r, \tilde{z})}{dr} \bigg|_{r=1, \tilde{z}=\tilde{H}_d} \leq 0$$

is satisfied, which requires

$$\tilde{\Omega} \geq \sqrt[3/2]{\frac{1}{1 + \tilde{H}_d^2}}.$$  

Substituting equation (7) into equation (15), the condition becomes

$$\beta \leq \frac{\kappa_0}{2 \tilde{H}_d} \left( \frac{1 + \tilde{H}_d^2}{(1 + \tilde{H}_d^2)^{3/2}} - 1 \right).$$

for the cold gas being able to leave the disc surface along the field line. In order to clarify the role of the radiation force in launching the jets/outflows, we analyse two special cases: (i) $f_{\text{rad}} \to 0$ and $\Omega \to 1$ and (ii) $f_{\text{rad}}$ is not considered and $\Omega < 1$.

### 3.1 Case (i): $f_{\text{rad}} \to 0$ and $\Omega / \Omega_K \to 1$

In our model, the circular velocity of the accretion discs deviates from the Keplerian value in the presence of magnetic fields. A lower $\beta$ leads to a larger angular velocity $\tilde{\Omega}$ for a fixed value of $\kappa_0$ (see equation 7), which helps to launch the outflow. The results here are different from those derived by Blandford & Payne (1982) for the gas driven from the mid-plane of a Keplerian disc. We expect our calculation to be able to reproduce the Blandford–Payne result on the critical angle of the field line with respect to the disc plane, below which the cold gas can be launched from the mid-plane of a Keplerian disc. For a radiation-pressure-dominated accretion disc, the gravity of the black hole is balanced with the radiation pressure of the disc in the vertical direction, which means that the disc thickness $H_d \to 0$ in the limit of $f_{\text{rad}} \to 0$ (see equation 2), and $\tilde{\Omega} \to 1$ is automatically satisfied (see equation 7). Thus, our model calculation corresponds to the case considered by Blandford & Payne (1982) for the cold gas from the mid-plane of a Keplerian disc in the limit of $H_d \to 0$. We find that $d\Psi_{\text{eff}}(r, \tilde{z})/dr = 0$ if $\tilde{H}_d = 0$ (see equation 13). This implies that the gas can always be in equilibrium independent of the field-line inclination $\kappa_0$. This is the same as in Blandford & Payne (1982). Therefore, we have to calculate the second derivative of the effective potential to check the stability of equilibrium:

$$\frac{d^2 \Psi_{\text{eff}}(r, \tilde{z})}{dr^2} = -\frac{2r^2 - 6\tilde{z} \kappa_0 - 2\tilde{z}^2 \kappa_0^2}{(r^2 + \tilde{z}^2)^{3/2}} - (r + \tilde{z}) \tilde{\Omega}^2.$$  \hspace{1cm} (17)

This needs to be negative at $r = 1$ and $\tilde{z} = \tilde{H}_d = 0$ for the cold gas to be launched from the mid-plane of the disc, and it leads to

$$\kappa_0 < \kappa_{0,\text{crit}} = \sqrt{3},$$  \hspace{1cm} (18)

which gives the same result as Blandford & Payne (1982). Our calculations show that gas at the disc surface is not in the equilibrium state when the angular velocity is greater than a critical value for the disc with finite thickness. Therefore, the launch condition for the cold gas at the disc surface can be derived by the first derivative of the effective potential $d\Psi_{\text{eff}}(r, \tilde{z})/dr < 0$ at $z = \tilde{H}_d$.

### 3.2 Case (ii): $f_{\text{rad}}$ is not considered and $\Omega < \Omega_K$

In most previous work, the effect of the radiation force exerted by the accretion disc on the outflow/jet has not been considered, while this effect is included in this work. We leave out the radiation pressure term, and reanalyse the effective potential along the field line. The analysis carried out here is, in principle, inconsistent with the assumption of radiation-pressure-dominated accretion discs. However, the analysis is only limited to the condition of the gas being able to leave the system, which is almost independent of the disc structure. This illustrates the role of the radiation pressure in launching the outflow from the surface of the disc. The effective potential along the field line threading the accretion disc with angular velocity $\Omega$ at radius $R_i$ can be written in a dimensionless form,

$$\Psi_{\text{eff}}(r, \tilde{z}) = \Psi_{\text{eff}}(R_i, \tilde{z}) = \frac{1}{2} \frac{\tilde{z}}{\Omega^2}^2 - \frac{\tilde{z}}{\Omega^2} \tilde{H}_d - \frac{\tilde{z}^2}{1 + \tilde{H}_d^2} \frac{1}{2} \Omega^2 r^2.$$  \hspace{1cm} (19)

Here, $r = R/R_i$, $\tilde{z} = z/R_i$ and the term due to the radiation force in equation (11) is omitted. Differentiating equation (19), the condition for the cold gas being able to leave the disc surface is available:

$$\frac{d\Psi_{\text{eff}}(r, \tilde{z})}{dr} \bigg|_{r=1, \tilde{z}=\tilde{H}_d} = \frac{r + \tilde{H}_d \kappa_0}{(1 + \tilde{H}_d^2)^{3/2}} - \tilde{\Omega}^2 \leq 0.$$  \hspace{1cm} (20)

We derive the lower limit on the angular velocity of the disc as

$$\tilde{\Omega} \geq \sqrt[3/2]{\frac{1}{1 + \tilde{H}_d^2}}.$$  \hspace{1cm} (21)

The constraint of the magnetic field strength is available,

$$\beta \leq \frac{\kappa_0}{2 \tilde{H}_d} \left( \frac{1 + \tilde{H}_d^2}{(1 + \tilde{H}_d^2)^{3/2}} - 1 - \tilde{H}_d \kappa_0 \right).$$  \hspace{1cm} (22)

by substituting equation (7) into equation (21). It is found that the critical angular velocity of the disc, above which the cold gas can be launched from the disc surface, should be greater than the Keplerian value when $\kappa_0$ is sufficiently large (see equation 20), if the role of the radiation force on the outflow is not considered. For the radiation force to be properly considered, we find that the critical angular velocity of the disc is always lower than the Keplerian value (see equation 15). This implies that the radiation force can help to launch the gas from the disc surface. We note that $d\Psi_{\text{eff}}(r, \tilde{z})/dr = 0$ when $\tilde{H}_d = 0$ from equation (20). As discussed above, the second derivative of the effective potential $d^2 \Psi_{\text{eff}}/dr^2 < 0$ at $r = 1$ and $\tilde{H}_d = 0$ is required for the cold gas to be able to leave. The last
term in the first derivative of the effective potential (equation 12) is left out when the role of the radiation force on the outflow is not considered. This term remains constant along the field line, and the second derivative of the effective potential has the same form as equation (17). Thus, our analysis where we do not consider radiation pressure can also reproduce the same result as in Blandford & Payne (1982) when $\tilde{H}_d \to 0$.

4 RESULTS

As discussed in Section 2, the angular velocity of the gas in the accretion disc is dependent on the magnetic field strength $\beta$ and the inclination of the field line $\kappa_0$ at the disc surface. In Fig. 1, we plot the angular velocities of the accretion disc as functions of $\beta$ and $\kappa_0$ with different values of $\tilde{H}_d$. We find that the angular velocity $\tilde{\Omega}$ increases with field-line inclination $\kappa_0$ at the disc surface. For a fixed value of $\kappa_0$, the angular velocity $\tilde{\Omega}$ increases with magnetic field strength $\beta$.

The launch of the cold gas in the disc is governed by the effective potential barrier, and the cold gas can be launched from the disc surface along the field line if the angular velocity of the gas in the disc is larger than a critical value (see equation 15), as plotted in Fig. 2. The critical angular velocity $\tilde{\Omega}_{\text{crit}}$ decreases with increasing disc thickness $\tilde{H}_d$. Because $\tilde{\Omega}$ is a function of $\beta$, $\kappa_0$ and $\tilde{H}_d$, the conditions in which the cold gas can be launched from the disc surface are available as functions of $\kappa_0$ and $\beta$ with given $\tilde{H}_d$ (see Fig. 3). There are upper limits on the magnetic field strength, which increase with the field inclination $\kappa_0$ and disc thickness $\tilde{H}_d$. For comparison, in the same figure, we also plot the results when we do not consider the effect of radiation pressure from the disc. We find stricter constraints on the magnetic field strength. The cold gas can be launched from the disc surface only if the field line is bent close to the disc surface.

5 DISCUSSION

We investigate the launch of the gas from the disc surface by the field lines threading a radiation-pressure-dominated accretion disc, in which the effect of the radiation pressure from the accretion disc is considered. The launch of the outflow is sensitive to the rotational angular velocity of the gas in the disc, which is determined by the balance between the gravity of the black hole and the magnetic force. The angular velocity of the gas in the disc $\tilde{\Omega}$ decreases with increasing field strength $\beta$, if the values of all other parameters are fixed. The angular velocity $\tilde{\Omega}$ becomes smaller for the field line inclined at a smaller angle with respect to the disc surface, which is caused by a stronger magnetic force for a smaller $\kappa_0$. We find that the angular velocity $\tilde{\Omega}$ decreases with increasing relative disc thickness $\tilde{H}_d$ for the same values of $\beta$ and $\kappa_0$. 

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Angular velocity of the accretion disc as a function of $\beta$ and $\kappa_0$. The solid lines represent the results with $\beta = 0.1$, while the dashed lines are for $\beta = 0.5$. The coloured lines correspond to results with different values of the disc scaleheight: $\tilde{H}_d = 0.01$ (red), 0.1 (green) and 0.5 (blue).

![Figure 2](https://example.com/figure2.png)

**Figure 2.** The condition in which the cold gas can be launched from the disc surface (see equation 15).

![Figure 3](https://example.com/figure3.png)

**Figure 3.** The solid lines represent the conditions in which the cold gas can be launched from the disc surface as a function of $\kappa_0$ and $\beta$ (see equation 16). The dashed lines are the results calculated without considering the effect of radiation pressure on the launch of the outflow/jet (see Section 2.2). The coloured lines are for the different disc thicknesses: $\tilde{H}_d = 0.05$ (red), 0.1 (green), 0.2 (blue) and 0.5 (black).
Similar to the discussion of Blandford & Payne (1982), we investigate the condition in which the cold gas can be launched from the disc surface. In the presence of magnetic fields, the rotational velocity of the gas in the disc is sub-Keplerian, which makes it more difficult for the gas to leave the disc surface than in the Keplerian case (Ogilvie & Livio 1998, 2001). In this paper, we include the effect of radiation pressure in launching the outflow. We find that the cold gas can be magnetically driven from the disc surface if the angular velocity of the disc is greater than a critical value \( \Omega_{\text{crit}} \) (see Fig. 2), which is a function of the disc thickness \( H_d \). For the radiation-pressure-dominated accretion disc, the disc thickness \( H_d \) describes the importance of radiation pressure (see equation 2). It is found that the critical value of \( \Omega_{\text{crit}} \) decreases with increasing \( H_d \), which indicates that the force exerted by the radiation from the disc does help to launch the outflow. The angular velocity of the gas in the disc is determined by the field strength and the inclination of the field line at the disc surface. Therefore, the condition in which the cold gas can be launched becomes a function of \( \kappa_0 \) and \( \beta \) (see Fig. 3). For the given magnetic field-line inclination \( \kappa_0 \), the cold gas can be driven from the disc surface only if the field strength is lower than a certain value (see equation 16). This is because a higher \( \beta \) leads to a lower angular velocity \( \Omega \) for a fixed value of \( \kappa_0 \). It is found that the launch of the cold outflow is suppressed if the magnetic field is too strong, which is because of the decrease of \( \Omega \) with increasing \( \beta \). A relatively thick disc, the upper limit on the field strength could be high because the cold flow can be launched from the disc surface with a relatively low \( \Omega \), with the help of the radiation force. This implies that a stricter constraint on the maximal jet power can be extracted from a radiation-pressure-dominated accretion disc than that derived conventionally on the equipartition assumption.

In Fig. 3, we also plot the results when we do not consider the effect of the radiation pressure exerted by the accretion disc (i.e. the radiation pressure term is left out in the effective potential), in order to explore the role of the radiation pressure in launching the outflow. It is found that the cold gas can be launched from the disc surface only if \( \kappa_0 \) is small (i.e. the angle of the field line inclined with respect to the disc surface is small, if the radiation pressure term is not included). This implies that the role of the radiation pressure in launching an outflow is important, even for thin accretion discs. The analyses in this work are carried out with the assumption of a radiation-pressure-dominated accretion disc, which is justified in the inner region of the accretion disc if the accretion rate is not very low (e.g. Laor & Netzer 1989). The calculations are done only for the cold gas driven from the disc surface, because the outflow can be efficiently driven from the place near the disc surface where the magnetic force is dominant over the gas pressure. The structure of the disc in the presence of a magnetic field is complicated, which should be considered by solving the differential equations governing the vertical structure of the disc and its magnetic field consistently. Such calculations, which have been done without considering the effect of the radiation force, have already been given previously (Ogilvie & Livio 1998, 2001). Similar investigations that incorporate the effect of the radiation force are beyond the scope of this paper, but they will be reported in our future work.

In most MHD simulations, the accretion flows have a relatively large thickness, and the gas is launched from the magnetic-pressure-dominated region near the disc surface (e.g. Koide, Shibata & Kudoh 1999; De Villiers & Hawley 2003; Moscibrodzka & Proga 2009; McKinney, Tchekhovskoy & Blandford 2012). Their rotational velocities deviate from the Keplerian value mainly because of the magnetic force and gas pressure gradient in the radial direction (e.g. Hawley 2000; Proga & Begelman 2003). Our present analysis of the gas launched from the disc surface describes a situation more akin to the numerical simulations than the scenario in Blandford & Payne (1982), which is valid only for gas launched from the mid-plane of a Keplerian disc. The radiation of the accretion flows is calculated in some previous works based on the structure given by MHD simulations, which are used to explain the observations (e.g. Moscibrodzka et al. 2007; Moscibrodzka et al. 2009). However, the radiation from the accretion flows has not been considered in these MHD simulations. The role of the radiation pressure on the magnetic outflows has been explored in a few MHD simulations (Proga 2000, 2003), but it is limited to the case of the Keplerian disc. Recent radiation-MHD simulations on the accretion discs and outflows around black holes have shown that the radiation force helps to launch outflows from luminous accretion discs (Takeuchi et al. 2010; Ohsuga & Mineshige 2011), which is qualitatively consistent with our analytical results.

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