Hydrodynamical winds from two-temperature plasma in X-ray binaries

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ABSTRACT

Hydrodynamical winds from a spherical two-temperature plasma surrounding a compact object are constructed. The mass-loss rate is computed as a function of electron temperature, optical depth and luminosity of the sphere, the values of which can be constrained by the fitting of the spectral energy distributions for known X-ray binary systems. The sensitive dependence of the mass loss rate with these parameters leads to the identification of two distinct regions in the parameter space separating wind-dominated from non wind dominated systems. A critical optical depth ($\tau_c$), as a function of luminosity and electron temperature, is defined which differentiates these two regions. Systems with optical depths significantly smaller than $\tau_c$ are wind-dominated.

The results are applied to black hole candidate X-ray binary systems in the hard spectral state (Cyg X-1, GX 339-4 and Nova Muscae), and it is found that the inferred optical depth ($\tau$) is similar to $\tau_c$ suggesting that they are wind regulated systems. On the other hand, for X-ray binary systems containing a neutron star (e.g., Cyg X-2) $\tau$ is much larger than $\tau_c$ indicating the absence of significant hydrodynamical winds.

Key words: binaries: accretion, accretion-discs - black hole physics - hydrodynamics

1 INTRODUCTION

X-ray binary systems containing a black hole candidate are typically found to be in two different spectral states. In the hard state, the broad band X-ray spectrum can be described as a power-law (photon spectra index $\approx 1.5$) with a high energy cutoff around 100 keV. In the soft state, the spectrum consists of two components. There is usually an extended power-law (with spectral index $\approx 2.5$) and a soft X-ray emission which has a spectral shape similar to that of a black body. For a recent review of the observations and phenomenological description of these sources see Tanaka & Shibazaki (1996).

The modeling of the hard state spectra can be described in terms of an unsaturated Comptonization process of soft photons in a region with hot electrons ($kT \approx 50$ keV) and electron scattering optical depths of order unity. In a pioneering study, Shapiro, Lightman & Eardley (1976) identified this hot region with a geometrically thick, optically thin, hot accretion disc. In this model, the gravitational energy dissipated in the disc, heats the ions which in turn transfer the energy to electrons by Coulomb interactions. However, the electron-ion Coulomb interaction rate is inefficient in such an environment of low density.
and high electron temperature, and this leads to a large difference in temperature between the electrons and ions, with the ion temperature reaching nearly virial values ($10^{11}$K). The importance of radial advection of energy in such a disc was noted by Ichimaru (1977). Taking advection into account Narayan & Yi (1994) constructed self-similar solutions for the disc equations called Advection Dominated Accreting Flows (ADAF) showing not only that the proton temperatures approach their virial values, but also that the radiative efficiency of accretion can be significantly reduced as a result of the advection of energy into the black hole. In an alternative description Chakrabarti & Titarchuk (1995) argued that under certain conditions a shock may arise in such accretion discs and identified the hot Comptonizing region with the post-shock flow. Despite the differences in the geometry, radiative processes and the detailed disc structure, both these models have in common the presence of a two-temperature plasma.

Such a plasma is a natural outcome of any accretion disc model which (a) identifies the hard state X-ray spectrum as a result of the unsaturated Comptonization process of soft photons, (b) assumes that the viscous energy dissipated heats the ions and (c) that the only mechanism for energy transfer between the ions and electrons is Coulomb interaction. We note here that these assumptions may not be valid since the viscous energy dissipated may heat the electrons preferentially if a strong equipartition magnetic field is present in the disc (Bisnovatyi-Kogan & Lovelace 2000). In addition, there could be unknown mechanisms which transfer energy between ions and electrons more efficiently than the Coulomb interaction. Thus, it will be useful to have an independent observational signature which could confirm the existence of two-temperature plasmas in black hole candidate systems.

The nearly virial proton temperature of this plasma suggests the possibility of a strong hydrodynamical wind arising from these systems (e.g., Piran 1977; Takahara, Rosner & Kusunose 1989; Kusonose 1991). Such an outflow could transport away a significant fraction of mass, energy and/or angular momentum, thereby affecting the structure and stability of the disc and affecting the radiative efficiency of accretion for a given mass transfer rate. Chakrabarti (1999) and Das (1999) have studied the possibility of outflows in the context of the shock/centrifugal barrier models. They find that for certain values of the disc parameters (e.g., accretion rate and specific entropy) a hydrodynamical wind occurs. For the ADAF disc solutions, Blandford & Begelman (1999) argued that only a small fraction (< 1%) of the gas actually falls into the black hole and the rest is driven away as a wind (in an advection dominated inflow-outflow solution - ADIOS), thereby effectively reducing the radiative efficiency. Beckert (2000) confirmed this result for different viscosity laws while Quataert & Narayan (1999) showed that the X-ray spectra from such a wind driven accretion process can explain the observed spectra of some black hole candidate systems in quiescence. These calculations were undertaken for low mass accretion rates, and it is not clear how the system will behave in the high accretion rate regime inferred for black hole candidate systems in the hard state.

The formation of hydrodynamical winds from accretion discs depends on the structure and geometry of the discs. Thus, detailed calculations of the outflow are intrinsically model dependent. Further, reliable calculations of the structure of such discs are difficult because uncertainties exist in the vertical distribution of energy dissipation in the disc associated with our lack of detailed understanding of the viscosity. We note that internal magnetic fields in the disc could also facilitate (or inhibit) the formation of winds. Here, electromagnetic forces may accelerate and collimate the wind to form high velocity jets as observed in microquasar systems (Mirabel & Rodriguez 1999). Considering these uncertainties a prudent approach would be to estimate the wind characteristics using only those parameters which can be directly constrained by the fitting of spectral energy distributions. Such an analysis
would allow a rough estimation of the magnitude of the mass and energy lost in the form of a wind for a system in question. With such an objective in mind, we report in this paper on calculations of the structure of an hydrodynamical wind similar to those found by Takahara et al (1989), but in the context of a uniform spherical two-temperature plasma around an accreting black hole. Rather than treating the entire disc/wind configuration with detailed heating and cooling processes as in Kusunose (1991) the calculations are parameterized in terms of the electron temperature of the cloud, $T_e$, the optical depth, $\tau$, and the total luminosity of the source. We adopt this approach as these parameters are constrained by spectral fitting analyses. In the next section, the formulation of the problem and the numerical results are presented. The application of these results to observed systems is given in §3 and discussed in the last section.

2 HYDRODYNAMICAL WINDS

The mass loss rate due to a hydrodynamical wind depends sensitively on the ion temperature. This allows a system to be defined as wind-dominated if the ion temperature is greater than some critical value ($T_c$), while for temperature less than this value the mass and energy loss rate is small enough not to affect the dynamics of the system. This critical temperature will scale as the virial one i.e. $kT_c \propto GM/R$ where $R$ is the size of the region and $M$ is the mass of the black hole. For a two-temperature plasma the power output is mediated by electron-proton Coulomb interactions and the luminosity, $L$, is given by

$$L/V = \frac{3}{2} n(kT_i - kT_e)\nu_{ep}$$

(1)

where $V = 4/3\pi R^3$ is the volume of the sphere, $n$ is the average number density, $T_i$ and $T_e$ are the ion and electron temperatures, and $\nu_{ep}$ is the frequency of the electron-ion Coulomb interaction. A critical optical depth $\tau_c(= n\sigma_T R)$ may be defined for the system, wherein for systems with $\tau < \tau_c$, the ion temperature is larger than $T_c$ (see below). Taking the above relationships into account with the Coulomb exchange rate given as (Spitzer 1962)

$$\nu_{ep} = 2.4 \times 10^{21} \ln\Lambda \rho T_e^{-3/2}$$

(2)

where $\ln\Lambda(\approx 15)$ is the Coulomb logarithm and $\rho$ is the mass density, it follows that

$$\tau_c \propto L^{1/2} T_e^{3/4} M^{-1/2}$$

(3)

Since $L$ and $T_e$ are parameters which can be constrained by spectral fitting, $\tau_c$ can be directly estimated for a black hole of a given mass. Spectral fitting can also give information about the optical depth of the system, which can then be compared with $\tau_c$, to determine whether the system could be wind-dominated or not. The above analysis shows that $\tau_c$ does not depend on the size of the system $R$. This is fortunate since $R$ is not well constrained by observations.

To quantify the above analysis we solve for the hydrodynamical wind structure from a spherical two-temperature plasma with an optical depth ($\tau$), electron temperature $T_e$ and luminosity $L$. The central mass is taken to $M = 10M_\odot$ and the radius of the sphere is fixed at $R = 20GM/c^2$. We use the basic equations of the hydrodynamical theory of stellar winds (Parker 1958) which are the conservation of radial momentum,

$$\rho v \frac{dv}{dr} = -\frac{dP}{dr} - \rho \frac{GM}{r^2}$$

(4)

and the conservation of mass, i.e. the mass outflow

$$\dot{M}_o = \rho v 4\pi r^2 = \text{constant}. $$

(5)
Here $v$ is the radial velocity, $P = K \rho^\Gamma$ is the pressure and $\Gamma$ is the adiabatic index. These equations can be combined to give,

$$\frac{dv}{dr} = \left[ \frac{2c_s^2 - \frac{GM}{r^2}}{v - c_s^2} \right]$$

where $c_s = (dP/d\rho)^{1/2}$ is the sound speed. At the sonic point, both the numerator and denominator vanish. Wind solutions were constructed by integrating from the sonic point. The inner boundary is taken at $R$ where $\frac{c_s}{v}$ the flow is supersonic at the surface i.e. the sonic point is actually located at a radius less than $R$. Here $v$ is the radial velocity, $P = K \rho^\Gamma$ is the pressure and $\Gamma$ is the adiabatic index. Thus we restrict this analysis only to those values of $\Gamma$ such that $kT_i < kT_{min} \approx (\frac{\Gamma+1}{\Gamma})GMm_p/R$. For high values of $kT_i > kT_{max} \approx (\frac{\Gamma+1}{\Gamma})GMm_p/R$, the flow is supersonic at the surface i.e. the sonic point is actually located at a radius less than $R$. Thus this analysis is restricted to values of $\Gamma < 5/3$. Such regimes have also been studied by Chakrabarti (1999) and for example, in the limit of efficient conduction of heat an isothermal wind flow results corresponding to $\Gamma \approx 1$. Radiative processes can also lead to redistribution of energy in the wind leading to $\Gamma < 5/3$ (Chakrabarti 1999).

In Figure 1, the calculated mass loss rate as a function of ion temperature is illustrated for a fixed optical depth ($\tau = 1$). The virial temperature $T_v \equiv GMm_p/kR$ for the sphere is $\approx 5 \times 10^{11}$ K. As expected, $\dot{M}_o$ is sensitive to the ion temperature: a factor of two increase in $T_i$ causes an increase of $\dot{M}_o$ by two orders of magnitude. This justifies defining a critical temperature beyond which the system is wind-dominated and below which it is not. For comparison, we note that the ion temperatures in ADAF type solutions correspond to $T_i \sim T_v$, in which the presence of winds are lowered (Misra & Taam 2000). The mass loss rate can be expressed in terms of luminosity, optical depth, and electron temperature. For a typical luminosity ($L = 10^{38}$ ergs/s) and electron temperature ($T_e = 50$ keV), the variation of mass loss rate with optical depth is shown in Figure 2. Here, the sensitivity of $\dot{M}_o$ with $\tau$ is apparent: a factor of two increase in $\tau$ decreases $\dot{M}_o$ by at least three orders of magnitude. We show the contour plots of $\dot{M}_o$ for the $\tau$, $T_e$ and $\tau$, $L$ planes in Figures 3 and 4 respectively. These plots highlight the steep variation of $\dot{M}_o$ with all three parameters.

The $\tau$, $T_e$ and $L$ parameter space can then be divided into two regions corresponding to high and low values of $\dot{M}_o$. In particular we define the wind dominated region as corresponding to $\dot{M}_o > \dot{M}_{crit}$ and the complementary region as the non wind dominated one. The choice of $\dot{M}_{crit}$ is ad-hoc and is chosen to be $10^{18}$ g/s. Since the dependence of $\dot{M}_o$ on the parameters is steep, choosing $\dot{M}_{crit}$ to be $10^{17}$ g/s still leads to a division of the parameters space to nearly similar regions. A critical optical depth $\tau_c$ can be defined as a function of $L$ and $T_e$ for which $\dot{M}_o = 10^{18}$ g/s. The topology of Figures 3 and 4 and the qualitative analysis described in the beginning of the section (eqn 3) suggests that $\tau_c$ can be represented as:

$$\tau_c = A(\frac{kT_e}{50 \text{ keV}})^{\alpha}(\frac{L}{10^{38} \text{ ergs/s}})^{\beta}$$

We constrain $A$, $\alpha$ and $\beta$ for different values of $\dot{M}_{crit}$, $\Gamma$, $M$, and $R$ and present the result in Table 1.

From these results it can be seen that $A$, $\alpha$ and $\beta$ do not vary greatly with changes in $\dot{M}_{crit}$, $\Gamma$, $M$ or $R$. Thus to within a factor of two, the critical optical depth can be represented as
Table 1. Values of $A$, $\beta$ and $\alpha$ in equation (7). Here $\dot{M}_o$ is in units of g/s and $R$ is in units of $r_s = 2GM/c^2$.

| log $\dot{M}_{crit}$ | $\Gamma$ | $M(M_\odot)$ | $R(r_s)$ | $A$ | $\alpha$ | $\beta$ |
|----------------------|---------|--------------|---------|-----|---------|---------|
| 18                   | 1.05    | 10           | 10      | 1.9 | 0.90    | 0.60    |
| 17                   | 1.05    | 10           | 10      | 2.5 | 0.84    | 0.56    |
| 18                   | 1.2     | 10           | 10      | 1.7 | 0.85    | 0.56    |
| 18                   | 1.05    | 30           | 10      | 1.3 | 0.86    | 0.57    |
| 18                   | 1.05    | 10           | 100     | 3.7 | 0.90    | 0.58    |

$$\tau_c = 2\left(\frac{kT_e}{50 \text{ keV}}\right)^{0.85}\left(\frac{L}{10^{38} \text{ ergs/s}}\right)^{0.55}$$

(8)

We can now use equation (8) to determine from observations if a particular system is wind dominated or not.

3 APPLICATION TO X-RAY BINARIES

Assuming that a two-temperature plasma configuration is established subject to the conditions described in §2, we discuss the possible applications of hydrodynamical winds to binary systems containing compact objects. In the following we first discuss the results for the black hole candidate systems Cyg X-1, GX339-4, and Nova Muscae. For convenience, the results are summarized in Table 2.

The hard state spectrum of Cyg X-1 has been fitted by Gierlinski et al. (1997) with a Comptonization model, and they obtained the following parameters: $\tau \approx 1, kT_e \approx 140$ keV and $L = 3.5 \times 10^{37}$ ergs/s (for a distance of 2.5 kpc). Using these values we find from equation (8) for a black hole of $10M_\odot$ that $\tau_c = 2.6$ which is on the order of the observed $\tau \approx 1$. Similarly for another black hole system, GX 339-4 in the low state, Zdziarski (1998) obtained $\tau = 1.93, kT_e = 48$ keV and $L = 3 \times 10^{37}$ ergs/s. For these values $\tau_c = 3.6$ which is again of the order of the observed $\tau$. Thus, our analysis of both Cygnus X-1 and GX 339-4 in their hard states indicates that these systems are on the borderline of having a strong or weak wind. This may point to the existence of a feedback mechanism wherein the energy and mass loss from the wind regulate the hot disc structure.

Unlike the persistent systems discussed above, black hole X-ray novae are transients. In these sources, the luminosity increases by several orders of magnitude in $\approx 10$ days and then decays exponentially in a time-scale of $\approx 1$ month. During the peak of the outburst the system is usually in the soft spectral state and makes a transition to the hard state in $\approx 2-3$ months (see Tanaka & Shibazaki 1996). Observations of the X-ray transient source Nova Muscae (GS 1124-68) by the Ginga satellite through most of its evolution were reported in Ebisawa et al. (1994). Since the Ginga energy band is restricted to $< 20$ keV, the roll-over of the spectrum at high energies was not observed. Thus, a Comptonization fit does not constrain both $T_e$ and $\tau$. In particular only a low energy spectral index ($\alpha_s$) (during different times of the evolution) was measured. For a Comptonized spectrum, $\alpha_s$ is approximately related to $T_e$ and $\tau$ by,

$$- (3 + \alpha_s) = -\frac{3}{2} \pm \sqrt{\frac{9}{4} + \frac{4}{y}}$$

(9)

where, $y = (4kT_e/m_e c^2) \max(\tau, \tau^2)$ is the Compton y-parameter. For Nova Muscae in the hard state, $\alpha_s$ was observed to $\approx 0.5$ and at a luminosity, $L = 4.3 \times 10^{36}$ ergs/s (Ebisawa et al. 1994). If we now assume that $T_e \approx 100$ keV one obtains from equation (9), $\tau \approx 1.7$. The
Table 2. Comparison of inferred and critical optical depth for various X-ray binaries. The luminosity, electron temperature ($T_e$) and optical depth ($\tau$) have been quoted from the references. The symbols WD, WR and NW stand for wind dominated, wind regulated and no wind respectively. For GS 1124-68 (Nova Muscae) and Cygnus X-1 (soft state) the electron temperature is assumed and the optical depth has been estimated using equation (9). Note that for the soft state, the assumptions used in this analysis may not be valid (see text).

| Source Name   | Luminosity (ergs/s) | $kT_e$ (keV) | $\tau$ | $\tau_c$ | Comment | ref. |
|---------------|---------------------|-------------|--------|----------|---------|-----|
| **Black Holes** |                     |             |        |          |         |     |
|               |                     |             |        |          |         |     |
| Hard State    |                     |             |        |          |         |     |
| Cygnus X-1   | $3.5 \times 10^{37}$ | 140         | 1      | 2.6      | WR      | 1   |
| GX 339-4     | $3 \times 10^{37}$  | 48          | 1.9    | 3.6      | WR      | 2   |
| GS 1124-68   | $4.3 \times 10^{36}$ | 100         | 1.7    | 0.6      | NW      | 3   |
| GS 1124-68   | $4.3 \times 10^{36}$ | 200         | 1.2    | 1.1      | WR      | 3   |
|               |                     |             |        |          |         |     |
| Soft State   |                     |             |        |          |         |     |
| Cygnus X-1   | $2.9 \times 10^{37}$ | 200         | 0.40   | 3.3      | WD      | 4   |
| GS 1124-68   | $2.5 \times 10^{37}$ | 200         | 0.37   | 3.0      | WD      | 3   |
|               |                     |             |        |          |         |     |
| **Neutron Stars** |                   |             |        |          |         |     |
|               |                     |             |        |          |         |     |
| Low luminosity |                     |             |        |          |         |     |
| XB 1608-52   | $4.1 \times 10^{36}$ | 7           | 7.6    | 0.13     | NW      | 5   |
| XB 1636-536  | $2.7 \times 10^{37}$ | 1.8         | 16.7   | 0.12     | NW      | 5   |
| XB 0748-676  | $3.7 \times 10^{36}$ | 2.4         | 24.1   | 0.04     | NW      | 5   |
| XB 1254-69   | $7.8 \times 10^{36}$ | 1.9         | 15.6   | 0.06     | NW      | 5   |
| XB 1820-30   | $1.4 \times 10^{37}$ | 3.5         | 13.2   | 0.15     | NW      | 5   |
|               |                     |             |        |          |         |     |
| High luminosity |                     |             |        |          |         |     |
| XB 1820-30   | $4.7 \times 10^{38}$ | 3.3         | 11.9   | 1.2      | NW      | 5   |
| Cyg X-2      | $1 \times 10^{38}$  | 3.7         | 9.4    | 0.5      | NW      | 5   |
| GX 17+2      | $2.5 \times 10^{38}$ | 3           | 13     | 0.8      | NW      | 5   |
| GX 9+1       | $1.7 \times 10^{38}$ | 3           | 11     | 0.6      | NW      | 5   |
| GX 349+2     | $2.2 \times 10^{38}$ | 3.7         | 10     | 0.9      | NW      | 5   |

References: 1: Gierlinski et al. (1997), 2: Zdziarski et al. (1998), 3: Ebisawa et al. (1994), 4: Gierlinski et al. (1999), 5: White, Stella & Parmar (1988).

Critical optical depth for such a system is then $\tau_c = 0.6$ which is less than the inferred $\tau$, indicating the absence of a strong wind. However, a strong wind is indicated if one assumes $kT_e \approx 200$ keV instead, since the inferred $\tau \approx 1.2$ which is close to the critical value of $\tau_c = 1.1$. Thus, hydrodynamical winds can be important in the hard state of Nova Muscae provided that the electron temperatures are $\gtrsim 150$ keV.

In the soft state of black hole candidate systems the power-law spectrum is steeper than the hard state. Gierlinski et al. (1997) analyzed the soft state Cygnus X-1 data and found that the energy spectral index $\alpha_s \approx 1.5$ and the power-law extends up to $\approx 200$ keV with no apparent cutoff. They argued that thermal Comptonization does not describe the spectra well. Instead, the power-law is probably due to non-thermal Comptonization. In this case, the presence of non-thermal electrons indicates that the electrons are probably heated directly instead of mediated by processes involving protons. Thus, the basic assumption underlying this study is probably not valid for the soft spectral state of Cygnus X-1. Nevertheless, from the observed $\alpha_s = 1.4$, $L = 3 \times 10^{37}$ ergs/s and assuming that $kT_e \approx 200$ keV, one would infer using equation (9) that $\tau \approx 0.4$. This is much smaller than the critical value of $\tau_c = 3.3$, perhaps indicating the presence of a strong wind. A similar result is obtained from the soft state of Nova Muscae (Table 2).

In addition to black hole candidates, the spectra from X-ray binary systems containing a neutron star can also be described as being due to Comptonization. Hot two temperature
accretion flows around neutron stars have been recently constructed by Medvedev & Narayan (2000). On the other hand, the hot region may not be the accretion disc itself but could be instead an extended corona surrounding the boundary layer between the disc and the surface of the star. This analysis can be still applied to these systems as long as the assumption that the total luminosity of the source is channeled by the protons to the electrons remains valid. The critical optical depth when $M = 1.4\, M_\odot$ and $R = 10\, \text{kms}$ is found to be

$$
\tau_c = 6\left(\frac{kT_e}{50\, \text{keV}}\right)^{0.95} \left(\frac{L}{10^{38}\, \text{ergs/s}}\right)^{0.62}
$$

Spectral fitting of EXOSAT data from several neutron star binaries has been undertaken by White, Stella & Parmar (1988) which are summarized in Table 2. For Cygnus X-2, they constrain $kT_e \approx 3.7\, \text{keV}$, $\tau = 9.4$ and $L = 10^{38}\, \text{ergs/s}$ (for a distance of 8 kpc). Using equation (10) we find that $\tau_c = 0.5$ which is significantly less than the observed value. Similar results were obtained for other neutron star systems in both the high and low luminosity levels (Table 2). This implies that unlike black hole candidate X-ray binary systems, their neutron star counterparts are not dominated by a hydrodynamic wind. This result is further supported by the analysis undertaken by Medvedev & Narayan (2000) who constructed self-similar accretion flows onto neutron stars and found that hydrodynamic winds are not important in these systems.

4 SUMMARY AND DISCUSSION

The possible occurrence of hydrodynamical winds in X-ray binary systems has been investigated. From simple considerations, the conditions under which these winds can be important have been identified. It is found that the mass loss rate in such winds depends sensitively on the luminosity of the source as well as the electron temperature and optical depth of the coronal region. The steep dependence of the mass loss rate on these parameters facilitates the use of a critical optical depth to indicate whether a given system can support such a wind. Application of the theory indicates that winds can exist in the hard state of the black hole candidates Cyg X-1, GX 339-4 and GS 1124-68.

Strong winds in these systems may decrease the radiative efficiency ($\eta = L/\dot{M}_i c^2$, where $\dot{M}_i$ is the mass inflow rate) by carrying away a substantial amount of matter and energy. For Nova Muscae, the radiative efficiency has been estimated to be $\eta = 0.01$ for the soft state and $\eta = 0.05$ for the hard state (Misra 1999). These values are lower than that expected from an Keplerian disc ($\eta \approx 0.1$) which could be due to the presence of a strong wind rather than energy advection into the black hole. Winds may also effect the thermal stability of accretion discs by introducing an additional channel for energy loss (e.g., Piran 1977).

We reiterate that the analysis undertaken in this paper is based on the assumption that the gravitational energy dissipated in the system is transferred to the electrons by the ions via Coulomb interactions. This naturally restricts the analysis to only certain systems where this is valid. As mentioned earlier, the soft state spectrum of black hole candidate systems is probably of a non-thermal origin and, hence, the analysis performed in this study cannot be applied. Even for the hard spectral states of compact X-ray binaries considered here, alternate models to a two-temperature plasma description have been proposed. For example, the X-ray spectra could be due to magnetic flare activity above a cold disc (Poutanen & Fabian 1999) or produced by a disc with a rapidly varying radial temperature profile (Misra, Chitnis & Melia 1998). Thus, it should be emphasized that the results presented here are specifically discussed within the framework of a two-temperature plasma model.

The spherical geometry assumed here is simplistic even though two-temperature discs
are geometrically thick. Further the effect of angular momentum or of convection on the dynamics of accretion and the wind outflow have not been taken into account. The former effect can increase the mass outflow rate as a result of centrifugal support, whereas the latter effect can affect the thermal structure of the underlying disk and, hence, the existence of a wind. In this context, the thermal structure is dependent on the direction in which angular momentum is radially transported by convection and the magnitude of the viscosity parameter (see Narayan, Igumenshchev, & Abramowicz 2000). A more detailed analysis should take these effects and radiative heating/cooling of the wind into account in at least two spatial dimensions (e.g., Chakrabarti & Molteni 1993). However, such analyses will, by necessity, be model dependent and limited by the uncertainties in the vertical structure and geometry of the hot disc.

The hydrodynamical winds described in this paper may be confined to form a jet-like structure by the geometry of the disc and magnetic fields. Further if they are accelerated to relativistic speeds by electromagnetic forces, they may provide the origin of the radio jets observed in the black hole candidate systems known as microquasars (Mirabel & Rodriguez 1998). On the other hand, the radio jets may be a different phenomenon unrelated to hydrodynamical winds. In that case it is desirable to have direct observational signatures of these outflows. Since the Thomson optical depth of the winds calculated here (i.e. the optical depth from the surface of the sphere $R$ to infinity) is typically $< 0.1$, column densities of the order of $10^{23}$ cm$^{-2}$ are indicated. Although the X-ray continuum spectra are not expected to be altered by the outflow, a significant fraction of the column density may not be highly ionised giving rise to observable absorption and/or emission lines. The detection of P-Cygni type profiles by high resolution X-ray satellites Chandra and Newton-XMM may provide evidence for the existence of such winds and serve as a useful diagnostic not only of the wind structure, but also the physics underlying the disc as well.

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REFERENCES

Beckert, T., 2000, ApJ, 539, 223.
Bisnovatyi-Kogan, G.S. & Lovelace, R.V.E., 2000, ApJ, 529, 978.
Blandford, R. D., & Begelman, M. C. 1999, MNRAS, 303, L1
Chakrabarti, S.K., 1999, A&A, 351, 185.
Chakrabarti, S. K. & Molteni, D., 1993, ApJ, 417, 671.
Chakrabarti, S. & Titarchuk, L.G., 1995, ApJ, 455, 623.
Das, T.K., 1999, MNRAS, 308, 201.
Ebisawa, K., et al., 1994, PASJ, 46, 375.
Gierlinski, M. et al., 1997, MNRAS, 288, 958.
Gierlinski, M. et al., 1999, MNRAS, 309, 496.
Ichimaru, S. 1977, ApJ, 214, 840
Kusunose, M., 1991, ApJ, 370, 505.
Medvedev, M.V. & Narayan, R., 2000, submitted to ApJ, (astro-ph:0007064)
Mirabel, I.F. & Rodriguez, L.F., 1998, Nat., 392, 673.
Mirabel, I.F. & Rodriguez, L.F., 1999, ARAA, 37, 409.
Misra, R., Chitnis, V.R. & Melia,F., 1998, ApJ, 495, 407.
Misra, R., 1999, ApJ, 512, 340.
Misra, R., & Taam, R. E. 2000, in preparation
Narayan, R., & Yi, I. 1994, ApJ, 428, L13.
Narayan, R., Igumenshchev, I. V., & Abramowicz, M. A. 2000, ApJ, 539, 798.
Parker, E.N., 1958, ApJ, 128, 664.
Piran, T., 1977, MNRAS, 180, 45.
Poutanen, J. & Fabian, A.C., 1999, MNRAS, 306, L31.
Quataert, E. & Narayan, R., 1999, ApJ, 520, 298.
Shapiro, S.L., Lightman, A.P. & Eardley, D.M., 1976, ApJ, 204, 187.
Spitzer, L. Jr., 1962, Physics of Fully Ionized Gases (New York: Wiley).

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Takahara, F., Rosner, R. & Kusunose, M. 1989, ApJ, 346 122.
Tanaka, Y. & Shibazaki, N. 1996, ARAA, 34, 607.
White, N. E., Stella, L., & Parmar, A.N., 1988, ApJ, 324, 363.
Zdziarski, A. A., et al., 1998, MNRAS, 301, 435.
Figure 1. The variation of the mass outflow rate with ion temperature for adiabatic indices $\Gamma = 1.01$ (nearly isothermal) and $\Gamma = 1.2$. The other parameters are: $M = 10M_\odot$, $R = 20GM/c^2$ and $\tau = n\sigma T R = 1$. 
Figure 2. The variation of the mass outflow rate with optical depth for adiabatic indices $\Gamma = 1.01$ (nearly isothermal) and $\Gamma = 1.2$. The other parameters are: $M = 10M_\odot$, $R = 20GM/c^2$, $kT_e = 50$ keV and $L = 10^{38}$ ergs/s
Figure 3. Contours of mass outflow rate ($\dot{M}_o$) for luminosity and optical depth. The contours correspond to from top to bottom $\dot{M}_o = 3 \times 10^{18}, 10^{18}, 3 \times 10^{17}, 10^{17}, 3 \times 10^{16}, 10^{16}$ g/s. The other parameters are: $M = 10M_\odot$, $R = 20GM/c^2$, $\Gamma = 1.01$, $kT_e = 50$ keV.
Figure 4. Same as in Figure 3, except that the contours are for electron temperature and optical depth for a luminosity of $L = 10^{38}$ ergs/s.