TESTING WIND AS AN EXPLANATION FOR THE SPIN PROBLEM IN THE CONTINUUM-FITTING METHOD

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ABSTRACT

The continuum-fitting method is one of the two most advanced methods of determining the black hole spin in accreting X-ray binary systems. There are, however, still some unresolved issues with the underlying disk models. One of these issues manifests as an apparent decrease in spin for increasing source luminosity. Here, we perform a few simple tests to establish whether outflows from the disk close to the inner radius can address this problem. We employ four different parametric models to describe the wind and compare these to the apparent decrease in spin with luminosity measured in the sources LMC X-3 and GRS 1915+105. Wind models in which parameters do not explicitly depend on the accretion rate cannot reproduce the spin measurements. Models with mass accretion rate dependent outflows, however, have spectra that emulate the observed ones. The assumption of a wind thus effectively removes the artifact of spin decrease. This solution is not unique; the same conclusion can be obtained using a truncated inner disk model. To distinguish among the valid models, we will need high-resolution X-ray data and a realistic description of the Comptonization in the wind.

Key words: accretion, accretion disks – black hole physics – X-rays: binaries

1. INTRODUCTION

The determination of black hole spin is one of the most intriguing issues in astrophysics. Knowledge of the spin sheds light on the evolution of X-ray binary systems. There are, however, still some unresolved issues with the underlying disk models. One of these issues manifests as an apparent decrease in spin for increasing source luminosity. Despite the overall success of the continuum-fitting method, one fundamental problem remains unsolved, namely, the apparent dependence of the spin on the source luminosity. During an outburst, XRBs go through a high/soft state where their spectra are dominated by emission that peaks at soft X-ray energies. This peak can be modeled by a multi-color blackbody disk. Thermal spectra with a disk flux contribution above $\geq 75\%$ to the total flux are suitable for the analysis (Remillard & McClintock 2006). The continuum-fitting method compares the observed shape of the thermal continuum spectrum to an accretion disk model spectrum. The sequence of such thermal state spectra has been modeled, e.g., for GRS 1915+105 (McClintock et al. 2006). There, the fits resulted in a black hole spin that significantly decreased with the modeled disk luminosity above $L \gtrsim 0.3 L_{\text{Edd}}$, where $L_{\text{Edd}} = 1.26 \times 10^{38} (M/M_\odot) \text{ erg s}^{-1}$. A plausible explanation is that the assumptions underlying the disk model in McClintock et al. (2006) break down at higher Eddington ratios. The standard accretion model describes an optically thick and geometrically razor thin ($H/R \ll 1$) gas disk that reaches all the way down to the innermost stable circular orbit (ISCO) and efficiently emits at each annulus (Novikov & Thorne 1973; Shakura & Sunyaev 1973). The standard disk is unable to cool efficiently with an increasing mass accretion rate. As the disk overheats, it expands vertically to scale heights that are no longer consistent with the initial assumptions and a significant fraction of energy is advected inward. The disk structure is then better described by the slim disk model (Abramowicz et al. 1988; Sadowski et al. 2011), which has a radiative efficiency that decreases with increasing mass accretion rate. The corresponding analysis has been performed, e.g., for LMC X-3 (Straub et al. 2011). The
is usually incorporated in accretion disk spectral models via the decrease in the spin. The luminosity for the advective slim disk.

The second reason is mass loss due to winds and possible disk models with wind. Section 4 shows the estimated black hole spin, however, still also decreases with luminosity for the advective slim disk.

There are two reasons that could explain this apparent decrease in the spin. The first one reason is the description of the disk atmosphere. Radiative transfer in the disk atmosphere is usually incorporated in accretion disk spectral models via the TLUSTY code (Hubeny & Lanz 1995), which locally computes the absorption opacities of various chemical elements in plane-parallel layers. In the X-ray spectral fitting software XSPEC (Arnaud 1996), a well known and widely used thin disk model with full radiative transfer is hspec (Davis & Hubeny 2006), while slim disks with full radiative transfer are available as slimbh (Sadowski et al. 2011; Straub et al. 2011). However, the physics of the disk atmosphere is very complicated and largely unknown, with magnetic fields, turbulent stress, and dissipation taking place (see, e.g., Blaes et al. 2011; Tao & Blaes 2013). This manifests in the fact that both hspec and slimbh seem to overestimate the amount of photons at the spectral peak (see Figure 4 in Straub et al. 2013).

The second reason is mass loss due to winds/outflows from the disk surface. In general, outflows are thought to become significant when the mass accretion rate through the disk increases, as discussed in a number of papers (King & Pounds 2003; Slone & Netzer 2012; Yuan et al. 2012, 2015; Cao 2014, 2016; Laor & Davis 2014). Outflowing winds have recently been detected in several XRBs and AGNs via blueshifted X-ray absorption lines which are observed in high-resolution spectra, for instance, in GRS 1915+105 (e.g., Neilsen & Lee 2009), GRO J1655–40 (e.g., Miller et al. 2006a; Kallman et al. 2009), IGR J17091–3624 (e.g., King et al. 2012), NGC 3783 (e.g., Kaspi et al. 2002), and PG 1211+143 (e.g., Pounds et al. 2003).

In the present paper, we perform simple estimates to check whether a wind scenario is likely to be responsible for the observed apparent spin decrease over luminosity. Given the fact that spin measurements from both thin and slim disks show the same type of deviation, we use the mathematically simpler standard Novikov & Thorne (1973) model to describe the underlying accretion disk. We then modify the mass accretion rate to incorporate mass loss due to an unspecified wind and calculate the energy spectra of such flows. In Sections 2 and 3, we present an estimate of the energy that is driven away by wind and possible disk models with wind. Section 4 shows the Comptonization of the disk spectrum by the wind. In the extended discussion in Section 6, we test our models against observational data of the two most explored sources: LMC X-3 and GRS 1915+105. We provide our conclusions in Section 7.

2. ANALYTICAL ESTIMATES

The apparent decrease of the black hole spin with increasing source luminosity reported in GRS 1915+105 and LMC X-3 is significant in both cases (McClintock et al. 2006; Steiner et al. 2010; Straub et al. 2011). For this reason, the disk is usually assumed to be reliably optically thick and geometrically thin only for modeled disk luminosities in the range . In the relativistic standard model (Novikov & Thorne 1973), the apparent decline of spin with luminosity can be directly translated into a decreasing accretion efficiency, . We now postulate that (i) this decrement in spin is rooted in the existence of wind and that (ii) the amount of energy driven away by this wind corresponds to the drop in accretion efficiency. The efficiency to convert mass into radiation is given by

\[ \eta = 1 - U_r \left( \frac{r_{\text{ISCO}}}{r_{\text{ISCO}}} \right), \]

where

\[ U_r \left( \frac{r_{\text{ISCO}}}{r_{\text{ISCO}}} \right) = \left( \frac{r_{\text{ISCO}} - 2r_{\text{ISCO}} + ar_{\text{ISCO}}^2}{r_{\text{ISCO}} - 3r_{\text{ISCO}} + 2ar_{\text{ISCO}}^2} \right)^{1/2} \]

is the covariant time component of the four-velocity of the gas. For convenience, we show the theoretical radiation efficiency for a relativistic thin disk in Figure 1. A more realistic modeling of how efficiency depends on spin can be found in Li et al. (2005). Wind then has to carry away the fraction of the total accretion energy

\[ \Delta \eta = \eta_0 - \eta, \]

where \( \eta_0 \) is the asymptotic flow efficiency at low luminosity.

Recent optical data lead to an improvement in the dynamical parameters of LMC X-3 (Orosz et al. 2014). The black hole mass, \( M \approx 6.98 M_\odot \), and the inclination angle, \( i \approx 69.72 \), result in a black hole spin of \( a \approx 0.25 \) (Steiner et al. 2014b). In the framework of our forthcoming Paper II (O. Straub et al. 2016, in preparation), we estimate the black hole spin in LMC X-3 based on the improved parameters using the slim disk model, following the methodology of Straub et al. (2011). For \( L \leq 0.3L_{\text{Edd}} \), we find a mean spin value of \( a = 0.2 \) that trails off to \( a = 0 \) very quickly beyond \( L \approx 0.3L_{\text{Edd}} \), which is consistent with previous work. Given the flat theoretical profile of \( \eta \) at small spins, the new values imply \( \Delta \eta = 6.46 - 5.72 = 0.74\% \).

Recent measurements of the GRS 1915+105 parameters yield a black hole mass of \( M \approx 12.4 M_\odot \), an inclination of \( i \approx 60^\circ \), and a source distance of about 8.6 kpc (Reid et al. 2014). These values entail a spin of \( a \approx 0.95 \) (Fragos & McClintock 2015) which falls off to \( a \approx 0.86 \) (assuming \( \alpha = 0.1 \); O. Straub et al. 2016, in preparation). This translates

\[ \text{Figure 1. Dependences of the theoretical mass to radiation conversion efficiency, } \eta, \text{ of a relativistic standard disk on the black hole spin, } a, \text{ and the inner disk radius, } r_{\text{ISCO}}. \text{ The efficiency that corresponds to the measured spins in GRS 1915+105 and LMC X-3 is highlighted in brown and dark green, respectively.} \]

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\[ \frac{1}{\pi} \approx 0.3183 \]

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to an asymptotic efficiency of $\eta_0 = 19.01\%$ that decreases to $\eta = 13.92\%$, resulting in $\Delta \eta \simeq 5.09\%$.

Throughout the paper, we adopt the above quoted dynamical parameters for LMC X-3 and GRS 1915+105, and the respective mean spin values that we found using the slim disk model.

3. SIMPLE WIND MODELS

In this section, we introduce a simple parametric description of the wind. First, we concentrate on the effect the wind has on the intrinsic shape of the thermal emission from an accretion disk. We describe the wind as a radially dependent quantity that decreases the accretion rate toward the black hole. In the following calculations, we adopt the code by Czerny et al. (2011), which is based on Novikov & Thorne (1973) and neglects self-irradiation of the disk as well as Comptonization in the disk atmosphere. Moreover, we assume that the disk thickness is small, so that the photons are emitted from the equatorial plane (Sadowski 2009). Therefore, the local disk emissivity is independent of any assumptions about the disk’s vertical structure, including viscosity. We assume zero torque at the ISCO.

The wind from the accretion disk surface that is required to cause the apparent change in the measured spin must have the appropriate radial distribution. Since the observed X-ray emission comes predominantly from the innermost tens of gravitational radii, the type of wind that can solve the spin drop problem must be localized there.

There are a number of ways to describe the mass loss due to wind. We define $M_{\text{in}}$ and $M_{\text{out}}$ as the accretion rates at the inner and outer disk radius, $r_{\text{in}}$ and $r_{\text{out}}$ respectively. $M(r)$ and $M_{\text{wind}}(r)$ are the inflow at a given radius, $r$, and total mass loss beyond this radius, respectively. We consider several wind models and calculate their spectra for a range of accretion rates $M_{\text{out}}$ and a fixed spin parameter $a$. Then, we fit the emergent spectra using the relativistic standard model (Novikov & Thorne 1973) without any wind, leaving the accretion rate $M_{\text{out}}$ and spin $a$ as free parameters. This procedure allows us to verify whether the measured spin is lower than the input spin in the disk–wind model as it is in the fits to observational data, i.e., if $a < a$.

We define the Eddington limit on the mass accretion rate as $M_{\text{Edd}} = L_{\text{Edd}} / c^2 = 7.57 \times 10^{17} (M/M_\odot) \text{ g s}^{-1}$, where $\eta = 19.01\%$ (a = 0.95) for GRS 1915+105 and $M_{\text{Edd}} = L_{\text{Edd}} / c^2 = 2.17 \times 10^{18} (M/M_\odot) \text{ g s}^{-1}$, where $\eta = 6.46\%$ (a = 0.2) for LMC X-3. With the above definitions of $M_{\text{Edd}}$, we have $L/L_{\text{Edd}} = M/M_{\text{Edd}}$ assuming that the efficiency is constant. In the following four wind basic models, we assume $M_{\text{out}} = 0.8 M_{\text{Edd}}$ and $r_{\text{out}} = 10^6 r_g$, where $r_g = GM/c^2$. The corresponding inflow and mass-loss profiles as a function of $r$ are shown in Figure 2 for $a = 0.95$, while Figure 3 illustrates the respective spectra.

1. In the first wind model, we simply assume that the radial distribution of the accretion rate has the form of an exponential function,

$$M(r) = M_{\text{out}} \exp \left[ -\frac{A}{(r/r_{\text{in}} - B)} \right] ,$$

where $A$ and $B$ are two free variables satisfying $A \geq 0$ and $0 < B < 1$. If there is no wind, then $M(r) = M_{\text{out}}$, which implies $A = 0$. Figure 2 shows the profile for $A = 1.24$, $B = 0.15$, $r_{\text{in}} = r_{\text{ISCO}}$, and a total mass-loss rate of $M_{\text{out}} = M(r_{\text{out}}) - M(r_{\text{in}}) \simeq 0.76 M_{\text{Edd}}$.

2. In the second model, we assume another simple power-law expression for the mass-loss rate (Laor & Davis 2014)

$$M_{\text{wind}}(r) = M_{\text{out}} (r/r_{\text{in}})^\beta ,$$

which gives the inflow rate

$$M(r) = M_{\text{out}} [1 - (r/r_{\text{in}})^\beta] ,$$

where $\beta < 0$. Figure 2 shows this profile for $\beta = -2.0$, $r_{\text{in}} = r_{\text{ISCO}}$, and the total mass-loss rate $M_{\text{out}} = 0.8 M_{\text{Edd}}$.

3. In the third model, we adopt the description of the wind suggested by Blandford & Payne (1982),

$$\frac{dM_{\text{wind}}(r)}{dr} = \frac{C}{r} .$$

The continuity equation reads

$$M(r) = M_{\text{in}} + \int_{r_{\text{in}}}^{r} dM_{\text{wind}}(r) .$$

Integrating Equation (6) from $r_{\text{out}}$ to $r_{\text{in}}$ and comparing it to Equation (7), we derive the inflow rate at a given radius

$$M(r) = M_{\text{in}} + \frac{M_{\text{out}} - M_{\text{in}}}{\ln(r_{\text{in}}/r_{\text{out}})} \ln(r_{\text{in}}/r_{\text{out}}) ,$$

where $M_{\text{in}}$ is a free parameter (see Figure 2 for $M_{\text{in}} = 0.3 M_{\text{Edd}}$, $r_{\text{in}} = r_{\text{ISCO}}$, and total mass-loss rate $M_{\text{tot}} = 0.5 M_{\text{Edd}}$).

4. Finally, in the fourth model, we release the assumption that the disk extends to the ISCO. Instead, we assume that the disk is truncated at $r_{\text{tr}}$ due to the wind and that the accretion rate is constant at all disk radii. For simplicity, we assume that $r_{\text{tr}}$ depends linearly on the accretion rate

$$r_{\text{tr}} = r_{\text{ISCO}} + r_{\text{ISCO}} + D \cdot \frac{M_{\text{out}}}{M_{\text{Edd}}} + E ,$$

where $r_{\text{ISCO}}$ is in units of $r_g$, $D$ and $E$ are two arbitrary free variables (see Figure 2 for inner truncation at $r_{\text{tr}} = 5 r_g$, and the total mass-loss rate $M_{\text{tot}} = 0.8 M_{\text{Edd}}$). This model may seem particularly unphysical, but it is useful as a parametrization. Its plausible physical interpretation is later discussed in Section 6.

We now try to recreate the measured accretion rate dependency of the black hole spin by fitting disk spectra based on the four wind models above with a standard windless thin disk model (Novikov & Thorne 1973). This part of the analysis does not involve any real spectral data but is based on a comparison of models with and without wind. We use the Fortran ray-tracing code described in Czerny et al. (2011) which includes all of the general relativistic effects. The local emissivity follows the Novikov–Thorne prescription, except the local accretion rate decreases inward with radius in the presence of winds. The disk spectra are parametrized by input mass accretion rate and spin ($M_{\text{out}}$, $a$) for an assumed viewing angle, $i$, plus the parameters of the individual wind model. We calculate the resulting spectra including light bending effects. In the next step, we treat these synthetic spectra as “observed spectra” and apply a maximum likelihood method to fit them (still using Fortran) with the original windless Novikov–Thorne prescription for the local flux. We compare the two models in
the range $\sim 0.1$–100.0 keV. The accretion rate $\dot{M}$ and the spin $a'$ are now the fit parameters. These are plotted in Figures 4 and 5 for GRS 1915+105 and LMC X-3, respectively. In both figures the red dashed line indicates the best linear fit to the bulk of spin measurements obtained from fitting the slim disk model to the actual source spectra. The question is whether the derived sets of $(\dot{M}_{\text{out}}, a')$ from fitting the synthetic spectra follow these reference lines from fits to real spectra. There are no observational errors or instrument sensitivity effects, and so the absolute values of $\chi^2$ are meaningless, but the procedure allows us to find the best match between the models with and without wind.

The radial mass-loss profiles presented in Figure 2 imply that Model (2) shows the steepest dependence on the radius.
However, the inflow rate only significantly decreases in a small portion of the disk close to ISCO and has little influence on the shape of the model spectrum compared to other models (see Figure 3). The radial change of the accretion rate in Model (1) is generally steeper than that in Model (3) at the inner radius. This means that Model (1) will more significantly affect the disk spectrum, especially the contribution from the inner disk radius, which makes it more interesting for our case. However, extending the analysis to spectra from \( L/L_{\text{Edd}} \approx 1.0 \) to \( L/L_{\text{Edd}} \approx 0.7 \), we note that Model (1) overproduces the mass-loss rate, which results in much lower black hole spins (green crosses in Figure 4) compared to the measured ones, since the character of the current radial change of the accretion rate is not coupled strongly enough with the accretion rate. The \( M_{\text{out}} \)-dependent Model (4) is the simplest possible model that is able to reproduce the observed apparent spin decrease. In the parameter space \( (D, L) \), when simulating the decline of spin with mass accretion rate, \( D = 8.55^{+3.31}_{-3.35} \) and \( E = 5.00^{+1.53}_{-1.80} \) give the best fits (the blue circles in Figure 4) to the red dashed line. The uncertainties are quoted at the 90% confidence level by assuming an error of \( \Delta a = 0.01 \) in the spin of the red dashed line. Interestingly, we can achieve an equally good match with Model (1) by assuming that parameter \( A \) depends linearly on the mass accretion rate, i.e., Model (1'), \( A(M_{\text{out}}) = A_1 \cdot M_{\text{out}}/M_{\text{Edd}} + A_2 \). On the one hand, this means that when no winds are present, the exponential function in Equation (3) must equal 1, and thus \( A(M_{\text{out}}) = 0 \). On the other hand, an increasing \( A(M_{\text{out}}) \) reflects an increasing contribution of winds which reduces the local mass accretion rate and modifies the spectrum. This works because a smaller \( A \) at low mass accretion rates provides a shallower shape for the radial distribution of the accretion rate. In this manner, the \( M_{\text{out}} \)-dependent Model (1') reduces the influence of the wind on the Novikov–Thorne spectrum at low accretion rates.

When simulating the behavior of \( a \) versus \( M_{\text{out}} \) for GRS 1915+105 in the range \( L > 0.6L_{\text{Edd}} \) with Model (1'), we explore the parameter space \((A_1, A_2)\). Parameter \( B \) is arbitrarily fixed at \( B = 0.15 \) since the radial distribution of the accretion rate is insensitive to this value. We find that \( A_1 = 3.98^{+1.23}_{-1.54} \) and \( A_2 = -2.54^{+1.02}_{-1.03} \) give the best fits to the observed spin trend (see the green stars on the red dashed line in Figure 4). We repeat the same analysis for LMC X-3 in the range \( 0.3L_{\text{Edd}} < L < 0.6L_{\text{Edd}} \). We again find that Model (1') can describe very well the observed spin trend with \( A = 1.57^{+0.40}_{-0.23} \cdot M_{\text{out}}/M_{\text{Edd}} - 0.39^{+0.17}_{-0.10} \). The reconstructed values of \((M_{\text{out}}, a')\) are plotted in Figure 5 as green stars. The use of fixed values \( A1 \) and \( A2 \) works only in a limited range of accretion rates, but this simple exercise shows that the requested wind is highly concentrated toward the ISCO: in GRS 1915+105, more than 50% of wind mass loss takes place below \( 5 \, r_g \) and, in LMC X-3, most of the wind occurs inside \( 14 \, r_g \). Thus, in both cases, the radial range for the apparent wind is only about three times the size of the ISCO.

From a cross-correlation analysis of optical/infrared (OIR) data and contemporaneous X-ray data, Steiner et al. (2014a) found that there is a nonlinear relation between the OIR flux and the time-lagged X-ray emission: \( F_{\text{OIR}} \propto F_X^b \) with \( b = 1.3 \). This may indicate that the rates of inflow at the inner and outer radii are not matched and that the ratio of the inflow rate scales inversely with the OIR flux, i.e., \( M_{\text{in}}/M_{\text{out}} \propto M_{\text{out}}^{-3/13} \). Disk winds are suggested to carry the accreted gas away from the disk. Given the above dependence of the parameter \( A \) on \( M_{\text{out}} \) and Equation (3), our Model (1') predicts a ratio of \( M_{\text{in}}/M_{\text{out}} \propto \exp(-M_{\text{out}}) \), which is fully consistent with the anti-correlation between the inflow rate and \( M_{\text{out}} \) found by Steiner et al. (2014a).

Our simple parametric discussion above shows that Model (1'), Model (4), or possibly more sophisticated models not considered here can describe such a mass loss and successfully reproduce the observed decrease in spin over a range of mass accretion rates. The removed material will be present between the disk and the observer and may contribute to additional modifications to the observed spectrum.

4. PHYSICS OF WIND AND COMPTONIZATION OF THE DISK SPECTRUM BY THE SURROUNDING MATERIAL

Our simple parametric description of the thermal emission from an accretion disk with mass loss used in Section 3 is too simplistic to predict the resulting effects of the removed material on the observed spectra.

The most general description of a one-dimensional (1D) disk structure with the wind should include both the mass loss from the disk, implying the dependence of the accretion rate on the radius, \( \dot{M}(r) \), as well as the energy extraction by the wind. Thus, in general, the local radiation flux, \( F(r) \), in the disk is given by

\[
F(r) = \frac{3GMM}{8\pi r^2} \mathcal{L}(r)(1 - f_{\text{wind}})
\]

if the particles in the wind carry more energy than the remaining particles in the disk. Here, \( \mathcal{L}(r) \) describes the standard term for relativistic effects in the Novikov–Thorne disk, and the energy fraction \( f_{\text{wind}} \) accounts for the additional removal of energy by the wind. We need to specify two arbitrary radial functions, \( \dot{M}(r) \) and \( f_{\text{wind}} \), to fully account for the impact of the wind on the disk structure. The relative importance of the two effects likely depends on the wind driving mechanism.
There are a number of proposed wind mechanisms which may act on a cold accretion disk surface: (i) thermally driven winds (Parker 1958; Balsara & Krolik 1993; Woods et al. 1996); (ii) magnetically driven winds (Blandford & Payne 1982; Contopoulos & Lovelace 1994; Konigl & Kartje 1994); (iii) radiation-pressure-driven winds, which in turn include Compton-driven and line-driven winds (Shlosman et al. 1985; Proga et al. 2000; Higginbottom et al. 2014). Thermally driven winds and radiation-pressure-driven winds do not require considerable energy segregation at the launch radius, and in this case the role of the $f_{\text{wind}}$ factor could possibly be neglected, although outflowing plasma needs extra energy to achieve escape velocity. In a Newtonian Keplerian motion, it requires doubling the test particle energy to unbind it. Thus, the effect is small as long as the ratio of the total wind mass flux and the accreted mass flux is not too high. On the other hand, most energy and angular momentum can be efficiently extracted from the accretion flow by a small fraction of the magnetically driven plasma (winds or jets).

In our description of the disk in Section 3, we assumed $f_{\text{wind}} = 0$ for simplicity. If the wind is actually a thermally driven wind, then our expression for mass loss indeed implies the true mass loss from observational constraints.

In any of these cases, the material may or may not be present along the line of sight since this will depend of the wind geometry for a given inclination of an observer. If the wind is mostly collimated, then the line of sight may miss most of the removed material, but if the wind is roughly spherical (or, accidentally, mostly toward an observer), then we should see signatures of this wind in the form of the Comptonization effect and/or absorption lines.

An example of a continuum-radiation-driven wind was discussed in detail by King & Pounds (2003; see also King & Muldrew 2016). Such an outflow is expected in sources radiating close to or above the Eddington limit. If most of the material does not reach the ISCO but flows out, then it may form a roughly spherical outflow or a collimated wind in a double cone. The analytic solutions for both geometries showed that the outflow may be Compton-thick and is a promising candidate for the soft excess observed in many AGNs and ultraluminous X-ray sources, given that much of the accretion energy must emerge as blackbody emission due to its large optical depth. The parameters of such an outflow were discussed by King & Pounds (2003). If the wind is spherical, then its optical depth can be described as

$$\tau_{\text{wind}} \propto \frac{1}{\eta} \frac{r_g M_{\text{out}} c}{r_m M_{\text{Edd}} v},$$

where $M_{\text{out}}$ is the total mass outflow rate, and $v$ is the wind velocity, which is higher than the escape velocity from a given radius. For sources that accrete close to the Eddington limit this optical depth is relatively large. However, the temperature, $T_{\text{wind}}$ of such an outflow is not very high since there is not enough additional energy to heat the plasma. Therefore, the temperature of the outflow remains close to the disk temperature. Another possibility that is also discussed in King & Pounds (2003) is that the outflow is highly collimated and jet-like in form.

In Figure 6, we show the predicted disk spectrum seen through such a cold, optically thick emerging wind for GRS 1915+105 predicted by Model (1'), before passing through a spherical wind layer (black solid line) and after Comptonization by a spherical wind with (i) $\tau \approx 5$ and $T = 1$ keV (red long dashed line) or (ii) $\tau = 0.05$ and $T = 100$ keV (blue short dashed line).

$$L_{\text{brem}} = 1.68 \times 10^{-27} T^{1/2} \int_{r_a}^{\infty} n^2(r) 4\pi r^2 dr = 1.68 \times 10^{-27} T^{1/2} \frac{4\pi r_a^2 \tau^2 (1 - \beta)^2}{\sigma_T^2 (2\beta - 3)} \text{erg s}^{-1},$$

where the density of the wind is assumed to be $n(r) = n_0 (r/r_m)^{-\beta}$, and then the optical depth $\tau = \int_{r_a}^{\infty} n(r) \sigma_T dr = n_0 \sigma_T r_a/(\beta - 1)$. For $T = 1$ keV, $\tau = 5.0$, $\beta = 2$, and $r_m = 1.94 r_g$ (at $a = 0.95$), one obtains $L_{\text{brem}} = 1.44 \times 10^{34} \text{erg s}^{-1}$, while the luminosity of the outflow spectra (black solid line) is $L_{\text{disk}} = 2.29 \times 10^{38} \text{erg s}^{-1}$. Therefore, the emergent spectra from the outflow are dominated by the disk emission and the Comptonization, and the model neglecting the bremsstrahlung radiation is self-consistent. Thus, the bremsstrahlung radiation will not be taken into account in further considerations.

On the other hand, the emerging wind may be magnetic in nature, or a weak static magnetic corona may be present above the accretion disk, as is frequently postulated for soft states (Done et al. 2007; Cao 2009; You et al. 2012). We then have no particular predictions for the properties of the Comptonizing
medium from our model. Therefore, we arbitrarily assume values of \( T = 100 \text{ keV} \) and \( \tau = 0.05 \), which implies a small fraction of energy in this component (Comptonization parameter \( y = 0.07 \)). We show this example for the same disk model in Figure 6 (blue short dashed line). A hot Comptonizing medium marginally hardens the spectral peak and produces a hard high-energy tail to the thermal component, which is generally rather steep due to the efficient supply of soft photons from the disk and the negligence of the outflow velocity.

In order to show the magnitude of the effect of Comptonization inside the wind more clearly, we plot the renormalized and shifted spectra in a linear scale, with peaks at the same energy, in Figure 7. We can now compare them at the energy where the initial Model (1') disk flux is a factor of 2 below its peak flux. At this location, the differences between the models should appear more clearly in the data, since at higher energies the data usually requires an additional hard X-ray component. We see that the spectrum where photons go through a cold optically thick wind is visibly steeper with fewer photons at the given energy, while the spectrum where photons go through a hot optically thin wind is less steep with slightly elevated flux. For comparison, we also added the Novikov–Thorne model without any form of outflow (magenta dotted line). This spectrum is also slightly harder than Model (1') and the cold wind case. The difference between the two disk models with/without outflows is at the level of \( \sim 4\% \), which is again at the energy where the flux of the disk before Comptonization is a factor 2 below the peak (see Figure 7). However, the difference between the disk without wind and the disk with wind and optically thin Comptonization (i.e., between the magenta dotted line and the blue short dashed line) is very small, only \( \sim 0.2\% \), which is almost invisible in the figure scale. Observational data of good quality could thus allow us to discriminate (within the observational error) between the different spectral shapes shown in Figure 7 and enable us to assess not only whether wind resolves the spin problem in accretion disks, but also which of the outflow/wind scenarios presented above is the preferred one.

The simple models discussed above are order of magnitude estimates and do not rely on detailed physical studies; they consider only the simplest geometry, which almost certainly differs from real accreting systems. Recent modeling of hard X-ray emission in soft state XRBs and AGNs with the Nuclear Spectroscopic Telescope Array (NuSTAR) indicates that the emission comes from a very compact region, \( 3-10 r_g \) in size, that is well approximated by a lamp-post located on the symmetry axis (e.g., Fabian et al. 2015). This region can be identified as the jet base. Although the jet seems to be suppressed in the high/soft state in XRBs (Fender et al. 1999, 2004), the jet base may remain present and be related to uncollimated winds and significant energy dissipation near the black hole. The material presumably comes from an accreted hot corona, as has been discussed in a number of papers over the past decade (e.g., Chakrabarti & Titarchuk 1995; Zycki et al. 1995; Liu et al. 2015; Wilkins & Gallo 2015). Since winds due to radiative or magnetic acceleration from the inner disk region must be Compton-thin, as demonstrated by Reynolds (2012), the general scenario of a cool, optically thick disk wrapped in a hot, optically thin corona, where a fraction of the coronal material is removed in the form of winds while the rest is accreted, applies. We sketch this in Figure 8 (see the discussion in the following section). A detailed computation of the emission from such a complex model is beyond the scope of the present paper because this would require knowledge of the dissipation in the coronal hot flow. However, we can verify whether or not the simple wind model discussed in Section 3 is self-consistent and determine which part of the flow is actually seen. We present such observational tests in the following Section 5 for LMC X-3 and GRS 1915+105 using Model (1').

5. TESTING THE WIND SCENARIO IN LMC X-3 AND GRS 1915+105

In the previous section, it was shown that, in principle, one can test the wind scenario if the observational data determine not just the position of the spectral peak and the normalization, but if they are also sensitive to the precise shape of the thermal component. In this section, we fit Model (1') against observational data of LMC X-3 and GRS 1915+105. The spectral analysis on all of the data sets is performed with the X-ray spectral fitting software package, XSPEC v.12.8.2. In order to implement our disk–wind model into the framework of

![Figure 7](image-url) Shape of the thermal component normalized to the peak position shown in a linear scale for a relativistic disk without outflow (magenta dotted line), a disk with outflow as in Model (1') but before passing through a spherical wind layer (black solid line), and after Comptonization by a spherical wind with (i) \( \tau = 5 \) and \( T = 1 \text{ keV} \) (red long dashed line) or (ii) \( \tau = 0.05 \) and \( T = 100 \text{ keV} \) (blue short dashed line). The vertical dashed line indicates the energy at which the flux of the outflow-disk spectrum before Comptonization (black solid line) is factor 2 below the peak.
XSPEC, we construct a table model diskw for which each individual spectrum is calculated with a modified version of the code by Czerny et al. (2011) based on Novikov & Thorne (1973), which accounts for the modified accretion rate given in Model (1'). The description of the hardening factor adopted in the model spectrum is done through the parametrization of BHspec results for the viscosity parameter \( \alpha = 0.1 \)

\[
f_h = \begin{cases} 
1.6 \left[ (\dot{m} + 0.1)/0.2 \right]^{0.24} & \text{for } T_4 > 10 \\
(T_4/3.6)^{0.3904} \left[ (\dot{m} + 0.1)/0.2 \right]^{0.24} & \text{for } 1 < T_4 < 10 \\
[\dot{m} + 0.1)/0.2]^{0.24} & \text{for } T_4 < 1,
\end{cases}
\]

where \( \dot{m} = \dot{M}/M_{\text{Edd}} \) and \( T_4 = T/10^4 \) K. It partially comes from Done et al. (2012) and Equation (A13) in Davis et al. (2006), but includes the explicit term in accretion rate which is absent in those papers. The hardening factor increases monotonically with temperature. Therefore, in our table model, there are only two free parameters: parameter \( A \) (see Equation (3)) and the initial mass accretion rate \( \dot{M}_{\text{in}} \) at the outer disk edge, i.e., before the disk is affected by mass loss due to the wind. The mass accretion rate, \( 0.15 \leq \dot{m} \leq 1.5 \), is scaled by the Eddington limit of a given source, \( \dot{m} \approx \dot{M}_{\text{in}}/M_{\text{Edd}} \) (see Section 3 for the definition of \( M_{\text{Edd}} \)). Unlike in the initial Model (1') in Section 3, the free input parameters \( A \) and \( \dot{m} \) are not coupled in the fitting here. Parameter \( B \) is fixed at \( B = 0.15 \), since the radial distribution of the accretion rate is insensitive to it. For each source, we use the respective up-to-date binary parameters given in Section 2 and the resulting mean spin values derived from the spectra obtained in low disk luminosities, \( L \approx 0.3 \) \( L_{\text{Edd}} \), in fits with the slim disk model (O. Straub et al. 2016, in preparation). Our base model to fit the soft state spectra of both sources reads

\( \text{TBABS} \ast (\text{DISKW} + \text{NTHCOMP}) \).

The component \( \text{TBABS} \) (Wilms et al. 2000) accounts for photon absorption by neutral hydrogen in the direction of the source. The column density toward LMC X-3 is \( N_H = 4 \times 10^{20} \) cm\(^{-2}\) (Page et al. 2003) and toward GRS 1915+105 it is \( N_H = 5 \times 10^{22} \) cm\(^{-2}\) (Lee et al. 2002). The disk component is normalized by a constant factor of 0.0575 which converts the units between the table model and the energy bins. Both sources require an additional component to account for the high-energy photons. We use the thermal Comptonization model \( \text{NTHCOMP} \) (Zdziarski et al. 1996; Życki et al. 1999). The photon counts at high spectral energies have fairly large uncertainties, and so to avoid degeneracies with other parameters the photon index which defines the power-law slope is allowed to vary only in the range \( 1.5 < \Gamma < 3.5 \). The electron temperature, \( kT_e \), and the normalization are left free, whereas the seed photon temperature, \( kT_{\text{bb}} \), is fixed. We obtain the lower limit on \( kT_{\text{bb}} \) by first running fits with the nonrelativistic disk model \( \text{DISKB} \) (Mitsuda et al. 1984) which are found to be reasonable values as for the temperatures of the disk with wind, and those inner disk temperatures are used as fixed seed photon temperatures in \( \text{NTHCOMP} \).

### Table 1

| Source       | Obs 1 | Obs 2 | Obs 3 | Obs 4 |
|--------------|-------|-------|-------|-------|
| LMC X-3      | 53607 | 52138 | 51172 | 52002 |
| GRS 1915+105 | 50763 | 50756 | 50190 | 52996 |

In the spectral fits with \( \text{DISKW} \), the vertical structure of the disk is not taken into account. In particular, the disk thickness is assumed to be small so that the photons are emitted from the equatorial plane, which is most likely inappropriate for high mass accretion rates.

#### 5.1. Observational Tests with LMC X-3

We look at the sample of 712 X-ray spectra that were obtained using the large-area Proportional Counter Array on board the Rossi X-ray Timing Explorer (RXTE). These data were extracted from the Proportional Counter Unit 2 (PCU-2), background subtracted and corrected for a detector dead time of \( \sim 1\% \), and classified as the soft states (a detailed description is given in Steiner et al. 2010, 2014b). We fit these soft state spectra with the above given base model \( \text{TBABS} \ast (\text{DISKW} + \text{NTHCOMP}) \) over the energy range \( 2.51\text{--}25.0 \) keV. A good fit satisfies (i) \( \chi^2 \sim 1 \) and (ii) the unabsorbed disks flux must be at least 75% of the total unabsorbed flux. Out of the total number of soft state observations, 381 spectra have mass accretion rates in our range of interest \( (\dot{m} \gtrsim 0.15) \) where winds are expected to play a role. We obtain 336/381 good fits. Parameter \( A \) decreases monotonically with mass accretion rate in the range of about 4.5--0.3, while \( \dot{m} \) decreases from 1.5 to 0.15 (see Figure 10). The behavior of the parameter \( A \) suggests that the wind in this source decreases markedly, but never entirely dies down. The estimated seed photon temperatures take values \( kT_{\text{bb}} \approx 1.5\text{--}0.9 \) keV and the electron temperatures lie in the range \( kT_e \approx 20\text{--}3.5 \) keV. From the goodness of fit and the residuals, we see that a disk--wind model based on a fixed spin, \( a = 0.20 \), well represents the LMC X-3 data. We choose four representative spectra in a wide range of mass accretion rates (Table 1) and show their data, the models, and the residuals in Figure 9. The results are summarized in Table 2.

The best fits for Observations 2 and 3 provide strong constraints on the Comptonizing medium since the electron temperature in \( \text{NTHCOMP} \) is well measured. As an example, we analyze in detail the solution obtained for Observation 2. \( \text{NTHCOMP} \) uses the slope, \( \Gamma \), as the second parameter but, for a given electron temperature, the optical depth is uniquely defined for a fixed geometry. Using the formulæ given in Czerny & Zbyszewska (1991) for a point-like source of photons and a spherical geometry of the Comptonizing medium (the same as adopted in \( \text{NTHCOMP} \)), we obtain an optical depth of \( \tau = 4.0 \) and the Compton parameter \( y = 0.63 \). The medium is therefore optically thick, but the Comptonization is still unsaturated due to the low value of the electron temperature. In the data, however, the normalization of the Compton component is much lower (below 10%) than the 63% expected from \( y \). This reveals that the material responsible for the fitted Comptonization does not cover the whole inner disk. In addition, the wind in this solution is strong; 84% of the material is removed from the disk at the ISCO.

On the one hand, the maximum of the local disk temperature is at 10 \( r_g \) where the mass accretion rate from the disk is
The best accretion rate between \( \approx 0.16 - 1.26 \ M_{\text{Edd}} \) fitted individually over the energy range 2.51 – 25.0 keV. The full model (solid lines) is composed of an absorbed outflow-disk component (short dashed lines) and a Compton component (long dashed lines). The fit results are shown in Table 2.

### Table 2

**DISKW Fits to LMC X-3 Soft State Spectra**

| Model   | Obs 1   | Obs 2   | Obs 3   | Obs 4   |
|---------|---------|---------|---------|---------|
| DISKW   |         |         |         |         |
| \( M_{\text{cor}} / M_{\text{Edd}} \) | 1.26 \( \pm 0.08 \) | 0.53 \( \pm 0.03 \) | 0.33 \( \pm 0.02 \) | 0.16 \( \pm 0.02 \) |
| \( A \) | 3.86 \( \pm 0.55 \) | 1.70 \( \pm 0.24 \) | 0.87 \( \pm 0.16 \) | 0.36 \( \pm 0.14 \) |
| NTHCOMP |         |         |         |         |
| \( \Gamma \) | 1.5 \( \pm 0.01 \) | 1.5 \( \pm 0.02 \) | 1.5 \( \pm 0.01 \) | 1.5 \( \pm 0.01 \) |
| \( kT_e \) (keV) | 9.57 \( \pm 0.06 \) | 3.87 \( \pm 0.05 \) | 5.03 \( \pm 0.07 \) | 5.80 \( \pm 0.07 \) |
| \( kT_{\text{bb}} \) (keV) | 1.26 | 1.17 | 1.13 | 0.92 |
| \( N \) \( \times 10^{14} \) | 1.10 \( \pm 0.10 \) | 1.81 \( \pm 0.24 \) | 2.01 \( \pm 0.08 \) | 0.59 \( \pm 0.04 \) |
| \( \chi^2 / \text{dof} (\chi^2) \) | 50.24 (1.12) | 45.03 (1.02) | 42.68 (0.87) | 21.32 (0.49) |

**Note.** The best-fitting spectral parameters. All errors are quoted at the 90% confidence level \( \Delta \chi^2 = 2.706 \). The asterisk, *, indicates an unconstrained upper or lower limit. The blackbody temperature, \( kT_{\text{bb}} \), has been estimated with diskbb and was subsequently kept frozen during the fit.

On the other hand, half of the total flux is emitted at 40 \( r_g \) where the removed mass fraction is 22%. If the hot, coronal material is predominantly inflowing (as a sub-Keplerian flow), then the second value is more representative for the overall Comptonization of the disk spectrum. From this, we can estimate the vertical optical depth of the inflow at a given radius using

\[
\tau_{\text{cor}}(r) = 4 \pi H_{\text{cor}} \rho_{\text{cor}} v_{\text{cor}} \quad \text{and} \quad \tau_{\text{cor}} = n_{\text{e}} H_{\text{cor}} \rho_{\text{cor}}
\]

where we only have to assume an inflow velocity, \( v_{\text{cor}} \), as both the corona density, \( \rho_{\text{cor}} \), and the corona thickness, \( H_{\text{cor}} \), cancel out. Assuming a velocity of 0.1c, one then obtains at 40 \( r_g \) an optical depth of only \( \tau = 0.9 \). This type of material would cover the whole inner disk. Given the low normalization of the Compton component in the data, however, it cannot be the material responsible for the fitted Comptonization. The optically thick Comptonizing medium seen in the data should rather be identified with a central, hard X-ray source (see Figure 8). In Observation 3, the optical depth, \( \tau = 3.7 \), of the medium is somewhat lower than in Observation 2, but otherwise the solution is very similar.

### 5.2. Observational Tests with GRS 1915+105

*RXTE* made pointed observations of GRS 1915+105 from April 1996 to April 2009. We use the steady-soft observations of Peris et al. (2015). These energy spectra were extracted from the data of the top layer of PCU-2 and the background was subtracted using the model applicable for bright sources. A systematic error of 1% has been added for each energy channel. From the total set of over 2000 continuous exposure segments (mean exposure time = 2.1 ks), 1257 spectra are steady, of which 264 are soft. The majority of these show absorption and/or emission as well as disk reflection features. In order to fit the soft state spectra of GRS 1915+105, we therefore include a broad Fe K emission line fixed at \( E_{\text{line}} = 6.4 \text{ keV} \) and modeled with Laor (Laor 1991), as well as an Fe absorption component (GABS) with a central energy fitted between 6.5 and 7.5 keV and fixed width \( \sigma = 0.5 \text{ keV} \). We use SMDEGE to describe a smeared Fe edge where we fit the edge energy between 7 and 9 keV, leave the maximum absorption factor \( \tau_{\text{max}} \) free, and fix the smearing width at \( W = 7 \text{ keV} \). We fit the full model TBABS \( ^{*} \) (DISKW + NTHCOMP + LAOR) \( ^{*} \) GABS \( ^{*} \) SMDEGE in the energy range 2.51 – 45.0 keV. Two hundred thirty-three spectra have luminosities in our range of interest \( (\dot{m} \approx 0.15) \) and we obtain 178/233 good fits. The modeled mass accretion rates lie between \( m = 0.15 \) and 1.2, over the range of which parameter \( A \) increases from near zero to 2.5 (see Figure 10). We note in particular that \( A \) already becomes infinitesimal at around 45% of the Eddington limit. Below, the disk is effectively a standard thin disk without winds. The electron temperature slightly increases with mass accretion rate from \( kT_e \approx 2.5 \) to 10 keV together with the seed photon temperature \( kT_{\text{bb}} \approx 1.5 - 2.5 \text{ keV} \). The latter remains roughly constant for \( \dot{m} > 0.3 \) and is substantially higher than in other Galactic XRBs but typical for the source. The absorption line energy which lies at about \( E_{\text{line}} \approx 7.2 \text{ keV} \) is practically independent of the accretion rate. Its strength, however, decreases with increasing mass accretion rate. We remind the reader that in GABS the line strength, \( N \), refers to the line depth and is related to the optical depth at the line center via \( \tau_{\text{line}} = N / (2 \tau_0) \). The anti-correlation between absorption line strength and mass accretion rate implies that an increasing amount of wind can effectively remove absorption line features. The Laor normalization which parametrizes the number of photons per area per time increases with the mass accretion rate. The Fe \( K_{\alpha} \) line is present in all of the spectra but more pronounced when wind is present. The central edge energy shows an increasing trend with mass accretion rate, \( E_{\text{edge}} \approx 7.25 - 8.75 \text{ keV} \). Although the goodness of fit is already good for \( \chi^2 \approx 1 \) without an Fe line component, there are still small residuals which seem barely visible in some of the spectra. Adding the Laor model component to account for the Fe line is, in fact, improving the fits. The disk–wind model...
based on a fixed spin, $a = 0.95$, can fit the GRS 1915+105 data very well. We choose again four representative spectra at widely different mass accretion rates (Table 1) and show the data, models, and model residuals in Figure 11. The results are summarized in Table 3.

The best fit found for Observation 1 is consistent with recent results based on data recorded with NuSTAR which operates in a wider bandpass (3–79 keV) than RXTE: Miller et al. (2013) measure a slope of $\Gamma = 2.07$ and an electron temperature of ~16 keV (see their Figure 2) while we have only a lower limit for the electron temperature and a very simplified description of reflection due to the lack of high-energy data in RXTE, which imply an optical depth of $\tau = 2.0$ for the geometry adopted in nTHCOMP ($\tau = 3.1$ for Observation 1 in this work). A similar value of the optical depth ($\tau = 1.5$) is obtained by Miller et al. (2013) using the EQPAIR model (Coppi 1999) where the optical depth is a free parameter. The derived Compton parameter for the NuSTAR data, $y = 0.86$ ($y = 0.91$ for Observation 1 in this work), is relatively high but, as in the case of LMC X-3, the Compton component contributes less than 10% to the total spectrum in the data; most of the emission stems from the disk component. This means that in Observation 1 the Comptonizing medium covers only a small part of the disk. Based on our model, the wind contribution during Observation 1 is extreme, with over 90% of the material being removed from the inner disk. On the one hand, half of the material has left the disk by the time the disk flow reaches 6.4 $r_g$. On the other hand, half of the flux is emitted at 14.3 $r_g$ where the disk has lost only 26% of its matter to the wind. The optical depth at the latter radius is expected to be $\tau = 0.7$ for an adopted corona flow speed $v_{\text{cor}} = 0.3c$, where the high corona speed reflects the fact that the inner disk region in a high spin source like GRS 1915+105 is closer to the black hole than in a low spin source like LMC X-3. A spherical wind would have to have a very high optical depth (see Equation (11)), and therefore the self-consistent picture is as follows. The Comptonized emission seen in Observation 1 originates from a central hard X-ray source and the wind material removed from the inner disk forms an inflowing coronal layer that is accreted onto the black hole. The emission from the optically thin corona in this scenario is not directly visible in the spectral data.

The situation during Observation 4 is quite different. First, the mass accretion rate is small and there is no significant presence of wind. Second, we obtain good limits on the temperature of the Comptonizing plasma since it is sufficiently low for the data to be properly recorded within the energy bandpass of RXTE. We derive the optical depth $\tau = 3.1$ from the measured electron temperature, $kT_e = 2.35$ keV, and the lower limit of the photon index, $\Gamma = 3.25$, for the geometry adopted in nTHCOMP. The corresponding Compton parameter is then only $y = 0.24$, which is much lower than in Observation 1 and indicates only weak Comptonization. The normalization of the Compton component is much higher, though, suggesting that a significant part of the inner disk is covered. The upper limit on the wind parameter $A$ implies an upper limit on the total wind mass loss of only 20%, while merely 4% of the disk mass is liberated at the location ($r = 8.7r_g$) where half of the flux is dissipated. This small amount of material is not enough to form an optically thick Comptonizing zone, particularly if the material flows in as rapidly as we previously assumed. The coronal optical depth estimated at this radius is $\tau = 0.03$, of its expected to be $\tau = 0.7$ for an adopted corona flow speed $v_{\text{cor}} = 0.3c$, where the high corona speed reflects the fact that the inner disk region in a high spin source like GRS 1915+105 is closer to the black hole than in a low spin source like LMC X-3. A spherical wind would have to have a very high optical depth (see Equation (11)), and therefore the self-consistent picture is as follows. The Comptonized emission seen in Observation 1 originates from a central hard X-ray source and the wind material removed from the inner disk forms an inflowing coronal layer that is accreted onto the black hole. The emission from the optically thin corona in this scenario is not directly visible in the spectral data.

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which is much less than what is measured for the spherical Comptonizing medium. It may imply, again, the presence of a central hard X-ray source. Given the high normalization during Observation 4, however, the result rather suggests that a significant part of the Comptonization may take place in a plane-parallel optically thin corona layer. To obtain such a geometry, the hot coronal inflow must be more than an order of magnitude slower than the free fall velocity.

6. DISCUSSION

We fit the bulk of our thermal spectra of LMC X-3 and GRS 1915+105 in a broad luminosity range with a simple disk–wind model that includes an inward radially decreasing accretion rate but neglects the problem of additional energy extraction from the disk by the wind. In data fitting, we do not use any coupling between the amount of the removed material and the properties of the Comptonizing medium (i.e., the possible geometry, the temperature and optical depth). The model fits the data well and there is no effect of decreasing spin with luminosity since the spin is fixed by definition. The required wind is negligible at low mass accretion rates, particularly in GRS 1915+105. For increasing (outer) mass accretion rates, as much as >80% of the material can be lost in the wind (see Tables 2, 3, and Equation (3)).

Both sources show significant Comptonization effects in the spectra. The Comptonization is consistent with the upscattering of the soft disk photons by the hot medium since the soft photon input temperature is comparable to the disk temperature. The temperature of the Comptonizing medium is higher than the maximum disk temperature by a factor of 2–10, and generally becomes higher for higher luminosities. The power-law slopes measured for GRS 1915+105 (see Table 3) range from $\Gamma = 1.5$ to 3.5 and are often not determined accurately due to the limited energy band of RXTE. The well-determined slopes combined with the corresponding plasma temperatures yield the optical depths of the Comptonizing plasma of the order of $\tau = 2 - 3$. Such a plasma phase is typical for many soft state sources (Walter & Fink 1993; Magdziarz et al. 1998; Zhang et al. 2000; Kubota & Done 2004; Done et al. 2012; Petrucci et al. 2013). A similar result was obtained by Miller et al. (2013) with NuSTAR data where the slope of the Comptonizing component is determined more reliably than with our data. For LMC X-3, we arrive at the same conclusion: whenever $\Gamma$ is well constrained, the optical depth of the Comptonizing medium is of the order of 3–4. The exact values depend on the geometry (plane-parallel or spherical) and the assumed photon distribution. Here, we use spherical symmetry, with photons at the center like in NTHCOMP, for consistency.

The problem is that the optical depth of the Comptonizing medium implied by the fits does not increase with the modeled disk luminosity but remains practically constant despite the sharp rise in the wind from the disk itself. Thus, the Comptonizing medium is present at low Eddington ratios, that is, when mass loss from the disk is not required as at high Eddington ratios and when the implied disk mass loss is strong. Moreover, the medium does not become optically thicker as the mass accretion rate rises and winds become more prominent. This seems to suggest that the wind material is not located along our line of sight. The behavior of the normalization of the Compton component also points toward an absence of Comptonizing material along the line of sight. Given the Compton parameter $y \sim 0.6$ (LMC X-3), for instance, the Comptonization is strong and the material should be optically thick. If this kind of material would cover a large part of the disk, then the disk itself would be barely visible as almost all of its energy would end up in the Compton component. This contradicts the nature of the data where the Compton component makes up only a very small fraction of the total flux and the disk is well observed, including the reflected

### Notes

- **Note:** The best-fitting spectral parameters. All errors are quoted at the 90% confidence level. The asterisk, *, indicates an unconstrained upper or lower limit. The blackbody temperature, $kT_{bb}$, in NTHCOMP has been estimated with diskbb and was subsequently kept frozen during the fit.

### Table 3

| Model   | Obs 1            | Obs 2            | Obs 3            | Obs 4            |
|---------|------------------|------------------|------------------|------------------|
| DISKWF  | $M_{\text{disk}}/M_{\text{Edd}}$ | 1.10 $^{+0.10}_{-0.06}$| 0.62 $^{+0.05}_{-0.03}$| 0.37 $^{+0.02}_{-0.01}$| 0.16 $^{+0.01}_{-0.00}$|
| $A$     | 2.29 $^{+0.59}_{-0.17}$| 0.92 $^{+0.25}_{-0.27}$| 0.0007 $^{+0.0002}_{-0.0002}$| $(2 \times 10^{-3})$ $^{+0.2}_{-0.1}$|
| NTHCOMP | $\Gamma$         | 1.66 $^{+0.12}_{-0.17}$| 1.5 $^{+0.6}_{-0.6}$| 3.5 $^{+0.6}_{-0.6}$| 3.5 $^{+0.25}_{-0.25}$|
|         | $kT_{e}$ (keV)   | 8.57 $^{+0.81}_{-0.15}$| 3.98 $^{+0.15}_{-0.41}$| 3.94 $^{+0.34}_{-0.71}$| 2.35 $^{+0.29}_{-0.13}$|
|         | $kT_{\text{bb}}$ (keV) | 2.08 | 2.06 | 2.18 | 1.77 |
|         | $N$ [$\times 10^{-2}$] | 0.85 $^{+1.72}_{-0.26}$| 0.50 $^{+1.26}_{-0.15}$| 4.48 $^{+0.41}_{-1.09}$| 0.10 $^{+0.02}_{-0.02}$|
| GABS    | $E_{\text{line}}$ (keV) | 7.27 $^{+0.13}_{-0.08}$| 7.24 $^{+0.10}_{-0.07}$| 7.23 $^{+0.07}_{-0.07}$| 7.07 $^{+0.08}_{-0.08}$|
|         | $N$              | 0.29 $^{+0.09}_{-0.09}$| 0.31 $^{+0.09}_{-0.09}$| 0.30 $^{+0.08}_{-0.08}$| 0.35 $^{+0.16}_{-0.11}$|
| SMEDGE  | $E_{\text{edge}}$ (keV) | 8.26 $^{+0.39}_{-0.22}$| 8.26 $^{+0.38}_{-0.23}$| 8.03 $^{+0.30}_{-0.29}$| 7.37 $^{+0.09}_{-0.09}$|
|         | $\Gamma_{\text{max}}$ | 0.86 $^{+0.38}_{-0.80}$| 0.70 $^{+0.38}_{-0.28}$| 0.63 $^{+0.20}_{-0.23}$| 3.06 $^{+0.72}_{-0.88}$|
|         | $\chi^2$/dof ($\chi^2_2$) | 43.23/70 (0.62) | 48.97/70 (0.7) | 44.53/69 (0.65) | 63.47/62 (1.02) |
component. Therefore, the material that has been removed from the disk by the wind cannot be fully identical to the Comptonizing medium. In general, this medium likely forms a kind of magnetized dissipative skin (e.g., Różańska et al. 2015); a small fraction of it may be outflowing, but most of it would be inflowing. We sketch this geometry in Figure 8. If the hard emission comes from a lamp-post-style hard X-ray source, then the question remains whether we have any method to prove or disprove the mass outflow from the disk. Our consistency check made for LMC X-3 and GRS 1915+105 implies that the actual wind material may be unnoticed since the data do not require a second Comptonizing medium and the model does not overpredict the optical depth of the corona skin at the radius where half of the disk flux is emitted.

In the high spin source GRS 1915+105 we detect an absorption feature along the line of sight, but we do not see it in the low spin source LMC X-3 despite their similar inclination angles, 60°–70°. If this absorption line at ~7.2 keV is caused by a hot plasma, then it must be blueshifted from its original value of 6.7 keV. This implies that the absorbing (wind) material has a speed of 0.07c. Such a wind may originate from the innermost part of the disk but does not have to. Hydrogen-like and helium-like iron lines are resonant lines and the line-locking mechanism can accelerate the flow very efficiently, independent of the launching radius. In comparison, broad absorption line features observed in AGNs have blueshifts that correspond to velocities of the order of 0.1–0.3c, but the launching radius is likely further than 0.1 pc from the black hole. Recent studies of a large sample of AGNs suggest typical launching radii of 10–1000 light days, and some features can come from distances as far as 100–3000 pc (Filiz et al. 2013). The lack of line absorption in LMC X-3 might be due to its low spin. Steiner et al. (2014b) tentatively suggested that there is a possible link between black hole spin and spectral complexity. They argued that some sources with known low spins have remarkably simple spectra with few spectral features, whereas high spin sources exhibit strong Comptonization/reflection and a rather large variety of spectral features.

Previous models of the outflows in GRS 1915+105 assumed magnetically driven outflows to reproduce the amplitude of the regular heartbeat bursts within the scenario of the radiation pressure instability (Nayakshin et al. 2000; Janiuk et al. 2002). However, models with a static corona and a time-dependent mass exchange between the disk and the corona (e.g., Janiuk & Czerny 2005) or models with different viscosity prescription (e.g., Merloni & Nayakshin 2006) worked equally well.

Model (4), which we used in Section 3 as one of the simple parametric prescriptions, implicitly refers to a magnetic outflow. In this model, formally, all of the matter is outflowing at the disk truncation radius. From an observational point of view, by fitting the broad asymmetrical Fe Kα line, Cowperthwaite & Reynolds (2012) find that the accretion disk in 3C 120 might be truncated at $r_{in} = 11.7 r_g$ independent of the spin configuration and at a moderately high luminosity $L = 0.23 L_{Edd}$. The authors suggest that the material in the inner disk, instead of transforming into an advection-dominated accretion flow (ADAF), could be ejected in the form of a jet. This could explain the observed periodic dips in X-ray luminosity that are accompanied by large radio bursts (King et al. 2011). From a theoretical point of view, models with an inner truncation radius are frequently considered, but in the context of a two-zone geometry where an inner hot optically thin and geometrically thick ADAF is enclosed by a truncated outer standard disk (Esin et al. 1997; Yuan et al. 2005; Liu & Taam 2009, 2013; Yuan & Narayan 2014). In this case, the ADAF fully describes the low luminosity/hard emission state where the accretion rate drops below a few percent of the Eddington limit (Zdziarski et al. 2004). However, this trend goes in the opposite direction compared to the trend required to solve the spin paradox in our paper: the transition radius in the case of the standard disk/ADAF hybrid solution decreases with the increase of the Eddington ratio while we need an opposite trend. Therefore, the mechanism that acts in high Eddington ratio sources must be a different one. Observationally, the presence of the relativistically broadened reflection provides support for the disk close to the black hole. We see it in some of the RXTE spectra of GRS 1915+105, and soft state reflection has been detected in some other galactic sources in the soft state, e.g., Cyg X-1 (Tomsick et al. 2014), XTE J1908+094 (Tao et al. 2015), LMC X-1 (Koyama et al. 2015), 4U 1543-47 (Morningstar & Miller 2014), as well as in AGNs, e.g., Mkn 335 (Wilkins et al. 2015). In this case, only a small fraction of material should be outflowing, but this is not fully self-consistently treated in Model (4) as the temperature of the disk with magnetically driven wind should be much lower than that for the absence of the $f_{wind}$ term in Model (4), which affects the color-correction term. Therefore, we do not use this model when fitting the observational data in Section 5.

6.1. Comparison between Disks With and Without Wind

There is only one significant difference between disks with and without wind, namely, the predicted mass accretion rate. For a given observation, a disk with an initial mass accretion rate modified by wind can exhibit accretion rates significantly larger than a disk without wind. This is a direct consequence of $m$ being measured at the outer disk edge and not being constant with radius due to wind mass loss. Accretion disks that self-consistently include winds are thus much less efficient at converting mass into radiation than a standard thin disk.

The spectral difference in the shape between the models with and without wind is very small when the model parameters are appropriately adjusted. In a given observation, the spin, accretion rate, and wind prescription are strongly degenerate. They are additionally masked by the Comptonization at higher energies. A sequence of disk-dominated spectra is necessary, since then the spin should remain the same independent of the source luminosity. Models without wind and with a hardening factor taken from HSPEC do not provide the correct solution for such a sequence for GRS 1915+105 and LMC X-3, while the wind model presented in this paper is satisfactory.

The comparison of the disk wind model with the data is a first step toward the assessment of the flow geometry. However, the next steps are very difficult, since the material removed from the disk flows out as a wind but also (mostly) flows in as a corona flow. Comptonization computations should be done in three dimensions for the adopted flow pattern. The basic difficulty is that we then need to know the temperature distribution inside the hot flow, which depends on the plausible local dissipation, and the global magnetic field will affect the global flow.

The success of the wind model in reproducing the right trends over a range of mass accretion rates does not mean that the wind is the only solution to the spin problem. Straub et al.
(2011) have shown that if a constant hardening factor is used instead of a variable hardening factor predicted by BHSPEC and SLIMBH, then the spin problem is significantly alleviated. We find that fits with SLIMBH are just as good as those with DISKWIN and, consequently, that the RXTE data are not sensitive to the shape of the disk model spectrum. Suzuki (Mitsuda et al. 2007) is a satellite that has a moderate spectral resolution CCD for the 0.7–10 keV band and a hard X-ray detector for the 12–30 keV band. Kubota et al. (2010) used Suzuki observations of LMC X-3 to constrain the spectral shape of the intrinsic disk emission in various models. They found that BHSPEC, which self-consistently includes radiative transfer through the vertical structure of the disk, gives an excess at the absorption edge energy below 1 keV compared to the data. This may suggest the need to include more physical processes in the disk atmosphere, i.e., atomic physics and better assumptions for the disk density and emissivity profile with respect to the disk height.

One way to prove the physical existence of the wind close to the black hole horizon would be to see it directly in the spectral shape of the pure disk component due to general relativity effects. However, this would require a data set with very low systematic errors, below 0.2%. In addition, the precision in the description of the Comptonization process would also matter in systematic errors, below 0.2%. In addition, the precision in the effects. However, this would require a data set with very low systematic errors, below 0.2%.

...the need to include more physical processes in the disk atmosphere, i.e., atomic physics and better assumptions for the disk density and emissivity profile with respect to the disk height.

6.2. Observational Evidence of Winds

Outflows are expected and actually observed in accreting systems. Their occurrence in the form of collimated jets is characteristic of low Eddington rate sources. While jets seem to be suppressed in the high/soft state of black hole XRBs (Qiao & Liu 2015), uncollimated outflows/winds are still found in high-luminosity sources (Miller et al. 2006b; King et al. 2014). However, the presence of the specific outflow we request here to solve the problem of the apparent spin decrease is difficult to test. The outflow temperature must be at least $10^4$ K or higher and the outflow may or may not be located along the line of sight depending on the collimation, which is unspecified. The material is thus highly or fully ionized, leaving only the possibility of emission/absorption from highly ionized iron.

There is ample observational evidence for outflows from accretion disks. Outflowing winds have recently been detected in several XRBs via blueshifted X-ray absorption lines which are observed in high-resolution spectra (see Miller et al. 2015, and references therein). Through modeling of the observed narrow absorption features recorded in GRS 1915+105 by Chandra High Energy Transmission Grating spectra (HETGS), the total mass outflow rate is estimated to be comparable to the mass accretion rate in the inner part of the disk (Ueda et al. 2009). A re-analysis of the Chandra HETGS spectroscopy data of GRS 1915+105 by Miller et al. (2015) with improved multi-zone photoionization models and with different ionization parameters and velocities reveals that $M_{\text{wind}}/M_{\text{Edd}} \approx 0.3$ when the accreted gas rate $M_{\text{accr}} \approx 6M_{\text{Edd}}$, where the Eddington accretion rate in that work is defined as $M_{\text{Edd}} = L_{\text{Edd}}/c^2$.

These detected winds, however, clearly do not correspond to the winds requested in our paper to solve the problem of the apparent spin evolution. Our winds should occur very close to the black hole, at a few gravitational radii, and with the terminal speed of the order of the local Keplerian velocity at these radii, i.e., at a large fraction of the light speed. All of the winds discussed above show narrow absorption features with shifts corresponding to a few hundreds to a few thousands km s$^{-1}$, e.g., 4U 1630–472: the velocity $v < 8.0 \times 10^3 c$ and the launching radius $r \sim 800$–6100 $r_g$; GRO J1655–40: $v < 11.8 \times 10^3 c$ and $r \sim 500$–1000 $r_g$; H 1743–322: $v < 4.3 \times 10^3 c$ and $r \sim 1100$–4900 $r_g$; GRS 1915+105: $v < 4.0 \times 10^3 c$ and $r \sim 1200$–23000 $r_g$ (see Tables 4–6 and 12 of Miller et al. 2015). Thus, observations usually give constraints on the partially ionized winds from the outer disk, while here we deal with the highly ionized winds from the inner disk.

Magnetically driven outflows have been postulated and studied from a theoretical point of view (e.g., Blandford & Payne 1982; Contopoulos & Lovelace 1994; Konigl & Kartje 1994), and efficient outflow close to the inner disk radius due to the bending of the poloidal field is expected (Campbell 2010). Observationally, magnetic assistance has been advocated in some outflows, like ultra-fast outflows in active galaxies. Ultra-fast outflows have been detected in a number of AGNs through analysis of their absorption features. For example, in PG 1211+143, Pounds et al. (2003) identified highly ionized outflows that had a velocity of $\sim 0.08$–0.1c and mass flux comparable to the mass accretion rate. A more recent spectral analysis of XMM-Newton/EPIC data of PG 1211+143 revealed an outflow velocity of $\sim 0.1$–0.2c, with most of the wind launched at 200 $r_{\text{ISCO}}$ and an inner wind truncation radius of 30$r_{\text{ISCO}}$ (Fukumura et al. 2015), which favors magnetic driving. The location of this wind, however, is still too far from the black hole for our purpose.

In principle, the motion of the plasma is encoded by how a fully ionized plasma up-scatters the photons. Since the terminal outflow velocities are large while the initial denser part of the wind has a lower velocity, the expected effects of bulk Comptonization are difficult to model without assuming a specific velocity profile. The issues of bulk Comptonization have occasionally been discussed, both in the case of an inflow (e.g., Chakrabarti & Titarchuk 1995; Liu et al. 2015) and an outflow (e.g., Beloborodov 1999). Computations of the Comptonization of the disk photons in the postulated winds with density/velocity/temperature gradients are beyond the scope of the present simple work.

7. CONCLUSIONS

The determination of the black hole spin in XRBs using advanced, fully relativistic disk models including full radiative transfer to account for Comptonization in the disk atmosphere leads to a paradox: the spin decreases with increasing source luminosity (McClintock et al. 2006; Steiner et al. 2010; Straub et al. 2011). Here, we analyze whether this effect might be explained by the presence of the winds from the innermost part of the accretion disk. We find that relatively smooth radial winds without an explicit dependence on the mass accretion rate (Models (1)–(3) in Section 3) do not provide the solution for this effect. However, if we assume in Model (1') that the parameter $A$ depends on $M_{\text{out}}$ (the mass accretion rate at the outer disk radius), then the apparent spin decrease can be reproduced (green stars in Figure 4). We can recover the observed trend also in Model (4) where the truncated inner disk radius depends linearly on $M_{\text{out}}$. The physical interpretation of
such a model is that either most of the material, or at least most of the energy and angular momentum, has to be removed from the disk in the form of a wind or an uncollimated jet, leaving behind a cold, non-radiating flow close to the black hole horizon.

In all of these scenarios the shape of the thermal disk component is modified, leaving a trace of the process in the spectral shape. We show that the spectra for the two cases of outflow discussed in Section 4, namely, the hot, optically thin and the cold, optically thick wind, are, in comparison to a spectrum without Comptonization, either visibly harder or softer, respectively. However, if the Comptonizing medium is chosen independently of the predicted outflow, then the difference between the models with and without outflow is very small, ~0.2% at the energy where the disk flux before Comptonization drops by a factor of two below the peak flux (see Figure 7).

We test in more detail the disk–wind scenario against the data for two bright XRBs, LMC X-3 and GRS 1915+105, using Model (1°) and assuming a Comptonizing medium surrounding the disk. For each source, we fit several hundreds of high/spectral soft photometric spectra providing an intrinsically constant black hole spin and the presence of wind that correlates with the mass accretion rate. We obtain good fit statistics as demonstrated for four representative spectra for each source (Figures 9, 11 and 2, 3). The apparent decrease of the black hole spin over a range of mass accretion rates in LMC X-3 and GRS 1915+105 could originate from the presence of wind or be due to an incomplete description of the disk atmosphere. The latter issue will be addressed in a forthcoming paper. Here, we show that the wind model with a fixed spin can fit the data.

However, the implied properties of the Comptonizing medium do not correlate with the required wind, as the wind intensity rises sharply with the luminosity while the Comptonizing medium properties remain almost unchanged. This implies the presence of a separate Comptonizing medium, likely in the form of an X-ray source located on the symmetry axis, while the material removed from the disk, albeit in large amounts, can escape detection if it flows predominantly inward as a corona flux. Thus, we have no direct observational evidence of the requested wind from the inner few gravitational radii.

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