On the spin of stellar-mass black hole by the continuum-fitting method

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1.Abstract

The continuum-fitting method is one of the two most important methods of determining the black hole spins in the accreting sources. Fits for a sequence of the increasing luminosities in a given source show an apparent decrease in the spin, which indicates a problem in the disk model.

We perform simple tests whether the outflow from the disk close to the inner radius can fix this problem. We design four simple parametric models of the outflow from the disk close to the inner radius, and we compare these models with the apparent decrease trend of the spins in LMC X-3 and GRS 1915+105.

Models without explicit dependence of parameters on the luminosity do not reproduce the spin measurements, but the simplest model with luminosity-dependent parameter (truncation radius of the disk) properly represents the trend.

We perform tests of the sensitivity of the RXTE data to various disk models. The assumption of an outflow removes the artifact of the spin decrease with an increase of the source luminosity, but the solution is not unique due to the too low quality of the RXTE data.

2.Motivation

The continuum-fitting method is based on the comparison of the observed shape of the thermal continuum spectrum with an accretion disk model spectrum .

Despite the overall success of the continuum-fitting method for Galactic sources, one problem remains unsolved. If the method is applied to the same source at different luminosities, the value of the spin resulting from the fitting procedure decreases monotonically with increasing source luminosity. This was shown for two sources: GRS 1915+105 (McClintock et al. 2006) and LMC X-3 (Steiner et al. 2010; Straub et al. 2011), also see Fig. 1. The apparent decrease of the spin must be the artifact of the adopted model.

There are two reasons which could be responsible for this effect. The first one is the description of the disk atmosphere (BHSPEC). The second possibility is the outflow from the disk surface very close to the innermost stable circular orbit (ISCO).

We perform simple estimates whether the outflow scenario is likely to be responsible for the observed apparent decrease of the spin.

3.Simple outflow models

The outflow from an accretion disk surface required to cause the apparent change in the spin must have the appropriate radial distribution. We define $\dot{M}_{in}$, $\dot{M}_{out}$ as the accretion rate at the inner r_{in} , and outer disk radius r_{out}, respectively. In addition we define $\dot{M}(r)$ and $\dot{M}_{wind}(r)$ as the inflow and outflow rate at a given radius r.

We specifically concentrate on the GRS 1915+105 case since the effect is stronger there. We consider four outflow models:

(1) In the first outflow model, the radial distribution of the accretion rate is in the form of exponential Function,

$$\dot{M}(r)=\dot{M}_{out}\exp\left(-A/(r/r_{in}-B)\right)$$

where A and B are model parameters, and A is positive, 0 < B < 1.

(2) In the second model, we assume another simple power law expression of outflow rate as Laor & Davis (2014):

$$\dot{M}_{wind}(r)=\dot{M}_{out}(r/r_{in})^{\beta}$$

which gives the inflow rate:

$$\dot{M}(r)=\dot{M}_{out}\left(1-(r/r_{in})^{\beta}\right)$$

where $\beta<0$ is a model parameter

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

$$\frac{d\dot{M}_{wind}(r)}{dr}=\frac{C}{r}$$

(4) Finally, we assume that the disk is truncated at r_{tr} outside the ISCO and the accretion rate is constant at all disk radii. For simplicity we assume that the truncation radius, r_{tr}, depends linearly on the accretion rate:

$$r_{tr}=r_{ISCO}+\Delta r\equiv r_{ISCO}+D*\frac{\dot{M}_{out}}{\dot{M}_{Edd}}+E$$

- We plot the inflow rates as a function of r for the four outflow models in Fig. 1
- Then we test if the outflow models can reproduce the observed decrease in the spin for GRS 1915+105 (see Fig.2).
  - -> We calculate the spectra for various outflow model parameters with a set of 'input' accretion rates $\dot{M}_{out}$ and the fixed spin a.
  - -> By fitting such spectra using Novikov & Thorne model without any outflow and treating the accretion rate $\dot{M}'_{out}$ and the spin a' as fitting parameters, we can then check whether the fitted spin is lower than the 'input' spin in the wind, i.e., if a' < a.

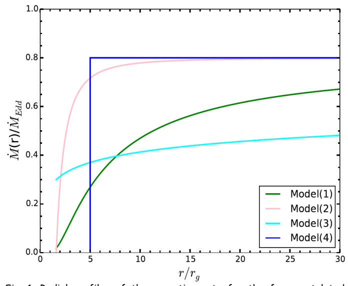

Fig. 1. Radial profiles of the accretion rate for the four postulated outflow models. In all cases we assumed $\dot{M}_{out}/\dot{M}_{Edd}=0.8$, a = 0.98; r_{in} = r_{ISCO} for models (1)-(3) and r_{in} = $5r_g$ for model (4). In addition, A = 3.22, B = 0.15, β = −2.0. For the first three models, the radial distributions of the accretion rate are given by an exponential function, a power law, and a differential function, respectively, while in model (4) $\dot{M}(r)$ is constant beyond the truncation radius.

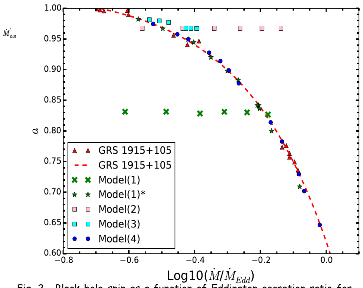

Fig. 2. Black hole spin as a function of Eddington accretion ratio for GRS 1915+105. Red triangles represent the result from McClintock et al. (2006). The red dashed line is the linear fits to the turquoise diamonds red triangles. The spectra of our four outflow models are calculated using a set of $\dot{M}_{out}$ and a constant black hole spin a=0.98 which is valid for L < $0.3L_{Edd}$. The green cross, pink square, cyan square, blue circle points represent $(\dot{M}'_{out},a')$ obtained by fitting our outflow model spectra with the Novikov & Thorne 1973 model without outflow, respectively. The green star points are the estimates from model (1) but with the assumption of the dependence of A on Eddington accretion ratio.

Results:

Both model (1) with the dependence of 'A' on luminosity and model (4) can reproduce the observed decrease of the spin with increasing luminosities for GRS 1915+105, LMC X-3.

4.Comptonization of the disk spectrum by the outflowing wind

- The outflow will be present between the disk and the observer, and may modify the observed spectrum by Comptonization.
- We consider two cases of the disk spectrum Comptonization by the outflow:
  - -> the cold optically thick outflow
  - -> the hot optically thin outflow
- In Fig. 3, we plot the renormalized thermal component in a linear scale for the two cases of Comptonization, with peaks at the same energy.

Results:

- There are apparent differences in the spectral shapes between various disk models.
- Next we perform observational test for LMC X-3 with RXTE data to see if such differences in the spectral shape can be discriminated

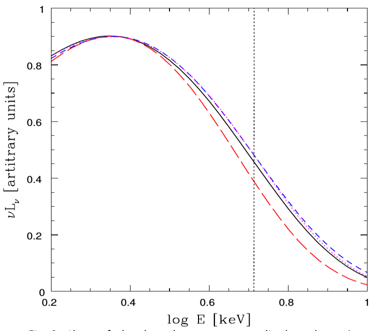

Fig. 3. Shape of the thermal component normalized to the peak position shown in a linear scale for a relativistic disk without an outflow (dotted magenta line), disk truncated at $r_{tr}>r_{ISCO}$ (black continuous line), truncated disk after Comptonization by a spherical wind with optical depth τ =5, T = 1 keV (red long dashed line) or τ = 0.05, T = 100keV (blue short dashed line). The black dashed line represents the energy at which the flux of the outflow disk spectrum before Comptonization (black continuous line) is factor 2 below the peak.

5.Observational test for LMC X-3

- We select the four longest exposure data sets of ~ 30 ks each among the 712 PCU-2 X-ray spectra from Steiner et al. (2010) obtained from RXTE.
- We have constructed a table model named **diskw** accounting for the modified accretion rate as in model (4), which can be implemented into the XSPEC software package.
- The full model used in the data fitting: tbabs*tbabs*(simpl ⊗ diskw+gaussian)

Results:

- Both our outflow model **diskw** and simple **diskbb** give good fits to four longest RXTE data (see Table 1 for the best fitting results with **diskw**).
- This means that RXTE data are not sensitive to the shape of the disk model spectrum, and is not sufficient to allow us to distinguish between different disk models

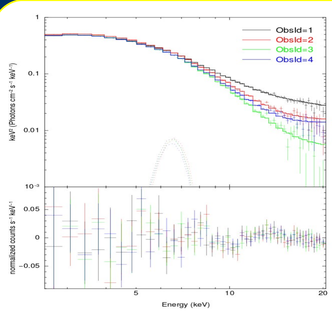

Fig.4.— Best fit to the four longest exposure RXTE spectra of LMC X-3 (top) and fit residuals (bottom). The full model used in the fitting procedure: tbabs*tbabs*(simpl⊗diskw+gaussian).

Table 1. Results of modeling the RXTE data of LMC X-3

Model Component	Parameter	(1)	(2)	(3)	(4)
tbabs	N_H	0.04*	0.04*	0.04*	0.04*
tbabs$^{(a)}$	N_H	$0.47^{+0.10}_{-0.06}$	$0.63^{+0.07}_{-0.07}$	$0.80^{+0.08}_{-0.07}$	$0.69^{+0.06}_{-0.06}$
simpl	Γ	$2.78^{+0.25}_{-0.23}$	$2.22^{+0.39}_{-0.45}$	$2.63^{+1.23}_{-0.86}$	$1.90^{+0.42}_{-0.40}$
	FracSctr	$(8.68^{+2.15}_{-1.59})\times10^{-2}$	$(2.50^{+0.89}_{-0.58})\times10^{-2}$	$(1.38^{+2.56}_{-0.61})\times10^{-2}$	$(1.74^{+0.52}_{-0.20})\times10^{-2}$
	UpScOnly	1.0*	1.0*	1.0*	1.0*
diskw	$\dot{M}$	$0.45^{+0.03}_{-0.02}$	$0.47^{+0.02}_{-0.02}$	$0.46^{+0.02}_{-0.02}$	$0.45^{+0.02}_{-0.01}$
	Δr	$8.09^{+1.16}_{-0.80}$	$7.96^{+0.66}_{-0.73}$	$8.29^{+0.82}_{-0.67}$	$7.60^{+0.59}_{-0.47}$
	norm	1.0*	1.0*	1.0*	1.0*
gaussian	LineE	$6.44^{+0.20}_{-0.20}$	$6.55^{+0.20}_{-0.20}$	$6.48^{+0.18}_{-0.20}$	$6.43^{+0.19}_{-0.19}$
	Sigma	0.5*	0.5*	0.5*	0.5*
	norm	$(2.25^{+0.70}_{-0.62})\times10^{-4}$	$(2.15^{+0.57}_{-0.59})\times10^{-4}$	$(2.10^{+0.60}_{-0.57})\times10^{-4}$	$(1.86^{+0.50}_{-0.49})\times10^{-4}$
constant factor		1.020*	1.021*	1.021*	1.016*
χ^2/ν			182.28/164 [1.1114]		

Best-fitting model parameters for the four longest exposure RXTE spectra of LMC X-3. All errors are quoted at the 90 % confidence level ($\Delta\chi^2$ = 2.706). Parameters which were fixed during the fit are marked with an asterisk. tbabs(a) is for local absorption which is likely connected to the wind from the companion star. The units are as follows: column density is in 10^{22} cm^{-2} , normalizations are in photons cm^{-2} s^{-1} , line energy and width are in keV, and accretion rate is in unit of Eddington accretion rate, Δr is in r_g .

6.Conclusions

- The apparent decrease of the spin in LMC X-3 and GRS 1915+105 with luminosity can be due to an outflow
- Here we show that a model with a fixed spin and a luminosity-dependent truncation radius can fit the data.
- We also show that in principle various scenarios can be differentiated by the measurement of the exact shape of the thermal disk component. However, the expected differences are small and the RXTE long exposure data are not sensitive enough to provide a unique answer.

7.Reference

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