Reverberation mapping of the disc wind in ultraluminous X-ray source NGC 5408 X-1

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Abstract. Recent observational evidences suggested that ultraluminous X-ray sources (ULXs) which are in supercritical accretion rate might release the outflowing wind and change the geometry to slim disc. However, the exact structure of the disc is still unclear. In this work, we develop a simple reverberation model to analyse the X-ray time lags of the ULX NGC 5408 X-1, in order to determine the geometry of the disc and the outflowing wind. The data of NGC 5408 X-1 from the XMM-Newton archive are binned into three groups based on the instrument count rates, i.e. low, medium and high count rates. The lag profiles are then extracted from each group. Fitting the models to the lag data suggests that the wind-launching radius tends to increase with the count rates, which is in agreement with the super-Eddington framework that prefers a stellar mass black hole (sMBH). The wind-launching radius for the sMBH is constrained to be in the order of $\sim 10^5 r_g$. We also report a degeneracy between the black hole mass and the wind launching radius. A more realistic geometry and model might be required to explain the time lags in NGC 5408 X-1.

1. Introduction

Ultraluminous X-ray sources (ULXs) are extragalactic, non-nuclear objects with X-ray luminosity ($L_X \gtrsim 10^{39}$ erg s$^{-1}$) for recent review, see [1]). Their extreme brightness could possibly be the results of the sub-Eddington accretion onto intermediate mass black holes (IMBHs) or super-Eddington accretion onto stellar mass black holes (sMBHs). Furthermore, coherent pulsations have been discovered in at least four ULXs, suggesting that they may also be super-Eddington accreting neutron stars (see [2] and references therein). The super-Eddington ULXs could release the exceeding luminosity by changing the geometry to the slim disc and launching the outflowing wind [3, 4]. Although the atomic features imprinting on the ULX spectra have confirmed the existence of outflowing wind, the exact structure of the disc and wind is still unclear.

The NGC 5408 X-1 is the nearby ULX ($d= 4$ Mpc) located in dwarf starburst galaxy, and is one of the brightest ULXs ($L_X \approx 1 \times 10^{40}$ erg s$^{-1}$) in the local Universe [5]. Previous studies reported that NGC 5408 X-1 exhibited the variability on both short and long timescales [6, 7]. The discovery of the soft lags as well as quasi-periodic oscillations (QPO) suggested that this ULX might be the IMBH [8]. However, there was also an argument that the QPO feature was not clear and distinct from those found in black hole binaries (BHBs), so the NGC 5408 X-1 is
unlikely to be the IMBH [9]. In this study, we revisit the observational data of NGC 5408 X-1 obtained from XMM-Newton. The reverberation mapping technique is employed to investigate the structure of the ULX disc wind as well as to estimate the central mass. This paper is organised as follows. In section 2, we describe the observations and data reduction. The data analysis, results and discussion are explained in Section 3. The conclusion is drawn in Section 4.

2. Observations and Data Reduction

The NGC 5408 X-1 observational data were obtained from the XMM-Newton Science Archive\(^1\); here, we selected only ones having exposure time longer than 10 ks to obtain high quality data. All observations used in this work are listed in Table 1. We performed the data reduction in the standard way\(^2\) using xmm-sas package. The periods of high background flaring activity were removed. We then extracted the light curves in soft (0.3–1 keV) and hard (1–7 keV) energy bands with the time bin resolution of 10.4 s from the 40′′circular region centred at the source position. The background was extracted from the source-free, rectangular region of 4500 × 2500 pixels. These steps were applied for all XMM-Newton data obtained from three cameras: pn, MOS1 and MOS2\(^3\). To study how timing properties depends on accretion rates, we divided the light curves into three groups according to the instrument count rates – low, medium and high count rate groups flagged in column 5 of Table 1. We then combined the pn, MOS1 and MOS2 light curves within each group to gain the best Signal-to-Noise (S/N) data, and these were used as the basis for further analysis.

![Table 1. Observations of NGC 5408 X-1 used in this study.](image)

| Observation ID   | Observed date | Exp. time\(^a\) (ks) | Count rate\(^b\) (count s\(^{-1}\)) | Group\(^c\) |
|------------------|---------------|-----------------------|-------------------------------------|------------|
| 0302900101       | 2006-01-13    | 88                    | 0.940 ± 0.004                       | Medium     |
| 0500750101       | 2008-01-13    | 52                    | 0.885 ± 0.004                       | Low        |
| 0653380201       | 2010-07-17    | 90                    | 1.029 ± 0.004                       | High       |
| 0653380301       | 2010-07-19    | 111                   | 1.021 ± 0.003                       | High       |
| 0653380401       | 2011-01-26    | 92                    | 0.974 ± 0.004                       | Medium     |
| 0653380501       | 2011-01-28    | 98                    | 0.925 ± 0.003                       | Medium     |

Notes. \(^a\)Useful exposure time after preformed data reduction. \(^b\)pn detector count rate in full band (0.3-10 keV). \(^c\)The analysis group classified by the count rate in column 4.

3. Data Analysis, Results and Discussion

The cross-spectra between the soft and hard band light curves in each group were computed and averaged over 1.3\(^{f}\) Fourier-frequency bin. The observed lags of NGC 5408 X-1 were calculated using the IDL routines xmm-extract\(^4\). The negative (positive) lags mean the soft band lagging (leading) the hard band. The errors were estimated using Poisson noise correction [10].

We produced a simple model based on the framework suggested in [11]. A sketch of our model geometry was presented in figure 1. The full-model parameters consisted of the black

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1. https://nxsa.esac.esa.int
2. XMM-Newton ABC Guide: https://heasarc.gsfc.nasa.gov/docs/xmm/abc/
3. XMM-Newton has three X-ray cameras simultaneously operating during the observations (see more in https://xmm-tools.cosmos.esa.int/external/xmm_user_support/documentation/uhb/epic.html).
4. www.star.le.ac.uk/sav2/idl/XMM_Extract.pdf
hole spin ($a$), the inclination angle of the observer ($i$), the disc-emission radius ($R_{\text{disc}}$), the angle of the disc wind ($\theta_w$), and the wind-launching radius ($R_w$). For simplicity, we fixed $a = 0.998$ (a maximally-rotating black hole) so that the innermost stable circular orbit is extended close to the event horizon. The angle of the wind surface was also fixed at $\theta_w = 45^\circ$. The hard photon emission was assumed to be isotropic and was originated at $R_{\text{disc}} = 2.3r_g$ on the inner disc. The wind-launching radius was allowed to be a free parameter.

Figure 1. Sketch of the model geometry.

According to this scenario, the negative-soft reverberation lags (hereafter soft lags) are due to the delays between the directly observed hard photons from the inner disc and the soft photons being scattered from the wind surface. We produce the response function, $\psi(t)$, by tracking the photon trajectories between the source, the wind surface, and the observer. The response function determines the amount of reflected flux from the wind that an observer will detect as a function of time. Following the method described in [12], the response function in the Fourier frequency domain, $\Psi(f)$, is calculated so that the phase difference between soft and hard energy band is given by

$$\phi(f) = \tan^{-1}\left(\frac{\text{Im}(\Psi)}{1 + \text{Re}(\Psi)}\right),$$

(1)

where $\text{Im}(\Psi)$ and $\text{Re}(\Psi)$ are the imaginary and real parts of the response function $\Psi(f)$. The time lags then are calculated via

$$\tau(f) = \frac{\phi(f)}{2\pi f}.$$  

(2)

Note that equation (1) assumed equal contribution of the hard continuum and soft reflected fluxes in the energy bands where time lags were estimated.

The models were fitted to the time-lag data of NGC 5408 X-1 using XSPEC.\(^5\) We assumed three possible types of central black hole: stellar mass black hole (sMBH; $M_{\text{BH}} \approx 10M_\odot$), massive stellar mass black hole (MSBH; $M_{\text{BH}} \approx 100M_\odot$) and intermediate mass black hole (IMBH; $M_{\text{BH}} \approx 1000M_\odot$). The fitting results were shown in figure 2 and the best-fit parameters were listed in Table 2. It is clear that the goodness of fit is not significantly different in all cases, so the black hole mass cannot be self-consistently constrained. Interestingly, with this simple model, there was probably a degeneracy between the black hole mass and the wind launching.

\(^5\) [https://heasarc.gsfc.nasa.gov/xanadu/xspec/]
Figure 2. The fitting results for NGC 5408 X-1 in case of 10M\(_\odot\) black hole mass. The data are shown in blue (low count rate), green (medium count rate) and red (high count rate) lines with error bars. The models are shown in black lines in all cases.

Table 2. The best-fitting model parameter for the lag-frequency data of NGC 5408 X-1.

| The Black hole type | Spectral bin | \(R_w \times 10^3 [r_g]\) | \(\chi^2 / \text{d.o.f.}\) |
|---------------------|-------------|---------------------------|-----------------------------|
| sMBH \((10M_\odot)\) | Low         | 106.04\(^{+64.49}_{-40.30}\) | 20.53/10                   |
|                     | Medium      | 146.48\(^{+22.95}_{-25.78}\) | 3.62/10                    |
|                     | High        | > 125.43                  | 28.44/10                   |
| MSBH \((100M_\odot)\) | Low        | 13.00\(^{+4.11}_{-3.47}\) | 19.31/10                   |
|                     | Medium      | 14.84\(^{+2.27}_{-1.88}\) | 2.43/10                    |
|                     | High        | 30.59\(^{+7.76}_{-21.83}\) | 28.70/10                   |
| IMBH \((1000M_\odot)\) | Low        | 1.05\(^{+0.63}_{-1.05}\)  | 20.18/10                   |
|                     | Medium      | 1.45\(^{+0.22}_{-0.24}\)  | 3.86/10                    |
|                     | High        | 2.61\(^{+0.82}_{-1.26}\)  | 27.19/10                   |

radius. If the black hole mass is larger, the same lag amplitude could still be explained by a smaller distance from the centre to the wind-launching radius.

However, the study [8] suggested that NGC 5408 X-1 contained IMBH based on the detection of type-C QPOs, analogous to those seen in BHBs. On the other hand, [9] argued that the detected lag-frequencies were extended much broader than that of QPOs so that they might not be comparable to that of BHBs. In addition, [9] suggested that the soft lags could be, perhaps, a result of hard photons scattering with the wind, supporting the super-Eddington accretion scenario. Crucially, the detection of the NGC 5408 X-1 outflowing wind have been recently confirmed by the work [4]. Even though we cannot rule out the IMBH scenario based on the fitting results, we might regard this as the model with a wrong disc geometry since the 1000M\(_\odot\) black hole with \(L_X \sim 10^{40}\) erg s\(^{-1}\) is \(~10\%\) Eddington luminosity so that it is unlikely to launch the strong, radiation pressure driven wind. Furthermore, we find that the values of \(R_w\) as shown in Table 2 tend to increase with the count rates, which is consistent with the super-Eddington
framework [3]. Given these, we argue that the super-Eddington models are the most feasible scenario to explain the soft lags.

In fact, the work [13] proposed that the hard photons from the disc could be reflected by optically thin material, i.e. the wind, from far above the black hole, and reprocessing on the disc at \( \sim 10^5 r_g \), which roughly the same order with the value of \( R_w \sim 10^5 r_g \) obtained by our sMBH models. However, the location of the wind constrained by observations is \( \lesssim 25r_g \) [4], which is substantially lower than that suggested by our models. This implies that the wind structure might be much more complicated than that of our simple model. We also attempted adding power-law components to take into account the positive lags, but the fits were not significantly improved. Nevertheless, our model could be further improved in several ways, for example, by allowing \( \theta_w \) and \( R_{\text{disc}} \) to be varied. A more complex geometry may be required but it could also lead to many model degeneracies. Simultaneously fitting the mean and lag spectra may help break these degeneracies.

4. Conclusion

We produced a simple model to explain the time lags in NGC 5408 X-1. The soft lags were the result of the additional time the photons take from the disc emission radius to the surface of the wind. There was probably a model degeneracy between the black hole mass and the the \( R_w \), hence the true value of mass could not be well constrained. Our results suggest that, regardless of the black hole mass, the values of \( R_w \) tend to increase with the count rates. This is in agreement with the super-Eddington framework that prefers the sMBH. The wind-launching radius is in the order of \( \sim 10^5 r_g \) in our sMBH case which somehow seems to be further than what estimated in previous literature. Strict to the sMBH scenario, the wind structure should be much more complicated than that of our simple model.

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