

Investigating unusual flux drops in 4U 1630–472 during its 2012 outburst

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The black hole X-ray binary 4U 1630–472 shows outbursts repeatedly with an interval of about 600 days. We studied the 2012 outburst, which was one of the biggest outbursts of the source. We found unusual X-ray flux drops by $\sim 50\%$ with a duration of ~ 1 day at its brightest phase, which is much shorter than the timescale of accretion but longer than the dynamical timescale in the inner region of the accretion disk. To understand the cause of the drops, we compared the *Swift* and MAXI spectra obtained during and outside the drops. We found that during the flux drops, the source decreased in flux without significantly changing its spectral shape. We consider a possible interpretation for the observed spectral variation: fully ionized, Compton-thick gas passed through our line of sight and reduced the apparent X-ray flux.

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1. INTRODUCTION

The Galactic transient black hole X-ray binary (BHXR) 4U 1630–472 was discovered by *Uhuru* [1] and has been monitored for several decades. It is known to exhibit recurrent outbursts with an interval of about 600 days (Fig. 1). The outburst activity of 4U 1630–472 has been discussed in the context of the disk instability model (DIM) [2]. Previous studies have reported that 4U 1630–472 shows distinct spectral states during the bright phases of its outbursts [3], like other typical BHXBs. The canonical spectral states include the high/soft state (HSS), in which the X-ray spectrum is dominated by thermal emission from the accretion disk; the low/hard state (LHS), whose spectrum is well described by a hard power-law component; and the very high state (VHS), which appears during a limited phase around the outburst peak and is characterized by strong Comptonized emission in addition to the disk component. These state changes provide important insights into the structure of the accretion disk and corona in the vicinity of the black hole and their evolution. In particular, during outbursts in which these transitions occur, 4U 1630–472 brightens up to several hundred mCrab, allowing detailed studies of its spectral and timing evolution on short time scales.

In this work, we focus on the 2012 outburst of 4U 1630–472, which was one of the brightest and longest outbursts ever observed and has been classified as a “superoutburst” of this source, and whose high-luminosity phases have been studied in detail in previous works [4]. Using X-ray light curves using public data from the MAXI/Gas Slit Camera (MAXI/GSC) and the *Swift*/Burst Alert Telescope (BAT), we found unusual flux drops on timescales of ~ 1 day, characterized by a significant decrease in flux without appreciable changes in the spectral shape.

In this proceeding, we present the details of the flux drops and show the results of spectral analysis around these unusual flux drops. We adopt a distance to 4U 1630–472 of 11.5 ± 1 kpc [5] and an inclination angle of 70° ([6], [7]) to estimate the inner disk radius (R_{in}). A more detailed analysis covering a broader phase of the outburst, including short-timescale variability, will be presented in a separate paper (Kang et al. in prep).

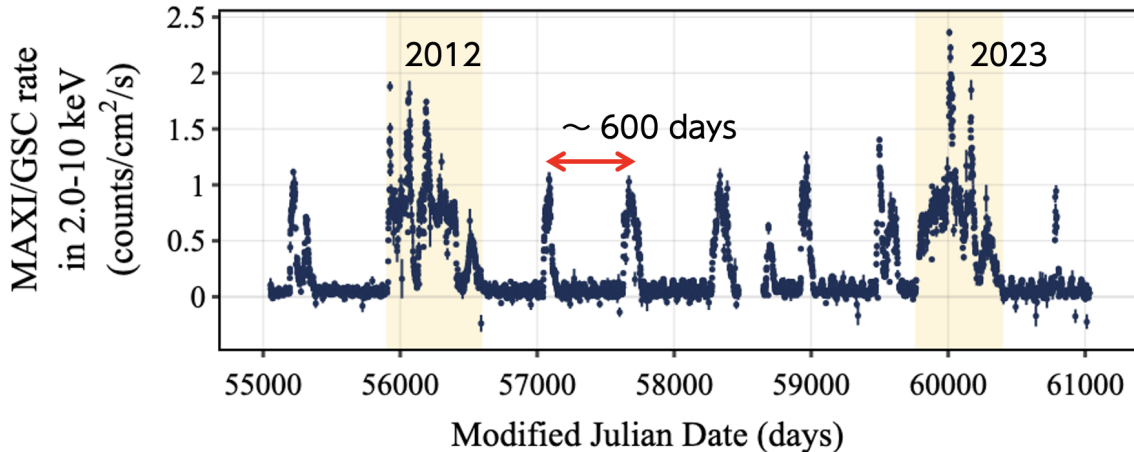


Figure 1: Long-term MAXI/GSC light curve of 4U 1630–472 in the 2.0–10.0 keV energy band. The source exhibits recurrent outburst with an interval of about 600 days. Superoutbursts during the shaded epoch lasted for a long time (~ 500 days) and was brighter than the normal outburst.

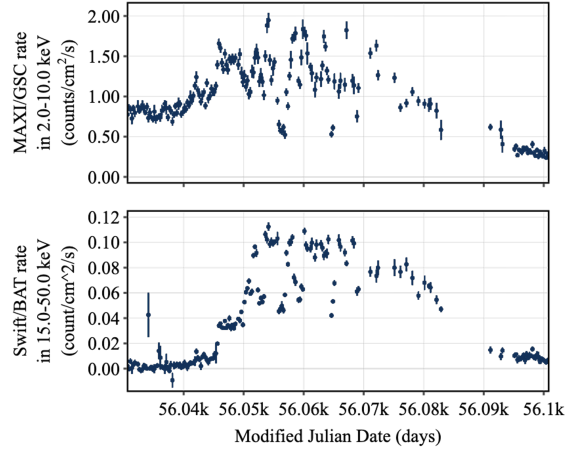


Figure 2: 6-hour binned light curves of 4U 1630–472 during the 2012 outburst, obtained with MAXI/GSC in the 2 – 10 keV band (top) and with *Swift*/BAT in the 15 – 50 keV band (bottom). Flux drops of about 50 % are observed at MJD 56056 and 56064 in both light curves.

2. OBSERVATIONS AND DATA REDUCTION

2.1 Light curve

Figure 2 shows the MAXI/GSC and *Swift*/BAT light curves during the period of interest in the 2012 outburst. MAXI/GSC has been monitoring 4U 1630–472 since the start of MAXI operation in 2009. We created the 6-hour binned light curve from the public MAXI/GSC orbital light curve¹. We also created the *Swift*/BAT light curve from *Swift*/BAT Hard X-ray Transient Monitor² using the same bin size and time intervals as those adopted for MAXI/GSC. As shown in Fig. 2, flux drops of about 50 % are observed in both light curves with a duration of ~ 1 day, at MJD 56056 and 56064. Such flux drops, occurring on timescales shorter than the overall outburst evolution yet longer than typical short-term variability, and appearing with comparable amplitudes in both the soft and hard X-ray light curves, have not been reported previously at least for this source.

2.2 Spectrum

Around the unusual flux drops, *Swift*/X-ray Telescope (*Swift*/XRT) observed the source several times in Windowed Timing (WT) mode (Tab. 1). Although a pointed observation was performed during the flux drop on MJD 56056, no such observation was available during the flux drop on MJD 56064. Therefore, we focus on the flux drop observed on MJD 56056 in this study. We obtained the *Swift*/XRT data from the HEADAS archive and created the *Swift*/XRT cleaned event lists and exposure maps using `xrtpipeline`. We extracted source events from a circular region (the radius were about 20 pixels) with the central several pixels excluded to mitigate pile-up effects, while background events were taken from a surrounding annular region including the outermost 20 pixels [5]. The centers of these regions were set at the pixel with the highest count rate. We created the ancillary response matrix files using `xrtmkarf` with the exposure

¹http://maxi.riken.jp/star_data/J1634-473/J1634-473.html

²<https://swift.gsfc.nasa.gov/results/transients/weak/4U1630-472/>

map created through `xrtpipeline`. We used the response matrix file in the calibration database (CALDB) corresponding to the observation period (`swxwt0to2s6_20110101v015.rm.f`). We also obtained the *Swift*/BAT data corresponding to the same MJDs as the *Swift*/XRT observations. We downloaded the *Swift*/BAT survey-mode data from the HEADAS archive³, processed them with the `ftool batsurvey`, and generated the spectrum for each MJD using the script `make_survey_pha`. We downloaded MAXI/GSC data with the `ftool mxdownload_wget` and created the spectra and response files with `mxproducts`.

Table 1: List of *Swift*/XRT observation of 4U 1630–472 around the unusual flux drops

Date	MJD	Obsid	Exposure (s)
2012-04-28	56045	00521085000	1340
2012-05-01	56048	00031224010	1148
2012-05-03	56050	00521442000	193
2012-05-09	56056	00031224011	998
2012-05-12	56059	00031224012	1022
2012-05-15	56062	00031224013	1001
2012-05-18	56065	00031224014	1023

3. SPECTRAL ANALYSIS AND RESULTS

We performed spectral analyses of simultaneous MAXI/GSC and *Swift* data around the flux drops. The spectra were grouped to have a minimum of 30 counts per bin, and the fitting was performed using the χ^2 statistic with XSPEC version 12.14.0. We fit the spectra with the multicolored disk blackbody model (`diskbb`) [8] and an additional Comptonisation component, multiplied by interstellar absorption (using the `TBabs` model; [9]). For the Comptonization component, we adopted the convolution model `simpl` [10]. We first fit the individual spectra allowing N_{H} to vary and obtained an averaged value of $N_{\text{H}} = 11.4 \times 10^{22} \text{ cm}^{-2}$. We then fixed N_{H} at this value and derived the final best-fit parameters.

Fig. 3 shows the representative spectra during and outside the flux drops. In the first observation (MJD 56045), the source was in the high/soft state. It then made a state transition to the very high state with strong Comptonisation from around MJD 56048. This state continued until the last observation on MJD 56065. Remarkably, the spectral shape during the flux drop remained almost the same as that in the normal very high state, despite the significant decrease in flux.

Fig. 4 plots the time variation of the best-fit parameters. In the high/soft state, the inner disk radius inferred from the `diskbb` normalization, using the distance and inclination adopted in Section 1, was $R_{\text{in}} = 20.8_{-0.6}^{+0.7} \text{ km}$, corresponding to $\sim 1.4 R_{\text{g}}$ (where R_{g} is the gravitational radius, GM_{BH}/c^2) for an assumed black hole mass M_{BH} of $10 M_{\odot}$. Here, we focus on relative changes in R_{in} rather than its absolute value. In the high/soft state, the standard accretion disk is generally expected to extend down to the vicinity of the innermost stable circular orbit (ISCO; e.g., [11]). We therefore assume that the inner disk radius measured in the high/soft state represents the minimum

³<https://heasarc.gsfc.nasa.gov/FTP/swift>

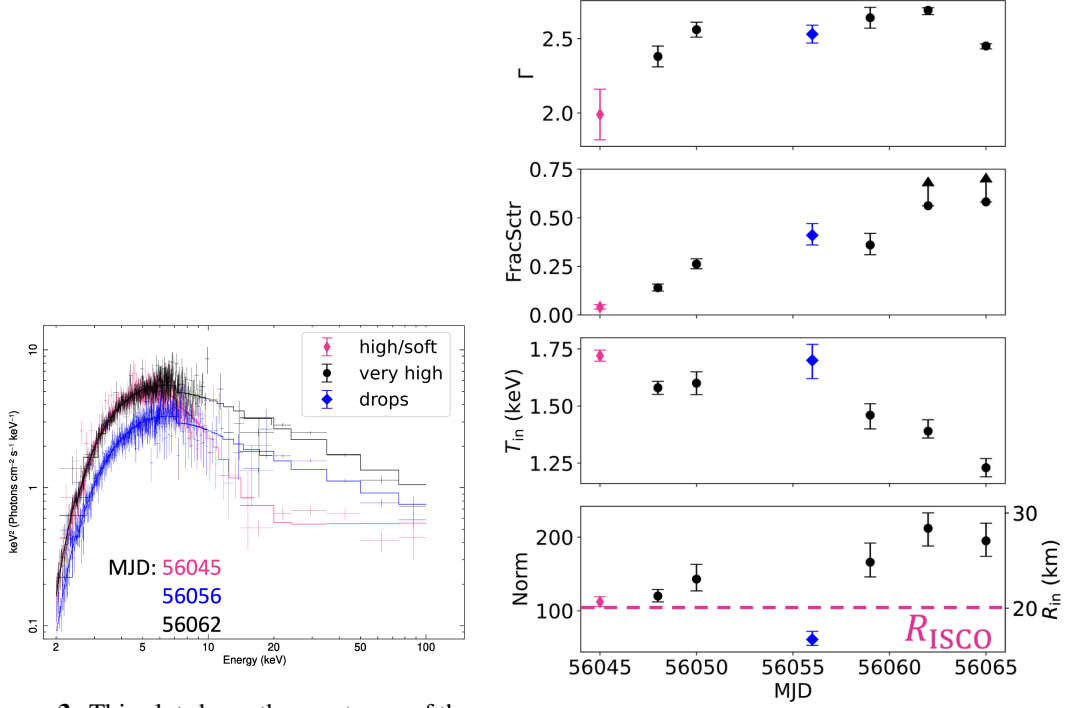


Figure 3: This plot shows the spectrums of three state. The magenta data point is in the high/soft state on MJD 56045. The blue point corresponds the best-fit parameters (TBabs \times diskbb \times simpl) to the flux drop. The black point is in the normal very high state.

Figure 4: This plot shows the time variation of state on MJD 56045. The data points are plotted using the same color scheme as in Fig. 3.

radius of the standard disk. Under this assumption, we found an unusual behavior that R_{in} during the flux drop appears smaller than that in the high/soft state.

4. DISCUSSION AND SUMMARY

We discovered unusual X-ray flux drops with a duration of ~ 1 day during the brightest phase of the 2012 outburst of 4U 1630–472. The timescale of the drops is much longer than the dynamical timescale of the accretion disk, $t_{\text{dyn}} \sim 1/\Omega \sim 10^{-3}\text{--}10^{-2}$ s at the radius of $r = 10\text{--}100R_g$, where Ω is Keplerian angular velocity, assuming the black hole mass of $M_{\text{BH}} = 10 M_{\odot}$. On the other hand, it can be comparable to the viscous timescale in the innermost disk region. We obtain $t_{\text{vis}} \sim \frac{1}{\alpha\Omega} \left(\frac{r}{H}\right)^2 \sim 10^{-3}\text{--}1$ day at the radius of $r = 10\text{--}100 R_g$, assuming the viscosity parameter $\alpha \sim 0.01\text{--}0.1$ [12] and the disk scale height with respect to the radius of $H/r \sim 0.01$. This is broadly consistent with the observed ~ 1 day flux-drop timescale. Variations in the mass accretion rate occurring close to the inner disk radius could therefore produce a flux change on this timescale. However, such variations would be expected to modify the spectral shape, which contradicts the present case, in which the flux decreased without significant spectral changes. For this reason, the observed variation is unlikely to arise from changes in the mass accretion rate.

One possible interpretation of these results is that highly ionized plasma, which is optically thick for scattering, temporarily passed through our line of sight. If the plasma is almost fully ionized,

the observed flux reduction could be caused mainly by Thomson scattering. In this scenario, the spectrum produced by the accretion disk and corona remains unchanged, while the apparent flux decreases, naturally explaining the nearly constant spectral shape. The apparent decrease in the inner disk radius could be caused by the reduction of the observed disk flux due to scattering.

This interpretation is distinct from classical dipping events, in which partially ionized material produces significant photoelectric absorption. In such cases, changes in the disk temperature and spectral shape are expected, whereas the nearly constant disk temperature observed during the flux drops in 4U 1630–472 provides a strong constraint against this possibility.

Taking into account that blueshifted absorption lines from disk winds are sometimes observed in such very bright intermediate states [13], the plasma responsible for the unusual changes in the continuum spectrum may be related to a wind. Indeed, previous studies of GRO J1655–40 reported similar behavior of the continuum spectrum, which was interpreted as being caused by an optically thick wind [14, 15], although it was suggested to have exceeded the Eddington luminosity, considerably higher than the luminosity of 4U 1630–472 in this study. If the wind is almost fully ionized, it would not produce detectable absorption lines, which is consistent with the absence of absorption features in the present XRT spectra. If scattering by such a wind, or other optically-thick gas, is the actual cause of the unusual behavior, the short-term variability may be reduced during the flux-drop phases. More comprehensive analyses over a broader range of the outburst, including short-timescale variability, will be presented in a forthcoming paper (Kang et al. in prep).

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