The spins of Galactic black holes from *Insight-HXMT*

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ABSTRACT

*Insight-HXMT* is the first Chinese X-ray astronomical mission. With a 1-250 keV bandpass, an energy resolution of 150 eV at 6 keV, and without being subject to pile-up distortions, it is suitable to study bright X-ray sources like Galactic black holes. In the present paper, we study *Insight-HXMT* observations of the X-ray binaries MAXI J1535–571 and 4U 1630–472 during their outbursts in 2017 and 2020, respectively. From the analysis of the reflection features, we are able to infer the black hole spin parameter in the two sources. For MAXI J1535–571, we find a spin parameter very close to 1, $a_*=0.9916\pm0.0012$ (90% C.L.), which is consistent with the previous NuSTAR measurement. For 4U 1630–472, we find a moderately high value of the black hole spin parameter, $a_*=0.817\pm0.014$ (90% C.L.), which is lower than the almost extremal value found with NuSTAR data.

Key words: accretion, accretion discs – black hole physics

1 INTRODUCTION

In 4-dimensional general relativity, black holes are relatively simple objects and completely characterized by only three parameters: the mass $M$, the spin angular momentum $J$, and the electric charge $Q$. This is the result of the no-hair theorem, which is valid under quite general and physically reasonable assumptions (Carter 1971; Robinson 1975; Chruściel et al. 2012). Astrophysical black holes are normally expected to have a negligible electric charge (Bambi 2017a), and therefore they should be described only by the mass and the spin angular momentum. The mass of a black hole can be inferred by studying the motion of material orbiting the compact object; in the case of black holes in X-ray binaries, we can study the orbital motion of the companion star (Casares & Jonker 2014). Measurements of black hole spin are more challenging: the spin has no gravitational effects in Newtonian gravity and therefore spin measurements require the analysis of relativistic effects occurring in the strong gravity region close to the black hole event horizon. On the other hand, accurate black hole spin measurements are important to understand the formation and the evolution of these systems (Reynolds 2014, 2019; Bambi et al. 2021). In the case of stellar-mass black holes, the spin is generally thought to reflect the formation mechanism of the object. For supermassive black holes in galactic nuclei, the black hole spin is thought to be determined by the merger history of the host galaxy as well as by the accretion history of the compact object.

X-ray reflection spectroscopy is currently the most popular method for measuring the spins of accreting black holes (Reynolds 2014; Brenneman 2013; Bambi et al. 2021). So far it has provided the spin measurement of over twenty stellar-mass black holes and about forty supermassive black holes (Bambi et al. 2021). The method relies on the analysis of the reflection spectrum generated from a cold and thin disk illuminated by a hot corona. The thermal spectrum of geometrically thin and optically thick accretion disks is peaked in the soft X-ray band for stellar-mass black holes and in the UV band for the supermassive ones. Thermal photons from the inner part of the accretion disk can inverse Compton scatter off free electrons in the corona, which is some hotter ($\sim100$ keV) plasma close to the black hole. A fraction of the Comptonized photons can illuminate the disk: Compton scattering and absorption followed by fluorescent emission generate the reflection spectrum (Ross & Fabian 2005; García & Kallman 2010). One of the most prominent features in the reflection spectrum is normally the iron Kα complex, which is around 6.4 keV in the case of neutral or weakly ionized iron atoms and can shift up to 6.97 keV in the case of H-like iron ions. Since the iron Kα complex is an intrinsically narrow feature, it is particularly suitable to measure the effects of relativistic blurring, estimate black hole spins, and even test fundamental physics (see, e.g., Bambi 2017b; Tripathi et al. 2021).

*Insight-HXMT* is the first Chinese X-ray astronomical mission (Zhang et al. 2014). It was successfully launched in June 2017. It has three slat-collimated instruments: the Low Energy X-ray Telescope (LE, 1-15 keV), the Medium Energy X-ray Telescope (ME, 5-30 keV), and the High Energy X-ray Telescope (HE, 20-250 keV) (Huang et al. 2018). The energy resolution of LE is 150 eV at 6 keV. The three instruments are hardly subject to pile-up distortions, which makes them suitable to observe bright sources. In this work, we present the analysis of *Insight-HXMT* observations of the Galactic black holes MAXI J1535–571 and 4U 1630–472. We select reflection dominated spectra of these sources and we are able to
measure the spin of the two black holes. The measurements of the black hole spins of MAXI J1535–571 and 4U 1630–472 were previously reported by Xu et al. (2018a) and King et al. (2014), respectively, in both cases by analyzing NuSTAR data (Harrison et al. 2013). Our work confirms the very high spin of the black hole in MAXI J1535–571 found by Xu et al. (2018a), while we do not find any very high spin parameter for the black hole in 4U 1630–472 as reported in King et al. (2014).

The paper is organized as follows. In Section 2, we present the sources and the observations of our study. In Section 3, we report our spectral analysis. Discussion and conclusions are in Section 4.

2 OBSERVATIONS AND DATA REDUCTION
Tab. 1 shows the list of Insight-HXMT observations of black hole binaries as of 30 September 2021. There are several observations of Cyg X-1 and GRS 1915+105, but there are no spectra with strong reflection features. In the case of MAXI J1348–630 and MAXI J1820+070, there are some Insight-HXMT spectra with reflection features, but the iron line is weak and/or not very broad, and eventually it is not possible to constrain the black hole spin. For GX 339–4, the analysis of the reflection features of this source is impossible to constrain the spin of the black hole. The spectra of Swift J1658.2–4242 are contaminated by some nearby sources, which cannot be removed and prevent any accurate analysis of the reflection features of this source. In the end, we found that black hole spin measurements from the analysis of relativistically blurred reflection features are only possible for MAXI J1535–571 and 4U 1630–472. In particular, we found 8 observations of MAXI J1535–571 and 5 observations of 4U 1630–472 suitable for our study.

Tab. 2 lists the black hole spin measurements obtained by the analysis of Insight-HXMT observations to date. There are two spin measurements obtained from the continuum-fitting method, namely the analysis of the thermal spectrum of the disk (Zhang et al. 1997; McClintock et al. 2014). For GRS 1915+105, an estimate of the black hole spin has been inferred using QPOs, but there is not yet a common consensus on the exact mechanism responsible for QPOs, so that measurement should be taken with caution even if it agrees with previous measurements obtained from the continuum-fitting and the iron line methods. For MAXI J1535–571, Kong et al. (2020) analyze only one of the 8 Insight-HXMT observations of MAXI J1535–571, so they have a very low statistics.

2.1 Observations
The X-ray binary transient MAXI J1535–571 was discovered by MAXI (Matsuoka et al. 2009) on 2 September 2017 (Nakahira et al. 2018). During the outburst, extremely bright radio and sub-mm counterparts were detected, suggesting that the source is a low-mass X-ray binary with a black hole (Sridhar et al. 2019). From the analysis of AstroSat data, Sridhar et al. (2019) inferred the black hole mass \( M = (10.4 \pm 0.6) M_\odot \) and the distance from us \( D = 5.4^{+1.4}_{-1.2} \) kpc.

4U 1630–472 is a recurrent black hole X-ray binary. It was discovered by the Vela 5B and Uhuru satellites in 1969 (Priedhorsky 1986; Jones et al. 1976) and has regular outbursts of 100-200 days followed by quiescent periods of about 500 days (Tetarenko et al. 2016). The hydrogen column density along its line of sight is very high, probably close to \( 10^{23} \text{cm}^{-2} \) (Gatuzz et al. 2019), which prevents a dynamical measurement of the mass of the black hole from the study of the motion of the companion star. From the scaling of the photon index with the mass accretion rate, Seifina et al. (2014) inferred a black hole mass around 10 \( M_\odot \). IR observations suggest a distance of 10-11 kpc from us (Augusteijn et al. 2001; Seifina et al. 2014).

Tab. 3 shows the observations of MAXI J1535–571 and 4U 1630–472 analyzed in our work. For MAXI J1535–571, we found 8 Insight-HXMT observations (out of 18) with strong reflection features. However, some observations are consecutive or almost consecutive. After checking the absence of variability in the flux and hardness of the source in the consecutive observations, we merged them together into three spectra as shown in Tab. 3. Fig. 1 shows the hardness-intensity diagram (HID) of the 2017 outburst of the source obtained from the MAXI observations and the location of our three Insight-HXMT spectra. In the case of 4U 1630–472, we found 5 observations (out of 51) with some reflection features. These observations are short and almost consecutive. Since the source does not show any variability in flux and hardness during the two day period of these observations, we merged them into a single spectrum. Fig. 2 shows the HID of the 2020 outburst of 4U 1630–472 as inferred from MAXI and the red start shows the position of the Insight-HXMT spectrum.

2.2 Data Reduction
Following the official user guide\(^1\), we extracted spectra using the software HXMTDAS v2.04 and the pipeline\(^2\). We also used the latest calibration database CALDBV v2.05. The criteria for estimating good time intervals is as follows: 1) the elevation angle is larger than 10 degree; 2) the geomagnetic cut-off rigidity is larger than 8 GeV; 3) the pointing offset angle is smaller than 0.1 degree; 4) at least 300 s away from the South Atlantic Anomaly (SAA). The spectral backgrounds were calculated by using the tools LEBKGMAP, MEBKGMAP, and HEBKGMAP (Liao et al. 2020b; Guo et al. 2020; Liao et al. 2020a).

3 SPECTRAL ANALYSIS
For the spectral analysis of MAXI J1535–571 and 4U 1630–472, we consider the energy bands 2-8 keV (LE), 10-20 keV (ME), and 30-80 keV (HE). The XSPEC v12.10.1s software package (Arnaud 1996) is used in our work. We bin the Insight-HXMT spectra in order to reach a minimal signal-to-noise ratio of 25. We adopt abundances from Wilms et al.

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1. [http://hxmten.ihep.ac.cn/SoftDoc.jhtml](http://hxmten.ihep.ac.cn/SoftDoc.jhtml)
2. [http://code.ihep.ac.cn/lljdirac/insight-hxmt-code-collection/-/blob/master/version2.04/HXMT_analysis_2.04_2020.py](http://code.ihep.ac.cn/lljdirac/insight-hxmt-code-collection/-/blob/master/version2.04/HXMT_analysis_2.04_2020.py)
The spins of Galactic black holes

Table 1. Summary of the Insight-HXMT observations of black hole binaries as of 30 September 2021.

| Source          | Number of observations | Total exposure time (ks) |
|-----------------|------------------------|--------------------------|
| 4U 1543–47      | 51                     | 1070                     |
| 4U 1630–472     | 55                     | 700                      |
| Cyg X-1         | 140                    | 1840                     |
| EXO 1846–031    | 42                     | 800                      |
| GRS 1716–249    | 2                      | 250                      |
| GRS 1915+105    | 150                    | 2600                     |
| GX 339–4        | 128                    | 1930                     |
| H 1743–322      | 40                     | 440                      |
| MAXI J1348–630  | 126                    | 2620                     |
| MAXI J1535–571  | 18                     | 430                      |
| MAXI J1543–564  | 1                      | 80                       |
| MAXI J1727–203  | 3                      | 30                       |
| MAXI J1820+070  | 146                    | 2560                     |
| Swift J1658.2–4242 | 23               | 470                      |
| Swift J1728.9–3613 | 23            | 250                      |

Table 2. Summary of black hole spin measurements with Insight-HXMT data as of 30 September 2021. CFM = continuum-fitting method; XRS = X-ray reflection spectroscopy; QPOs = Quasi-periodic oscillations.

| Source          | Spin measurement | Method | Reference                  |
|-----------------|------------------|--------|----------------------------|
| Cyg X-1         | > 0.967 (3-σ)    | CFM    | Zhao et al. (2020)         |
| GRS 1915+105    | 0.99836 ± 0.00028 (90% C.L.) | QPOs   | Liu et al. (2021)         |
| GX 339–4        | > 0.88 (90% C.L.) | XRS    | Liu et al., in preparation |
| MAXI J1535–571  | 0.7^{+0.2}_{-0.3} (90% C.L.) | XRS    | Kong et al. (2020)        |
| MAXI J1820+070  | 0.2^{+0.2}_{-0.3} (1-σ) | CFM    | Guan et al. (2021)        |
| MAXI J1820+070  | 0.14 ± 0.09 (1-σ) | CFM    | Zhao et al. (2021)        |

Table 3. Summary of the Insight-HXMT observations of MAXI J1535–571 and 4U 1630–472 analyzed in the present work. We only report the LE exposure and counts. The observation IDs are in the form P011453500XXX (for MAXI J1535–571) or P020503000XXX (for 4U 1630–472). In the table, we only report the last three digits of the observation IDs.

| Source          | Observation | Observation ID | Observation date | LE exposure (ks) | LE counts (s^-1) |
|-----------------|-------------|----------------|------------------|------------------|------------------|
| MAXI J1535–571  | obs 1       | 101, 102, 103, 106, 107 | 2017 Sept 6-7  | 4.61             | 255.9            |
|                 | obs 2       | 144, 145        | 2017 Sept 12    | 4.32             | 981.7            |
|                 | obs 3       | 301             | 2017 Sept 15    | 0.598            | 1085             |
| 4U 1630–472     | obs 1       | 101, 102, 201, 202, 203 | 2020 Mar 19-20 | 13.87            | 56.03            |

(2000) and cross sections from Vernier et al. (1996). In what follows, the uncertainties on the estimates of the model parameters are at the 90% confidence level.

3.1 MAXI J1535–571

First, we fit the three spectra together with an absorbed continuum from thermal Comptonization (Model 0); in XSPEC language, the model is constant*tbabs*nthcomp. The multiplicative constant is the cross-calibration constant among the three instruments, LE, ME, and HE. tbabs describes the Galactic absorption (Wilms et al. 2000) and has only one free parameter, the hydrogen column density, \( N_H \). nthcomp describes the Comptonized photons from the corona (Zdziarski et al. 1996; Życki et al. 1999). We have three free parameters in nthcomp: the temperature of the seed photons from the disk, \( kT_{bb} \), the temperature of the electron in the corona, \( kT_e \), and the power-law photon index, \( \Gamma \). Fig. 3 shows the resulting data to best-fit ratio, where we can see a broad iron line peaked at 6-7 keV in the three spectra. The best-fit has \( \chi^2 = 8245.95/2529 = 3.26056 \).

To improve the fit, we add the model diskbb (Mitsuda et al. 1984), which describes the thermal spectrum of a thin accretion disk. This is our Model 1. We link the value of the inner temperature of the disk \( kT_{in} \) in diskbb with the temperature of the seed photons \( kT_{bb} \) in nthcomp. We find \( \chi^2 = 6703.98/2526 = 2.65399 \), and thus \( \Delta \chi^2 = -1541.97 \) with respect to Model 0.

For our Model 2, we add the reflection spectrum of the accretion disk. We use relxillCp (Daiser et al. 2013; García et al. 2013, 2014) and our total model is constant*tbabs*(diskbb+relxillCp). relxillCp includes nthcomp when the reflection fraction \( R_f \) is positive, so we remove nthcomp from the total model. The spacetime is de-
Figure 1. HID for the 2017 outburst of MAXI J1535–571 from MAXI/GSC (2-20 keV). The red, purple, and blue stars mark the observations analyzed in this work.

Figure 2. HID for the 2020 outburst of 4U 1630–472 from MAXI/GSC (2-20 keV). The red star marks the observation analyzed in this work.

Figure 3. Data to best-fit model ratios for obs 1 (top quadrant), obs 2 (central quadrant), and obs 3 (bottom quadrant) of Model 0 of MAXI J1535–571. Black, red, and green crosses are, respectively, for LE, ME, and HE data. In all observations we see a broad iron line peaked at 6-7 keV.

scribed by the dimensionless black hole spin parameter $a_*$, while the black hole mass does not directly enter the calculations of the reflection spectrum and therefore it is not a parameter of relxillCp. The black hole spin $a_*$, the inclination angle of the disk with respect to our line of sight $i$, and the iron abundance of the disk $A_f$ are left free in the fit and we impose they do not change values over the three spectra. The inner edge of the accretion disk $R_{in}$ is assumed to be at the innermost stable circular orbit (ISCO) of the spacetime, so it is not a free parameter in our fit and depends only on the value of the black hole spin $a_*$, as it is measured in units of the black hole gravitational radius $r_g = G M / c^2$. The outer edge of the accretion disk $R_{out}$ is fixed to 400 $r_g$. For the emissivity profile of the accretion disk, we adopt a broken power-law, so the have three parameters: the inner emissivity index $q_{in}$, the outer emissivity index $q_{out}$, and the breaking radius $R_{br}$. For obs 1, we find that a simple power-law is enough, so we set $q_{out} = q_{in}$ and we have only one free parameter. For obs 2 and obs 3, we find that a broken power-law provides a better fit than a power-law and we thus leave $q_{in}$, $q_{out}$, and $R_{br}$ free. The ionization parameter of the disk $\xi$ is left free in the fit and allowed to vary over obs 1, 2, and 3. Since relxillCp includes nthcomp, the model has also the photon index $\Gamma$ and the temperature of the electrons in the corona $kT_e$.

Tab. 4 shows the best-fit values for Model 2. The spectra and the data to best-fit model ratios for obs 1-3 are presented in Fig. 4. Compared to Model 1, $\Delta \chi^2 = 4036.55$ and $\chi^2 = 1.06527$. Our measurements of the black hole spin parameter and of the inclination angle of the disk are, respectively, $a_* = 0.9916 \pm 0.0012$ and $i = 74.2^{+0.7}_{-0.7}$ deg.

Last, we consider the possibility of the presence of a distant reflector and we add xillverCp (García & Kallman 2010) to the total model of Model 2. We impose that the distant reflector is neutral and we fix $\log \xi = 0$. However, we find that this new model does not improve the fit and $\Delta \chi^2 = 2666.51/2501 = 1.06618$, so we do not report here its results and our final model remain Model 2.

3.2 4U 1630–472

As in the case of MAXI J1535–571, even for the spectrum of 4U 1630–472 we start with an absorbed continuum from thermal Comptonization and the XSPEC model is constant*tbabs*nthcomp (Model 0). We find $\chi^2 = 9294.76/815 = 11.4046$.

In our Model 1, we add diskbb to include the thermal spectrum from the disk and the fit improves significantly with $\chi^2 = 1100.88/814 = 1.35244$ ($\Delta \chi^2 = -8193.88$ with respect to Model 0). The data to best-fit ratio of Model 1 is shown in Fig. 5.

For Model 2, we add a relativistically blurred reflection component with relxillCp and our total model becomes constant*tbabs*(diskbb+relxillCp). The emissivity profile of the accretion disk is still modeled with a broken power-law and we have three free parameters in the fit; namely $q_{in}$, $q_{out}$, and $R_{br}$. We find $\chi^2 = 937.00/804 = 1.1654$ ($\Delta \chi^2 = -163.88$ with respect to Model 1). Fig. 6 shows the model and the data to best-fit ratio. The estimates of the model parameters are reported in Tab. 5. Our measurements of the dimensionless black hole spin parameter and inclination angle of the disk are, respectively, $a_* = 0.817 \pm 0.014$ and
Table 4. Summary of the best-fit values of Model 2 and Model 2b of MAXI J1535–571. The reported uncertainties correspond to the 90% confidence level for one relevant parameter ($\Delta\chi^2 = 2.71$). We note that $q_{\infty}$ is allowed to vary from 0 to 1 in the fit, $A_F$ from 0.5 to 10, and $kT_e$ from 1 to 400 keV; in some observations, the fit is stuck at one of the boundaries of the parameter and there is no upper/lower uncertainty.

| Parameter                        | obs 1     | obs 2     | obs 3     | obs 1     | obs 2     | obs 3     |
|----------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| $t_{	ext{babs}}$ $N_{\text{H}}$ [10$^{22}$ cm$^{-2}$] | 6.39$^{+0.21}_{-0.14}$ | 6.05$^{+0.07}_{-0.05}$ | 7.19$^{+0.24}_{-0.12}$ | 6.40$^{+0.19}_{-0.22}$ | 5.99$^{+0.09}_{-0.07}$ | 7.12$^{+0.26}_{-0.19}$ |
| $T_{\text{in}}$ [keV]           | 0.269$^{+0.016}_{-0.016}$ | 0.225$^{+0.015}_{-0.015}$ | 0.230$^{+0.014}_{-0.014}$ | 0.269$^{+0.014}_{-0.015}$ | 0.220$^{+0.015}_{-0.014}$ | 0.227$^{+0.014}_{-0.015}$ |
| relxillCp                        |           |           |           |           |           |           |
| $q_{\infty}$                     | 1.83$^{+0.07}_{-0.07}$ | 1.0.0.3  | 1.0.0.9  | 1.79$^{+0.07}_{-0.07}$ | 1.0.1.4  | 9.8$^{+0.2}_{-0.16}$ |
| $q_{\text{out}}$                 | 0.8$^{+0.3}_{-0.4}$ | 0.9$^{+0.4}_{-0.4}$ | 1$^{+0.4}_{-0.4}$ | 0.9$^{+0.4}_{-0.4}$ | 0.9$^{+0.4}_{-0.4}$ | 0.9$^{+0.4}_{-0.4}$ |
| $R_{\text{br}}$ [$r_g$]          | 4.1$^{+1.2}_{-0.4}$ | 3.6$^{+1.6}_{-0.6}$ | –         | 3.8$^{+1.4}_{-0.6}$ | 3.3$^{+0.8}_{-0.9}$ | –         |
| $a_*$                            | $0.9916^{+0.0001}_{-0.0002}$ | $0.9978^{+0.0002}_{-0.0001}$ | $0.9991^{+0.0002}_{-0.0001}$ | $0.9978^{+0.0002}_{-0.0001}$ | $0.9991^{+0.0002}_{-0.0001}$ | $0.9978^{+0.0002}_{-0.0001}$ |
| $i$ [deg]                        | 74.2$^{+0.6}_{-0.7}$ | –         | –         | 76.4$^{+0.6}_{-0.7}$ | –         | –         |
| $\alpha_{13}$                    | 0.5$^{+0.05}_{-0.01}$ | 0.5$^{+0.04}_{-0.01}$ | 0.5$^{+0.04}_{-0.01}$ | 0.5$^{+0.04}_{-0.01}$ | 0.5$^{+0.04}_{-0.01}$ | 0.5$^{+0.04}_{-0.01}$ |
| $A_F$                            | –         | –         | –         | –         | –         | –         |
| log $\xi$ [erg cm s$^{-1}$]      | 3.0$^{+0.05}_{-0.08}$ | 2.43$^{+0.05}_{-0.04}$ | 2.69$^{+0.03}_{-0.05}$ | 3.0$^{+0.05}_{-0.08}$ | 2.43$^{+0.05}_{-0.04}$ | 2.70$^{+0.02}_{-0.05}$ |
| $\Gamma$                         | 1.89$^{+0.02}_{-0.02}$ | 2.57$^{+0.04}_{-0.00}$ | 2.58$^{+0.03}_{-0.05}$ | 1.89$^{+0.02}_{-0.02}$ | 2.57$^{+0.04}_{-0.00}$ | 2.57$^{+0.08}_{-0.00}$ |
| $kT_e$ [keV]                     | 36$^{+3}_{-2}$ | 400$^{+132}_{-128}$ | 400$^{+132}_{-128}$ | 36$^{+3}_{-2}$ | 400$^{+132}_{-128}$ | 400$^{+132}_{-128}$ |
| $R_L$                            | 0.39$^{+0.05}_{-0.04}$ | 0.319$^{+0.011}_{-0.012}$ | 0.52$^{+0.03}_{-0.04}$ | 0.36$^{+0.05}_{-0.06}$ | 0.320$^{+0.015}_{-0.017}$ | 0.52$^{+0.04}_{-0.05}$ |

$\chi^2/\nu$                     | 2667.43/2504 | –1.06527 | 2663.40/2503 | –1.06408 |

Figure 4. Best-fit models and data to best-fit model ratios for obs 1 (left panel), obs 2 (central panel), and obs 3 (right panel) of Model 2 of MAXI J1535–571. In the ratio plots, black, red, and green crosses are for LE, ME, and HE data, respectively.

$i = 4^{+6}_{-3}$ (B) at 90% confidence level, where (B) simply indicates that we reach the lower boundary $i = 0$ deg.

4 DISCUSSIONS AND CONCLUSIONS

4.1 MAXI J1535–571

In the previous section, we fit the Insight-HXMT spectra of MAXI J1535–571 assuming a broken power-law emissivity profile. Our final estimates of the black hole spin parameter $a_*$ and of the inclination angle of the disk are (90% C.L.)

$$a_* = 0.9916 \pm 0.0012, \quad i = 74.2^{+0.6}_{-0.7} \text{ deg}.$$

These measurements can be compared with those reported in Xu et al. (2018a) from the analysis of a NuSTAR observation on 7 September 2017, so overlapping our obs 1. For a broken power-law emissivity profile with $q_{\text{out}}$ fixed to 3 and $R_{\text{br}}$ fixed to 10 $r_g$, Xu et al. (2018a) obtain

$$a_* > 0.987, \quad i = 75^{+1}_{-3} \text{ deg},$$

which are in perfect agreement with our Insight-HXMT estimates. On the other hand, there are some discrepancies.
in the estimates of the other model parameters between our obs 1 and Xu et al. (2018a). In Xu et al. (2018a), $kT_{\text{in}} = 0.40 \pm 0.01$ keV in diskbb and $kT_{t} = 21.9 \pm 1.2$ keV and $R_{t} = 0.60^{+0.06}_{-0.16}$ in relxillCp, while the photon index $\Gamma$ and the ionization parameter $\xi$ are consistent with our estimates. However, there are also some differences in the model. First, Xu et al. (2018a) assume $q_{\text{out}} = 3$ and $R_{\text{br}} = 10 r_{g}$, so the only free parameter of the emissivity profile is $q_{\text{in}}$. Second, their model includes a distant reflector described by xillverCp. The inner edge of the disk is free in Xu et al. (2018a), not like in our case fixed to the ISCO radius, but they find it is consistent with the ISCO radius.

Xu et al. (2018a) consider even a lamppost emissivity profile (Dauer et al. 2013) and obtain a slightly higher $\chi^{2}_{\nu}$ ($\Delta \chi^{2} = 23$) with one less free parameter. For the lamppost model, their measurements of the black hole spin parameter and of the inclination angle of the disk are, respectively, $a_{*} > 0.84$ and $i = 57^{+1}_{-2}$ deg. Fitting our Insight-HXMT data with the lamppost model for the three spectra (not only obs 1), we find a worse fit with $\chi^{2}_{\nu} = 2864.76/2508 = 1.14225$. The measurement of the black hole spin parameter and of the inclination angle of the disk are now $a_{*} > 0.91$ and $i = 37.0^{+2.1}_{-1.4}$.

We note that there are other three spin measurements of MAXI J1535–571 reported in the literature. From the analysis of NICER data, Miller et al. (2018) find $a_{*} = 0.994 \pm 0.002$ (1-$\sigma$), which is consistent with our measurement and that in Xu et al. (2018a). From the analysis of AstroSat data, Sridhar et al. (2019) find $a_{*} = 0.67^{+0.16}_{-0.04}$ employing the lamppost emissivity profile of relxillCp. They also find an inclination angle around 40 deg when they do not include the distant reflector and around 80 deg with the distant reflector.

From the spectral analysis of the Insight-HXMT observation P011453500107 (one of the five observations in our obs 1 of MAXI J1535–571, see Tab. 3), Kong et al. (2020) infer the black hole spin parameter $a_{*} = 0.77^{+0.02}_{-0.01}$ (90% C.L.) employing the lamppost version of relxillCp. However, Kong et al. (2020) is mainly devoted to the timing analysis of the Insight-HXMT observations of MAXI J1535–571 and the measurement of the black hole spin is inferred from a short observation with a low number of photon counts.

For obs 2 and obs 3, we find that $q_{\text{in}}$ is stuck at the upper boundary of the parameter range and the value of $q_{\text{out}}$ is quite low. Such an emissivity profile is common in Galactic black holes (see, e.g., Xu et al. 2018b; Zhang et al. 2019; Tripathi et al. 2021) and may be interpreted as generated by a ring-like geometry located above the accretion disk (Miniutti et al. 2003; Wilkins & Gallo 2015; Riaz et al. 2020). We also note that in obs 2 and obs 3 the photon index $\Gamma$ is around 2.6 (it is $\sim 1.9$ in obs 1) and the coronal temperature is significantly higher than in obs 1. The differences in the emissivity profiles and in the values of the photon index and of the electron temperature between obs 1 and obs 2/obs 3 suggest important changes in the properties of the corona between 7 September 2017 and 12 September 2017.

\begin{table}[h!]
\centering
\begin{tabular}{|c|c|c|}
\hline
   & Model 2 & Model 2b \\
\hline
$N_{\text{H}}$ [10$^{22}$ cm$^{-2}$] & $10.37^{+0.15}_{-0.19}$ & $10.33^{+0.12}_{-0.09}$ \\
\hline
diskbb & & \\
$T_{\text{in}}$ [keV] & $1.47^{+0.03}_{-0.05}$ & $1.48^{+0.03}_{-0.03}$ \\
\hline
relxillCp & & \\
$q_{\text{in}}$ & $6.55^{+0.78}_{-0.14}$ & $6.1^{+0.4}_{-0.2}$ \\
$q_{\text{out}}$ & $2.5^{+0.2}_{-0.2}$ & $2.48^{+0.26}_{-0.15}$ \\
$R_{\text{br}}$ [r$_{g}$] & $8.7^{+1.3}_{-1.0}$ & $8.9^{+1.8}_{-1.6}$ \\
$a_{*}$ & $0.81^{+0.04}_{-0.04}$ & $0.998^{*}$ \\
$R_{\text{in}}$ [r$_{g}$] & $R_{\text{ISCO}}^{*}$ & $2.58^{+0.06}_{-0.07}$ \\
i [deg] & $4^{+6}_{-0}$(B) & $4^{+5}_{-0}$(B) \\
$A_{\text{Fe}}$ & $10.0^{+0.8}_{-0.8}$ & $10.0^{+0.4}_{-0.4}$ \\
log $\xi$ [erg cm s$^{-1}$] & $3.94^{+0.08}_{-0.15}$ & $3.96^{+0.08}_{-0.18}$ \\
$\Gamma$ & $2.204^{+0.012}_{-0.011}$ & $2.201^{+0.063}_{-0.008}$ \\
k$T_{e}$ [keV] & $400^{+198}_{-0}$ & $400^{+186}_{-0}$ \\
$R_{t}$ & $0.58^{+0.25}_{-0.09}$ & $0.61^{+0.12}_{-0.09}$ \\
$\chi^{2}/\nu$ & 937.00/804 & 934.52/804 \\
& $=1.1654$ & $=1.1623$ \\
\hline
\end{tabular}
\caption{Summary of the best-fit values of Model 2 ($a_{*}$ free and $R_{\text{in}} = R_{\text{ISCO}}$) and Model 2b ($a_{*} = 0.998$ and $R_{\text{in}}$ free) of 4U 1630–472. The reported uncertainties correspond to the 90% confidence level for one relevant parameter ($\Delta \chi^{2} = 2.71$). * indicates that the value of the parameter is frozen in the fit. \textit{We note that $A_{\text{Fe}}$ is allowed to vary from 0.5 to 10 and $kT_{e}$ from 1 to 400 keV; in both models, the best-fit value of these two parameters is stuck at the upper boundary of the parameter range and there is no upper uncertainty. (B) in the lower uncertainty of the inclination angle means that we reach the lower boundary $i = 0$ deg.}}
\end{table}
The spins of Galactic black holes

Figure 7. Constraints on the spin parameter $a_\ast$ and on the Johannsen deformation parameter $\alpha_{13}$ from Model 2b of MAXI J1535–571. The red, green, and blue lines indicate, respectively, the 68%, 90%, and 99% confidence level contours for two relevant parameters ($\Delta \chi^2 = 2.30, 4.61$, and 9.21, respectively).

Last, considering the good quality of these Insight-HXMT data, we replace relxillCp with relxillCp_nk (Bambi et al. 2017; Abdikamalov et al. 2019) (Model 2b), which is designed to test the Kerr spacetime around astrophysical black holes (see, e.g., Tripathi et al. 2021; Bambi 2021). In relxillCp_nk, the spacetime metric includes some “deformation parameters” that are introduced to quantify possible deviations from the Kerr solution. The Kerr metric is recovered when all deformation parameters vanish and, as in a null experiment, the spirit is to check whether observations require vanishing deformation parameters. Here we employ the version of the model in which deviations from the Kerr background are described by the deformation parameter $\alpha_{13}$ of the Johannsen metric (Johannsen 2013). We refit the data with $\alpha_{13}$ free. The best-fit has $\chi^2_\nu = 2663.40/2503 = 1.06408$ and improves only marginally the fit of Model 2 ($\Delta \chi^2 = -4.03$). The estimates of the other model parameter do not show any significant change. The best-fit values of Model 2b are reported in the right part of Tab. 4. The constraints on the black hole spin parameter $a_\ast$ and on the deformation parameter $\alpha_{13}$ after marginalizing over all other free parameters are shown in Fig. 7. The Kerr metric is recovered at a confidence level a bit larger than 2-σ, where $\Delta \chi^2 = 4$.

4.2 4U 1630–472

For 4U 1630–472, we find the following estimates of the black hole spin parameter $a_\ast$ and inclination angle of the disk $i$ (90% C.L.)

$$a_\ast = 0.817 \pm 0.014, \quad i = 44^{+6}_{-3}(\circ) \text{ deg}. \quad (1)$$

From the NuSTAR observation on 9 March 2013, so in some previous outburst of the source, King et al. (2014) find the following estimates of $a_\ast$ and $i$

$$a_\ast = 0.985^{+0.005}_{-0.014}, \quad i = 64^{+2}_{-3} \text{ deg}. \quad (2)$$

where here the uncertainties are at 1-σ. King et al. (2014) employ the reflection model refbhb (Ross & Fabian 2007; Reis et al. 2008), which is designed for modeling the reflection spectrum of Galactic black holes in the soft or intermediate states, when the thermal soft X-ray photons of the accretion disk can contribute to the reflection spectrum. With the same NuSTAR data and employing the lamppost version of relxillCp, Tripathi et al. (2021) still find a very high black hole spin parameter, $a_\ast = 0.990^{+0.003}_{-0.005}$ even if the inclination angle of the disk is $i = 84^{+2}_{-2}$ and consistent with our Insight-HXMT measurement. So the reflection model does not seem to be responsible for the discrepancy in the black hole spin parameter while it may have a role in the estimate of the inclination angle of the disk. Since the NuSTAR and Insight-HXMT observations are not simultaneous, as it was in the case of MAXI J1535–571 for obs 1, we cannot compare the estimates of the other model parameters, which are expected to change rapidly.

From the analysis of AstroSat and Chandra data, Pahari et al. (2018) report the black hole spin parameter $a_\ast = 0.92 \pm 0.04$ (99.7% C.L.). Such a measurement is obtained from the analysis of the thermal spectrum of the disk, not from that of the reflection features of the disk as in our work and in King et al. (2014). Spin measurements of 4U 1630–472 from the analysis of reflection features in NuSTAR and Swift/XRT data are reported even in Connors et al. (2021). However, the authors employ different models and eventually get two possible values of the black hole spin: $a_\ast = 0.989^{+0.001}_{-0.002}$ or $a_\ast = 0.85 \pm 0.07$. The latter measurement, which is statistically preferred, would be consistent with our measurement from Insight-HXMT data.

A lower value of the black hole spin parameter can be easily obtained in the case of a truncated disk, namely if the inner edge of the disk is not at the ISCO but at some larger radius. To check whether the accretion disk could be truncated during the Insight-HXMT observation on 19-20 March 2020, we refit the data assuming $a_\ast = 0.998$ and leaving the inner edge of the disk $R_{\text{in}}$ free in the fit (Model 2b). The results of the new fit are reported in Tab. 5. The fit is slightly better ($\Delta \chi^2 = -2.48$) and we find $R_{\text{in}} = 2.58^{+0.06}_{-0.07} r_g$. However, assuming that the black hole mass is $10 M_\odot$ (Seifina et al. 2014) and that the distance of the source from us is 10 kpc (Augusteijn et al. 2001), the Eddington-scaled disk luminosity during the Insight-HXMT observation is very close to 30%. From the HID, we also see that the source was in an intermediate state. This is not the situation in which we would expect a truncated disk, so it is not natural to explain the discrepancy between our spin measurement with that in King et al. (2014) with a truncated disk in the Insight-HXMT data.

Last, we add xstar to describe the absorption (Model 2c). The fit is a bit better with $\chi^2_\nu = 900.70/801 = 1.1245$ ($\Delta \chi^2 = -36.3$ with respect to Model 2), but the measurement of the spin parameter does not change significantly: $a_\ast = 0.833^{+0.006}_{-0.013}$.

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DATA AVAILABILITY

The Insight-HXMT raw data analyzed in this work are available to download at the IHEP website http://hxmten.ihep.ac.cn.

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