AstroSat and Chandra View of the High Soft State of 4U 1630–47 (4U 1630–472): Evidence of the Disk Wind and a Rapidly Spinning Black Hole

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Received 2018 June 16; revised 2018 September 26; accepted 2018 September 27; published 2018 November 2

Abstract

We present the X-ray spectral and timing analysis of the transient black hole X-ray binary 4U 1630–47, observed with the AstroSat, Chandra, and MAXI space missions during its soft X-ray outburst in 2016. The outburst, from the rising phase until the peak, is detected neither in hard X-rays (15–50 keV) by the Swift/BAT nor in radio. Such nondetection, along with the source behavior in the hardness-intensity and color–color diagrams obtained using MAXI data, confirms that both Chandra and AstroSat observations were performed during the HS spectral state. The High Energy Grating (HEG) spectrum from the Chandra High-Energy Transmission Grating Spectrometer shows two strong, moderately blueshifted absorption lines at $6.705^{+0.002}_{-0.002}$ keV and $6.974^{+0.004}_{-0.003}$ keV, which are produced by Fe XXV and Fe XXVI in a low-velocity ionized disk wind. The corresponding outflow velocity is determined to be $366 \pm 56$ km s$^{-1}$. Separate spectral fits of Chandra/HEG, AstroSat/SXT+LAXPC, and Chandra/HEG+AstroSat/SXT+LAXPC data show that the broadband continuum can be well described with a relativistic disk blackbody model, with a disk flux fraction of $\sim 0.97$. Based on the best-fit continuum spectral modeling of Chandra, AstroSat, and Chandra+AstroSat joint spectra and using the Markov chain Monte Carlo simulations, we constrain the spectral hardening factor at $1.56^{+0.14}_{-0.06}$ and the dimensionless black hole spin parameter at $0.92 \pm 0.04$ within the 99.7% confidence interval. Our conclusion of a rapidly spinning black hole in 4U 1630–47 using the continuum spectrum method is in agreement with a previous finding applying the reflection spectral fitting method.

Key words: accretion, accretion disks – methods: data analysis – stars: black holes – X-rays: binaries – X-rays: individual (4U 1630)

1. Introduction

A transient black hole X-ray binary (BHXB) traces several X-ray spectral states during its outburst. Among these states, physical processes associated with the high-intensity, soft, thermal-emission-dominated state or the high soft (HS) state are possibly the best understood, due to the relatively simple, nondegenerate spectral modeling. The HS state emission is dominated by a blackbody emission from a geometrically thin and optically thick accretion disk, with the ratio of the disk flux to the total flux greater than 0.7–0.8 (Remillard & McClintock 2006). In particular, the Shakura–Sunyaev prescription (Shakura & Sunyaev 1973) predicts that the emitting disk may extend down to the innermost stable circular orbit (ISCO) around the black hole. In addition to the disk blackbody emission, a low-luminosity, nonthermal, hard power-law tail with a variable photon index $> 1.75$ (may reach $\sim 5$; Remillard & McClintock 2006; Motta et al. 2009; Titarchuk & Shaposhnikov 2010) has also been observed in the HS state. Such a tail is often explained by the presence of “patchy,” magnetized, active coronal blobs, which are largely independent of underlying accretion and Comptonization details around the thin disk (Haardt et al. 1994).

Using a large number of HS state spectra obtained from different outbursts in X-ray binaries using different satellites, it has been found that the observed disk luminosity and the observed disk temperature follow an $L \propto T^4$ relationship, and the apparent inner disk radius remains constant in spite of a variable disk luminosity (Muno et al. 1999; Steiner et al. 2010). Therefore, it is reasonable to assume that such a stable inner disk radius is the ISCO radius ($r_{\text{ISCO}}$). For the Kerr spacetime, and assuming a corotating disk, the black hole dimensionless spin parameter $a_*$ (= $cJ/GM^2$) can be uniquely estimated from a measured value of $r_{\text{ISCO}}/M$, where $M$ and $J$ are the black hole mass and total angular momentum, respectively (e.g., McClintock et al. 2006). Therefore, fitting of the thermal component of the continuum spectrum has been used to estimate $r_{\text{ISCO}}/M$, and hence $a_*$, of several accreting black holes (e.g., Shafee et al. 2008; Fragos & McClintock 2015). The continuum spectrum fitting method is often used when the source inclination angle ($i$), distance ($D$), and $M$ are independently known. The method is particularly promising, if almost the entire X-ray emission is from the disk, which significantly reduces systematic uncertainties. Note that $r_{\text{ISCO}}/M$, and hence $a_*$, can also be estimated by an alternative method, namely, the fitting of the energy and shape of a broad relativistic spectral line. Such a fluorescent line is believed to originate from the reflection of hard X-rays off the inner disk, and the line is shaped by the Doppler effect, special relativistic beaming, gravitational redshift, etc. (e.g., Miller 2007).

The black hole HS state is also ideal for observing signatures of wind from the accretion disk (e.g., Neilson & Lee 2009). Such features are usually narrow, blueshifted spectral lines that...
can be observed with Chandra gratings. These lines can provide information about the wind velocity and ionization state and can generally be useful for understanding the matter inflow–outflow mechanism.

In this paper, we focus on the transient BHXB 4U 1630–47 (Jones et al. 1976; Parmar et al. 1995), which goes into outbursts with a typical interval of 600–690 days (Abe et al. 2005; Tomzick et al. 2014). No dynamical mass measurement was possible for 4U 1630–47 because the optical counterpart has not been identified owing to the high extinction in the direction of the source near the Galactic plane. Therefore, the identification of the source as a black hole (Parmar et al. 1986) was based on the similarity of its spectral and timing properties to those of BHXBs with measured black hole masses (e.g., Barret et al. 1996; Abe et al. 2005). Nevertheless, using the correlation between photon index, low-frequency quasi-periodic oscillations (QPOs), and mass accretion rate, Seifina et al. (2014) estimated a compact object mass and inner disk inclination angle of $10 \pm 0.1 \, M_{\odot}$ and $\lesssim 70^\circ$, respectively. Note that the observations of flux dips, but a lack of full eclipses, imply a high (but not edge-on) inclination angle ($\sim 70^\circ$); Kuulkers et al. 1998; Tomzick et al. 1998; King et al. 2014) for 4U 1630–47, which is in agreement with the finding of Seifina et al. (2014).

While the distance of 4U 1630–47 is not known with certainty, the presence of heavy absorption (hydrogen column density $N_H = (5–12) \times 10^{22} \, cm^{-2}$; Tomzick et al. 1998), a faint optical counterpart (>20 mag), probably due to the high extinction in the Galactic plane (monochromatic extinction at $5495 \, \AA$ is >9 at the Galactic latitude of $<5^\circ$; Sale et al. 2014), and reddening (Seifina et al. 2014) suggest a large distance (>8 kpc) of source. Moreover, in the direction of 4U 1630–47, the presence of a Giant Molecular Cloud (MC–79) at a measured distance of 11 kpc (Augusteijn et al. 2001; Kalemci et al. 2018) behind the source is consistent with the assumed distance to the source and provides an upper limit to the distance of the source.

The black hole spin $a_*$ value for 4U 1630–47, to the best of our knowledge, has so far not been estimated using the continuum spectrum method mentioned above. However, King et al. (2014) reported, for the first time from this source, a broad relativistic spectral iron emission line using NuSTAR data. During this NuSTAR observation, 4U 1630–47 was in an intermediate state, showing the signature of an accretion disk, a hard Comptonized tail, and reflection features from the inner disk. By fitting the reflection spectrum, King et al. (2014) estimated $a_* = 0.985^{+0.005}_{-0.014}$ ($1\sigma$ statistical errors) and $i \approx 64^\circ \pm 2^\circ$.

Suzaku spectra of 4U 1630–47 showed H-like and He-like Fe absorption lines at $\sim 6.96$ and $\sim 6.7 \, keV$ (Kubota et al. 2007). These lines were thought to originate from the strongly ionized material in a disk wind. However, using the same Suzaku spectra, Róžańska et al. (2014) proposed the accretion disk atmosphere as an alternative origin of the absorption lines. A signature of thermally/radiatively driven disk wind with its ionization having a positive correlation with the source luminosity was noted by Díaz Trigo et al. (2014) using XMM-Newton spectra of 4U 1630–47 during the 2012–2013 outburst. They found that the absorption features disappeared and an emission line appeared at very high luminosity, which implies a significant change in the degree of ionization of wind with increasing luminosity. Later, using a simpler model for the same XMM-Newton spectra, Wang & Méndez (2016) showed the presence of a variable element abundance and a strongly ionized absorber near the black hole. Using Chandra/High-Energy Transmission Grating Spectrometer (HETGS) grating spectra of 4U 1630–47, Neilsen et al. (2013) and Neilsen et al. (2014) found robust and strong absorption lines caused by the outflowing wind launched during the outburst phase of 4U 1630–47. Neilsen et al. (2014) showed that the detection of ultrarelativistic wind from 4U 1630–47 (Díaz Trigo et al. 2013) is ambiguous, and the radio emission from this system may be unrelated to the X-ray emission lines. Miller et al. (2015) found a disk wind that requires magnetic launching from two absorption zones at different radii having velocities of $\sim 270$ and $\sim 2100 \, km \, s^{-1}$.

With this background, here we study the 2016 X-ray outburst of 4U 1630–47 in its HS state. We report the results from the first AstroSat observation of this source. Besides, we analyze Chandra data of the same outburst. These provide us with a rare opportunity to fit high spectral resolution grating spectra and the $\sim 0.3–80 \, keV$ broadband spectra in the same state of the same outburst. Using this Chandra grating and AstroSat broadband spectra, and with the continuum spectrum method, we confirm the previously inferred high $a_*$ of the black hole. We also report strong and blueshifted Fe XXV and Fe XXVI absorption lines in the Chandra grating spectra, implying a low-velocity, ionized disk wind in 4U 1630–47 during our observation.

2. Observations and Data Reduction

2.1. AstroSat Data Reduction

AstroSat continuously observed 4U 1630–47 between 2016 October 01 09:16:32 and 2016 October 02 16:43:39, covering 15 consecutive satellite orbits. The total observation duration is 94.6 ks. For the broadband spectroscopic purpose, we use simultaneous observations from the Soft X-ray focusing Telescope (SXT) and Large Area X-ray Proportional Counter (LAXPC) instruments.

SXT is a focusing telescope with a cooled color–color diagram (CCD) camera that can perform X-ray imaging and medium-resolution spectroscopy in the 0.3–8.0 keV energy range (Singh et al. 2016, 2017). Level-1 Photon Counting mode data, along with the SXT calibration database, are processed through a pipeline software (AS1SXTLevel2–1.4a; release date: 2017 December 06) to produce level-2 event files, and then a good time interval corrector and SXT event merger script is used to create a merged event file using all the clean events from different orbits with the corrected exposure time. We use XSELECT V2.4e in HEASOFT 6.24 to extract light curves and spectra using source regions between 1′ and 13′. An off-axis auxiliary response file (ARF) appropriate for the source location on the CCD is generated from the provided on-axis ARF using sxtmkarf tool. A blank-sky SXT spectrum, provided by the SXT team, is used as the background spectrum. As suggested, while fitting the SXT spectrum we use the gain command that modifies the response file gain linearly. The slope of the linear fit is fixed to 1, and the offset is free to vary.

LAXPC consists of three large-area ($\sim 6000 \, cm^2$), almost identical but independent X-ray proportional counters

8. http://www.tifr.res.in/~astrosat_sxt/page1_data_analysis.php
(LAXPC10, LAXPC20, and LAXPC30) having absolute time resolution of 10 μs in the energy range 3.0–80.0 keV (Yadav et al. 2016a, 2016b; Agrawal et al. 2017; Antia et al. 2017). Owing to the high time resolution and high efficiency in hard X-rays, the LAXPC demonstrates remarkable capabilities in spectro-tempo imaging analysis of X-ray binaries like GRS 1915 +105 (Yadav et al. 2016b), Cyg X-1 (Misra et al. 2016), 4U 1728-34 (Verdhan Chauhan et al. 2017), and Cyg X-3 (Pahari et al. 2018, 2017). Event mode data from LAXPC were acquired in 1024 channels and analyzed using the LAXPC software. Details of the response matrix computation and the generation of background spectra based on sky background model can be found in Antia et al. (2017). Due to the gas leakage issue in LAXPC30, we do not include its spectra for further analysis. Since the energy spectra during the soft state are dominated by the LAXPC background above 23 keV, we consider the energy range of 4–23 keV for spectral analysis.

2.2. Chandra Data Reduction

During the peak of the outburst, Chandra observed 4U 1630–47 starting from 2016 October 21 01:24:58 (Observation ID: 19904; PI: Sudip Bhattacharyya) with an effective exposure of 30.93 ks. The observation was performed using the HETGS instrument, which disperses the incident X-ray photons onto the Advanced CCD Imaging Spectrometer spectroscopic array (ACIS-S). To avoid the photon pileup issue in the CCD, caused by the HS unabsorbed X-ray flux of ~300 mcrab in 0.2–10 keV during the present observation of 4U 1630–47, the ACIS-S array was operated in continuous clocking (CC-GRADED) data mode, which activates fast frame transfer and reduces the frame accumulation time from 3.2 s to 2.85 ms. In our analysis, we determine the location of the zeroth order, and owing to the highest number of events, we extract and use the first-order grating spectra only.

Data reduction was accomplished using the Chandra Interactive Analysis of Observation software (CIAO version 4.10; Fruscione et al. 2006). The Calibration Database version 4.7.8 is used. Time-averaged first-order High Energy Grating (HEG) and Medium Energy Grating (MEG) spectra are extracted from the level-2 event file. Redistribution matrix files (RMFs) and ancillary response files (ARFs) are generated using the tools mkgrmf and mkarf, respectively. To obtain a reasonable number of energy spectral bins for the continuum spectral modeling, we group every eight spectral channels into a reasonable number of energy spectral bins for the continuum spectral modeling, we group every eight spectral channels into one. All spectral analyses were conducted using XSpec version 12.10.0c. All errors quoted in this paper are 1σ errors, unless mentioned otherwise.

The HEG effective area below 1 keV is very low owing to soft X-ray absorption in its polyimide structure and to truncation of the dispersion by the CCD array (Canizares et al. 2005). During the Chandra CC mode observations of bright and absorbed sources, a diffraction scattering halo is observed that significantly dominates the continuum spectra below 2 keV and acts as a background for the source spectrum. Therefore, considering the best HEG spectral calibrations during the CC mode observations, we use the energy range of 2.0–8.0 keV for spectral analysis.

3. Timing Analysis and Spectral State Determination

3.1. MAXI and Swift/BAT View of the Outburst

To understand the nature of the 2016 X-ray outburst from 4U 1630–47, we analyze MAXI 1-day averaged light curves in different energy ranges, as shown in Figure 1. The top three panels show the 2–4 keV, 4–10 keV, and 10–20 keV light curves covering the entire outburst, which lasted for ~150 days and is significantly visible only in 2–4 keV (~200 mcrab at the peak) and 4–10 keV (~300 mcrab at the peak) energy ranges but not visible in the 10–20 keV energy range during the outburst duration. Therefore, the hard X-ray flux is not high enough to be detected with MAXI. To confirm the hard X-ray behavior further, we plot the 15–50 keV 1-day-averaged Swift/BAT (Krimm et al. 2013) light curve of 4U 1630–47 during the same outburst. The source is not detected with the Swift/BAT during the first 90 days of the outburst, although an increase in the BAT count rate is observed during the decay phase of the outburst. Therefore, the nondetection of 4U 1630–47 in hard X-rays at the beginning of the outburst implies that the source went into a soft X-ray outburst. The times of observations from Chandra and AstroSat are shown by vertical lines in Figure 1. We note that, although there is a gap of ~20 days, both observations were taken during the spectral state when hard X-rays are not detected with Swift/BAT.

3.2. Hardness–Intensity Diagram (HID) and CCD Analysis

To show that both of our observations belong to the canonical soft state and not the intermediate state, we plot HID and CCD, which are shown in the left and right panels of Figure 2, respectively. The hard color is defined as the ratio of background-subtracted count rate between 10–20 keV and 2–10 keV, while the soft color is defined as the ratio of background-subtracted count rate between 4–10 keV and 2–4 keV. To plot HID and CCD, we use 1-day-averaged data.
MAXI data (Matsuoka et al. 2009) of the last three major outbursts from 4U 1630–47 in 2016, 2015, and 2012. MAXI hard and soft colors during the current Chandra and AstroSat observations are shown by a blue star and a red square, respectively. From both HID and CCD, we may note that the hard color and soft color are not significantly different during Chandra and AstroSat observations. The similarities in the CCD and HID imply that, although these observations are separated by ∼20 days, the spectral states are same. If we compare the HID of 4U 1630–47 from MAXI with that from RXTE as presented by Remillard & McClintock (2006), we find that the source spent most of the time in the canonical HS state (close to the lowest hard color or the leftmost section of the “q” diagram), and not in the intermediate state (horizontal tracks of the “q” diagram). Therefore, both our Chandra and AstroSat observations were performed during the canonical HS state.

3.3. AstroSat Observations

The AstroSat/LAXPC background-subtracted light curves combining three LAXPC units in the 3–80 keV light curve are shown in the left panel of Figure 3, while the 0.3–8 keV AstroSat/SXT light curve is shown in the right panel. Time bin size of both light curves is 10 s. No strong variation in count rate is observed. To check for the presence of any QPOs in the light curve, we plot power density spectra (PDS) in Figure 4. PDS are extracted using LAXPC data in the energy ranges 3–6 keV and 6–10 keV. PDS are dead time corrected, Poisson noise subtracted, and also corrected for background. PDS are dominated by a red-noise component, and no significant power is observed above ∼1 Hz at the significance level of 2σ. The total rms power integrated over 0.1–10 Hz is less than 3% in 3–80 keV. These PDS properties are similar to the characteristics of the canonical HS state (e.g., Remillard & McClintock 2006).

3.4. Radio Observations

4U 1630–47 was also observed in radio wavelength using the Australian Telescope Compact Array on 2016 September 28 and October 21, which was simultaneous with the Chandra observation. Both observations were taken at 5.5 and 9 GHz. At these frequencies, no source at the position of 4U 1630–47 was
detected at the 3σ rms noise level of 17 and 16 μJy, respectively, on 2016 October 21. At the same rms level, no source was detected on 2016 September 28. The radio nondetection during our observation is in agreement with the HS spectral state of the source (Remillard & McClintock 2006).

4. Spectral Analysis and Results

As described in Section 3, using MAXI, Swift/BAT, and AstroSat data, and from light curves, HID, CCD, and PDS, we conclude that both Chandra and AstroSat observations were performed in the HS state. Therefore, it is meaningful to do combined Chandra and AstroSat spectral analysis. But, to be cautious, first we carry out Chandra grating spectral analysis and AstroSat/SXT+LAXPC joint spectral analysis separately.

4.1. Chandra Grating Spectral Analysis

To understand characteristics of the Chandra/HETGS spectra, we fit the binned, first-order HEG spectrum with a thermal disk blackbody model along with the line-of-sight absorption model phabs in XSpec. The abundance is set to aspl from Asplund et al. (2009). Due to calibration issues, we do not use spectra from the MEG. Motivated by the previous work by King et al. (2014), which demonstrated the presence of a fast-spinning black hole, we use a multitemperature, relativistic, disk blackbody model kerrbb for a thin, steady-state, general relativistic accretion disk around a Kerr black hole (Li et al. 2005). This model fits the broadband continuum well. The residual of the fitting shows two strong absorption features. Due to symmetric shapes of the absorption profiles, we use a Gaussian absorption model to account for the two strong absorption lines at ~6.7 and ~6.97 keV. In our XSpec model phabs *(kerrbb+gabs+gabs), we fix the inclination at i = 64°, the black hole mass at M = 10.1 M⊙, and the distance at D = 10 kpc, based on our discussion in Section 1. The torque at the inner disk boundary is assumed to be zero. The effects of limb darkening and self-irradiation are also included. The HEG spectrum can be well fitted by the best-fit model (χ²/dof = 250/252 (0.99)). However, to determine the nature and characteristics of absorption lines, we use the original unbinned spectrum to retain the original spectral resolution. The left panel of Figure 5 shows a zoomed-in portion of the unbinned, continuum-fitted spectra between 5 and 8 keV, where two absorption features at ~6.7 and ~6.97 keV are observed from the residual in the bottom panel. These line energies correspond to Fe XXV and Fe XXVI absorption lines at the rest energy of 6.697 and 6.966 keV, respectively (Bianchi et al. 2005). Best-fit Fe XXV and Fe XXVI absorption line energies are found to be 6.705±0.002 keV and 6.974±0.004 keV, which are blueshifted from their rest-frame energies by an amount that corresponds to an outflow velocity of ∼0.0012c. The blueshift is measured with 3σ significance, and 1σ, 2σ, and 3σ contours are shown in the right panel of Figure 5, along with the rest-frame energies marked by a vertical and a horizontal line. From the shift in line energies, we estimate that the wind velocity is 366 ± 56 km s⁻¹. Significances are calculated based on Markov chain Monte Carlo (MCMC) simulations of fitted parameters, which are described later. Best-fit spectral parameters are given in Table 1, and the fitted spectra, along with residuals, are shown in the top left panel of Figure 6. The best-fit black hole spin parameter and spectral hardening factor are 0.928±0.029 and 1.56±0.08 respectively. The spectral hardening factor, defined as a multiplicative factor to relate the effective temperature and the color/observed temperature of the accretion disk (Shimura & Takahara 1995), is low, possibly as a result of the soft, thermal nature of the spectra (Salvesen et al. 2013).

4.2. AstroSat Spectral Analysis

To check the Chandra spectral fitting consistency and to examine the hard X-ray behavior above 8 keV, we jointly fit the simultaneous AstroSat/SXT and AstroSat/LAXPC spectra in the energy range of 0.5–23.0 keV. By fitting with the above-mentioned continuum model, we find a significant residual above 16 keV, and the fit is unacceptable (χ²/dof = 624/214). To account for this, we use a convolving Comptonization model simpl in XSpec. Model simpl is an empirical but self-consistent model of Comptonization, in which a fraction of the thermal photons from a thin disk work as an input seed spectrum (Steiner et al. 2009). With this modification, the spectrum is fitted well with a χ²/dof = 209/212 (0.99). AstroSat/SXT and AstroSat/LAXPC spectra are not sensitive enough to model two absorption features similar to that shown by the Chandra/HEG spectrum. Therefore, we fix absorption-line parameters to that from Chandra/HEG fitting. Best-fit spectra, along with the residual, are shown in the top right panel of Figure 6, while the best-fit parameter values are given in Table 1. Since the spectral hardening factor is not constrained, we fix it to 1.57 (see Section 4.1). The best-fit black hole spin parameter is found to be 0.91±0.028 (3σ errors), which is close to that estimated from Chandra/HEG spectral fitting. From Table 1, we may note that kerrbb best-fit parameters for AstroSat and Chandra data are close to each other. A direct implication of such similarity in spectral parameters is that spectral states do not evolve between the AstroSat and Chandra observation periods. This motivates us to perform Chandra and AstroSat joint spectral analysis.
Figure 5. Absorption lines from Chandra grating spectra. Left panel: zoomed, unbinned first-order Chandra/HEG spectrum of 4U 1630–47, when fitted with an absorbed single disk blackbody model, along with the residual. Two strong absorption lines visible at ~6.7 and ~6.97 keV, which are due to the ionized Fe XXV and Fe XXVI absorption features, are fitted with Gaussian absorption profiles. Bottom left panel: residual without the line absorption models. Right panel: 1σ, 2σ, and 3σ integrated contours from marginal probability distribution of Fe XXV absorption line energy versus Fe XXVI absorption line energies as obtained from Chandra/HEG spectral analysis. The horizontal and the vertical magenta lines denote the rest-frame energies of Fe XXV and Fe XXVI lines at 6.697 and 6.966 keV, respectively. A blueshift of ~0.0012c is detected for both absorption lines with at least 3σ significance.

Table 1

| Model       | Parameters | Chandra HEG | SXT+LAXPC | Chandra+AstroSat HEG+SXT+LAXPC |
|-------------|------------|-------------|-----------|-------------------------------|
| Constant    | ...        |             |           |                               |
| phabs       | $N_{\text{HI}}$ (10^{22} cm^{-2}) | 11.5±0.7 11.2±1.3 | 11.5±0.7 11.2±1.3 | 11.5±0.7 11.2±1.3 |
| kerrbb      | $M$ (10^{10} g s^{-1}) | 1.49±0.07 2.17±0.11 | 1.51±0.11 1.84±0.08 | 1.51±0.11 1.84±0.08 |
| a_s (3σ)    | 0.92±0.03 0.913±0.02 | 0.924±0.016 0.924±0.016 | 0.924±0.016 0.924±0.016 |
| h_d         | 1.57±0.07 | 1.57±0.07 | 1.56±0.07 | 1.56±0.07 |
| simpl       | Γ ... | 2.79±0.08 3.83±0.15 | 2.84±0.08 3.33±0.12 | 2.84±0.08 3.33±0.12 |
|             | $F_{\text{sc}}$ (%) | ... | ... | 3.33±0.12 | 3.33±0.12 |
| gabs        | $E_{\text{gabs1}}$ (keV) | 6.705±0.002 | ... | 6.708±0.004 | 6.708±0.004 |
|             | $\sigma_{\text{gabs1}}$ (eV) | 12.8±1.3 | ... | 11.3±1.3 | 11.3±1.3 |
|             | $S_{\text{gabs1}}$ | 0.76±0.12 | ... | 0.72±0.05 | 0.72±0.05 |
| gabs        | $E_{\text{gabs2}}$ (keV) | 6.974±0.004 | ... | 6.975±0.007 | 6.975±0.007 |
|             | $\sigma_{\text{gabs2}}$ (eV) | 19.6±1.79 | ... | 18.1±3.2 | 18.1±3.2 |
|             | $S_{\text{gabs2}}$ | 1.15±0.11 | ... | 1.49±0.06 | 1.49±0.06 |
|             | $F_{9.2-2}$ (10^{-8} ergs s^{-1} cm^{-2}) | 0.81±0.08 | 1.04±0.11 | 1.05±0.11 | 1.05±0.11 |
|             | $F_{2.10}$ (10^{-8} ergs s^{-1} cm^{-2}) | 0.93±0.09 | 1.45±0.11 | 1.33±0.05 | 1.33±0.05 |
|             | $F_{10-20}$ (10^{-8} ergs s^{-1} cm^{-2}) | 0.15±0.03 | 0.16±0.02 | 0.16±0.02 | 0.16±0.02 |
|             | $F_{20-100}$ (10^{-8} ergs s^{-1} cm^{-2}) | ... | 0.02±0.01 | 0.03±0.01 | 0.03±0.01 |
| $\chi^2$/dof | 250/252 (0.99) | 222/219 (1.01) | 507/477 (1.06) | 507/477 (1.06) |

Note. $N_{\text{HI}}$ is the line-of-sight absorption column density, $M$ is the mass accretion rate in $10^{10}$ g s^{-1}, $a_s$ is the black hole spin parameter, $h_d$ is the spectral hardening factor, $\Gamma$ is the photon power-law index, and $F_{\text{sc}}$ is the scattered Comptonization fraction. $E_{\text{gabs1}}, E_{\text{gabs2}}, \sigma_{\text{gabs1}}, \sigma_{\text{gabs2}}, S_{\text{gabs1}}, S_{\text{gabs2}}$ are the energies and widths of the Gaussian-shaped absorption lines in keV and eV, respectively, while $S_{\text{gabs1}}$ and $S_{\text{gabs2}}$ are the strengths of these absorption features. $F_{9.2-2}, F_{2.10}, F_{10-20}, F_{20-100}$ are unabsorbed fluxes in the energy ranges 0.2–2 keV, 2–10 keV, 10–20 keV, and 20–100 keV, respectively, in units of $10^{-8}$ ergs s^{-1} cm^{-2}.

4.3. Chandra+AstroSat Joint Spectral Analysis

We perform Chandra/HEG and AstroSat/SXT+LAXPC joint spectral analysis to check whether spectral parameters from Chandra and AstroSat individual spectral modeling match with Chandra+AstroSat joint fitting. We use the continuum model similar to that used for SXT+LAXPC joint spectral analysis discussed above (see Section 4.2). Absorption-line parameters for the SXT spectrum are tied to that with the HEG. Best-fit spectra ($\chi^2$/dof = 507/477), along with the residual, are shown in the bottom left panel of Figure 6, while best-fit parameter values are given in Table 1. The unfolded best-fit model spectra excluding the absorption are shown in the bottom right panel of Figure 6.
The best-fit black hole spin parameter and spectral hardening factor with 3σ errors are 0.924 ± 0.007 and 1.56 ± 0.06, respectively. All best-fit parameters are found to be similar to those estimated from separate AstroSat and Chandra spectral analyses.

4.4. MCMC Simulations and Results

To check whether best-fit parameter values from Chandra, AstroSat, and Chandra+AstroSat joint spectral analyses represent global solutions, we perform MCMC simulations of spectral parameters of all three spectral fits. If a large number of free parameters are involved in spectral modeling (e.g., our best-fit spectral model has a maximum of 13 free parameters, including cross-calibration factors), then the use of the $\chi^2$ minimization technique is not always reliable for estimating the model parameters (Reynolds et al. 2012). As an independent check, we employ the following MCMC simulation technique for validation of results obtained from our $\chi^2$ minimization method. As X-ray spectral counts usually follow a Poisson distribution, we replace the conventional $\chi^2$ fit statistic with the appropriate statistic for Poisson data ($\text{pgstat}$ in XSpec). This assumes a Poisson distribution of source spectral counts but a Gaussian distribution of background counts. The derivation of the profile likelihood of $\text{pgstat}$ is similar to that of the likelihood of the $C$-statistic. With the new fit statistics, we run $5 \times 10^5$ element chains starting from a random perturbation away from the best fit and ignoring the first 50,000 elements of the chain. The distribution of the current proposal (i.e., an assumed probability distribution for each Monte Carlo step to run the simulation) is assumed to be Gaussian with a rescaling factor of 0.001. We use the Goodman–Weare algorithm for MCMC simulations with 10 walkers.

The top left panel of Figure 6 shows the black hole spin parameter as a function of the number of MCMC chain steps during Chandra/HEG, AstroSat/SXT, and Chandra+AstroSat joint spectral fitting, which is shown in the top right panel along with the residual. Bottom left panel: joint fitting of Chandra/HEG and AstroSat/SXT+LAXPC10+LAXPC20 spectra, which is shown in the top right panel along with the residual. Bottom right panel: unfolded model spectra without the absorption in the unit of $E^*E/\epsilon_f$. The model spectrum peaks at $\sim 3$–4 keV.

Figure 6. Top left panel: Chandra/HEG spectral fitting (with a spectral bin size of eight channels), and the residual using an absorbed, relativistic, disk blackbody model $\text{kerrbb}$ along with Gaussian absorption features. With this model an additional convolution Comptonization model $\text{simpl}$ is used to fit AstroSat/SXT, AstroSat/LAXPC10, and AstroSat/LAXPC20 joint spectra, which is shown in the top right panel along with the residual. Bottom left panel: joint fitting of Chandra/HEG and AstroSat/SXT+LAXPC10+LAXPC20 spectra, which is shown in the top right panel along with the residual. Bottom right panel: unfolded model spectra without the absorption in the unit of $E^*E/\epsilon_f$. The model spectrum peaks at $\sim 3$–4 keV.
parameter is known to have a dependency on the spectral hardening factor. To check the relation between the spin parameter and the spectral hardening factor, we extract MCMC-derived $\sigma$, $2\sigma$, and $3\sigma$ integrated contours of the black hole spin parameter as a function of the spectral hardening factor from the marginal probability distribution of fitted spectral parameters from Chandra/HEG and Chandra/HEG+AstroSat/SXT+AstroSat/LAXPC and plot them in the top left and top right panels of Figure 8, respectively. From both panels, it is clear that the spectral hardening factor is constrained in the range of 1.5–1.7 with the 99.7% confidence level. This is a little lower than the typically used value of the spectral hardening, i.e., 1.7, but it is in agreement with the fact that both Chandra and AstroSat spectra are observed during the HS state. This is because Salvesen et al. (2013) showed that during the HS state and at an X-ray flux $>10^{-8}$ ergs s$^{-1}$ cm$^{-2}$ in the 0.1–10 keV range, the spectral hardening factor is usually less than 1.7.

To check whether there is degeneracy among model components, e.g., degeneracy between simpl and kerrbb model parameters, in Figure 8 we plot $1\sigma$ and $2\sigma$ contours of the MCMC-derived black hole spin parameter from the kerrbb model versus (1) MCMC-derived simpl photon power-law index (bottom left panel) and (2) simpl Comptonization scattering fraction (bottom right panel), used to fit Chandra/HEG+AstroSat/SXT+LAXPC spectra. Both plots show that the $3\sigma$ range of photon power-law index is between 2.7 and 3.0 and the Comptonization fraction is between 3.2% and 3.5%.

Such a result implies that the black hole spin parameter obtained from our analysis is robust, and with the measurement using independent instruments like Chandra/HEG, AstroSat/LAXPC, and AstroSat/SXT, it is well constrained in the range of 0.88–0.96 with the $3\sigma$ limit.

5. Discussion and Conclusions

In this work, we study the 2016 X-ray outburst from the black hole X-ray transient 4U 1630–47. Using MAXI and Swift/BAT 1-day-averaged light curves in different energy bands, we show that the outburst is visible in the 2–4 keV and 4–10 keV energy ranges and is marginally detected in the 15–50 keV hard X-ray band only during the decay phase of the outburst. During the rising phase, the nondetection in the hard X-ray and radio bands confirms that the source has undergone a
soft X-ray outburst. Similar bursts were also seen previously from this source. Very close to the peak of the outburst, AstroSat and Chandra observed the source with 94.6 and 30.9 ks exposure times, respectively. Although these observations were taken ~20 days apart, using the HID and the CCD diagram from MAXI data, we show that the hard and soft color values at the times of AstroSat and Chandra observations were not significantly different, and these two observations were performed during the canonical HS spectral state of the source. To further confirm the spectral state, we model the Chandra/HEG spectra and find that the continuum is well fitted with a single relativistic, disk blackbody model. When we extend the broadband fitting up to 23 keV by including the AstroSat/LAXPC, we find that a very steep power law (index >2.5) is required at a marginal scattering fraction of 3%–4%. Using Chandra grating spectra, we notice very strong absorption lines at 6.70±0.02 keV and 6.97±0.03 keV, which we identify as the mildly blueshifted Fe XXV and Fe XXVI absorption lines corresponding to the rest-frame energies at 6.697 and 6.066 keV, respectively. If these blueshifted lines originated from an outflowing wind, then the velocity of the wind would be 366 ± 56 km s⁻¹.

We find no evidence of a broad Fe emission line or any other signature of reflection features in either the Chandra or AstroSat spectra. This is not surprising, as previously the reflection spectral component from 4U 1630–47 (King et al. 2014) was observed during the intermediate state, while our observations were performed in the more luminous HS state. We may note that using XMM-Newton spectra, Díaz Trigo et al. (2014) found evidence of the Fe emission line at the 2–10 keV unabsorbed flux of 2.12 × 10⁻⁸ ergs s⁻¹ cm⁻². The 2–10 keV unabsorbed flux computed from our Chandra and AstroSat joint spectral modeling is 1.33±0.08 ergs s⁻¹ cm⁻², which is lower by a factor of ~2 than that reported by Díaz Trigo et al. (2014). However, 2–10 keV unabsorbed flux during their Obs 3 (also see Table 2) matches with our value, and rather than the Fe emission line, they found absorption lines during the Obs 3, similar to what we found in the current study. Therefore, the accretion geometry as observed from the XMM-Newton and the present Chandra grating spectra of 4U 1630–47 may be similar at similar flux levels.

Assuming a black hole mass of 10 M☉, the Eddington luminosity of 4U 1630–47 would be 1.26 × 10³⁰ erg s⁻¹. The unabsorbed X-ray flux in 0.1–100 keV inferred from the joint Chandra and AstroSat spectral fitting is 2.81 × 10³⁸ erg s⁻¹. Therefore, the source was accreting at ∼22% of the Eddington accretion rate during our observations. We further note that a very weak Comptonization component, inferred from our spectral fitting, implies a low hard X-ray flux available for

Figure 8. The top left and top right panels show MCMC-derived 1σ (red), 2σ (green), and 3σ (blue) integrated contours from the marginal probability distribution of the black hole spin parameter as a function of the spectral hardening factor obtained from Chandra/HEG spectral fitting and Chandra/HEG+AstroSat/SXT+AstroSat/LAXPC joint spectral fitting, respectively. The bottom left and bottom right panels show (for Chandra+AstroSat) the black hole spin parameter as a function of the simpl power-law index and the simpl Comptonization scattering fraction, respectively.
reflection from the disk. Such a low fraction of hard X-ray flux may be a reason for the nondetection of a reflection spectral component.

There are two widely used techniques for the black hole spin measurement, based on (1) the modeling of the broad relativistic Fe emission line and other reflection features and (2) the modeling of relativistically modified thermal continuum spectra. In this paper, we use the latter one. For the thermal continuum modeling, the spectral data selection has the following critical criteria: (1) the continuum spectrum should have a dominant thermal disk blackbody emission from a geometrically thin and optically thick accretion disk; (2) a significant presence of other spectral components, like the reflection or Comptonization continuum, is undesirable, since their presence complicates the spectral modeling and introduces systematic uncertainties in spin measurement; and (3) the X-ray luminosity should be fairly high, but \( \lesssim 30\% \) of the Eddington luminosity, so that the accretion disk is not radiation pressure dominated, and the geometrically thin disk assumption still holds true. Our continuum spectrum, as observed with both Chandra and AstroSat, satisfies all these criteria. This is because no reflection features are observed, X-ray luminosity is \( \sim 22\% \) of the Eddington luminosity, and \( \sim 95\% \) of the X-ray emission is from a geometrically thin disk. Therefore, our continuum spectra are ideal to determine the black hole spin.

5.1. On Black Hole Spin Measurement

By independently modeling Chandra/HEG, AstroSat, and Chandra+AstroSat broadband spectra, and using MCMC simulations on fitted spectral parameters, we find that the 3\( \sigma \) range of the black hole spin parameter is 0.88–0.96, which indicates the presence of a rapidly spinning black hole in 4U 1630–47. This is close to the spin parameter value of 0.985\( ^{+0.009}_{-0.014} \) estimated from modeling reflection spectra of 4U 1630–47 (King et al. 2014). Note that we fix \( i, D, \) and \( M \) in our spectral fitting. Our assumption of \( i = 64^\circ \) should be reasonable because independent methods have argued or predicted similar values (e.g., \( i \lesssim 70^\circ \); see Section 1; \( i = 64^\circ \pm 2^\circ \); King et al. 2014). As argued in Section 1, our assumption of \( D = 10 \) kpc should also be reasonable. While our assumption of \( M \approx 10 M_\odot \) was adopted from the estimated mass reported in Seiﬁna et al. (2014), the absence of a dynamical measurement of mass implies the lack of a conﬁdent value. Therefore, considering reasonable limits of the typical stellar black hole mass range, we ﬁx the black hole mass at 5 and 15 \( M_\odot \), in our joint spectral modeling of Chandra and AstroSat, ﬁx the best-ﬁt spin values, and keep the distance free to vary between 2 and 50 kpc. The best ﬁt returns an acceptable \( \chi^2 / \text{dof} = 533/477 \) (1.12) and 549/477 (1.15) for the black hole mass of 5 and 15 \( M_\odot \), respectively. This implies for a reasonable range of black hole masses and distances that the spectral ﬁtting supports the high black hole spin. Therefore, our ﬁnding of a rapidly spinning black hole in 4U 1630–47 should be reliable.

We thank the referee for constructive comments that improved the quality of the manuscript. We acknowledge the strong support from the Indian Space Research Organization (ISRO) during the instrument building, testing, software development, and mission operation. We also acknowledge the support from the LAXPC Payload Operation Center (POC), TIFR, Mumbai. This work has used the data from the Soft X-ray Telescope (SXT) developed at TIFR, Mumbai, and the SXT POC at TIFR is thanked for verifying and releasing the data via the ISSSD data archive and providing the necessary software tools. The scientiﬁc results reported in this article are based on observations made by the Chandra X-ray Observatory. This research has made use of the software provided by the Chandra X-ray Center (CXC) in the application packages CIAO, ChIPS, and Sherpa. This research has made use of the MAXI data provided by RIKEN, JAXA, and the MAXI team. M.P. thanks TIFR, Mumbai, for the support and hospitality during this work and acknowledges Royal Society-SERB Newton International Fellowship support funded jointly by the Royal Society, UK, and the Science and Engineering Board of India (SERB) through the Newton-Bhabha Fund. M.P. and P.G. acknowledge the support from the UGC-UKIERI Phase 3 thematic partnership grant 2017/18 at the School of Physics and Astronomy, University of Southampton, UK. P.G. acknowledges the support and funding from STFC (ST/R000506/1).

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