CONSTRAINING DISTANCE AND INCLINATION ANGLE OF V4641 SGR USING SWIFT AND NuSTAR OBSERVATIONS DURING LOW SOFT SPECTRAL STATE

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ABSTRACT

We present results from NuSTAR and Swift/XRT joint spectral analysis of V4641 Sgr during a disk dominated or soft state, as well as a power law dominated or hard state. The soft state spectrum is well modeled by a relativistically blurred disk emission, a power law, a broad iron line, two narrow emission lines, and two edges. The Markov Chain Monte Carlo simulation technique and the relativistic effects seen in the disk and broad iron line allow us to self-consistently constrain the inner disk radius, disk inclination angle, and distance to the source at $2.43_{-0.12}^{+0.32}R_{\odot}$ ($GM/c^2$), $69.5_{-4.2}^{+12.5}$ degrees and $10.8_{-2.5}^{+1.6}$ kpc respectively. For the hard state, the spectrum is a power law with a weakly broad iron line and an edge. The distance estimate gives a measure of the Eddington fraction, $L_{2.0-8.0\text{keV}}/L_{\text{Edd}}$, to be $\sim1.3 \times 10^{-2}$ and $\sim1.9 \times 10^{-3}$ for the soft and hard states, respectively. Unlike many other typical black hole systems, which are always in a hard state at such a low Eddington fraction, V4641 Sgr shows a soft, disk dominated state. The soft state spectrum shows narrow emission lines at $\sim6.95$ and $\sim8.31$ keV which can be identified as being due to emission from highly ionized iron and nickel in an X-ray irradiated wind respectively. If this is not due to instrumental effect or calibration error, this would be the first detection of a Ni fluorescent line in a black hole X-ray binary.

Key words: accretion, accretion disks – black hole physics – X-rays: binaries – X-rays: individual (V4641 Sgr)

1. INTRODUCTION

Relativistically skewed iron line complex at $\sim6.5$ keV is a frequently observed phenomenon in X-ray spectra of a range of objects—from Seyfert galaxies (Fabian et al. 2000) to low mass X-ray binaries harboring neutron stars and black holes (Cackett et al. 2008; Kolehmainen et al. 2014). These features reveal the general relativistic nature of these objects and can be used to probe the spacetime metric near black holes. Such broad lines have also been reported for galactic X-ray binaries which harbor either a black hole or a neutron star. Among these galactic black hole X-ray binaries (BHXBs), until now, few transient sources—GRO J1655–40 (Tomsick et al. 1999), XTE J1550–564 (Sobczak et al. 2000), XTE J1650–500 (Done & Gierliński 2006), XTE J1752–223 (Reis et al. 2011), Swift J1753.5–0127 (Hiemstra et al. 2009), SAX J1711.6–3808 (int Zand et al. 2002), GX 339–4 (Feng et al. 2001)—and two persistent sources, Cyg X-1 (Miller et al. 2002b; Duro et al. 2011) and GRS 1915+105 (Miller et al. 2013), have shown strong, relativistically broad Fe Kα lines. At lower luminosities, broad iron line has been reported only for two sources, GX 339–4 (Miller et al. 2006) and XTE J1650–500 (Done & Gierliński 2006).

BHXBs show a variety of spectral states, each with its distinct timing properties (e.g., Remillard & McClintock 2006). These states have been primarily classified based on the outburst behavior of transient black hole systems with low mass companions, i.e., low mass black hole X-ray binaries (LMXBs). These outbursts, which typically last for a few months, often trace out a “q” shaped figure in the luminosity hardness diagram (Homan et al. 2001; Fender et al. 2004). The outburst starts at the bottom right-hand part of the diagram - where the source has low luminosity ($L/L_{\text{Edd}} < 0.01$) and is hard. Then, roughly maintaining its hardness ratio, the source increases its luminosity until it reaches near the peak of the outburst ($L/L_{\text{Edd}} > 0.3$). From this point, at nearly similar luminosity level, the sources softens, i.e., it moves horizontally left in the luminosity hardness diagram. From this Eddington limited soft state the source luminosity decreases as the outburst decays while maintaining its soft nature, until the luminosity falls to roughly 0.01–0.03 times of its Eddington value. From this point onward the source makes a transition from soft to hard state, i.e., it moves to the right in the luminosity hardness diagram. After reaching the hard state the source luminosity starts dropping further until it reaches its quiescent value ($L/L_{\text{Edd}} \sim 10^{-5}$ to $10^{-6}$). Broadly speaking, in the soft state (especially in the low luminosity soft states) the spectrum is dominated by a standard accretion disk extending to the innermost stable orbit close to the black hole. In the hard state (especially in the low luminosity hard state) the disk emission is weak, probably because it is truncated at a large radius away from the black hole and the spectrum is dominated by the hard power law from a hot inner corona. Currently, the origin of relativistically broadened iron line is usually associated with a standard accretion disk extending close to the black hole. Hence it is surprising that such lines have been detected during the hard states of GX 339–4 and XTE J1650–500. However, in an alternate scenario, it has been observed that the cold material rotating close to a central black hole (e.g., Cyg X-1; Fabian et al. 1989) can be illuminated by the primary power-law photons to give rise to the broad iron emission line (Ballantyne et al. 2001).

While the transition from soft to hard occurs at different luminosity levels, no source has ever shown a soft state for luminosities below $<0.01 L_{\text{Edd}}$. At these luminosities all black hole binaries show hard spectrum with very weak disk emission.

Black hole systems with high mass companions, i.e., high mass X-ray binaries (HMXBs), are typically persistent sources with luminosities ranging from 0.01 to $0.1L_{\text{Edd}}$. They also show a few spectral states that can be broadly classified into hard and
soft, but not as many as those of the LMXBs. This is expected since a persistent HMXB varies over a much narrower range of luminosity. Like LMXBs, in the hard state, they show a weak disk emission, while in the soft state the disk emission is significantly stronger, although an extreme soft state, where the disk totally dominates the emission, is rarely seen in HMXBs. Hence, HMXBs should also show broad iron lines in the soft state and this is seen, e.g., in Cyg X-1 and also in LMC X-1. A fundamental difference between the LMXBs and HMXBs is the presence of a strong wind from the companion, and one of the consequences of this wind is that the X-ray irradiation on it is significantly stronger, although an extreme soft state, where the disk totally dominates the emission, is rarely seen in HMXBs. Hence, HMXBs should also show broad iron lines in the soft state and this is seen, e.g., in Cyg X-1 and also in LMC X-1. A fundamental difference between the LMXBs and HMXBs is the presence of a strong wind from the companion, and one of the consequences of this wind is that the X-ray irradiation on it can produce emission lines and edges which can appear in the iron line band. These features carry important information regarding the structure and composition of the wind, but, when observed through low spectral resolution instruments, they may lead to improper modeling of the broad iron line originating from the disk.

Discovered during the historical outburst with an intensity of 12.2 Crab by RXTE/ASM, V4641 Sgr reveals itself as the only transient high mass black hole binary (HMBHXB) with a dynamically confirmed black hole mass of $6.4 \pm 0.4 M_\odot$ and a companion mass of $2.9 \pm 0.4 M_\odot$ (MacDonald et al. 2014). Using ellipsoidal model fitting to the photometric data during an optically passive state, MacDonald et al. (2014) determined the disk inclination angle to be $i = 72.3 \pm 4^\circ$. Prior to this, a qualitative argument, favoring $i \leq 10^\circ$, was provided in order to explain the high beamed jet expanding at a velocity between 0.22 and 1$^\circ$ per day (Hjellming et al. 2000). In another study, based on high amplitude folded light curve analysis, the inner disk inclination angle was derived between 60$^\circ$ and 70$^\circ$ and the distance to the source was predicted to lie between 7 and 12 kpc (Orosz et al. 2001). Fitting the Chandra spectra from this source in the energy range 0.5–10.0 keV during the quiescent state requires partial covering absorption and distant reflection (Morningstar et al. 2014), similar to model components required to fit spectra from Seyfert-2 Active Galactic Nuclei (AGNs). A strong Fe emission line from this source was first detected by BeppoSAX (int Zand et al. 2000) with the equivalent width between 0.3 and 1 keV. Later, using RXTE data, the presence of a Compton reflection hump around 20–30 keV along with a strong iron line have been observed (Maitra & Bailyn 2006).

Miller et al. (2002a) re-analyzed the BeppoSAX/MECS data, and reported a broad Fe Kα emission line complex and preferred it over a model consisting of two narrow emission lines. Given that one may expect narrow emission lines from the wind, it is important to measure the spectra of V4641 Sgr with a high resolution instrument. Moreover, the uncertainties in its distance and inclination angle do not allow it to be compared to other black hole systems. An independent distance analysis is required to understand whether this HMXB, at a certain Eddington luminosity ratio, has the same or different spectral shape compared to others.

Until the advent of the NuSTAR satellite, XMM-Newton, Chandra, and Suzaku were the only instruments for sensitively measuring the broad relativistic iron line, although they were highly restricted by their pile-up limit. With its pile-up free operation (up to $\sim$100 mCrab), good calibration, and high energy resolution ($\sim$400 eV at 0.1–10 keV), NuSTAR provides a unique opportunity to study relativistically skewed fluorescent line profiles accurately and to constrain other features of the reflection component in the 3.0–79.0 keV energy band (Harrison et al. 2013). For example, a 15 ks exposure of GRS 1915+105 reveals an extremely skewed Fe emission line which allowed for an estimation of the black hole spin to be $0.98 \pm 0.01$ (Miller et al. 2013). NuSTAR has already shown promising results regarding detection of lines other than Fe Kα. For example, the Fe Kβ line is observed from the Compton thick AGNs—NGC 424, NGC 1320, and IC 2560—using both XMM-Newton and NuSTAR spectra (Baloković et al. 2014). The truly complex nature of the X-ray spectra in BHXBs are often demonstrated by high resolution spectroscopic instruments, and careful attention is required while modeling to obtain truly robust information. For example, reanalysis of the complex Suzaku spectra in the Seyfert 1.5 galaxy NGC 3783 using the Markov Chain Monte Carlo (MCMC) simulation technique shows that the data strongly requires both super-solar iron abundance as well as a rapidly spinning black hole (Reynolds et al. 2012), which was inconclusive from previous attempts that use conventional methods. Therefore, although the good spectral resolution of NuSTAR provides a unique opportunity to discern narrow emission lines and edges while simultaneously measuring the broad iron line profile, proper statistical analysis like MCMC simulations of the best-fit model is needed for the bias-free determination of probable interdependent parameters from different model components.

NuSTAR has observed V4641 Sgr twice, once when the source was soft and the other when it was hard. We analyze these observations along with quasi-simultaneous Swift data. Our motivation is to use the broad band 0.5–70 keV data to constrain the disk emission, the hard X-ray power law, the broad iron line, and any narrow emission features that may arise from the wind. As we shall see, simultaneous measurement of the disk emission and the broad iron line will allow us to constrain the distance to the source as well as its inclination angle. Observation details and data reduction procedure are provided in Section 2. Spectral analysis, modeling, and results are discussed in Section 3. Section 4 provides a comparison with other transient BHXBs. Discussion and conclusions are provided in Section 5.

2. OBSERVATIONS AND DATA REDUCTION

NuSTAR observed V4641 Sgr on 2014 February 14 00:36:07 (8000212002) and on 2014 April 17 22:46:07 (8000212004) with exposure times of 24 ks and 26 ks, respectively. During this period the source was variable, as seen in the left panel of Figure 1 where the $2-20$keV MAXI/GSC light curve is shown. The two vertical gray lines mark the time of the NuSTAR observations, in between which one can see flaring activities. From the MAXI light curve, a drop in count rate by a factor of $\sim$3 is observed at the time of the second NuSTAR observation compared to the first. Not only that, the hardness ratio, as observed from the left panel of Figure 1, increases by a factor of $\sim$2 at the time of the second NuSTAR observation.

Background subtracted, NuSTAR/FPMA and FPMB averaged, 3 ks light curves with 30 s bin time are shown in the right panel of Figure 1 during the first and second observations, respectively. The average source and background count rate from NuSTAR data during the first observation are $5.35 \pm 0.02$ counts s$^{-1}$ and $0.81 \pm 0.03$ counts s$^{-1}$ respectively, while the same during the second observation is $0.31 \pm 0.05$ and $0.042 \pm 0.008$ counts s$^{-1}$ respectively. The 0.01–5.0 Hz integrated rms power from the white noise subtracted power density spectra (PDS) of the second NuSTAR
observation is $\sim3$ times that observed during the first NuSTAR observation. The above facts indicate that during the first NuSTAR observation the source was in soft spectral state, while during the second observation it was in hard spectral state. Later in this work we confirm soft-to-hard spectral state transition from (1) spectral analysis where the soft disk blackbody flux dominates the spectra ($>80\%$) during the first NuSTAR observation while the power law flux dominates the spectra ($>80\%$) during the second NuSTAR observation. (2) In the Hardness Intensity Diagram (HID), the first NuSTAR observation occupies the place where other canonical BHXBs usually show soft state, while the second observation resides near the hard state position of other BHXBs.

NuSTAR data from the co-aligned telescope with two focal plane modules, FPMA and FPMB, are extracted and analyzed using nustardas v. 1.3.1, FTools v 6.15.1, and XSPEC v. 12.8.1g. A circular region of 40$''$ radius is used in the detector plane to extract source spectrum and light curve. A large area from the remaining part of the detector, which is at least thrice the size of the source extraction area, is used to extract background spectrum and light curve. NuSTAR data reduction procedure is guided by the NuSTAR Data Analysis Software Guide; v 1.7.1 provided by HEASARC and the latest calibration database (CALDB version 20150702) is used. Observation specific response matrices and ancillary response files are generated using the numkrmf and numkarf tools.

Swift/XRT observations were also performed with 1.9 and 3.9 ks exposures simultaneously with NuSTAR. Following the standard procedure of filtering and screening criteria, Swift/XRT data are reduced using the xrtpipeline v. 0.13.0 tool. A 30$''$ circular region is used to extract the source spectrum, and a 30$''$ source-free region is used to extract background spectra using XSELECT v 2.4. The latest Swift/XRT spectral redistribution matrices are used. The xrtmkarf task is used along with the exposure map file to generate an auxiliary response file for the current observation.

In NuSTAR observations the background subtracted total counts during soft state and hard state are 106,980 $\pm$ 327 and 5853 $\pm$ 68, respectively. We also study the signal-to-noise ratio (S/N) as a function of channels. Around channel number 100, the S/N profile peaks at $\sim$5--6, and it falls below 1 at channel numbers less than 10 (corresponds to the energy $<3$ keV) and at channel numbers above 230 (corresponds to the energy $>11.0$ keV). Therefore, to obtain good spectral quality, data was grouped such that a minimum of 20 counts were obtained per bin. However, it is important to note that binning is not effectively applied to the largest part of the spectrum (3.0--15.0 keV) since background-subtracted source counts per channel $>200$. There were too few counts in the NuSTAR data above 30 keV, hence we restricted the analysis to 30 keV. In case of Swift/XRT, background subtracted total counts during soft and hard state are 22,916 $\pm$ 134 and 1855 $\pm$ 33, respectively. Because of poor signal strength in the Swift/XRT spectra above 6 keV (less than 10 counts), the energy range for simultaneous spectra fitting using XSPEC v 12.8.1 was restricted to 0.3--6.0 keV (Swift/XRT) and 3.0--30.0 keV (NuSTAR).

3. SPECTRAL ANALYSIS AND RESULTS

3.1. Soft State Spectral Analysis

To understand the complexities of the soft state spectra we used a power law modified by the galactic absorption. Throughout our analysis we obtained a galactic absorption column density between 0.2 and $0.4 \times 10^{22}$ cm$^{-2}$ which is consistent with previous results (Dickey & Lockman 1990; Miller et al. 2002a). As it turns out, besides the power law component, two basic components are required: an optically thick, soft blackbody emission that is revealed by a large excess in low energies, and strong reflection features that consist of emission lines and edges between 5.8 and 10.0 keV.

The large residuals in the high energy region are examined in detail. To highlight the features we show the residuals in the 5--11 keV band in Figure 2. Visual inspection of the figure suggests several features: (i) a broad iron line peaking at $\sim$6.9 keV and extending perhaps to $\sim$5.5 keV, (ii) an emission line-like feature at $\sim$8.1 keV, and (iii) an edge at $\sim$9.6 keV. With these suggested features as guidelines we undertook a systematic analysis of the broadband data. As compared to a base model of a disk emission and a power-law component, a broad iron line is required, resulting in a $\Delta \chi^2 > 700$. We chose the relativistic line model $\text{laoir}$ (Laor 1991) available in XSpec to represent the relativistically blurred iron line.
emission. This model is parametrized by the line rest frame energy, an emissivity index, inner radii in terms of $r_s = GM/c^2$, inclination angle, and normalization. We fixed the outer radius of the emission to a large value of 400 $r_s$. Like any other complex reflection models, for example, reflionx (Ross & Fabian 2005) and relxill (Garcia et al. 2013) which are frequently used to describe complex reflection features (e.g., reflection hump at 20–30 keV) from the AGN spectra in a self-consistent manner, the laor model provides an equally good description of the broadening of emission lines due to general relativistic effects. Since we do not have sufficient S/N at energies $>15$ keV, reflection humps are not detected in the spectra. Therefore, spectral quality do not meet the requirement of applying relativistic reflection models more complex than the laor model.

For consistency, we modeled the disk emission using the relativistic disk model kerrd (Ebisawa et al. 2003) in XSpec. This disk model uses the same formalism as the laor model to take into account relativistic effects. The model has convenient parameters such as the black hole mass, which we fixed to the measured value of 6.4 $M_\odot$, and a color correction factor, which we fixed to the standard value of 1.7 (Shimura & Takahara 1995). The other free parameters are the distance to the source and the accretion rate, inner disk radius, and disk inclination angle. The kerrd model assumes a Kerr metric around a spinning black hole with spin parameter $a = 0.998$ for which the last stable orbit should be at $\sim 1.235 r_s$. A larger inner radii may signify a truncated disk or that the spin parameter is less than what was assumed in the model, a point which we discuss in the last section.

The model, consisting of a disk, power law, and broad line emissions, is not an adequate representation of the high quality data with $\chi^2/\text{dof} = 1332/705$. Corresponding to broad K$_{\alpha}$, represented by the laor model, a K$_{\alpha}$ line is expected with the same shape parameter. The fit is significantly improved by the addition of a narrow emission line at $\sim 6.95$ keV ($\chi^2/\text{dof} = 807/703$) and another at $\sim 8.13$ keV ($\chi^2/\text{dof} = 776/700$). Examination of the residuals showed the presence of an absorption edge at $\sim 9.6$ keV ($\chi^2/\text{dof} = 738/698$) and another one at $\sim 7.1$ keV ($\chi^2/\text{dof} = 721/696$). In the fitting process previous model components were free to vary while the new one was being fitted. The best-fit parameters for this model are listed in Table 1, and the unfolded spectrum with residuals are shown in Figure 3. To check the goodness of the fit we use the Kolmogorov–Smirnov test statistic that uses the Empirical Distribution Function (EDF), and performs the goodness of fit Monte Carlo simulation to check what percentage of these simulations can reproduce the observed data. If the model produces the observed spectra then this value should be around 50%. For each of $10^6$ simulations we use parameter values drawn from best-fit model. For the best-fit model a 46% realization is less than best-fit statistics, while it is very high, >90%, if any of the model components are removed from the best-fit model. This indicates that the model, which has one less component than the current best-fit model, can be rejected with 90% confidence. In order to check whether an empirical comptonization fits better than a simple power law, we replace the power-law model with a simpl model in XSpec. The simpl model allows us to scatter a fraction of seed photons into the power-law component. The best-fit model with simpl returns reduced $\chi^2$ similar to the simple power-law model with power-law index of $1.70^{+0.01}_{-0.02}$ and a scattered fraction of $0.011_{-0.006}^{+0.011}$ when both up and down scattering are allowed. Therefore, allowing comptonization instead of a simple power law does not affect our results.

The fitting of the soft state spectra allows for an estimation of the distance to the source. The top left panel of Figure 4 shows the variation of $\Delta \chi^2$ as a function of distance, which illustrates the range of acceptable values. The normalization of the disk component depends on the distance, the inner radius, and the inclination angle. In order to compute $\Delta \chi^2$ variations in the parameters we use steppar in XSpec.

In this fitting a distance estimate is possible because the inclination angle and the inner radius are independently constrained, being parameters of the relativistic iron line as well as for the relativistic disk emission. It should be emphasized that it is not the iron line alone that determines these two parameters, but the shape of the relativistically blurred disk emission also helps in constraining their values. We illustrate this in the top middle panel of Figure 4. Here we fit the model by untying the inner radius for the disk and line components, i.e., we allow them to vary independently, but keeping the disk inclination angle of the kerrd model tied to that of the laor model while the disk inclination angle of laor is kept free. We run steppar independently on the inner disk radius parameter from the kerrd and laor models, and the result is shown in the top middle panel of Figure 4. The figure shows that the variation of $\Delta \chi^2$ as a function of the inner radius obtained from the disk and iron line components provide similar estimates of the inner radius. If instead we fit the model by tying the inner radius of the kerrd model component to that of the laor model component and let the inclination angle parameters from both model components vary independently, we get similar constraints on disk inclination angle from both components (by running steppar on the disk inclination angle parameters of the kerrd and laor model components separately). The result is shown in the top right panel of Figure 4. During the above exercises of computing $\Delta \chi^2$ variations in disk inclination angle and inner disk radius, the distance parameter was allowed to vary during the fitting. Thus, the relativistic nature of the disk emission contributes to the estimation of the inner radius and disk.
Table 1
Observation and Spectral Fitting Details of V4641 Sgr Using Simultaneous Data from Swift/XRT and NuSTAR During Soft State and Hard State

| Parameter | Soft State | Hard State |
|-----------|------------|------------|
| Date      | 2014 Feb 14 | 2014 Apr 17 |
| Obs ID    |            |            |
| Nustar    | 80002012002 | 80002012004 |
| XRT       | 00030111030 | 00030111046 |
| Exposure time (s) |            |            |
| Nustar (DT corrected) | 26420 | 24045 |
| XRT       | 1944       | 3983       |
| Model     | tbabs'edge'edge'(powerlaw+kerrd+laor+ga+ga) | tbabs'edge'(powerlaw+ga) |

\[
\begin{array}{l|cc|cc}
N_H  & 10^{22} \text{ cm}^{-2} & 0.21 \pm 0.02 & 0.31 \pm 0.04 \\
\Gamma_f & & 1.79 \pm 0.09 & 2.12 \pm 0.06 \\
E_{\text{edge1}} (\text{keV}) & & 7.21 \pm 0.14 & \ldots \\
\tau_{\text{edge1}} & & 0.21 \pm 0.01 & \ldots \\
E_{\text{edge2}} (\text{keV}) & & 9.61 \pm 0.01 & 8.74 \pm 0.21 \\
\tau_{\text{edge2}} & & 0.22 \pm 0.07 & 0.47 \pm 0.11 \\
E_L (\text{keV}) & & 6.36 \pm 0.28 & \ldots \\
\alpha_L & & 2.02 \pm 0.05 & \ldots \\
R_{\text{in},\text{L}} (R_g) & & 2.43 \pm 0.23 & \ldots \\
R_{\text{out},\text{L}} (R_g) & & 2.56 \pm 0.55 & \ldots \\
i_L (\text{degrees}) & & 400 (fixed) & \ldots \\
\iota_{\text{in}} (\text{degrees}) & & 69.5 \pm 0.2 & \ldots \\
\omega_{\text{eq},\text{L}} (\text{eV}) & & 76.1 \pm 0.1 & \ldots \\
W_{\text{eq},\text{L}} (\text{eV}) & & 292.8 \pm 0.6 & \ldots \\
E_{\text{Fe}1} (\text{keV}) & & 6.95 \pm 0.01 & 6.61 \pm 0.04 \\
E_{\text{Fe}2} (\text{keV}) & & 140.4 \pm 18.5 & 526.8 \pm 54.7 \\
E_{\text{Ni}} (\text{keV}) & & 8.31 \pm 0.14 & \ldots \\
W_{\text{eq},\text{Ni}} (\text{eV}) & & 193.6 \pm 24.7 & \ldots \\
M_{\text{acc}} (10^{18} \text{ gm s}^{-1}) & & 0.065 \pm 0.015 & \ldots \\
D (\text{kpc}) & & 10.5 \pm 0.6 & \ldots \\
F_{\text{total}} (10^{-10} \text{ erg s}^{-1} \text{ cm}^{-2}) & & 5.87 \pm 0.11 & 0.36 \pm 0.04 \\
F_{\text{laor}} (10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}) & & 1.25 \pm 0.06 & \ldots \\
F_{\text{power}} (10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2}) & & 2.41 \pm 0.11 & \ldots \\
\chi^2/\nu & & 721/696 & 284/247 \\
\end{array}
\]

Note. The best-fit model of the soft state spectrum consists of the optically thick, relativistic accretion disk model (kerrd), relativistic line emission model (laor), power-law component (powerlaw), two narrow emission lines modeled by two Gaussians (ga), and two absorption features modeled by two edges (edge). The TBars model is used for Galactic absorption. For the hard state, the power-law model is sufficient to fit the continuum spectrum. Cross-calibrations between different instruments are taken care of by const. In the table $N_H$ is the neutral hydrogen column density, $\Gamma_f$ is the power-law index, $E_{\text{edge1}}$ and $E_{\text{edge2}}$ are two absorption edge energies, and $\tau_{\text{edge1}}$ and $\tau_{\text{edge2}}$ are their optical depths, respectively. $E_L$ is the Laor line energy and $W_{\text{eq},\text{L}}$ is its equivalent width, where $\alpha_L$ is the emissivity index. $R_{\text{in},\text{L}}$ and $R_{\text{out},\text{L}}$ are the inner and outer disk radius from the laor model. $R_{\text{in,kerrd}}$ is the inner disk radius from the kerrd model. $i_L$ and $\iota_{\text{in}}$ are the disk inclination angle obtained from the laor and kerrd models, respectively. While fitting, no two similar parameters are tied. $E_{\text{Fe}1}$ is the narrow iron line energy. $W_{\text{eq},\text{Fe}}$ is the equivalent width of the narrow iron line, $E_{\text{Ni}}$ is the Ni Kα line energy, and $W_{\text{eq},\text{Ni}}$ is its equivalent width. $M_{\text{acc}}$ is the mass accretion rate, $D$ is the distance to the source, and $F_{\text{total}}$, $F_{\text{laor}}$, and $F_{\text{power}}$ are total flux and fluxes due to the laor and power model components. MCMC derived 2σ errors are quoted for parameters.

inclination angle. To check whether relativistic corrections to the emission process is absolutely necessary we use non-relativistic, optically thick disk models like diskbb, diskpn, and ezdiskbb. They either provide unusually large reduced $\chi^2$ ($>2$) or unacceptably high inner disk temperature ($>2$ keV). Therefore, relativistic treatment is required for the observed data, and the requirement is consistent with both disk emission and line profile measurements.

3.1.1. MCMC Simulations and Results

The use of $\chi^2$ minimization technique is not always reliable for determining model parameters with high significance when a large number of free parameters are involved (for example, our best-fit spectral model has 23 free parameters including model normalization and cross calibration factors). For an independent check on our results we employ the MCMC simulations technique for validation of results obtained from the $\chi^2$ minimization technique. The procedure is as follows: we
accretion flow and very large disk inclination angle. Additionally, Figure 4 shows that results obtained from Delta statistics (top panels) are consistent with that from MCMC simulation chains (middle and bottom panels).

The spectral analysis of the soft state using $\chi^2$ minimization as well as MCMC simulations allows us to estimate the distance $10.8^{+1.5}_{-2.2}$ kpc, the inner radius of the disk $2.43^{+0.39}_{-0.17}$ $R_g$ (average of parameters obtained from the kerrd and laor models), and disk inclination angle of $69.5^{+12.8}_{-4.2}$ degrees (average of parameters obtained from the kerrd and laor models). The inner radius and the inclination angle are constrained self consistently and independently by the relativistic effects seen in both the broad iron line and the disk emission.

The distance estimated by the spectral fitting and the MCMC simulation $(10.8^{+1.5}_{-2.2}$ kpc) allows us to compute the luminosity of V4641 Sgr for the two observations and subsequently the Eddington fraction. In the complete 0.3–30.0 keV energy band the luminosity during the soft state was $4.59 \pm 0.65 \times 10^{36}$ erg s$^{-1}$ and $1.03 \pm 0.12 \times 10^{37}$ erg s$^{-1}$, considering the distances to be 8.3 kpc and 12.4 kpc, respectively. This corresponds to an Eddington ratio $L/L_{\text{Edd}} = 12.07 \pm 0.87 \times 10^{-3}$ and $5.74 \pm 0.33 \times 10^{-3}$ for a 6.4 $M_\odot$ black hole.

### 3.2. Hard State Spectral Analysis

For the second observation the source was harder and significantly less luminous. There is no evidence for disk emission. An absorbed power law fit reveals features in the 5–10 keV band as shown in Figure 5. There is a broad line at ~6 keV and an absorption edge around ~9 keV. Indeed, an absorbed power law, a slightly broad emission line at 6.5 keV, and an edge at 8.74 keV provides a reasonable fit with $\chi^2$/dof = 284/247. The best-fit parameters listed in Table 1 and the unfolded spectrum with residuals are shown in Figure $\chi^2$/dof = 284/247 (top and middle panels of Figure 6). During the hard state, the luminosity was $6.91^{+3.04}_{-2.85} \times 10^{35}$ erg s$^{-1}$ and the Eddington ratio $L/L_{\text{Edd}} = 7.28^{+3.26}_{-1.71} \times 10^{-4}$.

The residual plot in the middle panel of Figure 6 shows an emission line-like feature at ~1 keV, as well as an edge-like feature at ~0.4 keV in the XRT spectrum. To account for these features we add an edge and a Gaussian line to the best-fit model. The fit improves with $\chi^2$/dof = 254/242, and the improved residual is shown at the bottom panel of Figure 6. The Gaussian feature at ~1.1 keV has the line width of $<40$ eV (3$\sigma$ significance), which is narrower than the instrumental response at that energy. Uncorrelated residual features are also observed at <0.5 keV from Figure 2. These two facts indicate that the observed features are possibly due to calibration uncertainties rather than real features from a physical process. Additionally, calibration residual at the energy <0.5 keV has been observed for Swift/XRT Window Timing (WT) mode data. Using the best-fit model without the low energy edge and narrow Gaussian line, we fit the spectra excluding the energy range 0.3–1.2 keV in the Swift/XRT band during both soft state and hard state. In doing so, we do not observe any change in the fitted parameter values within error bars other than those reported in Table 1. Reduced $\chi^2$ is also unaffected by this exercise. Therefore, these low energy features do not affect the overall fitting.

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Figure 3. Simultaneously fitted Swift/XRT, NuSTAR/FPMA, and FPMB energy spectra during soft state along with model components and residual contribution to $\chi^2$ are shown. The model consists of relativistic disk emission, power law, Laor line profile, Gaussians at ~6.95 and ~8.14 keV, and absorption edges at ~7.1 and ~9.6 keV.

Proceed with fitting the background-subtracted spectra using $\chi^2$ statistics. Since X-ray spectral counts usually follow Poisson distribution, we replace the fit statistic with the appropriate statistic for Poisson data (pgstat in XSpec) which assumes Poisson distribution on source spectral count, but Gaussian distribution on background counts. The profile likelihood of pgstat derived in the same way as the likelihood of C-statistic is obtained. While fitting, the distance, disk inclination angle, and inner disk radius parameters from the kerrd and laor models are kept free to vary. With the new fit statistics, we run 50,000 element chains starting from a random perturbation away from the best fit, and ignoring the first 5000 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 the rescaling factor of 0.001. The source of the proposal is drawn from the diagonal of the covariance matrix resulting from the fit.

The middle panels of Figure 4 show the parameter values of distance (from the kerrd model), inner disk radius, and disk inclination angle (from laor model) through the 50,000 elements of the chain. Every 10th element of the chain is plotted for clarity. For all chain steps, highly constrained simulated parameter values confirm that the global best fit of the spectral parameter has been achieved. Using a different proposal (i.e., Cauchy distribution instead of Gaussian) also converges on the same best fit with high repeatability fraction in the chain. The best-fit parameter values and MCMC derived 2$\sigma$ errors for the soft state spectral fitting are provided in Table 1, and the bottom panels of Figure 4 show the one-dimensional probability distribution for distance (from the kerrd model), inner disk radius, and disk inclination angle (from the laor model) resulting from best-fit spectral model.

Using the MCMC technique, we obtain the distance to the source, $D$, between 8.3 and 12.4 kpc, the inner disk radius, $R_{in}$ between 2.3 and 2.7 $R_g$ (from laor model) and <3.2 $R_g$ (from kerrd model), and the disk inclination angle, $i$, between 64°–72° (from laor model) and 68°–82° (from kerrd model). Therefore, the parameters, $R_{in}$ and $i$, obtained from different models are consistent with moderately relativistic inner
During the declining phase of the 2004 outburst of V4641 Sgr, as the source approached quiescence, Chandra ACIS-S spectrum in 0.5–10.0 keV showed an absorption-like depression between 1 and 5 keV (Morningstar et al. 2014) that mimics spectra from typical Seyfert-2 galaxies and includes partial covering and distant reflection. We fit the same model used by Morningstar et al. (2014), i.e., \( \text{tbabs x pcfabs x pexmon} \), to fit the soft state data and find an unacceptable reduced \( \chi^2_{\text{red}} \) even when we add an extra Gaussian model. For the hard state, the reduced \( \chi^2_{\text{red}} \) was found to be 1.76. Thus our analysis shows that for both the soft and hard states the model is not necessary.

4. COMPARISON WITH OTHER BLACK HOLE X-RAY BINARIES

The fact that V4641 Sgr shows a soft state at such a low Eddington ratio makes it unique compared to other black hole systems. To illustrate this we compare it with three well known black hole systems: GX 339−4, XTE J1859+226, and XTE J1550−564, by reproducing the results obtained by Fender et al. (2004). We have chosen these systems not only because data is available for their various spectral states, but also their black hole masses and distance are similar to those of V4641 Sgr (see Table 1 of Fender et al. 2004, and references therein). For the following analysis we considered RXTE observations of outbursts of these sources that occurred during 2002 March–2003 May (Belloni 2004), 1999 October–December (Brocksopp et al. 2002), and 1998 August–1999 May (Sobczak et al. 2000). Following Fender et al. (2004), we fitted each of the observations with a disk emission, power law, and a Gaussian line modified by galactic absorption. We used only the PCU2 of the RXTE/PCA since it was the best calibrated proportional counter. We defined luminosity to be in the 2−80 keV range and the hardness ratio (HR) as the ratio of the flux between 6.3−10.5 and 3.8−6.3 keV. The Eddington ratio versus hardness obtained from the analysis is shown in Figure 7. The approximate “q” shapes obtained from our
analysis are consistent with previous analysis (e.g., Fender et al. 2004, and references therein).

In Figure 7, the points corresponding to the hard and soft observations of V4641 Sgr are plotted for comparison. The soft state of V4641 Sgr is significantly less luminous when compared to the other three sources. In fact, it seems that the position occupied by V4641 Sgr in the soft state has not been observed in any other black hole systems. In the hard state the Eddington ratio is \(\sim 1 \times 10^{-3}\), which is close to the ratio value below that which black hole systems are considered to be in quiescence (Plotkin et al. 2013).

5. DISCUSSION

In this paper we have performed joint spectral analysis of the high mass BHXB V4641 Sgr using observations from the Swift/XRT and NuSTAR satellites in the energy range 0.3–30.0 keV for two different spectral states. While for the lower flux level hard state the spectrum can be simply described by a power law and a slightly broad iron line, the higher flux soft state reveals complex components that include a power law, a relativistic disk component, a relativistic broad iron line, two narrow line emission, and two edges.

With the 2\(\sigma\) distance measurement from our analysis (10.8\(\pm\)3 kpc), one can estimate the upper and lower limit of the Eddington fraction for the soft state to be \(L/L_{\text{Edd}} = 12.07 \pm 0.87 \times 10^{-3}\) and \(5.74 \pm 0.33 \times 10^{-3}\), respectively. The upper limit and lower limit of \(L/L_{\text{Edd}}\) are estimated using the upper and lower limit of distances which are 12.4 kpc and 8.3 kpc, respectively. It is important to note that if the actual distance is lower than 8 kpc then \(L_{2-80}\) luminosity will diminish. As a consequence, \(L_{2-80}/L_{\text{Edd}}\) will be lower.

Such a low \(L/L_{\text{Edd}}\) fraction for a soft disk dominated state is rare and matches closely with that observed from XTE J1859+226. In the Eddington ratio hardness plot, BHXBs typically form a "q" diagram, and the soft state of V4641 Sgr is located at a position that can be considered as the lowest limit of three other typical BHXB systems as observed from Figure 7. For a typical BHXB, the hard to soft transition occurs for \(L/L_{\text{Edd}} \sim 0.50\)–1.0 and the reverse occurs when \(L/L_{\text{Edd}} \sim 10^{-2}\). This itself suggests that the spectral state of a BHXB is not just a function of the accretion rate but also depends on how the overall accretion rate is changing with time. In one interpretation of the soft to hard transition, a standard optically thick disk evaporates into a hot optically thin one (Meyer & Meyer-Hoffmeister 1994), and perhaps the rapid variability of the source does not allow for the evaporation to
take place. Such speculations require sophisticated theoretical modeling for confirmation and more deep observations of this source at different flux levels are required to understand its temporal behavior.

The inner disk radius during the soft state is found to be \( r_{\text{in}} \sim 2.5 r_g \). If identified with the last stable orbit of a disk, this would suggest that the black hole has a moderate spin. However, we note that both the laor and kerd spectral models used for the disk and line emissions assume an extremal spin of 0.998, and hence the actual value of the inner radius may be different if the spin is moderate. A more general prescription that takes into account different spin values of the black hole may be used to fit the disk emission, as has been done for some black hole systems (McClintock et al. 2014). In such an analysis, one should also consider more realistic color factors than the universal 1.7 assumed in this work. However, such analysis has been undertaken on good quality clean data where the power-law component is very weak, i.e., \(<10\%\). Nevertheless, it will be interesting to see whether the spin of the black hole can be constrained using sophisticated spectral models, an analysis which is beyond the scope of the present work.

5.1. Effects of the Companion Star on Observed Spectra

First, it is important to explore the role of strong wind from the companion star in explaining observed features in the spectra. The optical depth of the nickel edge during the soft state observation is found to be unusually large and varies significantly while transitioning from the soft state to the hard state (e.g., for the absorption edge at \( \sim 9\, \text{keV} \), \( \tau \) increases from \( \sim 0.22 \) to \( \sim 0.47 \)). During the soft state, two narrow emission lines and edges are clearly detected in the spectrum. Since the lines are narrow, they should arise from regions far from the black hole. Therefore, the presence of highly ionized wind from the disk/binary companion seems to be of natural origin. The emission line at \( \sim 6.95\, \text{keV} \) can be identified due to ionized iron in the X-ray irradiated wind. The emission line at \( \sim 8.1\, \text{keV} \) is more uncertain. The line energy suggests that it could arise due to highly ionized nickel as can be seen in Figure 2 of Turner et al. (1992).

However, the nature of the wind needs to be investigated carefully. A relationship between the kinetic power of the wind (per unit filling factor, \( C_\nu \)) and the bolometric luminosity, log \( (L_{\text{wind,42}}/C_\nu) = 1.58 \pm 0.07 \) log \( (L_{\text{bol,42}}) - 3.19 \pm 0.19 \), is obtained by King et al. (2013) by studying the Chandra grating spectra across the black hole mass scale—from BHXBs to AGNs. If the above relationship is true for V4641 Sgr, then using the bolometric luminosity for the soft spectral state in our analysis we obtain log \( (L_{\text{wind,42}}/C_\nu) = -2.46 \), which significantly deviates from the value observed for canonical BHXBs and is consistent with low ionization. In order to produce the large optical depth of the edges, circumstellar wind from the binary companion in V4641 Sgr needs to be very strong. From the observation, the mass of the binary companion of V4641 Sgr is found out to be 2.9 \pm 0.4 \( M_\odot \) which is a reddened B9III star with relatively low rotational velocity \( (V_{\text{rot}}\sin i = 100.9 \pm 0.08 \, \text{km s}^{-1}) \). The measured velocity is lower than the predicted minimum threshold for launching highly ionized stellar wind \( (V_{\text{rot}}\sin i \sim 150-200 \, \text{km s}^{-1}) \) from the UV survey of 40 B-type stars covering luminosity classes V–III; Grady et al. (1989). From the spectroscopic study, the possibility of radiation driven wind from the surface of the companion star can be ruled out since the surface temperature of the companion star in V4641 Sgr is derived to be 10,250 \pm 300 \, \text{K} (MacDonald et al. 2014), which is relatively low and not hot enough to produce an effective radiation driven wind. This indicates that the possibility of very strong wind in this source may not be the only explanation for the observed features. Multiple and strong emission lines and absorption edges, even at hard state, may possibly indicate the over-abundance of elements like iron (\( A_\text{Fe} > 2 \) present in the spectra. However, high resolution grating spectroscopy using Chandra or XMM-Newton during soft state in V4641 Sgr may provide compelling evidence for any possible nature of disk wind in this source.

It is interesting to note that for the Galactic jet source SS 433, the nickel over-abundance by a factor of 20 (Kotani 1997) and high disk inclination angle causes the visibility of the nickel emission line in the spectra (Kotani 1997), and nickel emission lines are expected from ionized medium surrounding Active Galactic Nuclei (Turner et al. 1992). A detailed work focusing on the physics of the X-ray irradiated wind is required to understand the narrow emission lines and edges seen in V4641 Sgr. Although there does not seem to be any issues regarding NuSTAR calibration during these observations, it would perhaps be prudent to reconfirm these emission lines with a second observation by NuSTAR during a similar spectral state or by other high resolution instruments.

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REFERENCES

Ballantyne, D. R., Ross, R. R., & Fabian, A. C. 2001, MNRAS, 327, 10
Baloković, M., Comastri, A., Harrison, F. A., Alexander, D. M., & Ballantyne, D. R. 2014, ApJ, 794, 111
Belloni, T. 2004, NuPhS, 132, 337
Brockopp, C., Fender, R. P., McCollough, M., et al. 2002, MNRAS, 331, 765
Cackett, E. M., Miller, J. M., Bhattacharya, S., et al. 2008, ApJ, 674, 415
Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215
Done, C., & Gierliński, M. 2006, MNRAS, 367, 659
Duro, R., Dauser, T., Wilms, J., Pottschmidt, K., et al. 2011, A&A, 533, L3
Ebisawa, K., Zycki, P., Kubota, A., Mizuno, T., & Watarai, K. 2003, ApJ, 597, 780
Fabian, A. C., Iwasawa, K., Reynolds, C. S., & Young, A. J. 2000, PASP, 112, 1145
Fabian, A. C., Rees, M. J., Stella, L., & White, N. E. 1989, MNRAS, 238, 729
Fender, R. P., Belloni, T. M., & Gallo, E. 2004, MNRAS, 355, 1105
Feng, Y. X., Zhang, S. N., Sun, X., et al. 2001, ApJ, 535, 394
García, J., Dauser, T., Reynolds, C. S., et al. 2013, ApJ, 768, 146
Grady, C. A., Bjorkman, K. S., Snow, T. P., et al. 1989, ApJ, 393, 409
Harrison, F. A., Craig, W. W., Christensen, F. E., et al. 2013, ApJ, 770, 103
Hjelm, B., Soleri, P., Mendez, M., et al. 2009, MNRAS, 394, 2080
Hjellming, R. M., Rupen, M. P., Hurstead, R. W., et al. 2000, ApJ, 544, 977
Homan, J., Wijnands, R., van der Klis, M., et al. 2001, ApJS, 132, 377
Inoue, H. 1989, Proc. of the 23rd ESLAB Symp. on Two Topics in X-Ray Astronomy, Vol. 2, ed. J. Hunt & B. Battrick (Esra Publications), 783
Inui Zand, J. J. M., Markwardt, C. B., Buzzanno, A., et al. 2000, A&A, 357, 520
King, A. L., Miller, J. M., Reynolds, C., et al. 2013, ApJ, 762, 103
Kolehmainen, M., Done, C., & Diáz Trigo, M. 2014, MNRAS, 437, 316
Kotani, T. 1997, PhD thesis, University of Tokyo
Laor, A. 1991, ApJ, 376, 90
MacDonald, R. K. D., Bailyn, C. D., & Buxton, M. 2014, ApJ, 784, 2
Maitra, D., & Bailyn, C. D. 2006, ApJ, 637, 992
McClintock, J. E., Narayan, R., & Steiner, J. F. 2014, SSRv, 183, 295
Meyer, F., & Meyer-Hoffmeister, E. 1994, A&A, 288, 175
Miller, J. M., Fabian, A. C., In't Zand, J. J. M., et al. 2002a, ApJL, 577, L15
Miller, J. M., Fabian, A. C., Wijnands, R., & Remillard, R. A. 2002b, ApJ, 578, 348
Miller, J. M., Homan, J., Steeghs, D., et al. 2006, ApJ, 653, 525
Miller, J. M., Parker, M. L., Fuerst, F., et al. 2013, ApJL, 775, L45
Morningstar, W. R., Miller, J. M., Reynolds, M. T., & Maitra, D. 2014, ApJL, 786, L20

Orosz, J. A., Kuulkers, E., van der Klis, M., et al. 2001, ApJ, 555, 489
Plotkin, R. M., Gallo, E., & Jonker, P. G. 2013, ApJ, 773, 59
Reis, R. C., Miller, J. M., Fabian, A. C., Cackett, E. M., & Maitra, D. 2011, MNRAS, 410, 2497
Remillard, R. A., & McClintock, J. E. 2006, ARA&A, 44, 49
Reynolds, C. S., Brenneman, L. W., Lohfink, A. M., et al. 2012, ApJ, 755, 88
Ross, R. R., & Fabian, A. C. 2005, MNRAS, 358, 211
Shimura, T., & Takahara, F. 1995, ApJ, 440, 610
Sobczak, G. J., McClintock, J. E., Remillard, R. A., Cui, W., et al. 2000, ApJ, 544, 993
Tomsick, J. A., Kaaret, P., Kroeger, R. A., & Remillard, R. A. 1999, ApJ, 512, 892
Turner, T. J., Done, C., Mushotzky, R., & Madejski, G. 1992, ApJ, 391, 102