



First Look at the High-resolution X-Ray Spectra in the Highly Absorbed High-mass X-Ray Binary IGR J16318–4848 with Chandra

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Abstract

We present a comprehensive analysis of the X-ray spectrum of the highly obscured high-mass X-ray binary IGR J16318–4848 based on ~ 250 ks Chandra/HETGS observations covering different orbital phases. We detected a strong narrow Fe K α emission line and interpret our finding as the iron line originating in the stellar wind close to the compact object. We tentatively identify a Compton shoulder associated with the Fe K α line. The ratio of the Compton-shoulder flux to that of the Fe K α core exhibits orbital-phase variability, reaching a maximum of $\sim 10\%$ around orbital phase $\phi_{\text{orb}} \simeq 0.33$. In addition, we do not detect ionized lines, implying that the plasma in the system is predominantly cold. We preliminarily report that the Fe K α line centroid exhibits an orbital modulation with an amplitude of $167 \pm 32 \text{ km s}^{-1}$, adopting the best-known circular orbit in the source. This study presents the first detailed view of the high-resolution X-ray spectra of IGR J16318–4848 across different orbital phases, providing timely context for the newly taken XRISM observations of the source.

Unified Astronomy Thesaurus concepts: High mass x-ray binary stars (733); High resolution spectroscopy (2096)

1. Introduction

The Galactic plane survey by INTEGRAL at hard X-rays (e.g., R. A. Krivonos et al. 2017) discovered many highly obscured ($N_{\text{H}} \gtrsim 10^{23} \text{ cm}^{-2}$) high-mass X-ray binaries (HMXBs) that were previously undetected in soft <10 keV X-ray surveys. Most of these sources are thought to be supergiant X-ray binaries (SGXBs) undergoing a transition from stellar wind accretion to

Roche lobe overflow (R. Walter et al. 2015). The most common hypothesis for their highly obscured nature is that the compact object is embedded in a dust-filled shell surrounding the companion star (see, e.g., N. Iyer & B. Paul 2017). Some studies indicate that such sources may represent a previously unknown evolutionary phase of X-ray binaries with early-type optical companions (D.-S. Moon et al. 2007).

Among these highly obscured X-ray binaries, the most extreme example is IGR J16318–4848, with a column density of $N_{\text{H}} \sim 10^{24} \text{ cm}^{-2}$ (Figure 1 of P. Pradhan et al. 2018). It was first discovered in 2003 by the IBIS/ISGRI on board INTEGRAL (T. J.-L. Courvoisier et al. 2003, H. Murakami et al. 2003). The companion star was identified as a sgB[e] star with a dense equatorial disk (P. Filliatre & S. Chaty 2004) in

²⁵ deceased 2025 June 17.



which the compact object is embedded. The source exhibits quasi-transient behavior, with a complex, multi-peaked orbital profile (orbital period of ~ 80 days) found in the long-term Neil Gehrels Swift Observatory Burst Alert Telescope (Swift/BAT) light curves (C. Jain et al. 2009; N. Iyer & B. Paul 2017). The nature of the compact object in IGR J16318–4848 remains unclear, as neither cyclotron resonant scattering features nor coherent pulsations have been detected. N. Iyer & B. Paul (2017) place an upper limit of 1% on the X-ray pulsed fraction in the soft (<10 keV) band from XMM-Newton observations, and an upper limit of $\sim 4\%$ from NuSTAR in the hard band (up to 70 keV). Interestingly, this is similar to another supergiant HMXB, OAO 1657–415, which has a $\sim 2\%$ pulse fraction during the highly absorbed phases of its orbit (P. Pradhan et al. 2014, 2019). The lack of radio emission from IGR J16318–4848, which would be expected for a black hole X-ray binary following the radio–X-ray correlation of E. Gallo et al. (2003), further complicates the identification of the compact object (see Section 6.2 of P. Filliatre & S. Chaty 2004).

The exceptionally high absorption in IGR J16318–4848 is believed to be a result of the system being surrounded by a dense, dusty cocoon of material. This conclusion is supported by the presence of prominent iron ($K\alpha$ and $K\beta$) and nickel fluorescence lines and a deep Fe K edge at 7.1 keV (G. Matt & M. Guainazzi 2003; M. G. Revnivtsev et al. 2003; L. Barragán et al. 2009). The variability timescale and the maximum observed delay between the continuum variation and the delay in the Fe $K\alpha$ line constrain the maximum size of the fluorescent emission region and its distance from the X-ray source to approximately 10^{13} cm (R. Walter et al. 2003). Although the Fe $K\beta/K\alpha$ flux ratio of ~ 0.20 is higher than that expected for neutral material (S. T. Perkins et al. 1991; G. Matt & M. Guainazzi 2003), no ionized iron lines have been detected in IGR J16318–4848. Hitomi observed IGR J16318–4848 during its early instrument check-out phase, with the source positioned in (unintended) off-axis configuration. During this observation, no ionized lines were detected in the Soft X-ray Imager (SXI) data. The Soft X-ray Spectrometer (SXS) collected approximately 20 photons but still puts constraints on the Fe $K\alpha$ line centroid and width consistent with neutral Fe (Fe I–IV; Hitomi Collaboration et al. 2018).

In highly absorbed sources, the Compton shoulder of the iron $K\alpha$ should be detected. This “shelf” on the red wing of the Fe $K\alpha$ arises when the fluorescent photons are Compton downscattered by high-optical-depth material. In IGR J16318–4848, the existence of a Compton shoulder is debated—L. Barragán et al. (2009) placed an upper limit of $\sim 0.5\%$ of the $K\alpha$ flux using Suzaku, while A. Ibarra et al. (2007) have claimed detection of the Compton shoulder in XMM-Newton observations at $\sim 25\%$ of the $K\alpha$ flux, suggesting that the feature may be variable in time or orbital phase. To date, a Compton shoulder has been detected in only a few HMXBs, such as GX 301-2 and OAO 1657-415 (S. Watanabe et al. 2003; P. Pradhan et al. 2019), each with substantially lower N_H than IGR J16318–4848. Since the strength of the shoulder is generally expected to increase with column density (G. Matt 2002), its relative weakness in this highly absorbed system is especially puzzling. One proposed explanation invokes geometric effects: while a spherically symmetric distribution of material maximizes the probability of multiple Compton scatterings and thus produces a prominent Compton

Table 1

Details of Observations Performed by Chandra with Date of Observation, MJD, Orbital Phase ϕ_{orb} , ObsID of Observation, and Approximate Exposure

DATE-OBS (UTC)	MJD	ϕ_{orb}	ObsID	Exp (ks)
Group 1				
2021-01-17 16:13:14	59231.676	0.85	24767	30
2021-06-27 22:12:43	59392.925	0.86	25022	25
Group 2				
2021-06-06 03:03:53	59371.128	0.59	24765	18
2021-06-06 18:37:03	59371.776	0.59	24766	22
Group 3				
2021-08-13 18:21:26	59439.765	0.44	22700	31
Group 4				
2021-05-15 12:52:50	59349.537	0.32	23030	24
2021-05-15 21:16:21	59349.886	0.32	25034	22
2021-05-16 15:35:40	59350.650	0.33	23031	26
2021-08-05 09:31:24	59431.397	0.34	22699	25
Group 5				
2021-02-06 07:23:33	59251.308	0.09	23032	16
2021-02-01 12:37:34	59246.526	0.03	24944	13

Note. The orbital phases were calculated with reference to MJD 53477.577 and a period of 80.09 days taken from N. Iyer & B. Paul (2017).

shoulder, a nonspherical or clumpy absorbing structure can provide pathways with a lower scattering depth (H. Odaka et al. 2016), suppressing the shoulder even at high column densities. In such geometries, some fluorescent line photons may escape without any consecutive scattering, leading to a weaker Compton shoulder.

In addition to geometry, the dust content of the absorber may further influence the Compton shoulder strength. For a given column density, a higher dust-to-gas ratio reduces the effective electron scattering optical depth because dust grains contain little or no hydrogen and helium, which dominate Compton scattering. Consequently, the intensity of the Compton shoulder decreases in dusty absorbers (R. Ballhausen et al. 2020).

In this paper, we present a detailed analysis of the Chandra/HETGS observations of IGR J16318–4848 across multiple orbital phases. Our goals are to characterize the Fe $K\alpha$ and $K\beta$ emission lines, study the properties and variability of the Compton shoulder, and constrain the geometry and location of the absorbing and reprocessing material. The data reduction and analysis are given in Section 2, and results are given in Section 3, followed by discussion in Section 4, and a summary in Section 5.

2. Data Reduction and Analysis

The Chandra observations of IGR J16318–4848 were obtained as part of the HETG Guaranteed Time Observations (GTO) program in 2021. These observations span a range of orbital phases of the source (see Table 1). The data are available from the Chandra archive at doi:10.25574/cdc.556. To determine the orbital phase of the observations, we folded the daily Swift/BAT light curves²⁶ using a reference epoch of MJD 53477.577 and an orbital period of 80.09 days, as

²⁶ <https://swift.gsfc.nasa.gov/results/transients/>

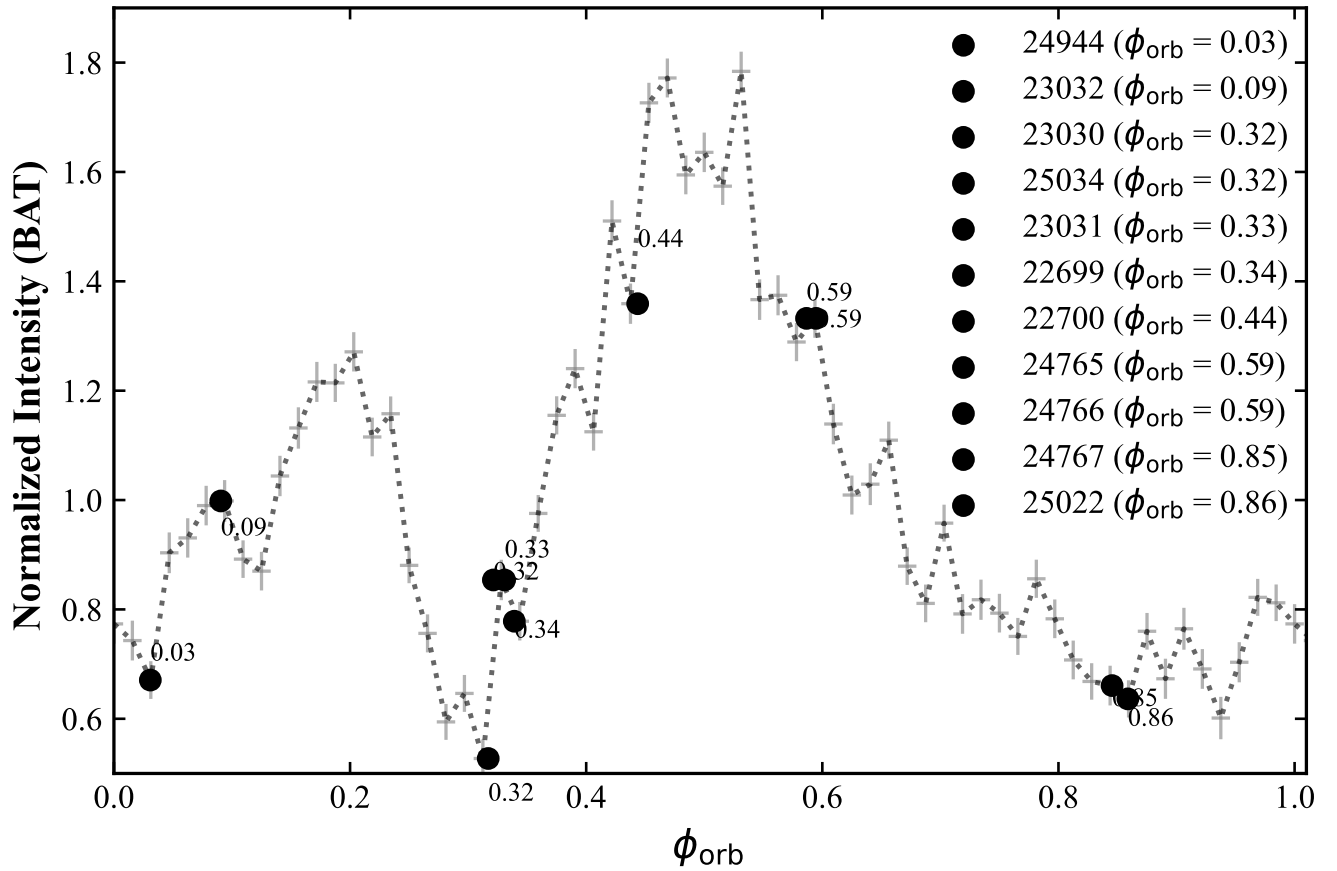


Figure 1. Orbital intensity profile of IGR J16318–4848 obtained by folding the Swift/BAT daily light curves with a period of 80.09 days (± 0.012) and a reference epoch of MJD 53477.577, adopted from N. Iyer & B. Paul (2017). The reference epoch is chosen such that the peak BAT flux occurs at an orbital phase of $\phi_{\text{orb}} = 0.5$. The orbital phases of the Chandra ObsIDs closest to the BAT data points (within a phase difference < 0.007) are listed on the right.

reported by N. Iyer & B. Paul (2017). The orbital phases corresponding to the Chandra observations are marked by black circles in Figure 1. The ObsIDs discussed in this paper, along with the MJD of observation, orbital phase (ϕ_{orb}), and approximate exposure times, are listed in Table 1.

To reduce the ACIS-S zeroth-order undispersed Chandra spectra, we ran the CIAO (A. Fruscione et al. 2006) command `chandra_repro` to reprocess and ensure that all data were up to date on calibration. CIAO version 4.15 was used for Chandra data reduction. For spectral and light-curve extraction of the zero-order undispersed ACIS-S events, we used the CIAO command `specextract`, which accepts the infile as the event files with a specified region to extract for the source and background as well as other necessary ancillary files. A circular region is chosen around the zeroth-order image and a region of the same size and shape, but away from the source, is used as background for light-curve and spectrum extraction. Detected zeroth-order count rates (i.e., filtered of bad events) ranged from 0.02–0.06 cps. With a frame time of 3.2 s, we then have 0.05–0.20 counts per frame (the important quantity in considering event pileup). According to the “ABC Guide,”²⁷ the pileup fraction is certainly less than 10% and likely no more than 3%. Since the zeroth-order rate changes linearly with the unpiled dispersed rate in each observation, and since the dispersed and zeroth-order mean fluxes agree very well, we find that pileup is negligible for these observations. For the dispersed grating

spectra of all ObsIDs, we downloaded the data from TGCat, which provides the processed spectral files ready for analysis (D. P. Huenemoerder et al. 2011). For both the zero-order and the dispersed spectra, the background is 10–1000 times lower than the source counts over the 5–8 keV range.

The extremely high absorbing column of IGR J16318–4848 usually results in very few counts below ~ 4 –5 keV. For the mean flux model, we jointly fit the 4–10 keV Chandra HETGS zeroth and first-order spectra. In high-resolution X-ray spectroscopy, accurate centroid and width determination of spectral lines are essential, and they depend on the spectral resolution of the instrument, as well as the choice of sampling. Meaningful constraints on the intrinsic line width require that it exceeds the instrumental width. For example, the Chandra High Energy Gratings (HEG) has a spectral resolution of $\text{FWHM} \simeq 0.01 \text{ \AA}$. At the wavelength of the Fe K α line ($\lambda \simeq 1.94 \text{ \AA}$), the instrument is sensitive to FWHM of about 1550 km s^{-1} . We see from the best confidence intervals on the spectral features, using only the high-dispersion data, that the line width of the K α line is resolved (more details below).

With good signal, line centroids can typically be determined to about 10% of the instrumental resolution. For a line with N detected photons and an instrumental line-spread function (LSF) of width σ_{LSF} (in wavelength units), the statistical uncertainty on the centroid scales as

$$\delta_{\text{centroid}} = \frac{\sigma_{\text{LSF}}}{\sqrt{N}} \quad (1)$$

(e.g., D. A. Landman et al. 1982).

²⁷ “The Chandra ABC Guide to Pileup,” https://cxc.harvard.edu/ciao/download/doc/pileup_abc.pdf.

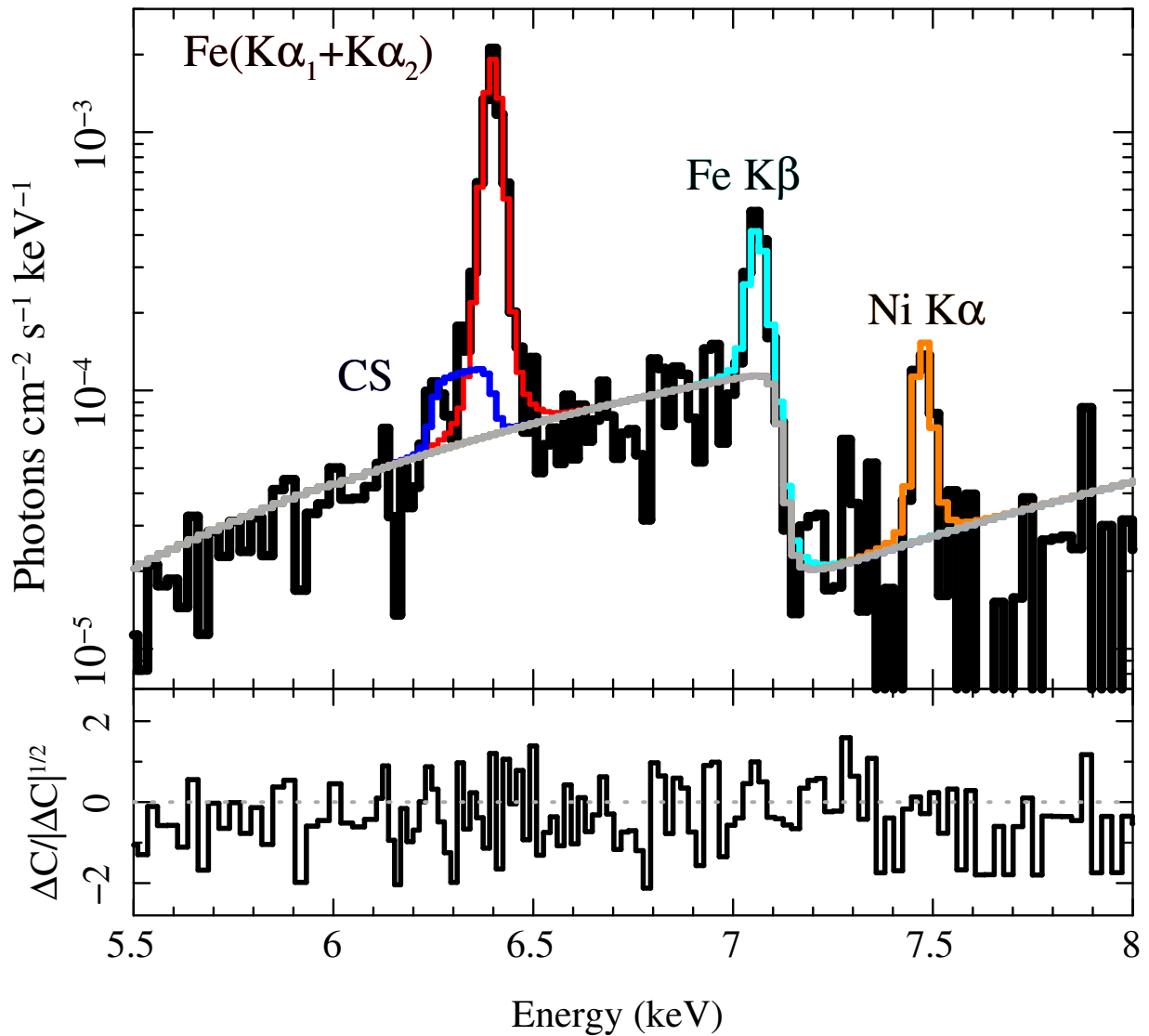


Figure 2. Zoomed-in first-order HETG unfolded spectra showing the major components of the model. The Compton shoulder (CS) is shown in blue, the Fe $K\alpha$ line in red, the Fe $K\beta$ line in cyan, and the Ni $K\alpha$ line in orange. The continuum is marked in gray.

We adopted the default 4 times oversampling of the instrumental LSF for HETG spectra. This results in bin sizes of $0.0025 \text{ \AA}$ for the HEG and of $0.005 \text{ \AA}$ for the Medium Energy Grating (MEG). Higher diffraction orders will have higher resolving powers in proportion to the order, but for HETG the efficiency becomes sufficiently low that the second- and third-order HETGS spectra are too noisy for meaningful analysis. See Figure 2 for the unfolded HETG spectra.

We fit the average spectra (all ObsIDs together) with an absorbed power law plus three Gaussian emission lines to model the iron $K\alpha$ and $K\beta$ lines and the Ni $K\alpha$ line. The spectral fitting uses maximum-likelihood statistics appropriate for Poisson-distributed data (Cash statistic; W. Cash 1979). The Fe K edge at 7.1 keV seen in earlier observations (e.g., R. Ballhausen et al. 2020) could not be modeled due to limited statistics above the K-edge energy. We also fixed the photon index to its best-fit value. The choice to fix the photon index is motivated by the very soft spectrum of the source, which does not allow the power-law slope to be reliably constrained in our fits, and in fact, it could not be reliably constrained even with broadband coverage (see Table 2 of N. Iyer & B. Paul 2017).

We fit the Fe $K\alpha$ line using two Gaussians, with the relative line normalizations of $E_{K\alpha_1}$ and $E_{K\alpha_2}$ held at the 2:1 ratio, widths tied to each other, and the Fe $K\alpha_2$ line centroid constrained to be 0.013 keV below the Fe $K\alpha_1$ line, as discussed in L. Barragán et al. (2009). While the doublet separation of $0.004 \text{ \AA}$ is below the instrumental resolution of $0.01 \text{ \AA}$ of HEG, we fit a two-component model to avoid any systematic errors marginally resolved lines might have on the centroid or width. We also detect an asymmetric excess on the low-energy side of the Fe $K\alpha$ line, suggestive of a Compton shoulder. To account for this asymmetry, we introduced an additional Gaussian component. Alternatively, we also modeled the Compton shoulder using a box function (P. Pradhan et al. 2019). The results of both fitting approaches are reported in Table 2, and the average spectra are shown in Figure 3. As seen in Table 2, the fit statistic ($C_\nu/\text{data bins}$) without a Compton shoulder is $12,446/37,312$. Including a Compton shoulder as a box improves the fit to $12,403$, with one additional free parameter (box amplitude). Modeling the Compton shoulder with a Gaussian component and fixed centroid gives $12,415$ ($\Delta C = 31$, with width and norm free).

Table 2
Best-fit Phase-averaged Spectral Parameters of IGR J16318–4848 for Zero-order Plus HETG

Parameter	With Additional Gaussian Component	With Additional Box Function	No Compton Shoulder Component
N_H (10^{22} atoms cm^{-2})	131^{+7}_{-3}	130^{+7}_{-4}	131^{+4}_{-7}
Γ_{norm}^a	$(9.84^{+0.03}_{-0.03}) \times 10^{-4}$	$(9.74^{+0.33}_{-0.33}) \times 10^{-4}$	$10.03^{+0.33}_{-0.32} \times 10^{-4}$
Γ	0.24	0.24	0.24
I_{box}^b	...	$(7.95^{+2.24}_{-2.15}) \times 10^{-4}$	...
E_{CS} (keV)	6.242	...	...
σ_{CS} (keV)	$0.010^{+0.001}_{-0.007}$	...	...
I_{CS}^c	$5.2^{+1.7}_{-1.7} \times 10^{-5}$	...	...
Fe $E_{K\alpha_1}$ (keV)	$6.403^{+0.001}_{-0.001}$	$6.404^{+0.001}_{-0.001}$	$6.402^{+0.001}_{-0.002}$
Fe $\sigma_{K\alpha_1}$ (keV)	$0.0134^{+0.0035}_{-0.0021}$	$0.0116^{+0.0024}_{-0.0024}$	$0.0141^{+0.0024}_{-0.0023}$
Fe $I_{K\alpha_1}^c$	$(7.22^{+0.02}_{-0.03}) \times 10^{-4}$	$(6.66^{+0.29}_{-0.29}) \times 10^{-4}$	$7.28^{+0.25}_{-0.24} \times 10^{-4}$
Fe $E_{K\alpha_2}$ (keV)	$E_{K\alpha_1} - 0.013$ keV	$E_{K\alpha_1} - 0.013$ keV	$E_{K\alpha_1} - 0.013$ keV
Fe $\sigma_{K\alpha_2}$ (keV)	$\sigma_{K\alpha_1}$	$\sigma_{K\alpha_1}$	$\sigma_{K\alpha_1}$
Fe $I_{K\alpha_2}^c$	$0.5 \times I_{K\alpha_1}^d$	$0.5 \times I_{K\alpha_1}^d$	$0.5 \times I_{K\alpha_1}^d$
Fe $E_{K\beta}$ (keV)	$7.059^{+0.006}_{-0.003}$	$7.059^{+0.005}_{-0.006}$	$7.060^{+0.005}_{-0.006}$
Fe $\sigma_{K\beta}$ (keV)	$0.0074^{+0.0095}_{-0.0073}$	0.01	$0.010^{+0.000}_{-0.010}$
Fe $I_{K\beta}^c$	$(1.06^{+0.01}_{-0.01}) \times 10^{-4}$	$(1.05^{+0.15}_{-0.14}) \times 10^{-4}$	$10.23^{+1.46}_{-1.41} \times 10^{-5}$
Ni $E_{K\alpha}$ (keV)	$7.469^{+0.011}_{-0.004}$	$7.469^{+0.010}_{-0.004}$	$7.469^{+0.002}_{-0.011}$
Ni $\sigma_{K\alpha}$ (keV)	5×10^{-5}	2.7×10^{-5}	6.5×10^{-5}
Ni $I_{K\alpha}^c$	$2.06^{+0.05}_{-0.05} \times 10^{-4}$	$(2.03^{+0.49}_{-0.45}) \times 10^{-4}$	$1.99^{+0.47}_{-0.45} \times 10^{-4}$
$C_{\nu}/\text{data bins}$	12,415/37,312	12,403/37,312	12,446/37,312

Notes. Errors quoted are for 90% confidence range, and parameters with no errors were frozen or tied.

^a Photons $\text{keV}^{-1} \text{cm}^{-2} \text{s}^{-1}$ at 1 keV.

^b Photons $\text{cm}^{-2} \text{s}^{-1}$ of a box function between $E_{K\alpha_1}$ and E_{CS} .

^c Photons $\text{cm}^{-2} \text{s}^{-1}$.

Overall, the improvement is modest, indicating only tentative evidence for the Compton shoulder.

The contour plots for the average spectra with a box for the Compton shoulder showing (i) the intensity of the Fe $K\alpha$ line versus the shift of the line expressed in km s^{-1} , Δv , and (ii) the centroid shift of the line (Δv) versus the width in km s^{-1} (FWHM) are shown in Figure 4. The velocity shift is defined as

$$\Delta v = \left(1 - \frac{E_{K\alpha_1}^{\text{obs}}}{E_{K\alpha_1}^{\text{rest}}} \right) c. \quad (2)$$

The full width at half maximum is given by

$$\text{FWHM} = \frac{\sigma(E_{K\alpha_1}^{\text{obs}}) \cdot 2.35 \cdot c}{E_{K\alpha_1}^{\text{rest}}}. \quad (3)$$

The $K\alpha$ widths are clearly resolved, as shown in the right panel of Figure 4. If the line were unresolved, one would instead expect open contours on the low-FWHM side, as illustrated in Figure 2 of T. Yaqoob et al. (2001). We note that similar closed contours are obtained when fitting the Compton shoulder with a Gaussian as well.

For orbital phase-resolved analysis, the 11 observations were grouped into five sets based on their orbital phases for phase-resolved spectral analysis (see Table 1). For each group, we take the average model obtained above as the baseline choosing a Gaussian line for the Compton shoulder, instead of a box. Doing this will allow us to readily calculate the fraction f , which is the ratio of the Compton shoulder flux to $K\alpha$ flux. For these orbital-resolved spectral fits (see Figure 5), we freeze the power-law index to the value from average spectra, but allow the absorption, the normalization of the power law, and

the normalization and centroids of the Gaussian components to vary. The results are presented in Section 3.

All spectral fitting was performed using the Interactive Spectral Interpretation System (ISIS) software²⁸ (J. C. Houck & L. A. Denicola 2000), which also provides interfaces to `xspec` (K. A. Arnaud 1996) models.

3. Results

Average spectra. Through a comprehensive analysis of a long observational campaign of IGR J16318–4848, we draw several significant conclusions that enhance our understanding of this source. In the time-averaged spectra, we detect strong and narrow Fe $K\alpha$, Fe $K\beta$, and Ni $K\alpha$ emission lines. We do not detect ionized lines, indicating that the fluorescent emission originates in cold or only mildly ionized material.

Orbital phase-resolved analysis. The narrow nature of the Fe $K\alpha$ line provides an excellent opportunity to determine any radial velocity shifts as the system moves through its orbit. We therefore perform orbital phase-resolved analysis grouping the spectra at five orbital phases. The orbital phases used for this analysis are based on the ephemeris provided by N. Iyer & B. Paul (2017). We used the baseline average model and froze the power-law photon index to the phase-averaged value to obtain meaningful constraints on the spectral fits. As shown in Figure 6, we see several key spectral components vary with orbital phase, including the absorption column density, the normalization of Fe $K\alpha$ and Fe $K\beta$ lines, and the Compton shoulder. We find that the absorption is variable, reaching its maximum at phase ~ 0.33 (best-fit spectral parameters for this phase are given in Table 3), which coincides with the largest

²⁸ <https://space.mit.edu/cxc/ISIS/index.html>

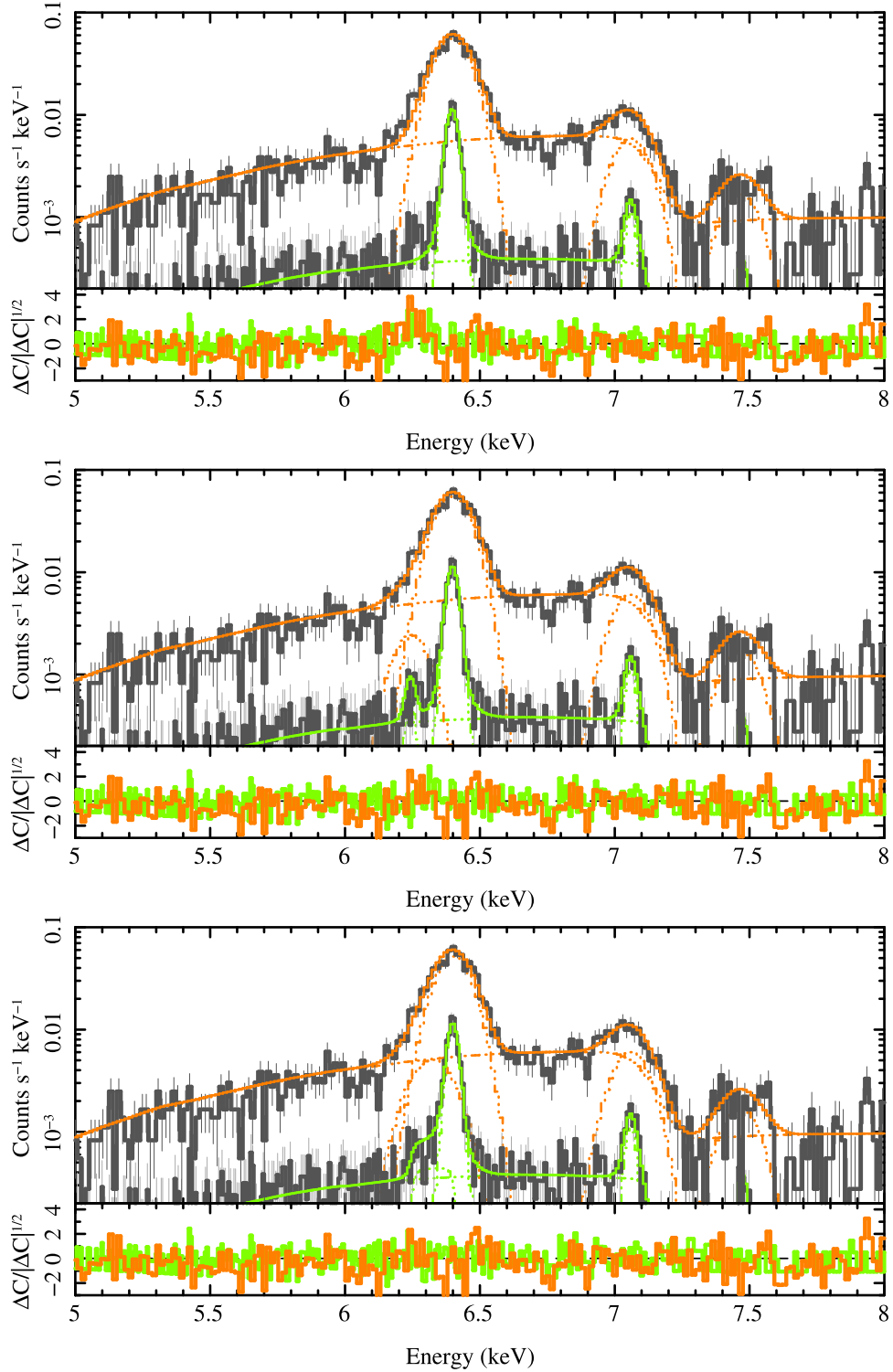


Figure 3. Zero-order spectra (model in orange) and HETG spectra (model in green), along with their corresponding residuals in the same colors, are shown stacked for all observations. Each set is fitted with an absorbed power-law plus (top) three Gaussian lines with no Compton shoulder, (middle) four Gaussian lines, including a Compton shoulder modeled as an additional Gaussian component, and (bottom) three Gaussian lines, with the Compton shoulder modeled using a box function.

value (10%) of the Compton shoulder flux (to the $K\alpha$ line). We also observe orbital modulation in the energy of the Fe $K\alpha$ line.

Radial velocity curve for individual ObsIDs. To furthermore investigate the Fe $K\alpha$ modulation in more detail, we fit the Fe $K\alpha$ line in each ObsID individually, first allowing N_H , the power-law normalization and the Gaussian centroid plus

normalization to vary to their best-fit values for that observation, and then freezing the absorption and normalization values when constraining the Fe $K\alpha$ line centroid. In 10 out of 11 ObsIDs (ObsID 23032 had very low statistics), we were able to constrain the line centroid.

Next, for the 10 ObsIDs, we applied heliocentric corrections to the measured line centroids. For each observation, we first

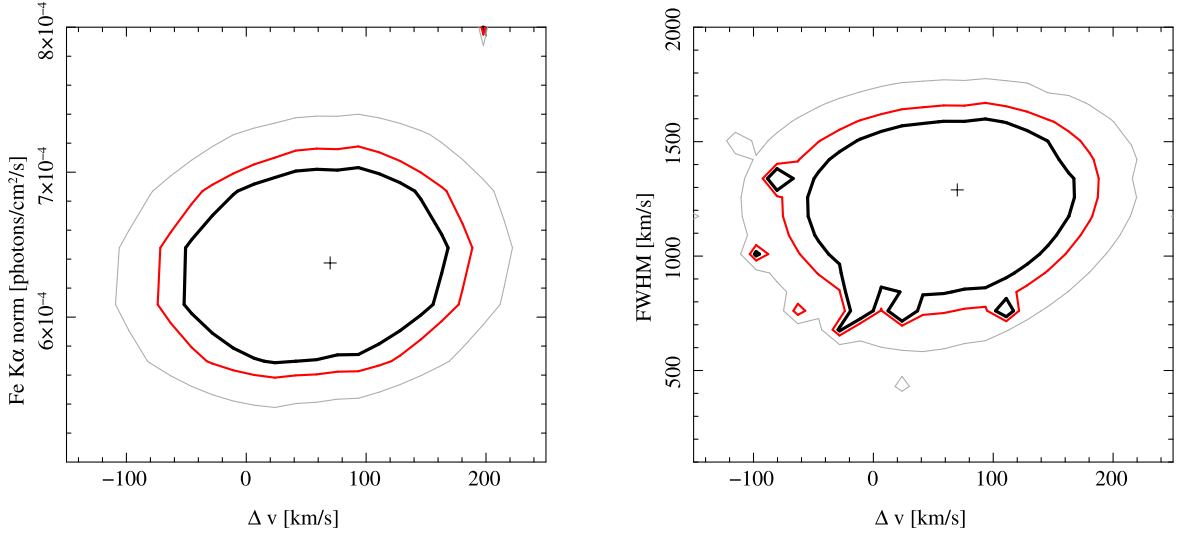


Figure 4. Left: contour plots of the flux of the Fe $K\alpha_1$ line versus the velocity of the line in km s^{-1} where the Compton shoulder is fit with a step function. Right: FWHM of the Fe $K\alpha_1$ line versus the velocity of the line in km s^{-1} . Note that the centroid and the width of the Fe $K\alpha_2$ line are tied to the Fe $K\alpha_1$ line as described in L. Barragán et al. (2009).

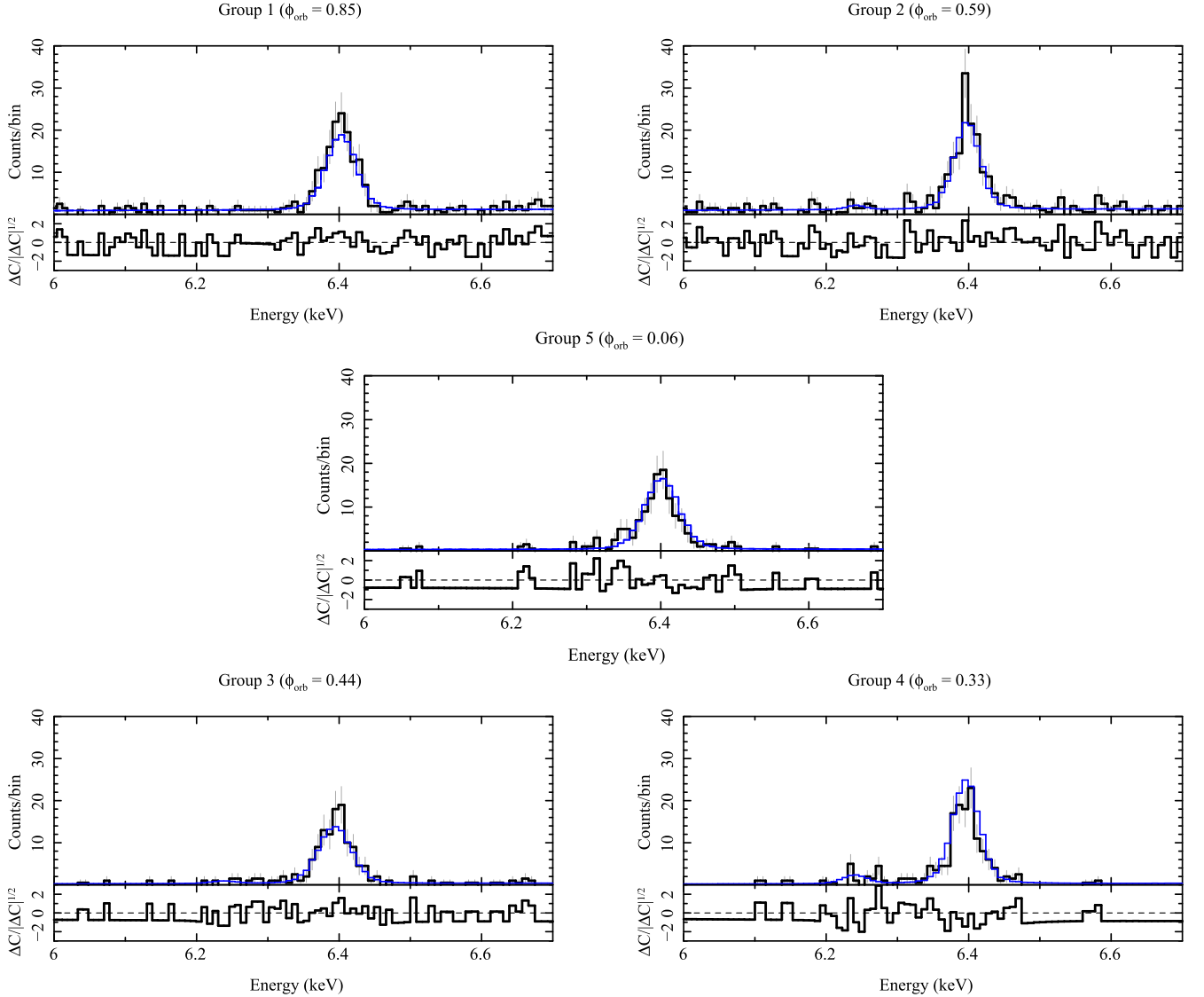


Figure 5. Orbital phase-resolved HETG spectra zooming into the Fe $K\alpha$ region. The groups and phases are given in the panel headings, with the corresponding ObsIDs outlined in Table 1. The Compton shoulder is fit with an additional Gaussian.

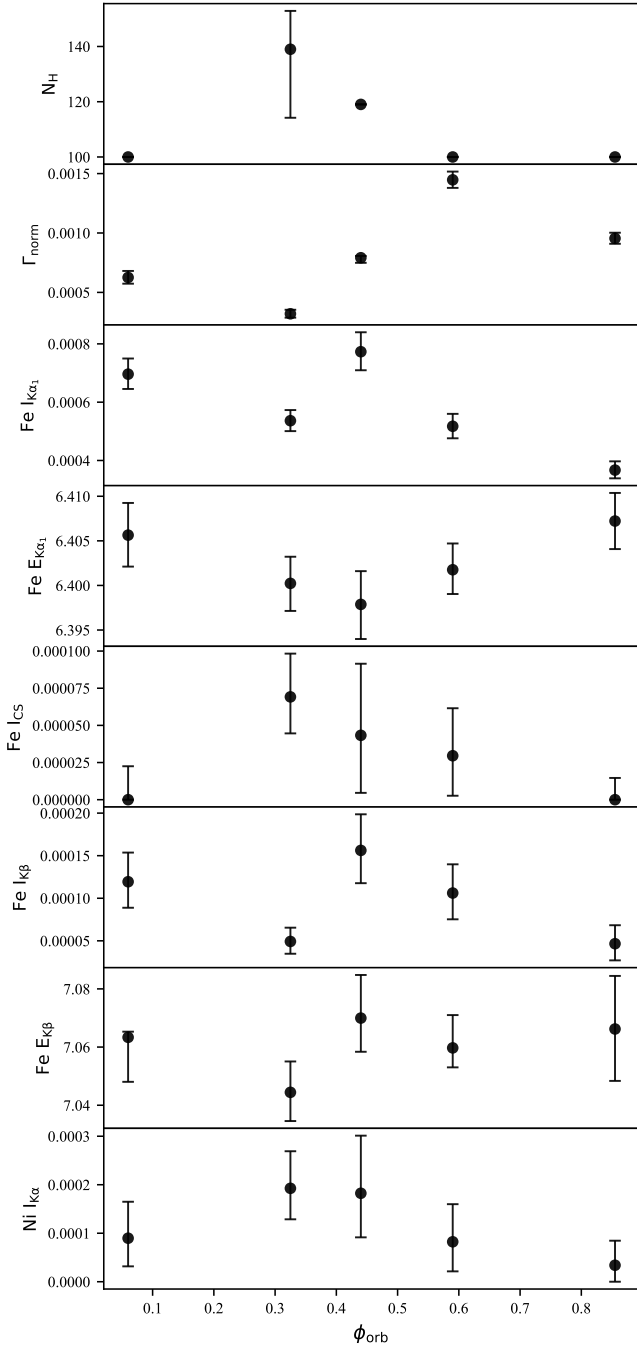


Figure 6. Variation of spectral parameters with orbital phase. From top to bottom: absorption (N_H , 10^{22} cm^{-2}), power-law normalization (photons $\text{keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$), Fe $K\alpha_1$ line intensity (photons $\text{cm}^{-2} \text{ s}^{-1}$), Fe $K\alpha_1$ line energy (keV), Compton shoulder normalization (photons $\text{cm}^{-2} \text{ s}^{-1}$), Fe $K\beta$ normalization (photons $\text{cm}^{-2} \text{ s}^{-1}$), Fe $K\beta$ line energy (keV), and Ni $K\alpha$ normalization (photons $\text{cm}^{-2} \text{ s}^{-1}$). The photon index and the Ni $K\alpha$ line energy were fixed to their phase-averaged values. Note the increased absorption at phase 0.33 is accompanied by larger normalization of the Compton shoulder. Also, note that the energy of the Fe $K\alpha$ line shows a periodic orbital modulation. Errors are quoted at 90% confidence level.

corrected for Earth’s motion around the Sun by computing the Earth’s velocity along the line of sight toward the source at the observation time using the `astropy.coordinates.SkyCoord.radial_velocity_correction` routine. We then obtained the Chandra spacecraft positions and velocities from the “orbit” file product during each observation and projected the spacecraft velocity along the same line of sight,

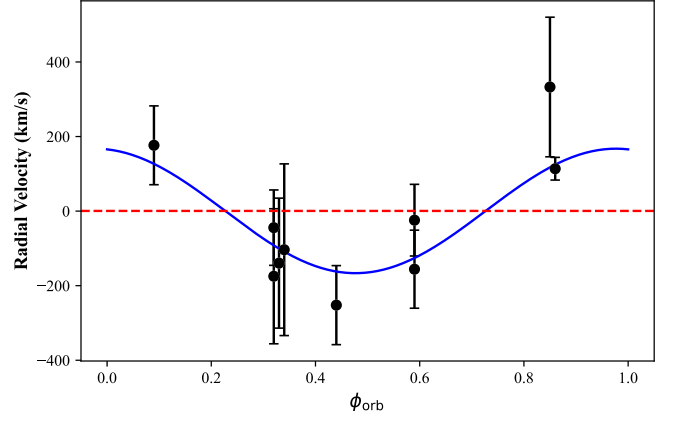


Figure 7. Radial velocities of the Fe $K\alpha$ line as a function of orbital phase (with 1σ errors). The velocities were derived from the measured line centroids relative to the Fe $K\alpha_1$ line at 6.404 keV and after heliocentric corrections, modeled with a sinusoid $v_{\text{rad}}(\phi) = K \sin(2\pi \phi + \phi_0) + v_0$, where K is the semi-amplitude, ϕ_0 is the phase offset, and v_0 is the systemic velocity. The blue line shows the best-fit sinusoidal model, with parameters $K = 167 \pm 32 \text{ km s}^{-1}$, $\phi_0 = (0.55 \pm 0.08) \pi$, and $v_0 = 0.5 \pm 23 \text{ km s}^{-1}$. The red dashed line represents a constant fit.

and applied this correction to the line centroids. Spacecraft velocities for each observation are taken to be at the start of each observation and are negligible, with the line-of-sight spacecraft velocities being at most 5 km s^{-1} , but usually $< 1 \text{ km s}^{-1}$, and with changes over the span of the observation remaining below 1 km s^{-1} . The resulting heliocentric-corrected centroids were then used in the radial velocity fits.

The Doppler velocity was modeled as a sinusoid in orbital phase according to $v_{\text{rad}}(\phi) = K \sin(2\pi \phi + \phi_0) + v_0$, where K is the amplitude of the velocity variation, ϕ_0 is the phase offset, and v_0 is the systemic velocity.

A weighted least-squares fit yields best-fit parameters of $K = 167 \pm 32 \text{ km s}^{-1}$, $\phi_0 = (0.55 \pm 0.08) \pi$, and $v_0 = 0.5 \pm 23 \text{ km s}^{-1}$. The improvement of the sinusoidal model over a constant velocity fit is highly significant: the constant fit yields $\chi^2 = 29.73$ for 9 degrees of freedom, while the sinusoidal fit gives $\chi^2 = 4.08$ for 7 degrees of freedom. This corresponds to $\Delta\chi^2 = 25.66$ for two additional parameters, indicating that the sinusoidal model provides a substantially better description of the data. Note that from the P Cygni profiles of the He I lines at 2.058 and $2.1126 \mu\text{m}$, A. Coleiro et al. (2013) inferred a wind velocity of $\sim 400 \text{ km s}^{-1}$, consistent with the value reported by P. Fillard & S. Chaty (2004) and of the same order as the full peak-to-peak shifts we observe here. The radial velocities, the sinusoidal fit (blue line), and the constant systemic velocity fit (red line) for the 10 ObsIDs fitted separately are shown in Figure 7. See illustration of the system in Figure 8.

Light curves for individual ObsIDs. In addition to the spectral analysis, we also examined the Chandra zero-order light curves for variability. As shown in Figure 9, the light curves, binned at 80 s, reveal evidence of variability on timescales of a few kiloseconds as seen earlier (e.g., R. Walter et al. 2003). This short-term variability could reflect changes in the structure of the absorbing material near the compact object. Of special interest is that the light curves around ϕ_{orb} of 0.33 show a lower count rate, consistent with the increased absorption seen in this dip and with the dip seen in the long-term Swift/BAT light curves.

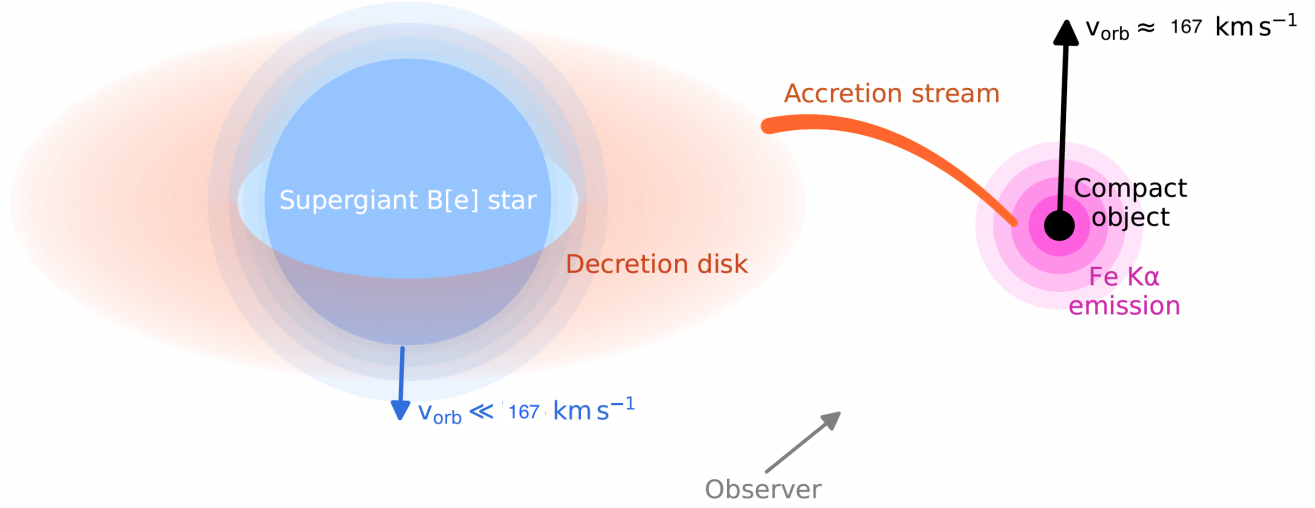


Figure 8. Illustration of IGR J16318–4848, showing the supergiant companion, the compact object (not to scale), and an accretion stream. The modulation of the Fe K α line, with a velocity of $\sim 167 \text{ km s}^{-1}$, suggests that it originates close to the compact object since the orbital velocity of the (heavier) companion around the center of mass is expected to be lower than this value. Our analysis also indicates that spectral variations likely follow an orbital-phase-locked behavior, as supported by dips in the long-term (Swift/BAT) and pointed (Chandra) observations, along with enhanced absorption and a larger Compton shoulder fraction, particularly around orbital phase $\phi_{\text{orb}} \sim 0.33$. This dip could be a geometric structure such as an accretion disk or the rim of the companion star (not shown in the sketch) occulting the X-ray emission, rather than stochastic clumps in the stellar wind.

Table 3

Comparison of Best-fit Spectral Parameters for the Two Models for Group 4 ($\phi_{\text{orb}} = 0.33$)

Parameter	ACIS+HETG: Step	ACIS+HETG: Gauss
N_{H}	138^{+14}_{-25}	138^{+14}_{-25}
Γ	0.24	0.24
$\Gamma_{\text{norm}}^{\text{a}}$	$(3.17^{+0.34}_{-0.31}) \times 10^{-4}$	$(3.20^{+0.34}_{-0.33}) \times 10^{-4}$
E_{CS} (keV)	$K\alpha-0.16$	$K\alpha-0.16$
$I_{\text{box}}^{\text{b}}$	$(10.6^{+2.30}_{-1.70}) \times 10^{-4}$	...
I_{CS}^{c}	...	$(6.92^{+2.91}_{-2.46}) \times 10^{-5}$
E_{CS} (keV)	...	$K\alpha-0.16$
σ_{CS} (keV)	...	0.01
Fe $E_{K\alpha 1}$ (keV)	$6.402^{+0.002}_{-0.003}$	$6.400^{+0.003}_{-0.003}$
Fe $\sigma_{K\alpha 1}$ (keV)	$0.0034^{+0.0066}_{-0.0030}$	$0.0102^{+0.0059}_{-0.0000}$
Fe $I_{K\alpha 1}^{\text{c}}$	$(4.63^{+0.39}_{-0.29}) \times 10^{-4}$	$(5.36^{+0.37}_{-0.36}) \times 10^{-4}$
Fe $E_{K\beta}$ (keV)	$7.046^{+0.012}_{-0.011}$	$7.044^{+0.005}_{-0.000}$
Fe $\sigma_{K\beta}$ (keV)	$0.00078^{+0.0167}_{-0.0007}$	$0.00123^{+0.0118}_{-0.0000}$
Fe $I_{K\beta}^{\text{c}}$	$(4.88^{+1.62}_{-1.40}) \times 10^{-5}$	$(4.06^{+0.92}_{-0.94}) \times 10^{-5}$
Ni $E_{K\alpha}$ (keV)	$7.486^{+0.017}_{-0.016}$	$7.484^{+0.005}_{-0.012}$
Ni $\sigma_{K\alpha}$ (keV)	$0.00035^{+0.009}_{-0.004}$	$0.00051^{+0.0227}_{-0.0000}$
Ni $I_{K\alpha}^{\text{c}}$	$(1.89^{+0.75}_{-0.63}) \times 10^{-4}$	$(1.93^{+0.92}_{-0.38}) \times 10^{-4}$
$C_{\nu}/\text{data bins}$	2661/13,568	2672/13,518

Notes. Errors quoted are for 90% confidence range and parameters with no errors were frozen or tied.

^a In units of photons $\text{keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ at 1 keV.

^b Photons $\text{cm}^{-2} \text{ s}^{-1}$ of a box function between $E_{K\alpha 1}$ and E_{CS} .

^c In units of photons $\text{cm}^{-2} \text{ s}^{-1}$.

4. Discussion

The narrow Fe K α line observed in IGR J16318–4848 exhibits a clear Doppler modulation over the binary orbit, and its origin can be interpreted in terms of two scenarios. In the first scenario, if the line is produced in a large, diffuse region around the companion star, the narrow width implies low-velocity material, yet such an origin cannot readily account for the observed orbital modulation. In the more likely scenario,

the line forms close to the compact object, where the Doppler shifts largely trace the orbital motion of material bound to the compact star (see Figure 8 for illustration). This interpretation is supported by high-resolution Hitomi observations (Hitomi Collaboration et al. 2018), which measured an exceptionally narrow line width of $\approx 160^{+300}_{-70} \text{ km s}^{-1}$, far below the Doppler broadening expected from a typical high-velocity stellar wind. They also constrained the Fe ionization state to Fe I–IV and the geometry of the reprocessing material, which is concentrated in a narrow solid angle rather than distributed throughout the donor wind.

Using the compact object velocity amplitude $K = 167 \pm 32 \text{ km s}^{-1}$ and the orbital period $P_{\text{orb}} = 80.09 \pm 0.012$ days (N. Iyer & B. Paul 2017), the standard mass function $f(M_{\text{SG}}) = \frac{P_{\text{orb}} K^3}{2\pi G}$ is calculated to be $39 \pm 22 M_{\odot}$. Assuming an inclination $i \sim 76^{\circ}$ (F. Fortin et al. 2020) and the compact object to be a neutron star with $M_{\text{CO}} = 1.4 M_{\odot}$, we obtain $M_{\text{SG}} \approx 45 M_{\odot}$ via $f(M_{\text{SG}}) = (M_{\text{SG}} \sin i)^3 / (M_{\text{SG}} + M_{\text{CO}})^2$. On the other hand, if we assume the compact object to be a black hole with average observed mass of $M_{\text{CO}} = 7 M_{\odot}$ (G. Wiktorowicz et al. 2014), we get $M_{\text{SG}} \approx 54 M_{\odot}$. At present, we cannot definitively determine the mass of the compact object, either because (i) the companion mass is not known well independently or (ii) there is no measurement of the companion’s orbital velocity amplitude available in the literature.

We caution the reader that the tentative result presented here is based on the currently best-determined circular orbital solution. It is likely that for an 80 day period of the system, an eccentric orbit could be more plausible. This is because tidal damping operates effectively at short orbital periods; in long-period binaries ($P \gtrsim 10$ days; S. Meibom & R. D. Mathieu 2005), orbits generally do not achieve full circularization, and many systems are observed with appreciable eccentricity. At the same time, if the line arises in the extended wind of the compact object rather than a pointlike region, the measured Doppler velocity combines orbital and wind motions, and the mass function no

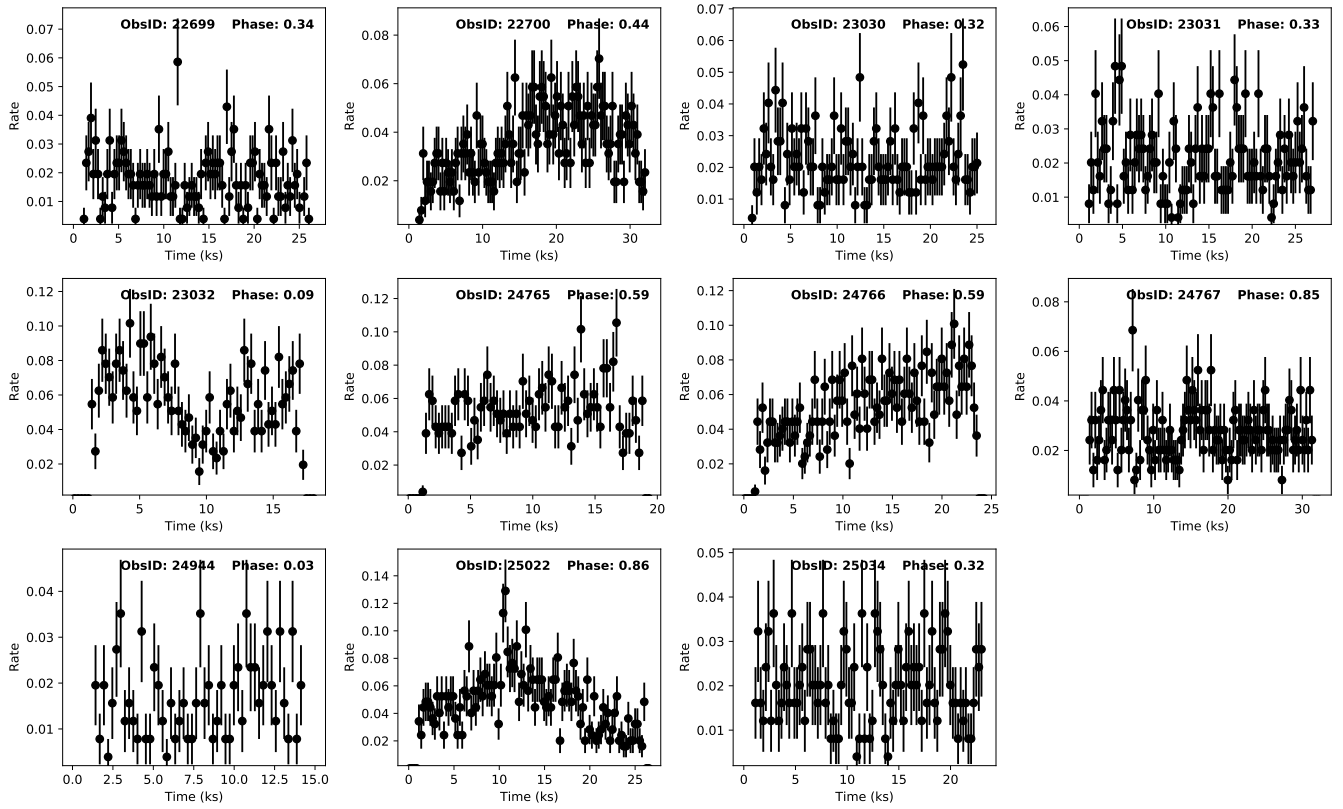


Figure 9. Chandra/ACIS-S (undispersed or zero-order) light curves binned with 80 s, and phases taken from N. Iyer & B. Paul (2017).

longer directly yields M_{SG} (see discussion regarding mass function estimation from Fe $K\alpha$ fits in C. Dashwood Brown et al. 2022). Finally, recent XRISM observations of other sources suggest that the Fe line region may be more complex (Y. Nagai et al. 2026), and may not simply trace the stellar rotation (N. Sameshima et al. 2026). We argue that further sampling of binary phases is important to confirm the orbital period and test the orbital solution.

In sources with large column densities greater than $\sim 10^{23}$ (G. Matt 2002), we expect in principle that the Fe $K\alpha$ line has a red wing or Compton shoulder that arises when the line photons are Compton scattered by high-optical-depth material. For IGR J16318–4848, a low Compton shoulder in the average Chandra/HETGS spectra is puzzling because IGR J16318–4848 (i) is bright in X-rays, (ii) exhibits a strong Fe $K\alpha$ line, generating enough 6.4 keV “seed” photons to undergo Compton scattering, and (iii) is surrounded by dense/optically thick material where the 6.4 keV photons can undergo Compton downscattering to produce the feature. It is possible that the Compton shoulder may be smeared due to free electrons with a temperature of several eV (S. Watanabe et al. 2003) and/or bound-electron scattering with neutral hydrogen (R. Sunyaev & E. Churazov 1996). Note that scattering off bound electrons is slightly less efficient than scattering off free electrons, resulting in but a minor reduction in the Compton scattering optical depth ($\sim 15\%$ at 6.4 keV; see Figure 4 of B. Vander Meulen et al. 2023).

The absence of a Compton shoulder may also be due to geometric factors: while the Compton shoulder would be brighter in a spherically symmetric medium, a nonspherical shell may produce a weaker shoulder (H. Odaka et al. 2016). Note that while the density and ionization of the absorbers could in principle influence the Compton shoulder, the

available statistics here do not allow these effects to be constrained robustly. Earlier constraints from the Fe $K\beta/K\alpha$ line ratio (~ 0.20) indicate that the fluorescence arises from neutral or very lowly ionized iron (Fe I–IV), corresponding to an ionization parameter of $\log(\xi) \lesssim -2$, consistent with previous Suzaku and Hitomi results (L. Barragán et al. 2009; Hitomi Collaboration et al. 2018). This suggests that ionization variations are unlikely to drive significant changes in the Compton shoulder.

However, the orbital phase-resolved analysis suggests that the absorption is variable, and around orbital phase ~ 0.33 , we tentatively detect a Compton shoulder. This phase likely corresponds to the compact object being behind the densest portion of the donor’s circumstellar material along our line of sight, leading to enhanced scattering that produces the strong Compton shoulder. Interestingly, the long-term Swift/BAT orbital profile also shows a dip at the same phase (see Figure 1; the Chandra light curves also show lower average count rate in Figure 9). In principle, a mildly eccentric orbit could cause the apparent phase-locked flux variations if the donor star is close to filling its Roche lobe (see Section 4.2.1 of P. Kretschmar et al. 2021). However, since both the stellar radius and the masses of the donor and compact object of IGR J16318–4848 are uncertain, we cannot estimate the Roche lobe filling factor meaningfully at this point.

Finally, no ionized lines were detected by Hitomi (Hitomi Collaboration et al. 2018) or even from the long exposure with Chandra. While the Chandra data have low signal-to-noise ratio above the Fe K edge to properly model the Fe K edge at 7.1 keV, such an edge in IGR J16318–4848 is quite deep. We also find short-scale variability in the Chandra zero-order light

curves, as seen in Figure 9. Such variability may indicate structures in the stellar wind of the companion star.

5. Summary

In this work, we have presented a comprehensive analysis of the high-resolution X-ray spectra of the highly obscured HMXB IGR J16318–4848 using ~ 250 ks Chandra/HETGS observations spanning different orbital phases. We detect a strong, narrow Fe K α emission line that shows clear orbital modulation with an amplitude of 167 ± 32 km s $^{-1}$, which we interpret as arising from the stellar wind near the compact object. A tentative Compton shoulder associated with the Fe K α line is identified, and its flux relative to the core exhibits orbital-phase variability, peaking at $\sim 10\%$ around orbital phase $\phi_{\text{orb}} \simeq 0.33$. No emission from ionized ions is observed, consistent with previous Hitomi results, indicating that the plasma in the system remains predominantly cold. Overall, this study provides the first detailed high-resolution spectral view of IGR J16318–4848 across orbital phases and establishes a baseline for XRISM observations of the source, improving our understanding of the wind environment in this enigmatic system.

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