

XRISM Spectroscopy of the Stellar-mass Black Hole GRS 1915+105

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ABSTRACT

GRS 1915+105 was the stellar-mass black hole that best reproduced key phenomena that are also observed in Type-1 active galactic nuclei. In recent years, it has evolved to resemble a Type-2 or Compton-thick AGN. Herein, we report on the first XRISM observation of GRS 1915+105. The high-resolution Resolve calorimeter spectrum reveals that a sub-Eddington central engine is covered by a layer of warm, Compton-thick gas. With the obscuration acting as a coronagraph, numerous strong, narrow emission lines from He-like and H-like charge states of Si, S, Ar, Ca, Cr, Mn, Fe, and Ni dominate the spectrum. Radiative recombination continuum (RRC) features are also observed, signaling that much of the emitting gas is photoionized. The line spectrum can be fit by three photoionized emission zones, with broadening and bulk velocities suggestive of an origin in the outer disk atmosphere and/or a slow wind at $r \simeq 10^6 GM/c^2$. The Fe XXV He- α and Fe XXVI Ly- α lines have a broad base that may indicate some emission from $r \sim 3 \times 10^3 GM/c^2$. These results broadly support a picture wherein the current state in GRS 1915+105 is due to obscuration by the irradiated outer disk. This could arise through disk thickening if the Eddington fraction is higher than inferred, but it is more likely due to a warped, precessing disk that has brought the outer disk into the line of sight. We discuss the strengths and weaknesses of this interpretation and our modeling, and possible explanations of some potentially novel spectral features.

Keywords: X-rays: black holes — accretion – accretion disks

1. INTRODUCTION

GRS 1915+105 is a stellar-mass black hole that acts as a bright, local laboratory for understanding accretion physics in active galactic nuclei (AGN). It is sometimes referred to as a “microquasar” for the variety of

continuous and discrete radio jet knots that it launches (for a review, see Fender & Belloni 2004). Recently, the impact of these jets on the local interstellar medium has been realized (Motta et al. 2025), potentially revealing scaled versions of the jet cavities that massive black holes inflate in diffuse cluster gas (see, e.g., Fabian et al. 2003). In soft, sub-Eddington, disk-dominated states, GRS 1915+105 launches disk winds with velocities as high as $v = 0.03c$ (Miller et al. 2016), similar to

“warm absorbers” and “ultra-fast outflows” in Seyferts and quasars (for a review, see Gallo et al. 2023; also see, e.g., Tombesi et al. 2010, Xiang et al. 2025).

In recent years, the character of GRS 1915+105 has radically changed. It no longer mimics unobscured Seyferts or quasars; rather, it more closely resembles highly obscured Seyfert-2 AGN or even Compton-thick AGN (CTAGN; $N_H \geq 1.6 \times 10^{24} \text{ cm}^{-2}$). Chandra grating spectra in this “obscured state” reveal that the internal column may be Compton-thick, and the result of failed disk winds (Miller et al. 2020). JWST observations of GRS 1915+105 in this state further confirm a large obscuring region, and a central source that continues to accrete at 5–30% of its Eddington limit (Gandhi et al. 2024). Extensive monitoring with the Neil Gehrels Swift Observatory suggests a median internal column density of $N_H = 7 \times 10^{23} \text{ cm}^{-2}$ (Balakrishnan et al. 2021).

GRS 1915+105 is a wide binary system, with a period of $P = 33.85 \pm 0.16$ days (Steeghs et al. 2013). In other wide binaries, super-orbital periods are sometimes observed that likely result from the precession of a warped accretion disk (e.g., Brumback et al. 2020, Kosec et al. 2023). Recent changes in the position angle of the radio jet in GRS 1915+105 may indicate that its disk is also warped and precessing (Rodríguez & Mirabel 2025). In the context of AGN unification models (Antonucci 1993) – which largely ascribe observational differences to viewing angle – such a geometrical change would be a particularly apt means of changing a “microquasar” into a micro-CTAGN.

The other key properties of GRS 1915+105 are known well, but are continually refined owing to its importance. Radio parallax measurements now place the source at a distance of $d = 9.4 \pm 0.6$ kpc (Reid & Miller-Jones 2023). When coupled with prior radial velocity studies, this distance gives a black hole mass of $M = 11 \pm 2 M_\odot$, an inclination of $\theta = 64 \pm 4$ degrees, and jet velocities between $0.68 \leq v/c \leq 0.91$ (Reid & Miller-Jones 2023; also see Reid et al. 2014). Initial fits to X-ray spectra obtained with NuSTAR measured a black hole spin parameter of $a = 0.98 \pm 0.01$ (where $a = cJ/GM^2$, and J is the angular momentum) and an inclination of $\theta = 71 \pm 1$ degrees (Miller et al. 2013). New fits to multiple spectra with improved models measure a black hole spin parameter of $a = 0.98 \pm 0.02$ and an inclination of $i = 60 \pm 8$ degrees (Draghis et al. 2024). It is particularly notable that the fully independent reflection modeling and radio parallax measurements yield commensurate inclination values. Using older values for the black hole mass, distance, and inclination, fits to the X-ray continuum from the disk measure black hole spin parameters of $a \geq 0.98$

(McClintock et al. 2006) and $a \simeq 0.7$ (Middleton et al. 2006).

This work summarizes an initial analysis of the first Resolve microcalorimeter X-ray spectrum of GRS 1915+105. Section 2 describes the observation details and data reduction procedures. The analysis and results are presented in Section 3. We discuss these results, important caveats, and questions for future work in Section 4. Finally, Section 5 restates our most important findings.

2. OBSERVATIONS AND DATA REDUCTION

GRS 1915+105 was observed with the X-ray Imaging and Spectroscopy Mission (XRISM; Tashiro et al. 2024) on 2024 October 17, starting at 01:40:18 UTC, with an associated observation identifier of 201068010. The total observation spanned 66.7 ks. XRISM carries two instruments: Resolve, an X-ray microcalorimeter (Ishisaki et al. 2022), and Xtend, a CCD imager and spectrometer (Hayashida et al. 2018)). At the time GRS 1915+105 was observed, the Resolve gate valve was closed, truncating the spectrum below 1.6 keV. Nevertheless, Resolve achieves a resolution of just 4.5 eV, extends smoothly to an energy of 17.6 keV, and offers fundamentally new insights into black hole accretion. For this reason, the Resolve data are the sole focus of this paper.

The data were reduced using the tools in HEASOFT version 6.34, and the associated calibration files. After accounting for efficiencies in low-Earth orbit and other filtering, the net exposure time was 35.7 ks. High-resolution primary (or, “Hp”) events were from the full 6x6 Resolve array, excluding the calibration pixel (36) and two pixels that sometimes give anomalous readings (11 and 27). Light curves generated from the resulting event list do not show strong variability, enabling an analysis of the full time-averaged spectrum. A spectrum was then extracted from the event list using standard 0.5 eV spectral bins, and the tools `rs1mkrmf` and `xaarfgen` were used to produce the required redistribution matrix file (rmf) and ancillary response file (arf). We elected to generate a “large” response matrix as the low energy continuum is not visible in GRS 1915+105.

3. ANALYSIS AND RESULTS

3.1. Model Construction

The time-averaged Resolve spectrum of GRS 1915+105 was analyzed using SPEX version 3.08.02 (Kaastra et al. 1996). The closed gate valve truncates Resolve spectra below 1.6 keV, and the spectrum approaches the background above 11.6 keV, so fits were made to the 1.6–11.6 keV band. All fits min-

imized a Cash statistic (Cash 1979). Prior to fitting, the spectrum was binned according to the “optimal” binning algorithm of Kaastra & Bleeker (2016). We utilized the “pion” photoionization model to describe the emitted spectrum (Miller et al. 2015, Mehdipour et al. 2016), which is native with SPEX. When utilized within SPEX, pion has the advantages of (1) illuminating the diffuse gas with the best-fit continuum at each step of the fitting process, and (2) layering different zones so that outer regions see a properly attenuated ionizing continuum. To capture the full ionizing band for pion calculations, luminosities were extrapolated to the 0.0136–13.6 keV band.

Figure 1 shows the spectrum over the 2–10 keV pass band, and Figure 2 expands the spectrum in 2 keV slices. The spectrum is dominated by extremely strong and narrow emission lines. In the case of the Fe XXV He- α complex between 6.6–6.7 keV, for instance, the lines are 8–10 times stronger than the local continuum (see Figure 3). This immediately points to a complex physical environment, wherein obscuration and other effects must be important. A completely unique characterization of the spectrum may not be possible. However, we constructed a plausible model based on key physical considerations and important precedents:

- The prior Chandra observations in the obscured state implied a luminosity as high as $L \simeq 10^{38}$ erg s $^{-1}$ (0.3–10.0 keV), or $\lambda_{Edd} \simeq 0.07$ (Miller et al. 2020). In this regime, the continuum should be a mixture of hot accretion disk and power-law components, so we allowed for both via the “dbb” and “pow” components. To avoid issues with the power-law in photoionization modeling, the “pow” component was bent to zero flux at low and high energy using two “etau” components. The associated free continuum parameters include the power-law index (Γ) and flux normalization, the disk peak temperature (about twice the temperature at the innermost orbit), and the disk flux normalization.
- The strength of the observed spectral lines helps to constrain the luminosity of the continuum components. Their luminosity must be much higher than is naively inferred, in order to produce the lines. Plausible columns of neutral gas predict a strong, sharp, Fe K edge that is not observed. This signals that the column must be warm, rather than cold and completely neutral. We modeled obscuration of the continuum using the “hot” model, leaving the gas column density, temperature, and covering fraction free to vary. We fixed an internal rms velocity of $\sigma = 1000$ km s $^{-1}$ as this value matches

the data but is otherwise poorly constrained.

- The presence of He-like and H-like RRCs in the spectrum (see Figures 1, 2, and 3) requires a prominent role for photoionization. The need for photoionization is also evident in the ratio of the lines in the Fe XXV complex between 6.6–6.7 keV, and other He-like complexes. We therefore allowed multiple “pion” emission zones to vary within our model, finding that *at least* three are required to fit the data (see Figure 4). Note that the continuum from the central engine “feeds into” each pion component. In our final model, the zones are layered assuming that ionization falls with radius. The free parameters for each pion emission zone include the gas column density (N_H), the log of the gas ionization parameter (ξ), the rms velocity of the gas within the zone (σ), the bulk velocity shift of the zone (v), and the covering factor of the emitting gas (Ω , measured as $\Omega/4\pi$).

In preliminary fits, the pion zones all adopted very high columns, covering factors significantly above unity, and super-solar elemental abundances. High columns are possible, but covering factors above unity are unphysical, and prior studies do not support extreme abundances (Keshet et al. 2025). The unphysical covering factors likely resulted from the gas density in each zone being left at minimum default values. Since recombination and collisional excitation (which must contribute at some level) depend on n^2 , higher density values will produce stronger line emission. Simple estimates and experimentation with fits suggest that a value of $n = 3 \times 10^{10}$ cm $^{-3}$ is sufficient to produce the observed lines, and compatible with expectations for the outer accretion disk (e.g., Shakura & Sunyaev 1973). This density was fixed in all three pion zones, and a limit of $\Omega/4\pi \leq 1$ was also enforced in each zone.

- The ratios of specific lines differ slightly from simple expectations, regardless of the emission mechanism. For instance, the two components of the H-like Fe XXVI line (nominally at 6.95 and 6.97 keV) should have a 1:1.7 flux ratio; instead, they are nearly equal in strength. This suggests that resonant scattering in a hot medium removes some photons to alter the flux ratio, similar to effects observed in the Hitomi spectrum of the Perseus Cluster (Hitomi Collaboration et al. 2016). We model this effect by covering all components with a “hot” component in SPEX, allowing the gas column density ($N_{H,RS}$), covering factor ($f_{cov,RS}$), and temperature to vary.
- To model the neutral Fe K emission in the spectrum via illumination of distant cold gas, we imported the “my-

torus” function (Murphy & Yaqoob 2009) and allowed for dynamical broadening via the “spei” component in SPEX (Speith et al. 1995). “Mytorus” includes the key atomic structure necessary for calorimeter resolution, including $K_{\alpha,1}$ and $K_{\alpha,2}$ lines, as well as K_{β} emission. The key parameters of “mytorus” include the gas column density, the power-law index of the incident radiation (fixed to $\Gamma = 2.2$ in our fits for simplicity), the inclination of the emitting gas, a velocity shift (set to zero in our fits), and a line flux normalization. For simplicity and because we anticipate the neutral line arises in the optically thick disk, we fixed the column density within “mytorus” to a value of $N_H = 1.6 \times 10^{24} \text{ cm}^{-2}$.

“Spei” is very sophisticated and allows for many specific realizations; we assumed an emissivity of $q = 3$ (where $J \propto r^{-q}$ and $q = 3$ corresponds to a flat disk), and measured the inner emission radius and inclination of the gas (the “mytorus” inclination parameter was coupled to this one). The outer emission radius was arbitrarily fixed to $r_{out} = 10^6 \text{ GM}/c^2$. In total, then, the neutral Fe K complex was modeled using three parameters: the line flux normalization, inner radius, and inclination. This scheme follows fits to the neutral Fe K_{α} and K_{β} lines in Resolve spectra of the Seyfert-1.5 AGN NGC 4151 (Xrism Collaboration et al. 2024).

- It is apparent that there may be a broad base to the Fe XXV He- α complex, and Fe XXVI Ly- α doublet. Simple Gaussian functions were added to model any broad line flux. Within SPEX, Gaussian parameters include the central energy, FWHM, and flux normalization of the line. The Fe XXV feature was constrained to have central energy between 6.65–6.70 keV, and a width less than $\text{FWHM} \leq 0.3 \text{ keV}$ (5700 km s^{-1}). The Fe XXVI feature was constrained to have a central energy between 6.95–6.70 keV, and a width less than $\text{FWHM} \leq 0.1 \text{ keV}$ (1800 km s^{-1}).

- All of these components are seen through the interstellar medium (ISM), which we modeled with a separate fixed “hot” component (with the gas temperature set to a minimum value of $kT = 1 \times 10^{-6} \text{ keV}$), assuming a covering factor of unity.

The full model can be written as:

$$N_{H,ISM} \times [N_{H,CE} \times N_{H,RS} \times (\text{dbb} + \text{pow}) + N_{H,RS} \times (\text{pion}_1 + \text{pion}_2 + \text{pion}_3 + \text{spei} \times \text{mytorus})],$$

where $N_{H,ISM}$, $N_{H,CE}$, and $N_{H,RS}$ refer to components accounting for absorption and scattering in the ISM, absorption and scattering of continuum emission from

the central engine, and resonant scattering of line emission, respectively. The results of fitting this model to the time-averaged Resolve spectrum of GRS 1915+105 are detailed in Table 1.

3.2. Oscillations in the Fe XXVI RRC?

RRCs arise through the recombination of hot electrons onto atoms. The energy of the emitted photon is the energy of the captured electron, plus the (negative) ionization threshold of the atom. A smooth distribution of electron energies therefore gives rise to a smooth flux decline above the threshold energy. However, a series of eight or more features – spaced by a regular interval of 30 eV – are evident in the spectrum of GRS 1915+105 (see Figure 5). If the oscillations are real, they are potentially consistent with recombination from electrons in Landau levels in a highly magnetized gas (e.g., in a corona above the disk). However, this explanation is not unique.

To explore these feature, a new version of “pion” was developed for this analysis and included in the latest publicly released version of SPEX (version 3.08.02). Within pion, the magnetic field of the gas can be determined through such oscillations and/or through Zeeman splitting effects. We made a number of additional fits in the 8.4-10.0 keV band, activating the magnetic features only in the most highly ionized “pion” component (pion₁ in Table 1). In total, the features require three additional free parameters: the electron magnetic field, the phase of the oscillations, and the amplitude of the oscillations.

3.3. Results

The results of fits to the Resolve spectrum of GRS 1915+105 with the (non-magnetic) model described above are detailed in Table 1, and shown in Figures 1–5. The model achieves a Cash statistic of $C = 3891$ for $\nu = 2933$ degrees of freedom. While this does not represent a formally acceptable fit, it is clear in Figures 1–5 that all of the strong emission lines are fit well, that key line ratios are largely reproduced, the evident red-shifts are accurately modeled, and that the predicted RRCs match the data.

In the obscured state of GRS 1915+105, the continuum has been particularly difficult to determine. Prior fits to Chandra spectra of the obscured state did not require a disk component (Miller et al. 2020), likely owing to the limited sensitivity of the gratings spectra. The continuum measured with Resolve is strongly dominated by the disk component, characterized by a temperature of $kT = 3.53^{+0.06}_{-0.05} \text{ keV}$. The best fit with this model does not strongly require a power-law, so we fixed a value of

$\Gamma = 2.5$ and measured a weak flux with large upper limits. The measured continuum gives a total continuum luminosity of $L = 8.8 \pm 0.6 \times 10^{37}$ erg s $^{-1}$ in the 0.0136–13.6 keV band, or $\lambda_{Edd} = 0.062$.

Within SPEX, the disk component temperature is measured at the radius of peak emissivity, which exceeds the temperature at the innermost stable circular orbit (ISCO) by a factor of approximately $\simeq 2$. A value of $kT \simeq 1.7$ –1.8 keV is likely more appropriate for comparisons to XSPEC models (Arnaud 1996), which measure temperatures at the innermost stable circular orbit (ISCO). Even this temperature is likely higher than the emitted temperature, owing to scattering in gas along the line of sight. In a disk-dominated, unobscured state of GRS 1915+105, Chandra measured an inner disk temperature of $kT = 1.6$ keV, and a power-law index of $\Gamma = 2.8$ (Miller et al. 2016). The broad similarity of these values to those measured with Resolve – despite very different obscuration profiles – suggests that Resolve observed GRS 1915+105 in an ordinary, sub-Eddington, “thermal-dominant” or “high soft” state, rather than a super- or hyper-Eddington state dominated by a geometrically thick inner disk. (For a review of black hole states, see, e.g., Remillard & McClintock 2006.)

As noted above, the obscuring column cannot be neutral, but gas temperatures of even $kT = 0.1$ keV are easily excluded. The model indicates that a warm, $kT = 0.002^{+0.008}_{-0.001}$ keV, Compton-thick column of $N_H = 3.0^{+0.3}_{-0.3} \times 10^{24}$ cm $^{-2}$ covers most of the central engine ($f_{cov} = 0.92 \pm 0.02$). The warm gas supplies the column required to match the observed continuum, while obscuring a central engine that is luminous enough to produce the observed emission lines. It also matches subtle features in the spectrum just above the neutral Fe K edge, where structure is expected owing to edges from low charge states of Fe.

Using a simple $T \propto r^{-3/4}$ scaling and the inferred inner disk temperature, the accretion disk would have a temperature of $kT = 0.002$ keV at $r \simeq 1.2 \times 10^5$ GM/ c^2 . The obscuring gas likely has something to do with the accretion disk itself, since the column is optically thick; however, at least some of the gas might instead be attributed to a warm disk atmosphere above a disk at even larger radii. It is notable that Keplerian orbital velocity at this radius is $\sigma = 840$ km s $^{-1}$, close to the rms value of $\sigma = 1000$ km s $^{-1}$ that matches the data well. In short, the nature of the obscuration indicates that the outer disk now occults the central engine in GRS 1915+105.

These radii are not compatible with the width of the neutral Fe K $_{\alpha}$ line. The observed blending of the two line components and the absence of an observable line

shift require a combination of a smaller radius and a low inclination. In broad terms, the neutral Fe K $_{\alpha}$ line originates 1–2 orders of magnitude closer to the central engine than the obscuring gas does (see Table 1). The low inclination of the neutral Fe K $_{\alpha}$ line, $i = 5^{+4}_{-2}$ degrees, is very different from that of the binary system ($i = 64 \pm 4$ degrees, Reid & Miller-Jones 2023), the innermost disk ($i = 60 \pm 8$ degrees, Draghis et al. 2024), and the jet ($i = 66 \pm 2$ degrees, Fender et al. 1999). Indeed, if the disk is *flat*, we should not see particular radii evident as a sharp line. These conditions needed to produce the neutral Fe K $_{\alpha}$ line are broadly consistent with a warp that first departs from a flat disk at $r \simeq 10^{3-4}$ GM/ c^2 , bringing the outer disk into the line of sight by $r \simeq 10^{5-6}$ GM/ c^2 .

The parameters of all three pion zones are very well determined. Figure 4 shows how the components contribute to the flux observed in the Fe XXV He- α and Fe XXVI Ly- α lines. The line widths and shifts are likely the best guide to the location of the emitting gas. Although the gas in each zone is highly ionized, the zones exhibits remarkably low internal rms velocities and low bulk velocities. None of the measured rms velocities and bulk shifts exceed $v \geq 350$ km s $^{-1}$. Given the high inclination of the binary system, our line of sight likely captures most of the orbital velocity of the gas. In principle, the gas may have a large vertical velocity (perpendicular to our line of sight), and continual acceleration could lead to even higher velocities over many scale heights. If the measured gas velocities are indicative of Keplerian orbital speeds, the gas must lie at $r \geq 7 \times 10^5$ GM/ c^2 . This indicates that the lines are produced just outside of the region that obscures the central engine, likely in a disk atmosphere (and/or the base of a wind).

The Gaussians added to the model to describe the broad base of the Fe XXV He- α and Fe XXVI Ly- α lines are well constrained. The width of broad Fe XXV line hits the imposed limit of FWHM ≤ 0.3 keV, or $\sigma \leq 5700$ km s $^{-1}$. The width of the broad Fe XXVI Ly α line is measured to be $\sigma = 700^{+100}_{-200}$ km s $^{-1}$. The Fe XXV line could arise as close as $r \simeq 3 \times 10^3$ GM/ c^2 – broadly compatible with the neutral Fe K $_{\alpha}$ emission line – and potentially indicating that the leading edge a putative warp could be a complex geometry that churns up a combination of neutral and ionized gas.

Using the most recent binary system parameters, the semi-major axis of the components in GRS 1915+105 is $a \simeq 7 \times 10^{12}$ cm, or $a = 4.2 \times 10^6$ GM/ c^2 . Using the approximations in Eggleton (1983), the radius of the Roche lobe around the black hole is likely $r_{roche} = 4.4 \times 10^{12}$ cm, or $r_{roche} = 2.7 \times 10^6$ GM/ c^2 . In most circumstances, the accretion disk is expected to fill about

two-thirds of its Roche lobe, which suggests that the outer disk extends to $r_{out} = 1.8 \times 10^6 \text{ GM}/c^2$. These estimates confirm that the disk is just large enough to produce the strong, narrow, ionized emission lines that we have observed.

Although the broadening and shifts observed in each photoionized emission zone are small, they are significantly different. It is not clear if this reflects radial or vertical stratification within a disk atmosphere or wind base, or if the differences indicate axial asymmetry. For instance, pion_1 is significantly blue-shifted ($v_1 = -90_{+10}^{-10} \text{ km s}^{-1}$), while pion_2 is significantly red-shifted ($v_2 = 342_{-7}^{+6} \text{ km s}^{-1}$), and pion_3 is hardly shifted at all ($v_3 = 28_{-6}^{+9} \text{ km s}^{-1}$). It is at least possible that these shifts reflect axial asymmetry brought about by a large-scale warp in the outer disk.

Thermal winds can be launched outside of the Compton radius, given by $R_C = 1 \times 10^{10} \times (M_{BH}/M_\odot) \times T_{C,8}^{-1}$ (where $T_{C,8}$ is the Compton temperature in units of 10^8 K ; Begelman et al. 1983). Approximating the Compton temperature as the disk temperature, $R_C = 1.6 \times 10^5 \text{ GM}/c^2$, inside the radius at which the photoionized lines are produced. It is therefore plausible that the narrow lines trace a thermal wind. Indeed, the large inferred distance from the central engine, high ionizations, and low velocities are all broadly consistent with numerical simulations of thermal winds (see, e.g., Higginbottom et al. 2017), but the inconsistent shifts may again point to potential axial asymmetry. The broad line that underlies the narrow Fe XXV He- α complex may not be part of a thermal wind, given an origin at $r \simeq 3 \times 10^3 \text{ GM}/c^2$.

The resonant scattering medium that is inferred via the Fe XXV He- α and Fe XXVI Ly- α line ratios likely represents a hot, fast, ionized wind. The inferred temperature, $kT = 48_{-6}^{+5} \text{ keV}$, is far above the escape speed in the outer disk. Moreover, the best-fit velocity of the inferred medium is $v = -610_{+30}^{-30} \text{ km s}^{-1}$, largely set by the ratio of the Fe XXVI Ly- α line. Given that the line of sight to the central engine in GRS 1915+105 is now blocked by the outer disk (or, skims along the surface of the disk), most of the velocity in this component may not be detected.

Our model requires only a few modest departures from solar abundances. The data weakly prefer 20–40% abundance enhancements for Si, Ar, Fe, and Ni, relative to solar values. However, the data require larger and more significant enhancements for other elements: $A_{Ca} = 1.54_{-0.14}^{+0.03}$, $A_{Cr} = 2.9_{-0.4}^{+0.2}$, and $A_{Mn} = 2.8_{-0.4}^{+0.2}$. Mn is the only element contributing strong lines with an odd atomic number (25), so its abundance measurement may be the most important. The value indicated by the

Resolve data is lower than the value of $A_{Mn} = 4 \pm 1$ reported by Keshet et al. (2025), but consistent within errors. The lower abundance that we have measured brings the overall abundance pattern in GRS 1915+105 closer to predicted SN yields (for a review, see Nomoto et al. 2013), and strengthens evidence that the progenitor event deposited some elements into the companion star.

3.4. The Fe XXVI RRC

Figure 5 shows the results of fits to the 8.4–10.0 keV band using the model detailed in Table 1, and using an alternative model with magnetic field effects activated. Over this pass band, the reference model delivers a Cash statistic of $C = 498$ for $\nu = 393$ degrees of freedom. With magnetic effects activated in the most highly ionized “pion” emission zone (pion_1 in Table 1), the Cash statistic improves to $c = 446$ for $\nu = 390$. Were these values strictly equivalent to χ^2 statistics, this improvement would be significant at the 5.5σ level of confidence.

The best-fit magnetic field is measured to be $B = 2.57 \pm 0.06 \times 10^9 \text{ Gauss}$. The phase of the observed oscillations is measured to be $\phi = 0.13_{-0.03}^{+0.08}$, and the amplitude is measured to be $A = 1.9 \pm 0.4$. This field is extremely high, commensurate with the surface magnetic field inferred in accreting millisecond X-ray pulsars (Patruno & Watts 2021). The putative field would have to exist in a hot, electron-dominated corona that may differ from the underlying accretion disk. However, assuming that these features are also produced in the outermost accretion disk, the implied magnetic field is several orders of magnitude greater than equipartition between magnetic pressure and gas pressure (Shakura & Sunyaev 1973; also see Miller et al. 2016). In short, a field this high would easily disrupt the disk. It is not clear how an equipartition field that might arise in the disk could be amplified to such a degree in a blanketing atmosphere or corona.

Moreover, the apparent oscillations are quite sharp. Whatever the exact orientation of the corona and field, separations of 30 eV would be completely blurred out at radii less than $r \leq 1.1 \times 10^5 \text{ GM}/c^2$ and so much larger radii – $r \simeq 1 \times 10^6 \text{ GM}/c^2$ – are likely. At this radius, however, the corona would be unbound, and could represent an ionized outflow. The distinct velocities are qualitatively similar to the wind observed in PDS 456, and so are the velocities (Xrism Collaboration et al. 2025). The lines cannot be dominated by H-like Fe XXVI, because the 18 eV spacing of the line components is incompatible with the data. Rather, intermediate charge states would be required, and velocities up to $v = 0.34c$. If

the wind is launched vertically, the true velocities would even higher.

4. DISCUSSION

We have analyzed the first XRISM/Resolve spectrum of the stellar-mass black hole GRS 1915+105. The source was captured in its “obscured” state. Our models suggest that the central engine remains in a disk-dominated, sub-Eddington accretion mode, but is largely occulted by the outer accretion disk. This situation is qualitatively similar to highly obscured and Compton-thick AGN, wherein the central engine is obscured by a molecular torus at the outer edge of the accretion flow. In this section, we discuss the nature of the “obscured” state in more detail, considering multi-wavelength observations and analogous sources. We also discuss the shortcomings of our model, alternative emission mechanisms that may contribute to the strong emission line spectrum, and comment on apparent structure in the Fe XXVI RRC.

4.1. *The nature of the obscured state*

Our model describes the Resolve spectrum of GRS 1915+105 in terms of a standard, sub-Eddington inner accretion flow that is obscured by warm, Compton-thick gas. The temperature of the obscuring medium is consistent with the outer accretion disk. The level of obscuration that is measured with Resolve exceeds values measured using Swift and Chandra (e.g., Balakrishnan et al. 2021, Miller et al. 2020). While this could indicate that the central engine in GRS 1915+105 is now even more deeply buried than it was in the recent past, the differences are more likely attributable to different levels of sensitivity and the modeling choices that follow. The role of warm gas absorption and the shortcomings of neutral obscuration were likely not apparent in spectra with more limited sensitivity and resolution.

A super-Eddington accretion rate could cause the inner accretion disk to assume a “funnel” geometry (King et al. 2001), blocking some of the ionizing flux and potentially accounting for some aspects of the “obscured” state. This configuration remained a possibility based on Chandra gratings spectra obtained in the “obscured” state, which did not require an accretion disk. The much higher sensitivity achieved even in this short Resolve spectrum does require a disk, but the disk temperature is typical of its standard, sub-Eddington “thermal-dominant” state (historically called the “high/soft” state; for a review of states, see Remillard & McClintock 2006).

The best explanation of the Resolve spectrum is that the “obscured” state is that the central engine is occulted by the outer accretion disk. This is indicated by

the nature of the obscuring gas itself, the radii and inclinations measured from the neutral Fe K_α line and broad ionized lines, and the radii inferred from the narrow ionized emission lines. The question, then, is why the outer disk obscures the central engine now, whereas it did not do so historically.

Seminal theoretical treatments find that radiation pressure on the outer accretion disk can drive a warp, leading to super-orbital periods (e.g., Pringle 1996). In sources that are viewed at a high inclination angle – just above the plane of the disk – precession may occasionally cause the outer disk to partly or completely occult the central engine. The condition is that the disk must be fairly large. This condition is surely met in GRS 1915+105, which has the longest orbital period and widest orbital separation among black hole X-ray binaries. The super-orbital periods and low flux states observed in neutron star X-ray binaries such as Her X-1, SMC X-1, and LMC X-4 are attributed to warping, precession, and occultation (see, e.g., Brumback et al. 2020, Kosec et al. 2023). The orbital periods of those systems are all less than four days, so similar phenomena in GRS 1915+105 should play out over much longer time scales.

Radio observations of GRS 1915+105 in 2023 reveal a 24 degree change in the position angle of the jets since 1999, as well as a 17 degree change in the inclination of the jets with respect to the line of sight (Rodríguez & Mirabel 2025). This degree of change in the broad accretion flow is likely sufficient to bring the outer disk into the line of sight to the central engine in GRS 1915+105. Recent observations with JWST measure an IR flux that is 10 times higher than in the past, and very strong IR recombination lines, indicating an enhanced role for reprocessing in the “obscured” state. Importantly, the brightest Pf(6-5) line lags the continuum by the expected light travel time from the central engine to the outer disk (Gandhi et al. 2024).

Taken as a whole, the Resolve data, radio data, and JWST data deliver a broadly self consistent picture: the “obscured” state of GRS 1915+105 is due to a warped, precessing accretion disk that is temporarily occulting the central engine. The length of the active period prior to the current “obscured” state, and the length of the “obscured” state itself, are likely a consequence of the fact that GRS 1915+105 is a very large X-ray binary, with a long orbital period. While the accretion flow occults the central engine, we are afforded an unprecedented multi-wavelength view of the outer accretion disk atmosphere and connected winds. Figure 6 shows a schematic representation of a geometry that could produce the Resolve spectrum. It is interesting to speculate

that GRS 1915+105 may be a persistent source, and that the central engine was merely obscured prior to its detection in 1992 (Castro-Tirado et al. 1992), not truly quiescent.

We note that while the multi-wavelength data and some details of the Resolve spectrum favor a warp, a less extreme version of the ULX scenario cannot be ruled out. It is possible that the inner flow is close to the Eddington limit, but buried by an even higher column than inferred by our model. In this case, the inner disk may not form into a funnel, but the outer disk would be more strongly illuminated and increase in scale height. In principle, at least, this could cause the outer disk in GRS 1915+105 to now intercept the line of sight, rather than a warp.

4.2. Model shortcomings

The model detailed in Table 1 captures many key aspects of the Resolve spectrum of GRS 1915+105, but it has some shortcomings. For instance, we have assumed that each zone has a gas density of $n = 3 \times 10^{10} \text{ cm}^{-3}$. This density value is driven by the need to produce strong lines while ensuring that $\Omega/4\pi \leq 1$. However, there is no reason why each zone must have the same density despite a range of ionizations and columns. Moreover, a covering factor of unity is unlikely and a modestly higher density of $n = 1 \times 10^{11} \text{ cm}^{-3}$ should drop the covering factor to $\Omega/4\pi \simeq 0.1$. Future modeling should explore higher fixed density values, and/or explicitly fit for the density of each zone.

Equally importantly, the model only includes three photoionized emission zones. The fact that the fit is not formally acceptable indicates that a more granular approach may be needed. For instance, while the model is an excellent match for the strongest Fe and Ni lines, the predicted Cr XXIV lines are broader than the data (see Figure 2). A model with a larger number of velocity and ionization pairings may enable improved fits.

Finally, the model neglects photoionized absorption. Potential absorption lines in this spectrum are easily neglected in favor of the emission lines, but a more complete treatment could yield additional physical insights. Apart from features that dip below the continuum in line-free regions, a number of the lines in the 8.0–10.0 keV band (for instance) appear to have a double-peaked structure that may indicate a role for absorption.

4.3. Alternative emission mechanisms

We have modeled the data successfully in terms of photoionized emission, but it is likely that collisional excitation and non-equilibrium emission contribute a degree of line flux. On their own, these mechanisms fail

to match the observed line ratios, and particularly fail to produce RRC features that match the data (as expected). A cooling, condensing disk atmosphere, for instance, is expected to produce particularly strong emission lines (see, e.g., Jimenez-Garate et al. 2001). To explore this possibility, we attempted a number of fits using the “nei” non-equilibrium plasma model in SPEX. For low gas densities, very strong resonance and forbidden lines are predicted, but intercombination lines fall short of the data. When the gas density reaches or exceeds $n = 10^{18} \text{ cm}^{-3}$, the predicted intercombination lines roughly match the data, but even then the model falls short of the RRC features. In our fitting experiments, models with single “nei” components yielded Cash statistics that were higher by $\Delta C \simeq 1000$, and combinations of two or more “nei” components (with or without photoionized zones) were higher by $\Delta C \simeq 500$. Nevertheless, future efforts to model this spectrum should explicitly consider small contributions from collisional plasmas and non-equilibrium plasmas.

4.4. Open questions

The three photoionization zones detailed in Table 1 exhibit low but inconsistent velocity widths and bulk shifts. This combination is necessary to match the profile of the strongest emission lines, particularly the Fe XXV He- α complex between 6.6–6.7 keV (see Figure 4). It is possible that the velocity structure reflects emission from different faces of a warp, with geometries on the near and far sides of the central engine contributing. The single, short observation that we have examined cannot test whether some of these velocities reflect axial anisotropy. Future XRISM observations that obtain Resolve spectra throughout the binary period can better determine the nature of the gas velocities.

If some of the gas velocities are driven by the binary system rather than Keplerian orbital motions, the emission lines could originate in other locations. It is possible that some of the line flux could arise on the irradiated surface of the companion star. In addition, some of the line flux could originate in a circumbinary disk; this possibility is also a plausible explanation of the JWST data (Gandhi et al. 2024). Finally, it is even possible that the very low velocities do not reflect Keplerian motion, but only bulk motion above the plane of the disk. In principle, the photoionized gas could have a cylindrical distribution above the disk, or even a polar distribution that is more centrally concentrated. Depending on its extent, this geometry could be the X-ray binary equivalent of the “narrow line region” in AGN (see, e.g., Wang et al. 2011), which is observed in extended polar regions that can be orders of magnitude larger than the torus.

Here again, future observations that can detect changes in the central engine and line spectrum are needed to test these possibilities.

4.5. Explaining the Fe XXVI RRC

Using a new capability within the “pion” model, we find that apparent oscillatory structure in the Fe XXVI RRC feature can be described in terms of recombination from Landau levels in a corona with a magnetic field of $B = 2.57 \pm 0.06 \times 10^9$ Gauss (see Figure 5). This change is likely significant over the model detailed in Table 1 at more than the 5σ level of significance. However, the implied field strength is so extreme – and so out of step with theoretical predictions – that it must be regarded with skepticism. Instead describing the features in terms of a relativistic outflow poses other severe challenges. We note that even more exotic explanations for the features include ionized charge states of gallium (requiring an over-abundance of $A_{\text{Ga}} = 5 \times 10^4$), or a resonance due to polarized electrons with aligned spins.

We investigated different means by which the oscillatory structure in the Fe XXVI RRC could arise through instrumental effects. The Resolve instrument team does

not know of any instrumental features in this range (Caroline Kilbourne, priv. comm.) There was no solar flaring reported during the observation; the astrophysical background was likely not enhanced nor anomalous. The presence of the features does not appear to depend on the inclusion nor exclusion of pixels 11 and 27, which can give anomalous readings.

Nevertheless, we currently favor an as-yet unknown instrumental artifact or unknown astrophysical effect. Resolve is the first (known) X-ray microcalorimeter to operate in the space environment for an extended period. There may not be any archival spectra, nor any XRISM spectra, with similarly strong Fe XXV and Fe XXVI RRC features. Observations of other systems may eventually reveal that the apparent oscillations are real but not tied to magnetic effects.

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Table 1. Spectral Model Parameters

Parameter	Value	Comments
disk kT (keV)	$3.53^{+0.06}_{-0.05}$	about 2X higher than at innermost orbit
disk norm. (10^9 cm^2)	$1.27^{+0.02}_{-0.02}$	–
pow. Γ	2.5*	fixed
pow. norm. ($10^{41} \text{ ph s}^{-1} \text{ keV}^{-1}$)	7^{+93}_{-7}	effectively an upper limit
pion ₁ $N_H(10^{22} \text{ cm}^{-2})$	$5.6^{+0.6}_{-0.5}$	–
pion ₁ $\log\xi$	$4.29^{+0.05}_{-0.03}$	–
pion ₁ $\sigma(\text{km s}^{-1})$	250^{+10}_{-10}	internal turbulent velocity
pion ₁ $v(\text{km s}^{-1})$	-90^{+10}_{-10}	bulk velocity shift
pion ₁ Ω	$1.00_{-0.01}$	–
pion ₂ $N_H(10^{22} \text{ cm}^{-2})$	$1.7^{+0.1}_{-0.1}$	–
pion ₂ $\log\xi$	$3.78^{+0.03}_{-0.03}$	–
pion ₂ $\sigma(\text{km s}^{-1})$	90^{+10}_{-10}	internal turbulent velocity
pion ₂ $v(\text{km s}^{-1})$	342^{+6}_{-7}	bulk velocity shift
pion ₂ Ω	$1.0_{-0.03}$	–
pion ₃ $N_H(10^{23} \text{ cm}^{-2})$	$3.3^{+0.3}_{-0.3}$	–
pion ₃ $\log\xi$	$3.36^{+0.03}_{-0.03}$	–
pion ₃ $\sigma(\text{km s}^{-1})$	294^{+7}_{-7}	internal turbulent velocity
pion ₃ $v(\text{km s}^{-1})$	28^{+9}_{-6}	bulk velocity shift
pion ₃ Ω	$0.23^{+0.06}_{-0.02}$	–
neutral Fe K line $N_H(10^{24} \text{ cm}^{-2})$	1.6*	via “mytorus”, fixed at Compton-thick value
neutral Fe K line norm. (rel. units)	$15.1^{+0.5}_{-1.5}$	via “mytorus”
neutral Fe K line $r_{in}(10^3 GM/c^2)$	$0.9^{+6}_{-0.2}$	via “spei”
neutral Fe K line $\theta(\text{deg.})$	5^{+4}_{-2}	via “spei”
broad Fe XXV He- α norm. ($10^{42} \text{ ph s}^{-1} \text{ keV}^{-1}$)	$4.8^{+0.5}_{-0.5}$	–
broad Fe XXV He- α E (keV)	$6.65^{+0.02}_{-0.02}$	range set to 6.65–6.70 keV
broad Fe XXV He- α $\sigma(\text{km s}^{-1})$	5700_{-300}	hit imposed upper limit
broad Fe XXVI Ly- α norm. ($10^{42} \text{ ph s}^{-1} \text{ keV}^{-1}$)	$5.2^{+0.5}_{-0.7}$	–
broad Fe XXVI Ly- α E (keV)	$6.97^{+0.03}_{-0.02}$	errors incl. both imposed limits
broad Fe XXVI Ly- α $\sigma(\text{km s}^{-1})$	700^{+100}_{-200}	–
$N_{H,RS}(10^{23} \text{ cm}^{-2})$	$1.1^{+0.1}_{-0.2}$	resonant scattering, via an “hot” component
$kT_{RS}(\text{keV})$	48^{+5}_{-6}	–
$\sigma_{RS}(\text{km s}^{-1})$	2^{+20}_{-2}	in addition to thermal broadening
$v_{RS}(\text{km s}^{-1})$	-610^{+30}_{-30}	–
$f_{cov,RS}$	1.0*	–
$N_{H,CE}(10^{24} \text{ cm}^{-2})$	$3.0^{+0.3}_{-0.3}$	warm partial covering of the the central engine
$kT_{CE}(\text{keV})$	$0.002^{+0.008}_{-0.001}$	–
$f_{cov,CE}$	$0.92^{+0.02}_{-0.02}$	–
$N_{H,ISM}(10^{22} \text{ cm}^{-2})$	$8.4^{+0.1}_{-0.1}$	column density in the ISM
Flux ($10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$, 0.0136–13.6 keV)	$3.0^{+0.3}_{-0.3}$	the observed flux
Luminosity ($10^{37} \text{ erg s}^{-1}$, 0.0136–13.6 keV)	$8.8^{+0.6}_{-0.6}$	the emitted luminosity
A_{Si}	$1.3^{+1.1}_{-0.5}$	–
A_S	$1.0^{+0.1}_{-0.1}$	–
A_{Ar}	$1.2^{+0.1}_{-0.1}$	–
A_{Ca}	$1.54^{+0.03}_{-0.14}$	–
A_{Cr}	$2.9^{+0.2}_{-0.4}$	–
A_{Mn}	$2.8^{+0.2}_{-0.4}$	–
A_{Fe}	$1.2^{+0.2}_{-0.1}$	–
A_{Ni}	$1.4^{+0.2}_{-0.2}$	–
C/ν	3891/2933	–

NOTE—Spectral model parameters values and 1σ errors. The time-averaged spectrum was fit after binning using the “optimal” binning algorithm (Kaastra & Bleeker 2016), minimizing a Cash statistic. Parameter values marked with an asterisk were held constant in the fit. The disk and power-law components from the central engine are listed first, followed by the photoionized emission zones that they illuminate (three pion zones), neutral Fe K emission line parameters (modeled with “mytorus” and “spei”), then broadened lines modeled with Gaussians, followed by a set of internal absorption and scattering columns. The continuum is covered with one column of warm gas via a “hot” absorption component. The line emission regions are covered by a hot resonant scattering zone. The entire model is covered by a neutral column in the ISM. Please see the text for a full description of the complex interplay between the central engine, emission regions, and absorption and scattering zones. The abundance constraints that the follow the other parameters were jointly determined by linking their values between the photoionized emission zones.

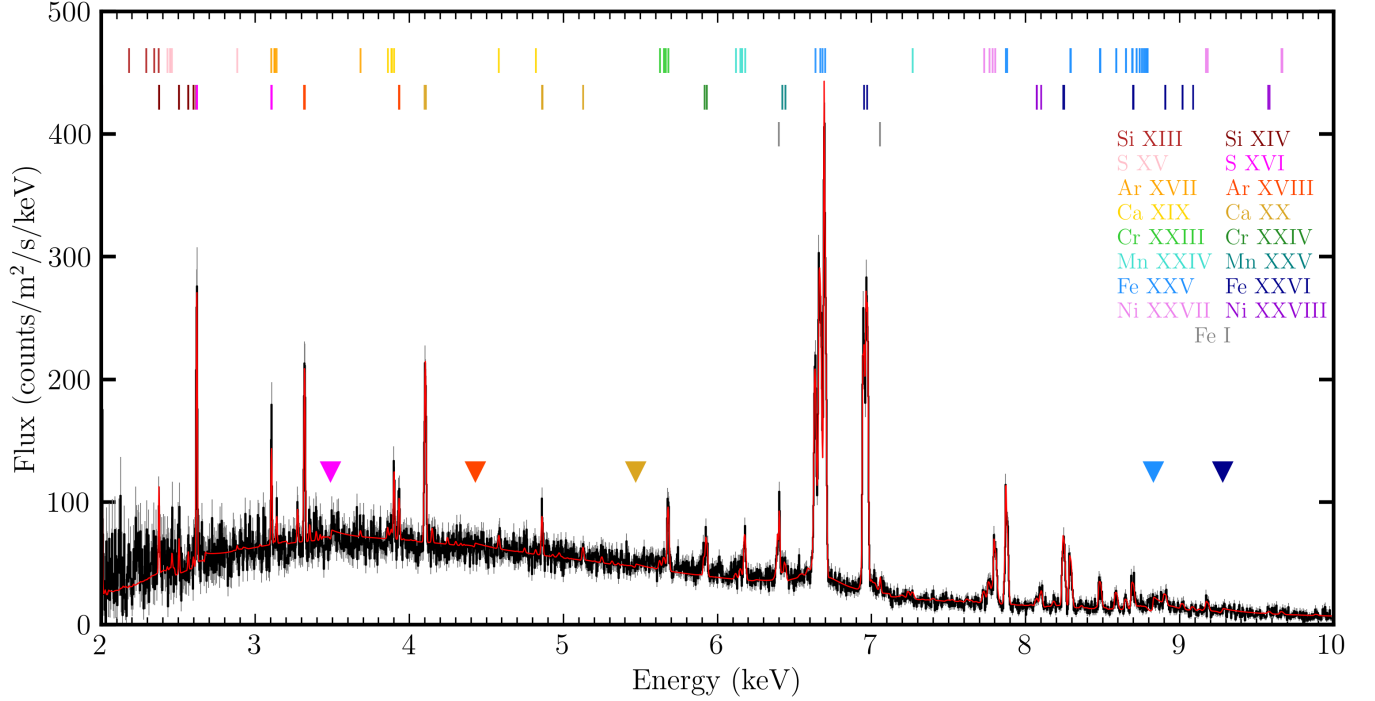


Figure 1. The XRISM/Resolve spectrum of GRS 1915+105 in its obscured state. The model in red is the best-fit model detailed in Table 1. It consists of a highly obscured disk plus power-law continuum and three photoionized emission zones in the outer accretion disk, weakly shaped by resonant scattering. The strongest lines are from He-like and H-like charge states of Si, S, Ar, Ca, Cr, Mn, Fe, and Ni. Solid vertical lines mark the lab energies of the observed He-like (top row) and H-like transitions (bottom row). A weak, narrow, neutral Fe K_{α} emission line is clearly detected at 6.4 keV, signaling the presence of cold gas at intermediate disk radii. Several RRC features are marked with triangles, including from He-like and H-like Fe at 8.8 and 9.3 keV, respectively. The data are binned using the “optimal” binning algorithm.

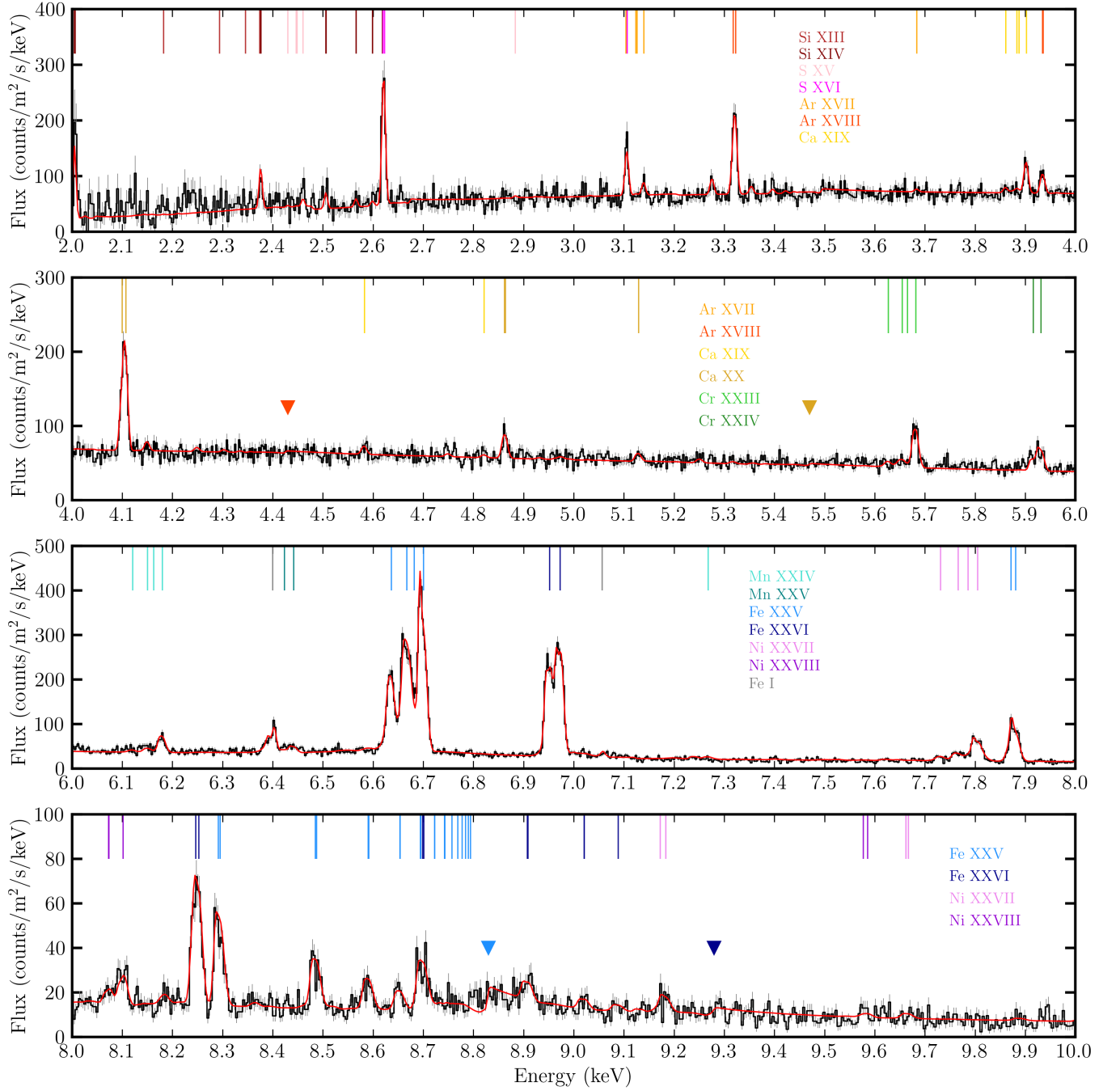


Figure 2. The XRISM/Resolve spectrum of GRS 1915+105, shown in 2 keV segments. The model in red is the best-fit model detailed in Table 1. Solid vertical lines mark the lab energies of the observed He-like and H-like lines, as well as neutral Fe. The red-shift of the bulk of the emitting gas relative to lab wavelengths is evident, especially in the strongest Fe XXV and Fe XXVI lines. RRC features are marked with triangles.

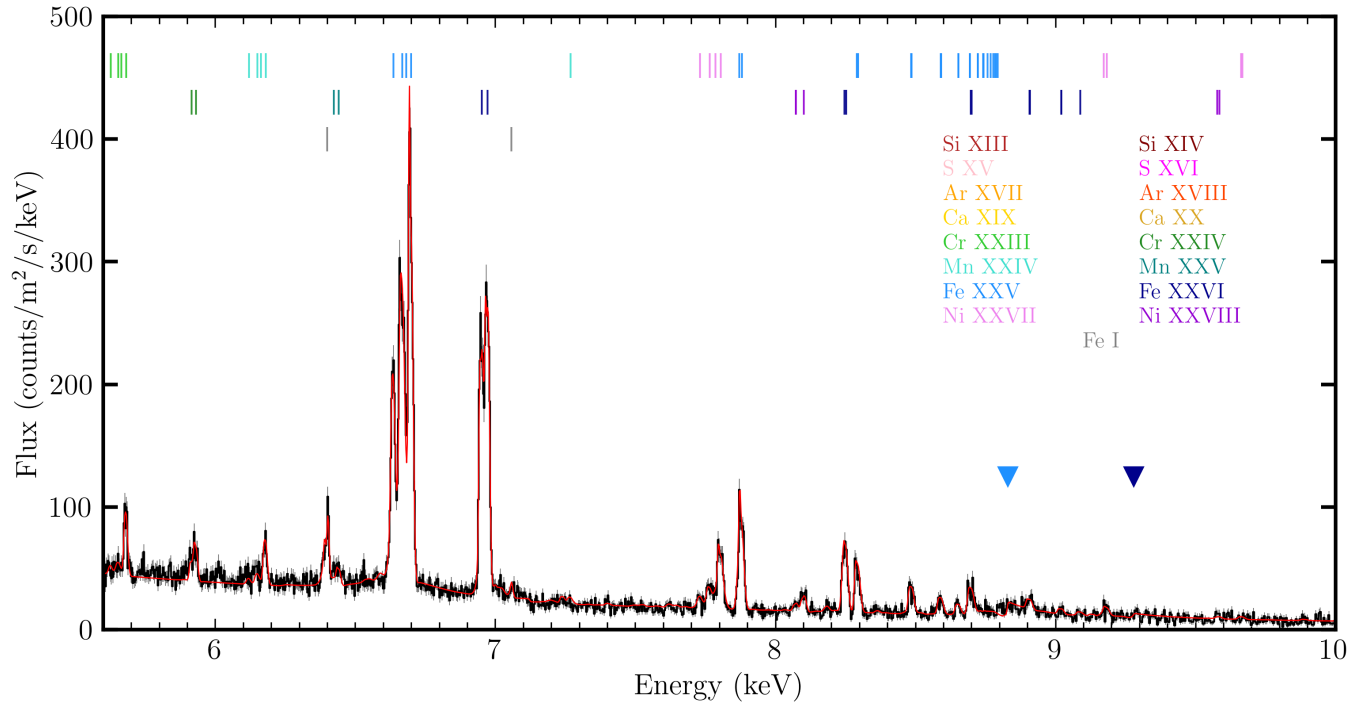


Figure 3. The XRISM/Resolve spectrum of GRS 1915+105, in the band containing He-like and H-like lines from Cr, Mn, Fe, and Ni. The model in red is the best-fit model detailed in Table 1. Solid vertical lines mark the lab energies of the observed He-like (top row) and H-like transitions (bottom row). RRC features are marked with triangles.

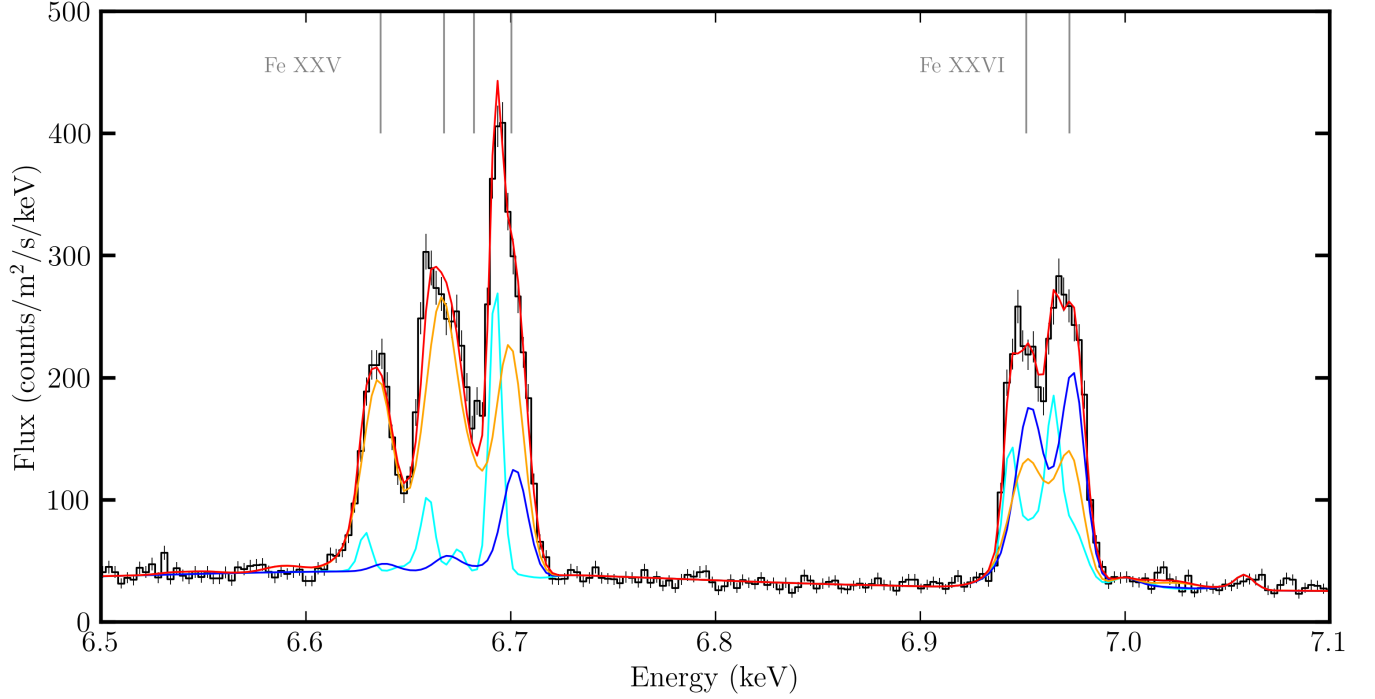


Figure 4. The XRISM/Resolve spectrum of GRS 1915+105 in the vicinity of the strongest emission line complexes (He-like Fe XXV, centered at 6.7 keV, and H-like Fe XXVI centered at 6.97 keV). The total best-fit model is shown in red, with individual photoionized components shown in blue (pion_1), cyan (pion_2) and orange (pion_3). In these and other lines from adjacent charge states, it is clear that multiple components are needed to describe He-like and H-like line fluxes, and detailed line shapes. It is evident that the lines are red-shifted with respect to their laboratory energy values, marked in gray at the top of the frame. Note that the component colors adopted in this plot are not connected to the elemental color scheme in other plots.

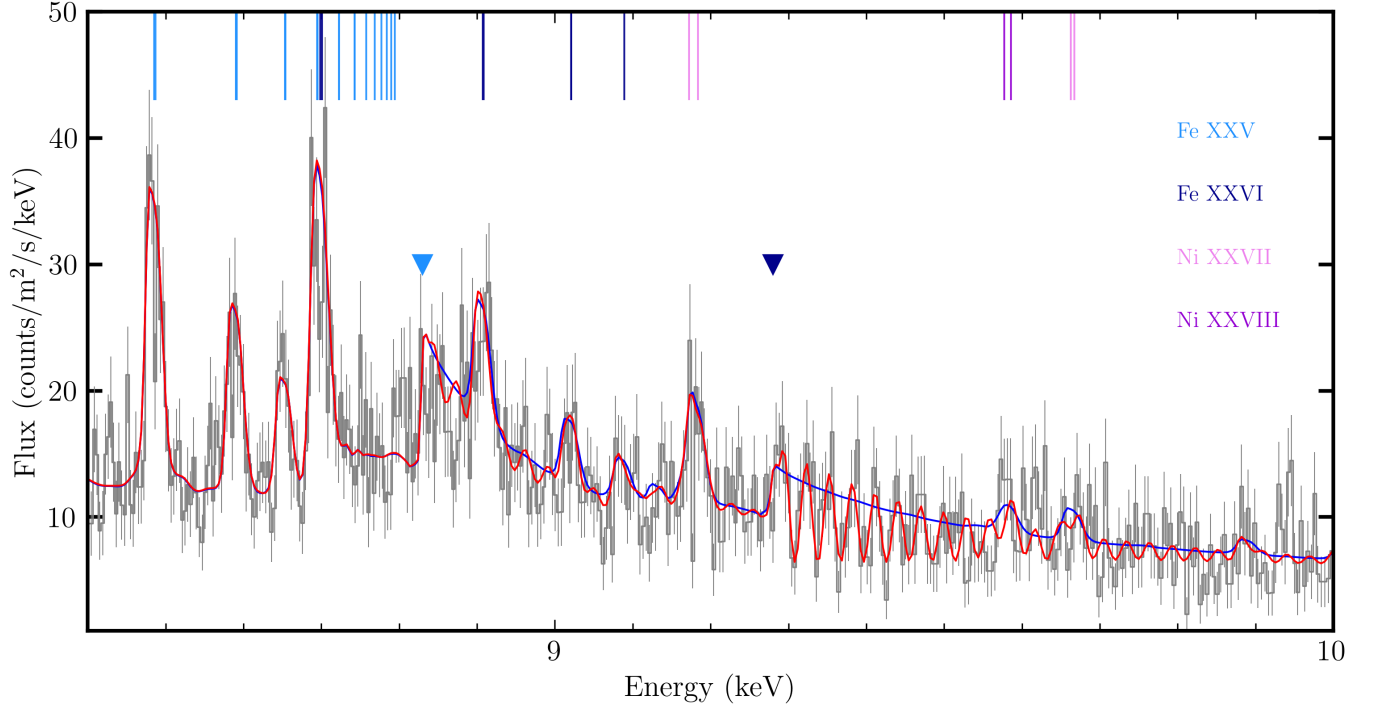


Figure 5. The XRISM/Resolve spectrum of GRS 1915+105 in the band containing Fe XXV and Fe XXVI RRC features (marked with triangles). The best-fit model in other figures is now shown in blue. The Fe XXVI RRC is clearly not smooth, as expected if recombining electrons are thermally distributed; instead, oscillatory structure with a spacing of 30 eV is evident. This structure is nominally consistent with recombination from Landau levels in a highly magnetized corona ($B = 2.5 \times 10^9$ Gauss; this model is shown in red). Alternatively, the lines could arise in a $v = 0.34c$ flow wind, wherein iron retains intermediate charge states. Both explanations are unsatisfactory.

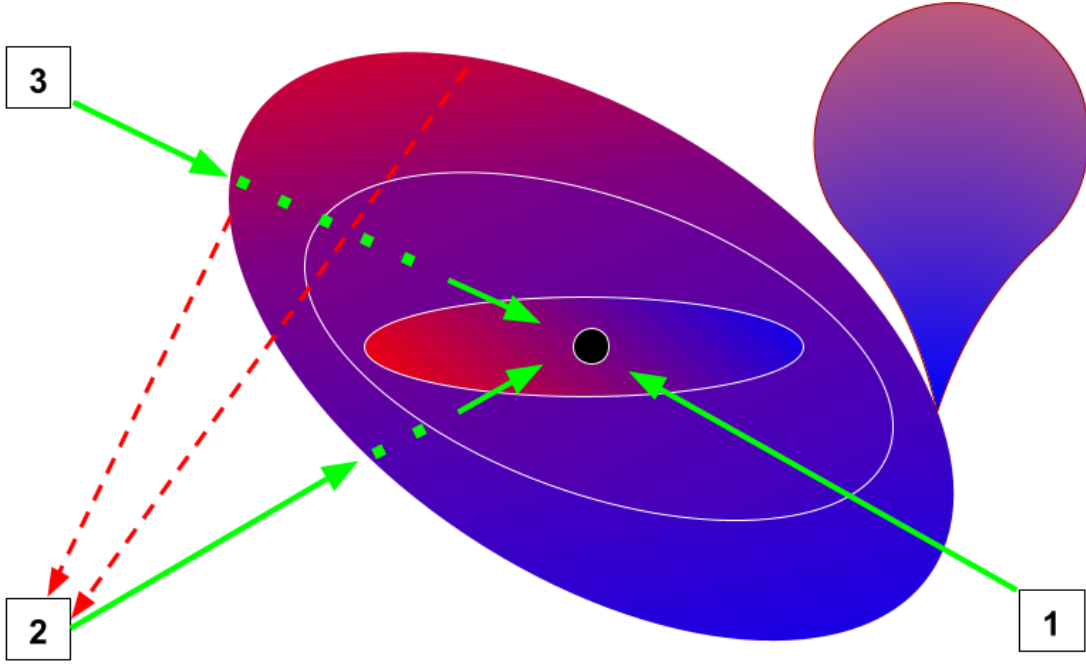


Figure 6. A diagram of a warped disk geometry that might lead to the spectrum observed from GRS 1915+105 with Resolve. Position 1 sees the central engine, only obscured by disk winds. At Position 2, the central engine is blocked by the warp in the outer disk, but emission from the face of the warp at Position 3 is visible. At Position 3, the central engine and irradiated face of the disk are both blocked. Note that the warp period is much slower than the orbital period of the system; it is not locked in orbital phase.