CHANDRA GRATING SPECTROSCOPY OF THE Be/X-RAY BINARY 1A 0535+262

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ABSTRACT

We present Chandra HETGS spectroscopy of the Be/X-ray binary 1A 0535+262 obtained during the 2009/2010 giant outburst. These are the first CCD grating spectra of this type of system during a giant outburst. Our spectra reveal a number of lines including a narrow Fe Kα emission line with an FWHM of ~5000 km s\(^{-1}\). For the first time, we detect the presence of a highly ionized outflow in a Be/X-ray binary. Assuming that the line is He-like Fe xxv, fits with a simple Gaussian imply an outflow velocity of ~1500 km s\(^{-1}\). However, self-consistent photoionization modeling with xstar suggests that Fe xxv-xxiv must also contribute. In this case, an outflow velocity of ~3000 km s\(^{-1}\) is implied. These results are discussed in the context of accretion flow in Be-star, neutron star, and black hole X-ray binaries.

Key words: accretion, accretion disks – stars: neutron – techniques: spectroscopic – X-rays: binaries – X-rays: individual (1A 0535+262)

Online-only material: color figures

1. INTRODUCTION

X-ray binaries are divided into a number of different categories based on their observational (e.g., X-ray/optical) and physical characteristics. The primary division is made based on the mass of the secondary star in the binary, with systems for which \(M_2 \lesssim 1 M_\odot\) being classified as low-mass X-ray binaries (LMXBs), \(1 M_\odot \lesssim M_2 \lesssim 10 M_\odot\) classified as intermediate mass X-ray binaries (IMXBs), and those with secondary masses greater than \(10 M_\odot\) classified as high-mass X-ray binaries (HMXBs). Approximately 300 X-ray binary systems have been detected in the Galaxy, with more than half of these being LMXBs. Of the approximately 115 known HMXB systems, Be/X-ray binaries comprise the majority (~70%; Liu et al. 2006, 2007).

Be/X-ray binaries comprised of a neutron star primary in a wide eccentric orbit with a Be-star secondary (no black hole/Be-star binaries have been discovered to date—see Belczynski & Ziolkowski 2009). X-ray outbursts in these systems typically occur during periastron passage of the neutron star close to the circumstellar excretion disk of the Be-star; see, e.g., Okazaki & Negueruela (2001). However, the X-ray outbursts have been observed to occur in two distinct flavors: (1) type I: regular outbursts which occur during periastron passage, generally repeating on the binary orbital period and (2) type II: also known as giant outbursts likely arising from a dramatic expansion of the circumstellar disk. In contrast to type I outbursts, type II outbursts do not have a strict phase dependence and typically last much longer than type I bursts, with the outburst time typically being measured in months; e.g., see Figure 1.

Cyclotron absorption lines have been detected in the X-ray spectra of a number of Be/X-ray binaries allowing accurate constraints to be placed on the neutron star magnetic field. Typically, magnetic flux densities in the range of \(\sim 10^{13}-10^{15} \text{ G}\) are measured (e.g., Nakajima et al. 2006, Terada et al. 2006, and Wilson et al. 2008). This opens up the possibility of studying the effect of the neutron star B-field on the accretion flow. In these HMXBs, the magnetic field is much larger than the B-field of the neutron stars in the much older population of neutron star LMXBs, e.g., a magnetic flux density of \(\sim 10^8 \text{ G}\) has been measured in the accreting millisecond pulsar SAX J1808.4-3658 (Cackett et al. 2009).

Reig (2008) has investigated the timing properties exhibited by a sample of four Be/X-ray binaries, which displayed a type II outburst that was observed by RXTE. A number of similarities with the well-studied behavior of LMXBs was detected when analyzing the color–color (CD) and hardness intensity diagrams (HIDs; e.g., Hasinger & van der Klis 1989 and van der Klis 2006). The main similarities are as follows: (1) similar spectral branches in the CD/HID as those observed in LMXBs, (2) smooth motion through the CD/HID, (3) larger variability at low intensities, (4) power spectra that can be described by a small number of Lorentzians, and (5) flat topped noise at lower frequencies in the horizontal branch that turns into power-law noise in the diagonal branch. A number of differences were also observed, namely (1) different patterns in the CD/HID, e.g., a low-intensity soft state, (2) slower motion through the various patterns (weeks/months as opposed to hr/days in LMXBs), (3) characteristic timescales that are an order of magnitude longer, and (4) no apparent correlation between the power spectral parameters (QPOs, rms) and the mass accretion rate. A number of features also hint at a B-field dependence of the timing properties, e.g., power-law noise in the HB branch in V0332+53 but flat topped noise in 4U0115+63 and EXO 2030+375, whose B-fields are \(\sim 2 \times 3\) lower than that of V0332+53. These observations demonstrate that the accretion flow in the Be/X-ray binaries is fundamentally similar to that in the more thoroughly studied LMXBs.

Simultaneous observations at optical/NIR and X-ray wavelengths have shown substantial changes in the structure of both the accretion and circumstellar disks, with both disks observed to disappear at times. This changing disk structure is responsible for the varying outburst phases (Wilson et al. 2002). The observed changes in the accretion and circumstellar disks have been successfully explained via the “truncated disk model” (Okazaki & Negueruela 2001). Here, the circumstellar disk is truncated due to tidal interaction with the neutron star. Detailed studies of EXO 2030+375 found that the circumstellar disk is likely truncated at the 4:1 tidal resonance radius. This is close to the critical radius at periastron. If the disk extends
In the first observation (ObsID: 12066–2009.12.28), the exposure time was ~9 ks, while the exposure time for the second observation (ObsID: 12067–2009.12.31) was ~11 ks. The HETGS was used to disperse the incoming photons onto the ACIS-S CCD array. As the source flux was high, observations were carried out in continuous clocking mode, with a nominal frame time of ~2.8 ms. In this data mode, the fast readout times are achieved by collapsing the data into a single dimension, preserving spectral and timing information at the price of losing one of the spatial dimensions.

Spectra and light curves were extracted from the Chandra event lists using CIAO V4.2. Response files were generated using the MKRMF and FULLGARF tasks and the first-order spectra from each grating were combined with the ADD_GRATING_ORDERS task resulting in a single HEG and MEG spectrum for each observation. The spectra were binned using the GRPPHA tool to ensure 10 counts per spectral bin before exporting to XSPEC for analysis.

2.2. RXTE

1A 0535+262 was also observed by RXTE during this outburst on an almost daily basis (Caballero et al. 2009). Data was obtained with both the Proportional Counter Array (PCA) and HEXTE. The RXTE observations were quasi-simultaneous with the Chandra observations with pointed observations occurring within a 12 hr period of our observations on each occasion (ObsID: 94323-05-03-03, -06; PI: Caballero). Spectra were extracted in the standard manner using the relevant ftools. For the PCA, spectra and background files were extracted from layer-1 of PCU2 alone, giving useful data in the spectral range 3–20 keV. HEXTE spectra were extracted from cluster-A, while backgrounds were extracted from cluster-B and converted to cluster-A background files using the ftool HEXTBACKEST1 giving useful data in the 15–100 keV band. As a number of background features were apparent at higher energies, data above 60 keV was ignored in all further analysis. Hence, the RXTE spectra resulted in a broadband detection of 1A 0535+262 in the spectral range from 3 to 60 keV.

3. ANALYSIS AND RESULTS

The HEG spectra immediately reveal the presence of an emission feature consistent with iron Kα at approximately 6.4 keV in addition to an absorption feature at ~6.7 keV. In contrast, outside of a number of line-like residuals in the Si/S region (2.1–2.4 keV), which are likely of an instrumental nature, there are no obvious spectral features in the MEG spectra. Before we examine in detail the emission and absorption lines in the spectrum, we first model the spectral continuum. To this end, we utilize the RXTE data in combination with the Chandra data (HEG and MEG) to constrain the continuum. All data analysis takes place within XSPEC 12.5.0.

3.1. Continuum Model

In Figure 2, we plot the broadband Chandra and RXTE spectrum of 1A 0535+262. The spectrum was fit with a model consisting of a disk blackbody and a blackbody plus a power law with a spectral cutoff containing a cyclotron absorption line modified by interstellar absorption $(\phi_{\text{abs}}(\text{cyclabs}\ast(\text{diskbb}+\text{bb}+\text{cutoffpl})))$, as this was consistent with the observed spectrum in the 2005 normal outburst.

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1 See http://heasarc.gsfc.nasa.gov/docs/xte/xhp_new.html.
The column density was held fixed at a value of \(4.5 \times 10^{21}\) cm\(^{-2}\) consistent with the measured value toward 1A 0535+262 (Kalberla et al. 2005) and with optical measurements (e.g., Steele et al. 1998). Allowing the column density to vary results in a best-fit value consistent with this value. At high energies, a broad absorption feature is observed consistent with the expected position of the fundamental cyclotron resonance absorption line in this system. The measured energies are consistent with measurements from the previous 2005 outburst (Terada et al. 2006; Caballero et al. 2008), and those measured earlier in the 2009 outburst (Caballero et al. 2009) implying a neutron star magnetic field of \(\sim 4 \times 10^{12}\) G.

The resulting best-fit model parameters are displayed in Table 1. At higher energies, no significant change is observed in the position of the cyclotron lines; however, as the background dominates above 60 keV, our limited ability to constrain the continuum above the cyclotron line will affect our ability to quantify any small changes that may be present. The simple cutoff power-law model that we have used to describe the high-energy continuum above the cyclotron line will affect our ability to quantify any small changes that may be present. The simple cutoff power-law model that we have used to describe the high-energy continuum above the cyclotron line will affect our ability to quantify any small changes that may be present. The simple cutoff power-law model that we have used to describe the high-energy continuum above the cyclotron line will affect our ability to quantify any small changes that may be present. The simple cutoff power-law model that we have used to describe the high-energy continuum above the cyclotron line will affect our ability to quantify any small changes that may be present.

Table 1

| Table 1: Broadband Continuum Fit Parameters |
|--------------------------------------------|
| Parameter      | Value (Units) |
| \(kT_{\text{disk}}\) (keV) | 0.15 ± 0.04 |
| \(kT_{\text{bb}}\) (keV) | 1.07 ± 0.04 |
| \(E_{\text{cut}}\) (keV) | 23.0 ± 0.2 |
| \(D_{\text{cyc}}\) (keV) | 42.85 ± 0.8 |
| \(L_{X_{\text{cyc}}}\) (keV) | 8.0 ± 1.0 |

Notes. Best model parameters for the 1A 0535+262 continuum in the spectral range 0.9–60 keV (see Figure 2), where the best-fit model is \(\text{pha*(cyclabs*(diskbb+bb+cutoffpl))}\). All errors are quoted at the 90% confidence level.

Having characterized the continuum, the spectra were then inspected for emission and absorption features. We concentrate on the HEG spectra as there are no obvious spectral features in the MEG spectra. A number of emission and absorption features are clearly detected in both observations and are consistent with no change within the errors. In contrast, absorption consistent with Fe XXV is only detected in the first observation. The exposure time was \(\sim 10\) ks in each observation. Note: the data have been rebinned for visual clarity.

(A color version of this figure is available in the online journal.)

and \(L_{X_{\text{cyc}}} = (1.17 ± 0.01) \times 10^{37}\) erg s\(^{-1}\), which correspond to Eddington scaled luminosities of \(\sim 9\%\) and \(6.6\%\) for the first and second observations, respectively.

3.2. Emission and Absorption Lines

Basic line parameters were obtained by fitting Gaussians to the detected lines, the parameters of which we display in Table 2. In Figure 3, we display the HEG spectra for each epoch with the best fit continuum model from Section 3.1 in addition to a number of Gaussian lines. The iron K-shell lines are detected in each observation and have the same equivalent widths (EWS) within the errors. The Kα line is resolved and hence we measure a line width of \(\sim 5000\) km s\(^{-1}\) in the first observation while the measured line width is lower in observation 2 at \(\sim 4100\) km s\(^{-1}\), it is nonetheless consistent with the presence of highly ionized Fe XXV also detected in the first observation alone; see Figure 3.

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states that would broaden the line, contributing to the observed Fe Kα line, i.e., Fe x. The measured line fluxes (see Table 2) return an Fe Kβ/Ke ratio of 0.21 ± 0.11 in agreement with the theoretically expected value within the errors (~0.13; Palmeri et al. 2003).

An absorption line, at an energy consistent with highly ionized Fe xxv, is detected in the first observation alone. We do not observe any absorption from Fe xxvi in either epoch, nor is there evidence for any additional absorption features in either observation. Assuming the detected absorption line is due to highly ionized Fe xxv, we measure a significant blueshift consistent with the presence of an outflowing wind in the 1A 0535+262 system. The measured line position implies a velocity for the outflowing material of $v_{\text{out}} = 1500 \pm 1000 \, \text{km} \, \text{s}^{-1}$.

### 3.3. Ionized Absorption

To provide a more physical description of the highly ionized absorption in the spectrum of 1A 0535+262, we generated a grid of models using xstar version 2.1kn9, and the “xstar2xspec” facility. For an input spectral form, we used the (unabsorbed) best-fit continuum model, extended to cover the 0.1–100.0 keV range. A covering factor of 0.2 was assumed, consistent with other X-ray binaries (e.g., Miller et al. 2008 on GRO J1655-40; Ueda et al. 2009 on GRS 1915+105), and consistent with the absence of any strong ionized emission lines. A maximum density of $n = 10^{12} \, \text{cm}^{-3}$ was assumed, and solar abundances were assumed initially for all elements. This xspec table model was then added to the continuum model in Section 3.1 as an additional absorption component, i.e., pha*(mtable{xstar.table}*(continuum)). The free parameters of this additional absorber are the column density, $N$; the log of the ionization parameter, $\xi$; and the redshift/blueshift, $v_{\text{in/out}}$.

Fits to the data with this grid of absorption models find the following best-fit parameters: $N = 2.9^{+2.2}_{-1.0} \times 10^{21} \, \text{cm}^{-2}$, $\xi = 3.4^{+0.8}_{-0.2} \, \text{erg} \, \text{cm} \, \text{s}^{-1}$, and $v_{\text{out}} = 5000 \pm 600 \, \text{km} \, \text{s}^{-1}$ (uncertainties are 1σ errors). However, this model predicts H-like Mg and Si absorption lines that are not observed in the data. Moreover, it appears that the absorption at ~6.73 keV also contains a contribution from Fe xxiii and Fe xxiv that is comparable to that from the Fe xxv line.

A model where iron is overabundant by a factor of 2 provides an improved fit to the data and does not predict observable Mg and Si lines. With such a model, the following absorption parameters are measured: $N = 2.0^{+0.8}_{-0.2} \times 10^{21} \, \text{cm}^{-2}$, $\xi = 4.0^{+0.5}_{-0.3} \, \text{erg} \, \text{cm} \, \text{s}^{-1}$, and $v_{\text{out}} = 3150 \pm 600 \, \text{km} \, \text{s}^{-1}$ (uncertainties are 1σ errors). This model provides a fit both to the entire spectrum and to the ionized Fe K region that is more reasonable.

In the Figure 4 inset, we display the best-fit model containing the xstar absorption component but with the normalization of the emission lines set to zero for clarity. The incident model spectrum is plotted to illustrate the contribution from the individual Fe ions. The absorption line is found to be the sum of absorption from a number of highly ionized Fe ions, i.e., Fe xxiii, Fe xxvi, Fe xxv; see Kallman et al. (2004) for details.

We emphasize that it is impossible to produce absorption solely due to Fe xxv. In each model where absorption due to Fe xxv is produced, we also obtain a contribution from the two preceding Fe ionization stages (xxiii, xxiv). We can estimate the column density in each ion via the standard relation between the line equivalent width and the curve of growth. Our best-fit model (see Figure 4) implies column densities of ~10$^{17}$ cm$^{-2}$ for Fe xxv and Fe xxiii, while the Fe xxiv column density is less than a third of this.

The best-fit xstar model also predicts absorption due to H-like iron. This absorption line is not detected in the data due to a combination of the narrow line width, low signal-to-noise ratio, and relatively low spectral resolution at this energy (~7.04 keV). This line will contribute to the red wing of the Fe Kβ line, resulting in a larger line EW than measured in Section 3.2. In turn, this will affect the measured Fe Kβ/Ke flux ratio, increasing it from the value measured earlier but nonetheless remaining consistent with the expected theoretical value within the errors, i.e., ~0.13 (Palmeri et al. 2003). However, further observations are required to test for the presence of this hydrogen-like absorption line.

### 4. DISCUSSION

We present the first high-resolution X-ray spectrum of a type II outburst from the Be/X-ray binary 1A 0535+262. In the spectra, we detect emission lines from Fe Kα & Kβ in two separate observations separated by 3 days, which do not display any significant evidence for variability between the observations. In the first epoch of observation alone, we find a blueshifted absorption line consistent with an origin in highly ionized Fe. Detailed modeling implies an outflow velocity of approximately 3000 km s$^{-1}$. We now proceed to discuss the observed spectrum in more detail.

#### 4.1. The Emission Line Spectrum

We can use the observed lines to place constraints on the accretion flow geometry. Firstly, we consider the observed fluorescence Fe Kα emission line. Assuming Keplerian rotation, the line FWHM implies an emission radius of $r = 7200^{+600}_{-3500} \, \text{km}$ in observation 1 and $r = 10800^{+3200}_{-6300} \, \text{km}$ in observation 2. This emission radius (i.e., ~10$^{4}$ km) is consistent with the Alfvén radius given the known magnetic field in 1A 0535+262 of
\[ \sim 4 \times 10^{12} \text{ G}, \text{i.e.,} \, r_A \approx 3.7 \times 10^3 M^{-2/7}_\odot \text{ km}, \] where the mass accretion rate is measured in units of \( \sim 10^{-8} M_\odot \text{ yr}^{-1} \). Hence, if the Fe fluorescence line originates at the inner edge of the accretion disk, which is truncated close to the Alfvén radius, this implies a mass accretion rate \( \lesssim 10^{-8} M_\odot \text{ yr}^{-1} \). This accretion rate is consistent with the observed X-ray luminosity during our observation, \( L_X \sim 0.09L_\text{Edd} \).

We must also ask if the observed fluorescent line strength is consistent with theoretical expectations for fluorescent line formation. George & Fabian (1991) predict the fluorescent line equivalent width to be \( \text{EW} \sim (\Omega/2\pi) \times 180 \text{ eV} \). Following Chen & Halpern (1989), we find the solid angle subtended by the disk to be \( \Omega \lesssim 0.25 \). The measured EW for the 6.4 keV iron line is \( \sim 25 \text{ eV} \) (see Table 2), implying a solid angle of \( \sim 0.15 \). For completeness, we can also ask if the observed line could be excited on the surface of the mass donor O9.7IIIe star; however, for the known orbital separation at periastron (\( \sim 1 \times 10^{13} \text{ cm} \); Coe et al. 2006; Haigh et al. 2004) the secondary star will subtend a solid angle over an order of magnitude less than that of the disk. Similarly, the observed line width is difficult to produce in a stellar wind; for example, the typical terminal velocity for the wind from a B-star is \( \lesssim 2000 \text{ km s}^{-1} \), which is inconsistent with the measured spectrum.

Iron fluorescence emission lines have been detected in numerous other neutron star X-ray binaries. Torrejon et al. (2010) have recently completed a systematic analysis of Chandra HETGS observations of 41 X-ray binary systems (10 HMXBs and 31 LMXBs). They find a narrow Fe Kα emission line to be present in all of the HMXBs studied while it is only present in a small fraction of the LMXB sample (\( <10\% \)). However, the width of this line is measured to be low, with a typical velocity width of \( \lesssim 800 \text{ km s}^{-1} \) and is found to be consistent with a wind-like origin. It is clear that the line width we measure in 1A 0535+262 (\( v \sim 5000 \text{ km s}^{-1} \)) is not consistent with having the same origin as the narrow Kα lines detected by Chandra in the majority of HMXBs observed to date. Nonetheless, we note that the line and continuum flux we measure for the Fe Kα line are consistent with the relation \( F_{\text{line}} \propto F_{\text{cont}}^{0.71} \) as measured by Torrejon et al. (2010) for the sample of systems they studied. This is to be expected given the small radius implied by the line width (\( \sim 10^7 \text{ km} \)).

The line we observe in 1A 0535+262 is produced in a similar manner to the relativistically broadened lines that are observed in many of the neutron star LMXBs, i.e., fluorescent X-ray emission from the surface of the accretion disk. However, in 1A 0535+262 the observed Kα line does not display any evidence of the characteristic relativistic red wing as expected if the line is formed deep in the gravitational well of the neutron star (e.g., Cackett et al. 2010). Instead, the line we measure is narrow, consistent with a much larger emission radius (\( \sim 10^4 \text{ km} \), see above).

The emission line spectrum that we observe in the 1A 0535+262 spectrum is fundamentally different from that observed in the high mass X-ray binary pulsars GX 301-2 (Watanabe et al. 2003) and 4U 1908+075 (Torrejon et al. 2010). Watanabe et al. (2003) observed GX 301-2 for 40 ks with Chandra HETGS and detected a fluorescent Kα line with an accompanying Compton shoulder. This line is formed in the dense wind from the B2 supergiant secondary star. Detailed XSTAR modeling of this X-ray spectrum found column densities of \( N_H \sim 10^{24} \text{ cm}^{-2} \). Analysis of a Chandra spectrum of 4U 1908+075 reveals a similar Compton broadened Fe Kα line.
(Torrejon et al. 2010). In contrast, the iron absorption lines detected in 1A 0535+262 are consistent with a much lower column density in the wind, \( N \sim 10^{21} \text{ cm}^{-2} \).

4.2. Wind Origin?

We have measured an absorption component consistent with a significant outflow in this system. Simple phenomenological modeling favors an outflow velocity of \( \sim 1500 \text{ km s}^{-1} \) consistent with absorption due to highly ionized He-like iron; see Section 3.2. Detailed modeling with the xstar plasma photoionization code reveals the absorbing component to consist of a number of highly ionized Fe ions from xxiii–xxv at a common blueshift of \( \sim 3000 \text{ km s}^{-1} \); see Section 3.3. This is the largest wind velocity measured from a Galactic X-ray binary to date.

We can estimate the maximum radius at which the absorption occurs via the measured ionization and column density from the xstar model, i.e., assuming \( N = nr \), we have \( r = L_x/N \xi \), which implies a radius of \( \sim 10^{12} \text{ cm} \). This radius is less than the estimated Roche lobe radius of the neutron star close to periastron \( (R_L \sim 3.5 \times 10^{12} \text{ cm}; \text{Co et al. 2006%; Haigh et al. 2004}) \) and implies a disk origin for the observed absorption component.

There are three well-studied mechanisms for launching a disk wind: (1) radiative—radiation pressure may drive a moderately ionized wind (Proga et al. 2008), (2) thermal—Compton heating of the accretion disk by the central X-ray source may raise the gas temperature to the escape velocity and drive a thermal wind from the system (Woods et al. 1996), and (3) magnetic—could be powered either by internal magnetic viscosity giving rise to a slow dense wind (Proga 2003) or rigid magnetic fields which would allow some material to be accelerated along magnetic field lines giving rise to a clumpy wind (Spruit 1996). Radiative and thermal winds are expected to be launched from significantly larger radii (e.g., \( 10^{10} \) cm versus \( 10^{9} \) cm for a \( 10 M_\odot \) BH) and have a lower density than a magnetic wind, a prediction that may be tested via detailed modeling of the disk absorption line spectrum as demonstrated by Miller et al. 2006a, 2008. The radius implied by our modeling favors a radiative/thermal origin for the large outflow velocity measured in 1A 0535+262.

4.3. Outflows in Other X-ray Binaries

Chandra observations of GRO J1655−40 (Miller et al. 2006a, 2008) have provided the most revealing insights into the structure of this accretion disk wind. Detailed studies of the wind absorption line spectrum favor a magnetic origin with an inner launching radius \( \sim 10^{9} \text{ cm} \). The mass flux in the wind was constrained to be at least 5%–10% of the total accreted mass and could easily be comparable with the mass accreted through the disk. Observations of the stellar mass black hole binaries H1743−322 (Miller et al. 2006b) and 4U 1630−472 (Kubota et al. 2007) have also displayed evidence for dense winds launched from the inner disk region. Recent observations of the Galactic microquasar GRS 1915+105 also display blueshifted absorption features consistent with an outflow velocity of \( 150–1500 \text{ km s}^{-1} \) (Ueda et al. 2009; Neilsen & Lee 2009), while observations of the Galactic high mass black binary Cyg X-1 also display evidence for a low velocity outflowing wind (Miller et al. 2002). The low outflow velocity here is interesting as in this system there is a large scale wind, due to the O-type secondary star, with an expected terminal wind velocity of \( u_\infty \leq 2100 \text{ km s}^{-1} \). In all of the above cases, the measured outflow velocity is low, \( \lesssim 500 \text{ km s}^{-1} \).

Similarly, Chandra observations of the neutron star LMXB GX 13+1 also measure a low velocity, highly ionized wind (Ueda et al. 2004). Detailed modeling of the observed absorption lines revealed the wind to be consistent with being radiatively driven. Of the sample of X-ray binaries observed with the HETGS, only a single system has displayed absorption lines with a velocity comparable to that which we observe here. Brandt & Schulz (2000) and Schulz \\& Brandt (2002) presented spectra of the neutron star binary Cir X-1 (Jonker et al. 2007). The Fe xxv absorption line was found to exhibit a P Cygni profile consistent with an outflow velocity of \( \sim 2000 \text{ km s}^{-1} \).

In this case, it is likely that both thermal and radiation pressure play a significant role in accelerating the wind to the measured velocity (Schulz & Brandt 2002). In a subsequent Chandra observation of Cir X-1, Schulz et al. (2008) unambiguously detect a number of absorption lines which they identify as highly ionized Fe xxii–xxv. The detection of these highly ionized iron lines in Cir X-1 would support the results of our xstar modeling which suggest a contribution from multiple Fe ionization levels to the measured absorption line in 1A 0535+262.

The fact that both of the X-ray binaries with the largest observed disk wind velocity (1A 0535+262, this paper; Cir X-1, Schulz \\& Brandt 2002) contain a neutron star primary suggests that the additional hard X-ray emission originating from the neutron star surface and the disk/neutron star boundary layer is crucial to accelerate a wind from the disk to the observed velocities \( (v_{\text{out}} \sim 3000 \text{ km s}^{-1}) \). Deeper future observations will no doubt shed light on precise nature of the observed absorption lines and the wind acceleration mechanism in Be/X-ray binary systems. Studies of Galactic OB associations often find that Fe is underabundant (e.g., Dalfon et al. 2001). The fact that our data and models would appear to require an overabundance of iron can be tested via future HETGS observations.

5. CONCLUSIONS

We have presented high-resolution X-ray grating spectroscopy of the Be/X-ray binary 1A 0535+262. For the first time we detect absorption consistent with the presence of a highly ionized outflow in this class of X-ray binary. When considered together with the previously detected X-ray ionized winds in a variety of other X-ray binary classes including black hole X-ray binaries (e.g., high-mass—Cyg X-1, low-mass—GRO J1655-40) and neutron star low-mass X-ray binaries (e.g., Cir X-1, GX 13+1), this would support the emerging picture of a continued large scale outflow at accretion rates but in a non-jet form.

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