

THE ORIGINS OF X-RAY LINE EMISSIONS IN CIRCINUS X-1 AT VERY LOW X-RAY FLUX

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ABSTRACT

Accretion conditions and morphologies of X-ray transients containing neutron stars are still poorly understood. Circinus X-1 is an enigmatic case where we observe X-ray flux changes covering four orders of magnitude. We observed Circinus X-1 several times at its very lowest X-ray flux using the high energy transmission grating spectrometer on board the Chandra X-ray Observatory. At a flux of 1.8×10^{-11} erg cm⁻² s⁻¹ we observed a single 1.6 keV blackbody spectrum. The observed continuum luminosity of 10^{35} erg s⁻¹ is about two orders of magnitude too low to explain the observed photoionized luminosity suggesting a much more complex structure of the X-ray source which is partially or entirely obscured as had been previously suggested. This affects most emissions from the accretion disk including previously observed accretion disk coronal line emissions. Instead, the strongest observed photoionized lines are blueshifted by about ~ 400 km s⁻¹ and we suggest that they originate in the ionized wind of a B5Ia supergiant companion supporting a previous identification. The neutron star in Cir X-1 is very young and should have a high magnetic field. At the observed luminosity the emission radius of the blackbody is small enough to be associated with the accretion hot spot as the X-ray emitting region. The small emission radius then points to a field strength below 10^{12} G which would be consistent with the observation of occasional type I X-ray bursts at high magnetic fields. We discuss Cir X-1 in the context of being a high-mass X-ray binary with some emphasis on a possible Be-star X-ray binary nature.

Subject headings: stars: individual (Cir X-1) — stars: neutron — X-rays: stars — binaries: close — accretion: accretion disks — techniques: spectroscopic

1. INTRODUCTION

Since its discovery in the early days of X-ray astronomy (Margon et al. 1971), Cir X-1 has shown a vast range of brightness levels, variability patterns, and spectral changes in its X-ray emissions. Despite significant advances in recent years these emissions remain poorly understood. Until about a decade ago it appeared fairly well established from photometric variability of the optical counterpart (Stewart et al. 1991; Glass 1994), its orbital parameters (Brandt & Podsiadlowski 1995; Tauris et al. 1999), as a well as its X-ray spectral and timing patterns (Tennant 1987; Shirey, Bradt & Levine 1999) that Cir X-1 is probably a low-mass X-ray binary containing a neutron star. The latter is now well determined through the direct observation of type I X-ray bursts (Tennant, Fabian & Shafer 1986) and their recent confirmation (Linares et al. 2010; Papitto et al. 2010). From kinematic parameters and the assumption that Cir X-1 is associated with the supernova remnant G321.9-0.3, Tauris et al. (1999) deduced a companion mass of about $2 M_{\odot}$ or less and a very extreme orbital eccentricity ($e \sim 0.9$). More recently Jonker, Nelemans & Bassa (2007) determined that the companion is more massive, most likely an A0 to B5 type supergiant and revised the orbital eccentricity to a more moderate value ($e \sim 0.45$) reviving an original identification by Whelan et al. (1977).

The picture definitely changed when Heinz et al. (2013) revealed a faint X-ray supernova remnant associated with Cir X-1. This allowed the determination of the age of the system to about 4500 years, which has two important consequences besides making Cir X-1 the youngest X-ray binary of its class

known today. It implies that the neutron star should have a magnetic field exceeding 10^{12} Gauss (Kaspi 2010), which is at odds with the occasional observation of type I X-ray bursts in this source. Such events are usually observed in old low-mass X-ray binaries with magnetic fields below 10^9 Gauss and where the accretion stream is hardly affected by such a low field. Such youth also re-affirms the determination that the companion is massive because a low mass star could not have had time to evolve to fill its Roche-lobe at periastron. In a core collapse, the progenitor star was also massive (Jonker, Nelemans & Bassa 2007), the companion star should then be a massive main sequence star which is a few tens of Myrs old. Once the binary orbit is largely circularized Cir X-1 will eventually become a high-mass X-ray binary as we know them today. The possibility that the supernova was caused by an accretion induced collapse (AIC, Bhattacharya & van den Heuvel (1991)) is unlikely as neutron stars in electron capture supernovae are not expected to receive a significant kick and is inconsistent with the dynamic orbital parameters and evolution of the system (Clarkson, Charles & Onyett 2004; Tauris et al. 2013; Heinz et al. 2013).

In X-rays, Cir X-1 exhibits two main variability patterns, one happens on short time scales related to its orbital period, another one spans over many years with X-ray fluxes changing from mCrab levels to several Crab. One orbit lasts about 16.5 days (Kaluzienski et al. 1976) and for most of its orbital tenure, X-ray emissions are fairly persistent. Due to its orbital eccentricity, the neutron star and its accretion disk actually spend most of the time detached from the companion star. Near zero

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phase (periastron) the Roche-lobe of the companion overflows and the neutron star/disk system attaches to the overflow stream and actively accretes matter. This results in a significant rise in X-rays at periastron passage, which at times can radiate up to super-Eddington fluxes (Brandt et al. 1996; Brandt & Schulz 2000; Schulz & Brandt 2002). The frequency and strengths of these periastron flares also seem to follow a long-term variability pattern that spans over 30 years (Parkinson et al. 2003).

This long-term lightcurve reflects the flux changes of 30 years measured with most of the major detectors and observatories available up to 2001. In the mid-1990s Cir X-1 was as bright as 2 Crab and exhibited relativistic radio jets (Stewart et al. 1993; Fender et al. 1998). ASCA observations showed that the accretion disk is probably viewed fairly edge-on (Brandt et al. 1996). One of the biggest revelations was delivered by the first *Chandra* observations, which showed strong P Cygni lines indicating a powerful and variable accretion disk wind (Brandt & Schulz 2000; Schulz & Brandt 2002). Heinz et al. (2007) discovered a parsec scale X-ray jet (see also Sell et al. (2010)) manifesting the picture that at times of high flux Cir X-1 behaves like a true micro-quasar (Mirabel 2001). Since then the X-ray source has dimmed steadily. In 2005 the source was already down in flux by more than an order of magnitude. While the P Cygni lines were gone, an emission line spectrum emerged rich in H- and He-like lines from high-Z elements such as Si, S, Ar, Ca, and Fe at very high neutral columns. There was a notable presence of an ionized absorber as well as some resonant absorptions indicating a rather weak disk wind. Since these observations the X-ray flux continued to drop into levels below 10 mCrab. In a rare event the X-ray source at periastron experienced a larger outburst in 2010 during which Cir X-1 exhibited type I X-ray bursts (Linares et al. 2010; Papitto et al. 2010). This period was extensively covered with *RXTE* and one *Chandra* observation providing much temporal and spectral information but no definite conclusions with respect to the origins of the X-ray continuum (D’Ai et al. 2012). However it confirmed that Cir X-1 is a neutron star X-ray binary.

In this paper we analyze a series of observations between 2008 and 2017 which were taken at the absolute lowest flux levels in decades with the goal to characterize the nature of the X-ray source at these levels as well as to find interfaces to the new evolving picture that Cir X-1 is a very young massive main sequence X-ray binary.

2. CHANDRA OBSERVATIONS

Cir X-1 was observed with the high energy transmission grating spectrometer (HETGS, see Canizares et al. (2005) for a detailed description) once in 2008 and a few times in 2017. Table 1 summarizes all its parameters. The 2008 observation we denominate as ‘V’, the 2017 observations as ‘VIIa-c’. We add one more observation done in 2010 (PI: D’Ai) and label this one as ‘VI’. This is in line with the denominations defined in Schulz et al. (2008) in sequence to the previous *Chandra* HETGS observations. Observations I and II are described in Brandt & Schulz (2000) and Schulz & Brandt (2002). observations III and IV in Schulz et al. (2008). Observations V and VIIa-c were all performed during periastron passage, observation VI was done at apastron passage.

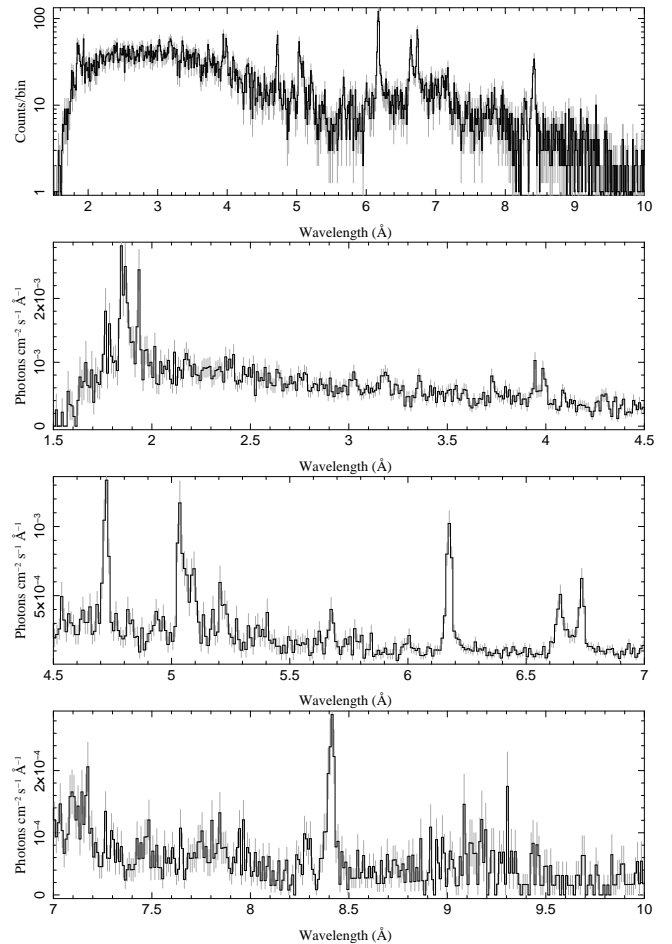


FIG. 1.— The raw-count HETG 1st order spectrum of the co-added observations (top panel). A more spread out unfolded spectrum of the HETG 1st order (bottom three panels). V and VIIa-c.

All observations were reprocessed using CIAO 4.9 using CIAO CALDBv4.7.7 products. Updates to CIAO and its products since then did not impact the analysis performed at the time of submission. The wavelength scale was determined by measuring the zero-order position to a positional accuracy of about half a detector pixel ensuring a wavelength scale accuracy of about a quarter resolution element, i.e. 0.005 \AA for MEG and 0.003 \AA for HEG spectra. For our previous observations we could not use a direct zero-order source detection because the point spread function of the source was too piled up. In that case we measured the zero position by determining the intersection between the readout streak and the grating dispersion arms. In this analysis we applied both methods and their results agreed well within the accuracy stated above. Note, in observation III (Schulz et al. 2008; Iaria et al. 2008) we did not even have a source readout streak which introduced a systematic uncertainty that resulted in slight redshifts in the detected lines. It is thus paramount that we maintain a high confidence in the location of the zero order position. For transmission gratings the dispersion scale is linear in wavelength, therefore we perform all analysis in wavelength space. This ensures the most accurate scales through multiple binnings. We used standard wavelength redistribution matrix files (RMF) but generated ancillary response files (ARFs) using the provided aspect solutions, bad pixel maps, and CCD window filters.⁷ For all the observations we generated spectra and analysis products for

⁷ see <http://asc.harvard.edu/ciao/threads/>

TABLE 1 CHANDRA X-RAY OBSERVATIONS

<i>Chandra</i> ObsID	Obs. ID	Start Date (UT)	Start Time (UT)	Exposure (ks)	Phase ...	HETG 1st rate (cts s ⁻¹)
8993	V	July 16 2008	07:57:55	32.7	periastron	0.12
12235	VI	July 04 2010	05:04:05	19.4	apastron	1.13
18990	VIIa	June 06 2017	12:35:21	13.2	periastron	0.14
20093	VIIb	June 06 2017	22:00:54	9.8	periastron	0.15
20094	VIIc	July 07 2017	06:50:07	35.3	periastron	0.22

the medium energy gratings (MEG) +1 and -1 orders, as well as for the high energy gratings (HEG) +1 and -1 orders. Figure 1 shows co-added 1st order HETG spectra for all periastron observations (V and VIIa-c) binned by a factor 4, which represents about one MEG resolution element per spectral bin. The lightcurves of the periastron observations are all very similar and flat without any structure and we therefore do not present any plots. Observation V is very faint with 0.12 c/s, VIIa,b are similar, observation VIIc is slightly brighter (see Table 1). The apastron observation (VI) was taken during a specifically strong outburst and is an order of magnitude brighter than all the other observations. This observation is shown in Figure 2.

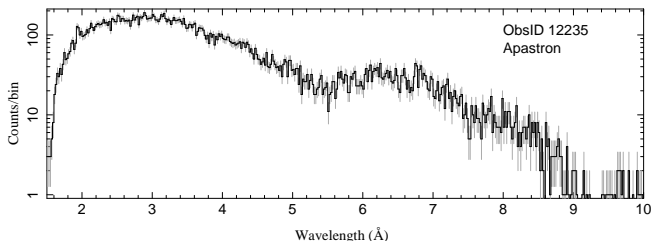


FIG. 2.— The X-ray spectrum at apastron during an intermediate outburst in 2010.

3. SPECTRAL ANALYSIS

For the spectral analysis we focus exclusively on the four periastron observations. Each individual observation does not have enough statistics to perform detailed line analysis and in general we co-add all of them in the plotting and fit simultaneously in the analysis. Due to the fact that these observations were over an order of magnitude fainter than the ones in Schulz et al. (2008) we used a *Cash* statistic (Cash 1979) for the fits. This only reflects a more accurate treatment of low statistics data while still allowing for a consistent comparison with previous much brighter observations.

Figure 1 shows faint and bright lines in the spectrum. For the determination of the continuum we remove these wavelength regions from the spectral model fit. The observed lines all appear at known line wavelengths for Mg, Si, S, Ar, Ca and Fe and they also appear quite narrow. We removed 0.05 Å regions around the detected line centroids for the line centroids (see Sect. 3.2) detected for these elements. All spectra then have 1011 data bins in the unbinned case. We do not bin the spectra during the fits as this introduces statistical biases. However, we do match the grids of the HEG to the MEG spectra to plot the combined spectrum.

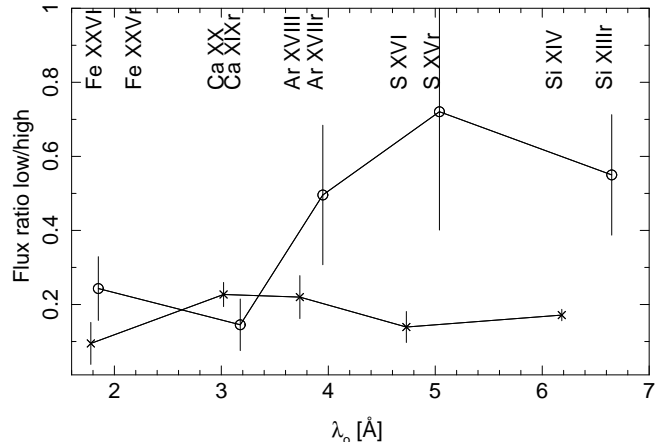


FIG. 3.— Line ratios of the H- and He-like resonance lines from the high flux observations in Schulz et al. (2008) and the low flux observations reported in this paper.

3.1. X-ray Line Analysis

The co-added spectrum in Fig 1 shows very strong H- and He-like lines for Mg, Si, and S with line counts between 150 and 320 cts/line. This is large enough to allow the determination of critical line parameters such as line shifts, widths, and flux. For this analysis we use Gaussian line functions. The H-like lines and the Fe K line are single Gaussians. We do not account for the spin-orbit split in the H-like lines which produces a separation of the α_1 and the α_2 line by 0.0056 Å and use the average line location as was done in Schulz & Brandt (2002) and Schulz et al. (2008). This allows us to better compare the line measurements. As a consequence we may slightly overestimate the line width in H-like lines. The He-like lines are triplets containing a resonance (r), an intercombination (i), and a forbidden (f) line with fixed line spacings. Here we froze the line spacings of the i and f lines relative to the r lines. We then divided the bandpass into five regions containing the Mg, Si, S, Ca + Ar, and Fe lines, respectively.

3.1.1. Line Fluxes

The results of the line fits to the periastron data in Table 1 are shown in Table 3. The first columns list the K-shell ion, the second column the theoretical line location as in Schulz et al. (2008), the third column is the measured wavelengths, the fourth column gives line fluxes in units of 10^{-5} photons $s^{-1} cm^{-2}$, the fifth column lists the sigma of line widths in $km s^{-1} (3 \times 10^5 (\sigma_{meas} / \lambda_{meas}))$. There are distinct differences in the line fluxes with respect to previous observations when the source was brighter. Figure 3 shows that the bulk of the

TABLE 3: X-RAY LINE PROPERTIES FROM THE PERIASTRON OBSERVATIONS IN TABLE 1

ion	$\lambda_o^{(1)}$ Å	λ_{maes} Å	Line Flux $10^{-5} \text{ ph s}^{-1} \text{ cm}^{-2}$	σ km s^{-1}
Fe XXVI	1.780	1.782±0.010	0.92±0.99	<3300
Fe XXVr	1.850	1.845±0.008	3.84±2.23	1000±820
Fe XXVi	1.859	1.858±0.008	0.10±8.38	1000±820
Fe XXVf	1.868	1.870±0.005	3.25±3.60	1000±820
Fe K	1.940	1.933±0.001	2.49±0.85	390±430
Ca XX L α	3.021	3.021±0.008	0.59±0.44	770±640
Ca XIXr	3.177	3.171±0.007	0.30±0.36	750±510
Ca XIXi	3.189	3.183±0.007	0.74±0.55	750±510
Ca XIXf	3.211	3.205±0.007	< 0.1	750±510
Ar XVIII L α	3.734	3.736±0.003	0.88±0.35	500±460
Ar XVIIr	3.949	3.946±0.004	1.19±0.39	600±310
Ar XVIIi	3.966	3.963±0.004	0.14±0.50	600±310
Ar XVIIf	3.994	3.991±0.004	1.32±0.49	600±310
S XVI L α	4.730	4.722±0.002	2.95±0.55	450±140
S XVr	5.039	5.036±0.003	2.45±0.54	470±130
S XVi	5.067	5.064±0.006	0.97±0.44	470±130
S XVf	5.102	5.093±0.003	1.32±0.43	470±130
Si XIV L α	6.183	6.175±0.001	2.64±0.28	420±70
Si XIIIr	6.650	6.640±0.003	1.32±0.24	500±80
Si XIIIi	6.669	6.678±0.003	0.63±0.34	500±80
Si XIIIf	6.740	6.734±0.002	1.40±0.24	500±80
Mg XII L α	8.422	8.409±0.004	0.94±0.18	530±140
Mg XI(r)	9.169	9.179±0.015	0.25±0.14	< 480
Mg XI(i)	9.230	9.228±0.012	< 0.1	< 480
Mg XI(f)	9.314	9.315±0.013	0.22±0.15	< 480

(1) see Schulz et al. (2008)

H-like line fluxes was of the order of 20% of the ones reported in Schulz et al. (2008), while the He-like lines are up to 70% of the previously reported fluxes. Calcium lines are the exception as they were generally weak in observations III and IV (Schulz et al. 2008). The lines in the Fe K line region follow this picture, the H-like Fe XXVI is very weak and the region is dominated by the Fe XXV triplet. However, the Fe K line (Fe I - X) is very similar in flux and width to the one we observed in observation III. The line widths cluster around 550 km s^{-1} , which is very similar to previous detections. The line widths at shorter wavelengths appear higher which is likely a consequence of the increasingly lower spectral resolution at shorter wavelengths. The size of an HETG resolution element of a dispersed grating order is constant in wavelength space and thus resolution element sizes increase in velocity towards higher energies.

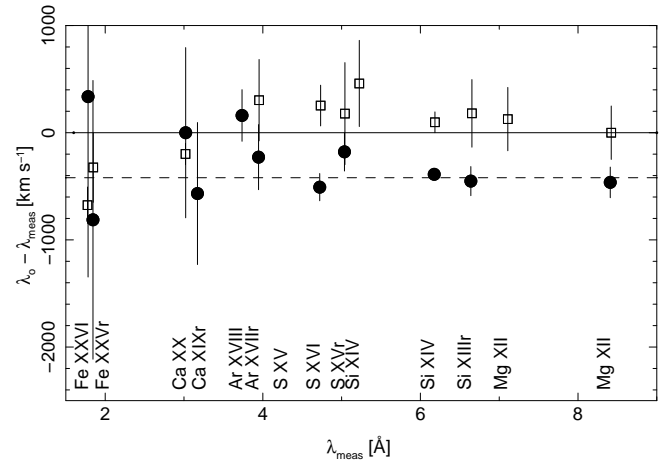


FIG. 4.— Measured line centroids with respect to theoretical values in velocity units. Negative values are blueshifts. The straight line are zero velocities from the theoretical line values. The dashed line marks the average blueshift of -410 km s^{-1} seen in the periastron observations V, VIa-c. The squares are the data from Schulz et al. (2008) for observation IV for reference.

3.1.2. Line Centroids

Figure 4 shows the line centroids with the expected rest positions in units of km s^{-1} . The filled black circles show the periastron observations from Table 1. The majority of the brightest lines concerning Mg, Si and S clearly show a line shift to the

blue of about 400 km s^{-1} . Higher Z element lines (Ar, Ca, and Fe) are fainter and uncertainties are larger.

For comparison we plot the results from observation IV from Schulz et al. (2008) for reference (squares). For this observation we had to refit the He-like triplets (Fe, Ca, Ar, S, and Si) because in that previous analysis the widths and line spacings were free parameters and not tied according to their triplet properties. In some cases, specifically for the Si, Ar, and Ca triplets, this produced line centroids that are much more consistent with the rest of the sample. The line centroids from observation IV are consistent with the expected rest wavelengths.

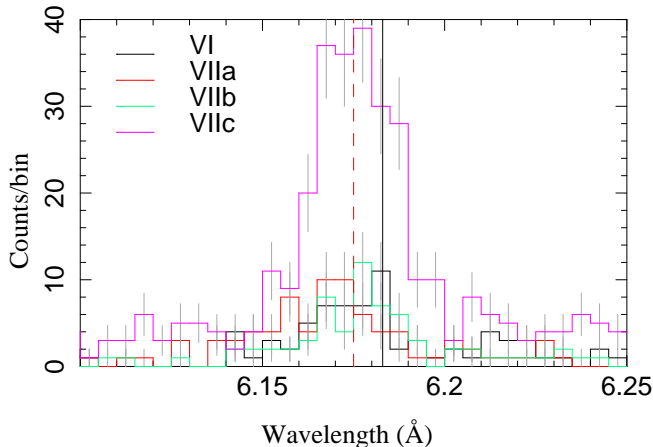


FIG. 5.— The Si XIV L_{α} line for all four observations plotted separately. The hatched line marks the centroid location of the co-added line fits. The solid line marks the rest wavelength location. It shows that all observations agree with a line centroid location blue-shifted by about 400 km s^{-1} .

The Si XIV L_{α} at the expected wavelengths is by far the most significant one in terms of total counts (> 300 cts) and here we can look at the individual observations. The brightest contribution comes from observation VIIc (~ 170 cts), the faintest from observation V (~ 35 cts), enough to allow centroid studies. Figure 5 shows the line counts of the unbinned data. The black line marks the expected rest wavelength at 6.183 \AA , the hatched line the fitted location of the co-added line data. It clearly shows that the blue-shift is present in all observation segments and appears persistent over many years. The lines of observations V and VIIa,b are symmetric around the fitted centroid (hatched line).

3.1.3. G and R Ratios

Line flux ratios are a powerful tool to diagnose detailed properties of an ionized gas (Bautista & Kallman 2000; Porquet & Dubau 2000). A gas at temperatures of $< 1 \text{ MK}$ that is photoionized is expected to emit lines primarily by recombination cascades and will have a G-line flux ratios of $G = (f+i)/r > 4$ or close to that value for atomic numbers Z of 12 and higher. From the fluxes in Table 3 we find G values of 1.53 ± 0.30 , 0.93 ± 0.60 , 1.22 ± 0.49 , 2.46 ± 1.11 , 0.87 ± 1.07 for Si, S, Ar, Ca, and Fe, respectively. These values appear well below the expectation for a pure photoionized plasma indicating some form of hybrid plasma. We rule out EUV photoexcitation as this would depopulate the α resonance line and produce higher order transitions which do not appear in Table 3. There are two processes that can lead to enhanced resonance line emissions, one is collisionally ionization in very hot plasmas, the other one is resonance scattering. We can rule out contributions from a collisionally ionized plasma as here the

excitation of K-shell ions with atomic number larger than 14 would also require temperatures in excess of 10 MK and the presence of a significant bremsstrahlung continuum which we do not observe. What we observe is likely photoionized plasma affected by resonance scattering. In that case the presence of a high optical depth medium can scatter resonance line fluxes unisotropically into preferential directions depending on geometry. Modeling of this effect requires extensive knowledge of the geometry and local plasma properties.

Gas densities can be diagnosed with the $R = f/i$ ratio for which we expect that at $R > 1$ densities are below a critical density for a specific atomic number Z . Our sample features He-like triplets for Si, S, Ar, Ca, and Fe and features critical densities of $\sim 10^{14}$, $\sim 10^{14}$, $\sim 10^{15}$, $\sim 10^{16}$, and $\sim 10^{17} \text{ cm}^{-3}$. In all cases we find R values much larger than 1 except for Ca, where we only detect an upper limit for the f line. This points to plasma densities lower than $\sim 5 \times 10^{14} \text{ cm}^{-3}$ assuming an isotropically mixed gas. The R ratio is also very susceptible to UV radiation where the metastable forbidden line levels get depopulated into intercombination line levels. Since the f-lines in Table 3 generally appear stronger than the corresponding i-lines shows that effects from UV radiation appear not to be significant.

The lines in the Fe K line region follow this picture, the H-like Fe XXVI is very weak and the region is dominated by the Fe XXV triplet. However, the Fe K line (Fe I - X) is very similar in flux and width to the one we observed in observation III.

3.2. Photoionization Modeling

Figure 1 features strong He-like lines with especially strong r-lines. The ionization parameter is defined as

$$\xi = L_x / (nd^2), \quad (1)$$

where L_x is the source luminosity, n the plasma density, and d the distance from the X-ray source. A multiple plasma environment requires a range of ionization parameters to engage in a fit. This complicates the modelling process in terms of fitting time and parameter range. In that light we try to limit the number of fit components to a very minimum. For the choice of continuum we modeled a few cases including combinations of powerlaws as reported by Schulz et al. (2008) and Iaria et al. (2008) as well as blackbody spectra. For the fit itself we use XSTAR's *phoemis* function available in Xspec, which allows for a pre-set atomic levels population file to calculate a photoionized spectrum for a single ionization parameter. For the final fit setup we used two different functions to account for two ionization parameters. Furthermore in order to be able to fit H- and He-like line morphology, the functions also needed individual absorption columns, for which we applied *pcfabs* functions. For the fits we fixed the interstellar column to $1.8 \times 10^{22} \text{ cm}^{-2}$ as reported by Heinz et al. (2013). The fits generally converged to a one component solution for the continuum, i.e. either a powerlaw or a blackbody spectrum. The powerlaw solution was ruled out because it completely overshoot the observed continuum above 2 \AA for the Fe K line region, whereas the 1.6 keV blackbody provided the necessary steep decline above 2 \AA (see Fig. 6). The fit result is summarized in Table 4. The uncertainties are 90% confidence limits calculated by *conf_loop* in ISIS. In the fit we also set the turbulent velocities to 600 km s^{-1} and in the final stages we fixed some of the abundances we let float. The redshifts were also fixed to -400 km s^{-1} (see dashed line in Figure 4) in the one of the *phoemis* components, let afloat in

TABLE 4 THE PHOTOIONIZATION FIT RESULTS

Parameter	Symbol	Units	
Absorption column density	N_H	10^{22} cm^{-2}	1.8
Blackbody temperature	kT	keV	1.57 ± 0.04
Blackbody normalization	$(R_{km}/D_{10kpc})^2$...	0.392 ± 0.026
Pcf absorption column 1	N_H^1	10^{22} cm^{-2}	2.4 ± 0.4
Photoionization normalization 1	K_1	$\text{erg cm}^{-1} \text{ s}^{-1}$	121.5 ± 12.7
Ionization parameter 1	ξ_1	erg cm s^{-1}	340 ± 135
Redshift 1	z_1	...	-0.0013334
Pcf absorption column 2	N_H^2	10^{22} cm^{-2}	2.8 ± 1.1
Photoionization normalization 2	K_2	$\text{erg cm}^{-1} \text{ s}^{-1}$	100 ± 65
Ionization parameter 2	ξ_2	erg cm s^{-1}	1500 ± 180
Redshift 2	z_2	...	-0.00062
Fit statistic	Cash/dof	...	1.42

the second. The fact that we need at least two ionization parameters is due to the fact that we observe Mg and Si lines as well as Ca and Fe lines, which cannot be modeled with a single ionization parameter (Kallman et al. 2004). The Mg abundance was slightly reduced to 0.93, which likely is a consequence of the statistically challenging Mg xi bandpass. The Si abundance was set to 1.73, the S abundance to 1.68 for both *photemis* components.

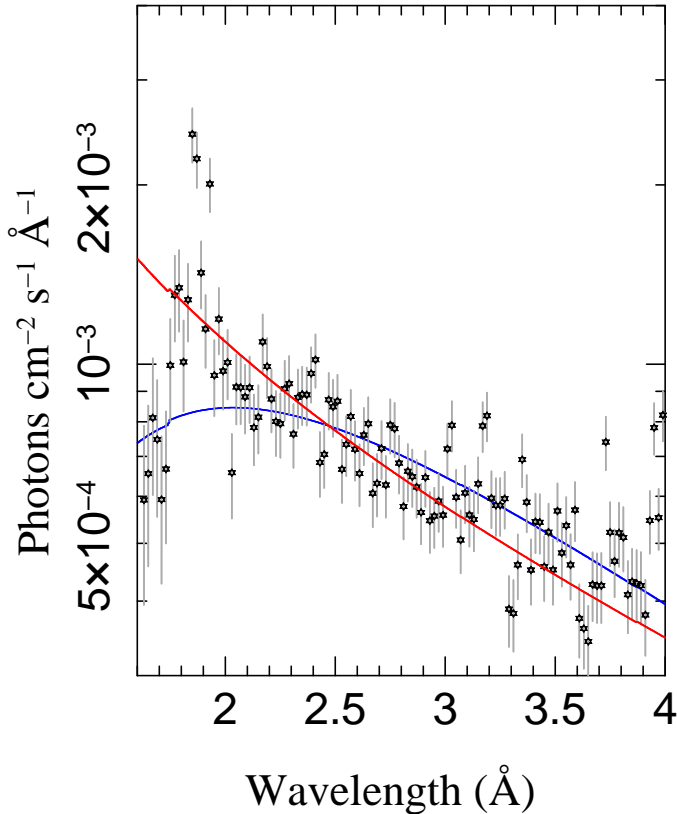


FIG. 6.— Comparison of the powerlaw fit (red) to the blackbody fit (blue) in the Fe K line region (the data are (black)).

The final ionization parameters obtained were $\xi = 340$ and $1500 \text{ erg cm s}^{-1}$ and both associated with high column densities. The covering fractions were free parameters but resulted in 0.99 in both cases. The plasma with ionization parameter

$340 \text{ erg cm s}^{-1}$ is responsible for bulk of the line fluxes, while the one with ionization parameter $1500 \text{ erg cm s}^{-1}$ contributes to some of the H-like line fluxes but mostly to the Fe region.

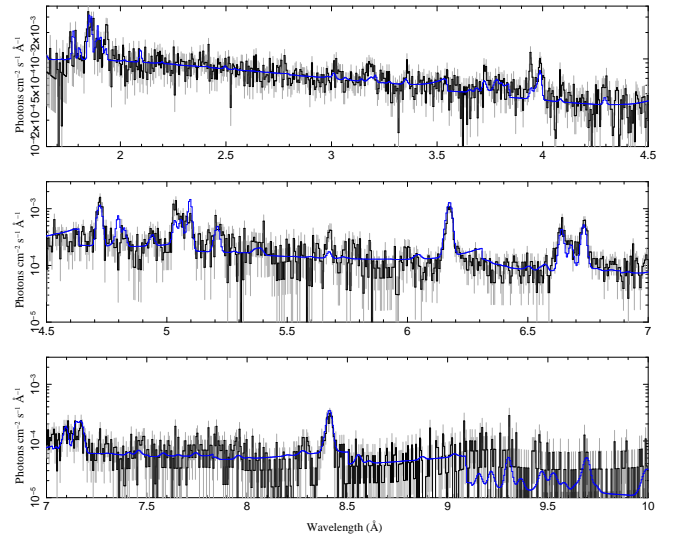


FIG. 7.— Photo-ionization model fit using *XSTAR:photemis* function.

The normalization of the photoionization model is defined by

$$K = \frac{EM}{4\pi D^2} \times 10^{-10}, \quad (2)$$

where EM is the emission measure of the gas in units of cm^{-3} at the involved ionization parameter, D is the distance to Cir X-1 in units of cm. For a distance of 9.4 kpc (Heinz et al. 2015) this leads to

$$EM = K \times 1.06 \times 10^{56}. \quad (3)$$

For the plasma with $\log \xi_1 = 340 \text{ erg cm s}^{-1}$ we obtain $EM_1 = 1.3 \times 10^{58} \text{ cm}^{-3}$, for $\log \xi_2 = 1500 \text{ erg cm s}^{-1}$ we obtain $EM_2 = 1.1 \times 10^{57} \text{ cm}^{-3}$. These emission measures are only slightly smaller than the one estimated by Schulz et al. (2008), the observed source luminosity, however, appears to be significantly lower.

This observed low X-ray luminosity from the continuum is inconsistent with the observed photo-ionized luminosity from

the X-ray line analysis. One of the difficulties is to maintain the observed ionization parameters at such a low luminosity over such a large volume. While to some extent one could offset a larger source distance d with a lower density in the wind n , this eventually breaks down due to the fact that the observed photo-ionized luminosity appears close to the actual source luminosity. Such a high ionization efficiency is nearly impossible to achieve under likely any circumstances. This points into the direction that parts of the X-ray source is still obscured, something we encountered during the analysis of observations I and II (Schulz et al. 2008). To simply assume that some the flux of our observed continuum is partially blocked and should be higher is possible but not a good solution as a 1.6 keV blackbody is inherently inefficient to ionize high Z atoms such as Fe and Ca at any possible luminosity. A more promising scenario relates back to our actual findings in Schulz et al. (2008). There we found that the observed photoionized lines are due to an accretion disk corona (ADC) and in order to sustain such a corona the source X-ray luminosity needed to be significantly higher than observed which lead to the conclusion that parts of the central X-ray source are obscured. This may still be the case. Figure 8 shows a recalculation of the content of Figure 5 in Schulz et al. (2008), including lower luminosity predictions and the locations of our photo-ionized data points in this picture. This indicates that for our results that the source still is at a luminosity close to 10^{37} erg s $^{-1}$, which allows to sustain a atatic ADC. This then leaves the possibility that we do observe some highly absorbed and obscured parts of the ADC in the high Z lines and the photo-ionized wind of the companion seen in the blue-shifted lower- Z lines.

The ionization parameter and emission measures then leave us with a wide range of viable plasma regimes. Two regimes that are opposite in character are of interest in the case of Cir X-1. One refers to the ADC emissions as described in Schulz et al. (2008) which are confined to the domain of the accretion disk. In that case we can assume that d , the distance to the X-ray source, is of the same order of magnitude as r , the size scale of the photo-emitting region. For distances of up to 10^{10} to 10^{11} cm from the neutron star surface we obtain ADC plasma densities between about 10^{12} and 10^{14} g/cm 3 in a compact volume within the accretion disk (see also Jimenez-Garate, Raymond & Liedahl (2002)).

The observed blueshifts point to another regime. For very low densities as they exist in weak stellar winds, i.e. densities $\ll 10^{11}$ g/cm 3 we also get viable solutions for values of d and r that are beyond the dimensions of the accretion disk. Weak low density winds are expected in mid-B type stars. For such low plasma densities the dimensional parameters are larger than 10^{12} cm consistent with ionized line emissions in a weak stellar wind.

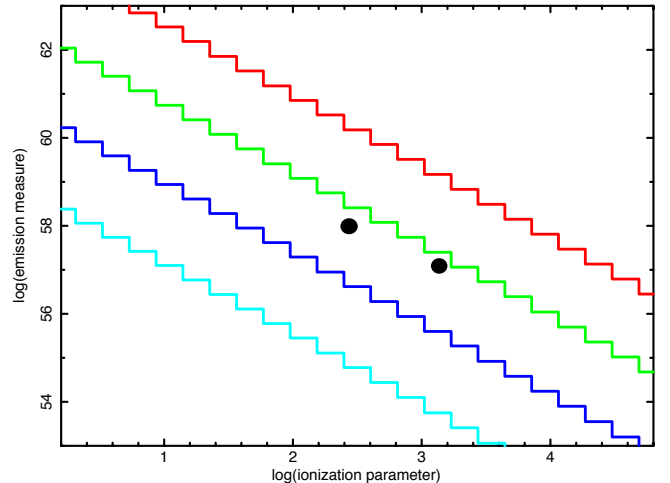


FIG. 8.— Calculation of emission measure in dependence of ionization parameter for a static corona as was done in (Schulz et al. 2008). The color lines are for various luminosities, $\log L_x = 38$ (red), 37 (green), 36 (blue), and 35 (light blue) in units of erg s $^{-1}$. The two black circles are the results from the photo-ionization modeling.

The *XSTAR:photemis* function applies a model describing a purely photo-ionized plasma. The fact that this model cannot properly account for the strength of the resonance lines in some of the He-like triplets confirms our findings from the G-ratios that there is a significant contribution from some recombination and resonance scattering. Future modeling of these effects should reveal the presence of such a scattering medium,

4. DISCUSSION

The X-ray source in the Cir X-1 binary has given us many different looks in the past in terms of variability, flux, and spectral properties. Since the first *Chandra* HETG observation in the year 2000, where the source flux still exceeded 1.5 Crab, the X-ray source has dimmed by more than three orders of magnitude until it went below one mCrab in 2009 (see Figure 3 in Heinz et al. (2013)). Its spectral continuum shape similarly has morphed from two partially covered blackbodies during its high state (Brandt et al. 1996; Schulz & Brandt 2002), to two or one partially covered powerlaws (Schulz et al. 2008; Iaria et al. 2008), and now to a single blackbody with just interstellar absorption. Besides exhibiting various levels of line emission and absorption there always was the presence of enormous levels of either partially covered cold or warm intrinsic continuum absorption. High levels of source intrinsic absorption are also present in the observations we report in this paper, except in these new observations these absorbers have only little effect on the continuum and mostly affect the photoionized regions. This is an aspect we have not seen before and it appears to be fundamentally different from the previous observations.

4.1. The Origin of the X-ray Continuum in this Very Low State

The final continuum spectrum in the photo-ionization fit turned out to be a 1.6 keV blackbody. We had fixed the interstellar column to 1.8×10^{22} cm $^{-2}$ which was found by Heinz et al. (2013) in the fit to the supernova remnant, consistent with the large amount of visible extinction towards Cir X-1 as well as a well established distance of 9.4 kpc (Heinz et al. 2015). Such a distance is also consistent with Cir X-1 radiating at Eddington peak fluxes when it was brightest (Jonker & Nelemans 2004) and when it exhibited P Cygni X-ray lines from a radia-

tion driven wind (Brandt & Schulz 2000). The property of the blackbody fit is rather peculiar as it exhibits a very small emission radius. It is also notable that there is no or only very little contribution of the accretion disk to the observed X-ray spectrum. The only clear signature from the disk may come from the Fe K fluorescence line observed at 1.93 Å.

The big problem arises when we realize that our observed continuum is quite insufficient to photo-ionize the plasma at the level observed. This gives reasons to assume that emissions from the accretion disk are there but are highly absorbed and obscured. This provides quite some uncertainty to the observed luminosity and nature of the X-ray spectral continuum as we have to consider that the bulk of the emission partly blocked and obscured.

Accreting neutron stars with magnetic fields significantly lower than 10^{10} Gauss are generally seen in LMXB, which are considered to be older systems in which the original field had enough time to decay to such low values. With only a very few exceptions where we do not know the field through cyclotron lines accreting neutron stars with high mass companions have all high magnetic fields as they are considered very young. However, we point out that the question of the companion nature is fairly irrelevant here. Homan et al. (2010) showed that transient sources can morph through atoll and Z-stages at various flux phases making these spectral variability imprints more related to effective Roche-lobe overflow accretion rather than binary types. In the following we discuss how the observed continuum rates to cases of low and high magnetic fields for the accreting neutron star.

4.1.1. The Low Field Case

One of the reasons why Cir X-1 used to be considered a LMXB was its spectral variation pattern during its brightest flux phases showing the nature of a Z-source. We then may compare it to a rare class of LMXB pulsars such as the transient Terzan 5 (IGR J17480-2446) or the persistent ultracompact binary pulsar 4U1626-67. At an estimated magnetic field between 10^9 and 10^{10} G Terzan 5 is much older and its accretion stream is likely only weakly affected by the magnetic field. As a consequence its spectral signatures are expected to be more comparable to neutron star atmospheres or normal LMXB emissions depending on whether the transient is in a subcritical or critical state (see Degenaar et al. (2013) and references therein). 4U 1626-67 with a magnetic field of 4×10^{12} G (Orlandini et al. 1998) is much younger but since its luminosity is persistently close to critical its continuum emission relates more to what we observed in Cir X-1 during its intermediate flux phases (Schulz et al. 2008).

A significantly higher blackbody luminosity also significantly increases the emission radius to sizes that are more reminiscent of neutron stars with low magnetic fields in which the accretion flow is hardly affected by the magnetic field and we can identify random hot patches or boundary layers on the neutron star surface as emission regions. Such blackbody continua are not particularly unusual in LMXB, prime examples are 4U1626-67 (Schulz et al. 2001), 4U1822-37 (Ji et al. 2011), Her X-1 (Ji et al. 2009) or Aqu X-1 (Sakurai et al. 2014). However, in all of these cases that blackbody component exhibits temperatures of about 0.5 keV. High temperatures like observed here are more prominent in the peaks of type I X-ray bursts and in fact the here observed continuum temperature is close to what (Linares et al. 2010) report for the top temperatures ob-

served in the 2010 X-ray bursts from Cir X-1. That is very unusual for LMXBs. The fact that this continuum is heavily absorbed and some of this absorption is unaccounted for changes little, as it is the part < 2 Å that defines the blackbody in the fit and its temperature. We note that neither Schulz et al. (2008) nor Iaria et al. (2008) observed a blackbody when the source was an order of magnitude brighter but report a more suitable powerlaw for the observed photoionizations as the continuum. The shape of a 1.6 keV blackbody is not particularly suited for K-shell ionizations of high Z atoms as its shape drops dramatically above 7 keV and lacks the harder photons. Should the neutron star have a low field as is common in LMXBs then the observed continuum properties are quite unusual and hard to explain, it would also make Cir X-1 the youngest neutron star with a low magnetic field known to date.

4.1.2. The High Field Case

However, what is very common is the fact that young neutron stars, accreting or isolated, have high ($\gg 10^{10}$ G) magnetic fields (Reig 2011; Özel & Freire 2016). In this case we consider the possibility that this observed blackbody continuum does not contribute much to the photo-ionization process at all and the photo-ionizing continuum is entirely obscured. In a high field accretion scenario matter is predominantly funneled by the field onto poles of the neutron star and the state of the accretion column depends on X-ray luminosity (see Becker & Wolff (2007) for an indepth review). At a critical luminosity of $L_{crit} = 1.5 \times 10^{37}$ erg s $^{-1}$ the accretion flow becomes radiation pressure dominated and X-ray emissions are defined by a complex mix of physical processes resulting in something close to a power law with an exponential cut-off or similar as observed when the source was brighter (Schulz et al. 2008). However, in the sub-critical case where the luminosity is $\ll 10^{37}$ erg s $^{-1}$ as is observed in the low state of Cir X-1, the emissions from the bare hot spot can be explained by such a hard blackbody.

In such a sub-critical environment we can expect that the X-rays are produced by impact onto or very close to the neutron star surface. If this is the accretion hot spot, its radius r_0 should fulfil the condition (Lamb, Pethick & Pines 1973)

$$r_0 < r_{ns} \left[\frac{r_{ns}}{r_A} \right]^{1/2}, \quad (4)$$

where r_A is the Alfvén radius given by Becker & Wolff (2007) as

$$r_A = 2.6 \times 10^8 B^{4/7} r_{ns}^{10/7} M_{ns}^{1/7} L_x^{-2/7}, \quad (5)$$

where B is the magnetic field in units of 10^{12} G, r_{ns} the neutron star radius in units of 10 km, M_{ns} the neutron star mass in units of M_\odot , and the X-ray luminosity L_x in units of 10^{37} erg s $^{-1}$. Figure 9 shows the evaluation of Equ. 4 and 5 for two different neutron star radii, 10 km (black) representing the lower end of most equations of state, and 15 km (red) representing the higher end of most equations of state (Özel & Freire 2016). Equation 5 has only a weak dependence on neutron star mass and here we used a canonical value of $1.4 M_\odot$. For L_x we applied the measured X-ray luminosity in Table 2. For a distance of 9.4 kpc (Heinz et al. 2015) we can determine limits to the blackbody emission radius depending on the blackbody fits provided in Table 2. This then amounts to a $r_{bb}=r_{min}=0.512$ km and a $r_{bb}=r_{max}=0.597$ km. At a distance of 9.4 kpc the observed emission radius in Table 4 is 0.589 ± 0.151 km consistent with these values. A relativistic color correction would do little to

the range of these values. From that we find a lower limit to the magnetic field strength of 4.0×10^{10} G for a 15 km radius and 2.8×10^{11} G for a 10 km radius. Note that these are only lower limits and the actual field can still be higher than these values.

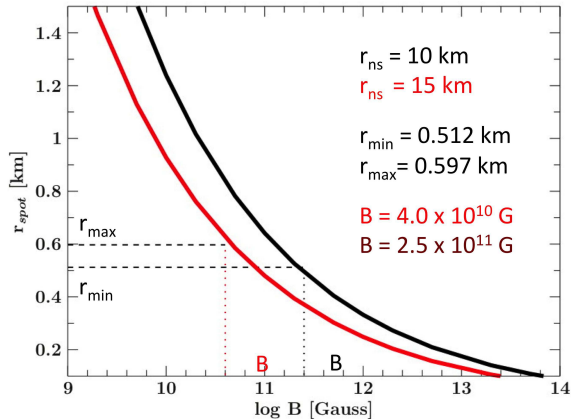


FIG. 9.— Evaluations of Equ. 4 and 5 for a neutron star radius of 10 km (black) and 15 km (red). The limits r_{min} and r_{max} are derived from the blackbody fit results in Table 2 for a distance of 9.4 kpc.

A survey of about 20 confirmed cyclotron line energies in HMXBs (Caballero & Wilms 2012) shows that all but one magnetic surface field strengths are above 10^{12} G, except for Swift J1626.6-5156 (DeCesar et al. 2009) which has a field slightly below 10^{12} G. The result in Figure 9 of course depends on distance, while a cyclotron line measurement does not (Coburn et al. 2006). However, we deem a distance of 9.4 kpc quite robust. In order to have both the 10 km and 15 km solutions above 10^{12} G, the distance has to be below 6 kpc, which is implausible because of the amount of extinction along the line of sight and it would take the X-ray luminosity in observations I and II (Brandt & Schulz 2000; Schulz & Brandt 2002) too far away from Eddington conditions to produce such a powerful disk wind. Higher distances do not change the result much unless they become unrealistically high. In order for the field values to drop below 10^{10} G, the blackbody radius has to be higher than 1 km and the source would reside outside the Milky Way. We therefore are confident that the surface magnetic field in Cir X-1 is somewhere between the values shown in Fig. 9.

The moderately high $\gg 10^{10}$ G magnetic field should still be consistent with a young system even though it is generally assumed that neutron stars are born with $> 10^{12}$ G (see Kaspi (2010) and references therein). The neutron star in Kes 79 (Halpern & Gotthelf 2010) with a magnetic field of only 3.1×10^{10} G is a good example for a younger neutron star with a moderate magnetic field (see also Shabaltas & Lai (2012)). Other examples are PSR J1852+0040 and 1E1207.4-5209 Halpern et al. (2007); Gotthelf & Halpern (2007) as well as PSR J0821-4300 in Puppis A (Gotthelf & Halpern 2009), even though these may not be quite as young as Cir X-1. Thus young neutron stars with lower magnetic fields of the order of 10^{11} G, also sometimes dubbed ‘anti-magnetars’, are not unusual anymore.

The observation of type I X-ray thermonuclear bursts (Tennant, Fabian & Shafer 1986; Linares et al. 2010) also implies a field of $\ll 10^{12}$ G (Fujimoto, Hanawa & Miyaji 1981). However, this criteria is more based on the lack of ob-

servations of type I bursts in X-ray pulsars rather than having a solid theoretical basis other than the suppression of convective motions to allow runaway burning in magnetic fields of about 10^{12} G and higher (Gough & Tayler 1966; Bildsten 1995). Bildsten (1998) outlined the conditions for neutron star nuclear burning for the case of high mass accretion rates ($\dot{M} > 10^{10} M_{\odot} \text{ yr}^{-1}$). At these rates unstable nuclear burning is more easily realized. The luminosity of Cir X-1 during its outburst in 2010 was still below the stable burning criterion and here the magnetic field may have been high enough to confine the accreted matter to the ignition pressure, but still low enough to allow convective motions. We therefore argue that in the case that the neutron star magnetic field in Cir X-1 is only moderately high, the two facts that the neutron is very young and that we observe type I X-ray thermonuclear bursts are consistent with what we know today.

4.2. The Nature of the Blueshifts

The most prominent difference in the observed line properties besides the fact that the He-like resonance lines appear enhanced are the blueshifts of about 400 km s^{-1} in most of the observed lines. In Schulz et al. (2008) the lines were at rest and identified as ADC emissions from the accretion disk. In this low state blueshifted line emissions now need a two orders of magnitude higher ionizing luminosity to sustain such an ADC in the accretion disk. The flux of the lines and the amount of blue-shift in the lines appear small, and may not have significantly affected the line profiles in observations III and IV specifically because the shifts are of the order of a grating spectral resolution element. However we note that Iaria et al. (2008) claim a faint blue component in their line profile analysis in observation III. This could mean that this blue-shifted emission is always present but gets overpowered by ADC emissions when the source gets brighter.

There is no viable explanation for blue-shifted lines within the accretion disk suggesting emission regions outside the disk. While Iaria et al. (2008) proposed possible jet emissions, the determined ionization parameters as well as emission measures and the amount of the blueshift are also consistent with X-ray illumination of a massive companion wind. A wind velocity of 400 km s^{-1} would point in direction of a B5Ia supergiant (Prinja & Massa 1998) as a companion confirming the identification from Jonker, Nelemans & Bassa (2007). There is not much room for later types as in this spectral type range terminal wind velocities decline rapidly with spectral type. We point out that B5 stellar winds themselves cannot produce X-rays through inner wind shocks as we observe in more massive stars. In this case the very low density outer terminal velocity zone of the wind gets illuminated by the X-ray source in Cir X-1. That we may observe the illumination of the stellar wind is also supported by an apastron observation taken during a more prominent outburst in 2010. Figure 2 shows a dominant continuum but no photo-ionized lines, which should have been detectable. Even with the brighter continuum the three brightest lines in the periastron spectrum should still be detectable above a 5σ level. Yet the only line detected is the Fe K fluorescence line which we commonly associate with the accretion disk. The absence of unshifted ADC lines at least with regards to S, Si and Mg from the accretion disk is peculiar because if it is true that the X-ray emissions have not changed in luminosity and are further obscured than what we observed in observations III and IV, then these lines should still be there unless they are

now also suppressed by heavy absorption. In that case the photoionized emissions from the stellar wind is all that's left to the observer as well as some weak higher Z lines from the ADC.

The amount of the shift would also rule out much later types as terminal wind velocities decline rapidly with type (Lamers, Snow & Lindholm 1995; Prinja & Massa 1998). Observations V and VIIa-c were taken between orbital phase 0.00 and 0.07 using the RXTE/ASM ephemeris (MJD = 50082.04) and orbital period of 16.54694 days from Shirey et al. (1998) (see also Clarkson, Charles & Onyett (2004)) for which the neutron star always illuminates the face of the star into a wind coming towards the observer, hence the blueshift. However, we point out that 400 km s^{-1} is also near the known rotational velocities of any Be-star in an X-ray binary (Reig 2011). So if it is not the wind but the stellar surface that gets ionized then we should see blue- and red-shifts depending on whether the compact object comes towards the companion or moves away and none when the compact object is a zero phase. With all the distractions from disk emissions in the previous observations gone, we believe that is the first time we might see the companion wind itself.

For this one can estimate the contribution of a spherical B-star wind with a constant velocity and a specific mass loss rate to the emission measure by integrating over the available volume from a B-star radius of 10^{12} cm to infinity. With a spherical mass loss rate of $10^{-8} M_{\odot} \text{ yr}^{-1}$ and a terminal wind velocity of 500 km s^{-1} this results to emission measures of the order of $10^{55} \text{ erg cm}^{-3} \text{ s}^{-1}$, which is only a fraction of what we observe. Increased emission measures require increased mass loss rates as well as non-spherical geometries. This indicates that if this is indeed the companion wind, it has to be enhanced. One indicator that this is the case could be the existence of significant amounts of resonance scattering in the He-like lines.

4.3. On the Possible High Mass Nature of the X-ray Binary

The photoionized plasma requires a substantial absorber in the line of sight in addition to absorption from the ISM. If the wind is indeed the emission line region, this absorber has to be able to cover the bulk of the stellar wind. Normal B5 supergiants are not well known to carry wind produced stellar disks. The only plausible protagonists we know today are magnetic stars and Be-stars, in the latter case also mostly much earlier type B-stars. In both cases an equatorial wind fed decretion disk can be produced under various critical circumstances. In the case of Be stars it may be a stellar rotation rate of more than 75% of the critical rate (see Rivinius, Carciofi & Martayan (2013) for a full review), while in the case of magnetic stars it is a strong magnetic field configuration confining the wind (see Gagné et al. (2005)). Such disks can provide not only the additional line of sight absorber but also account for the resonance scattering we observe.

However, while this is still a lot of speculation, we can in the following consider what is observationally known for the case of Be stars. Be-star X-ray binaries (BeXBs) are a sizeable sub-group in the category of high-mass X-ray binaries (HMXBs). Perhaps the most famous in the class of BeXBs is GX 301-2. This system consists of an accreting magnetized neutron star in an eccentric orbit ($e \sim 0.46$; Sato et al. (1986); Koh et al. (1997)). This is a very similar system except its orbit is three times as long and periastron passages are not as violent as in Cir X-1. Its optical counterpart is a B1.5Ia supergiant

with a lower mass limit of $39 M_{\odot}$, which is much larger than what is considered for Cir X-1 and here the Roche lobe overflow connection never breaks (Sato et al. 1986; Watanabe et al. 2003; Kaper, van der Meer & Najarro 2006). However, there are many similarities, such as an inclination larger than 44° which does not produce an eclipse but just barely misses the face of the star producing dips in the light curve by the dense stellar wind. Jonker, Nelemans & Bassa (2007) also concluded even though the inclination is high (Brandt et al. 1996) that in the case of Cir X-1 the neutron star never crosses the star (see also Iaria et al. (2008)). The X-ray spectrum in observation III (Schulz et al. 2008) is very similar to the one observed in GX 301-2, where the region above 5 \AA is dominated by line emissions from the ionized wind and below is dominated by accretion disk activity (Sato et al. 1986; Koh et al. 1997; Watanabe et al. 2003; Fürst et al. 2011).

In Be stars the regions above and below the disk are more or less equivalent to those surrounding normal B-stars (Rivinius, Carciofi & Martayan 2013). Fast rotation may even enhance the wind towards the polar regions (Puls, Vink & Najarro 2008). The fact that the companion in Cir X-1 is a supergiant does not make much of a difference. Most massive stars begin the main sequence as fast rotators and usually stay that way (Langer, Heger & Fliegner 1997), during the supergiant phase the star may see a reduction in the rotation rate due to the increasing stellar radius (Puls, Vink & Najarro 2008). Generally there is no reason why a fast rotator would not retain its disk in the supergiant phase and the case could be made that Cir X-1 might as well be the youngest known BeXB.

All BeXBs classified so far have orbital periods of 20 days and higher up to 300 days (see Reig (2011) for a review) and Cir X-1 with 16.5 days would mark the shortest period, which seems adequate since it would be the youngest in the sample. However, the list of known OBe stars mostly shows dwarfs (class V), subgiants (class IV) or giants (class III) and Cir X-1 would be the only other supergiant case (classes I and II) to GX 301-2. Supergiant X-ray binaries (SGXBs) tend to have shorter periods and here Cir X-1 would have the longest of this class. It is also the case that almost all BeXBs show X-ray pulsations ranging from a few seconds to a few hundreds of seconds. To date, no pulsations have been reported for Cir X-1 and we also did not detect any in the range where we are sensitive which is also above a few seconds. For the neutron star being that young we should also expect much shorter periods likely down to a few milliseconds. The lower magnetic field of 10^{11} G should not brake its period as fast as the other cases in 4000 yr. The mere fact that we do not observe pulsations is somewhat of concern but not completely unusual. To date no pulsations have been found in the SGXB 4U1700-37 (Seifina, Titarchuk & Shaposhnikov 2016) and in a few BeXBs (Reig 2011). New model calculations also show that at moderate magnetic field strength of the order of 10^{11} G and a high inclination of the system (Brandt & Podsiadlowski 1995), pulsations are quite impossible to detect if the angle between the neutron star rotation and magnetic field axis is small (Falkner et al. 2019, submitted⁸). We should also mention that Cumming (2008) proposed for the case of HETEJ1900.1-2455 and possibly other accreting millisecond pulsars that B-fields can be partially buried suppressing the observation of pulsations.

⁸ https://www.sternwarte.uni-erlangen.de/docs/theses/2018-07_Falkner.pdf

The fact that we know that the neutron star in Cir X-1 is very young combined with an identification of the companion as a B5Ia supergiant also can put some constraints on the evolutionary state of the entire binary. A formation scenario involving an AIC (Bhattacharya & van den Heuvel 1991) now seems highly unlikely. It also rules out that the progenitor star was a massive O-star as these only live less than 20 Myr whereas B3 stars and later live more than 30 Myr (Behrend & Maeder 2001). Since the companion in Cir X-1 is in its supergiant phase, which the star is in during its very late main sequence state, it must be much older than 20 Myrs. More plausible is that the progenitor was quite similar to the companion, maybe one or two types earlier. This would put the progenitor into likely the lowest mass range (8 - 10 M_{\odot}) that can produce a neutron star. Today we know little about neutron star progenitor masses and if this conclusion is true, it is quite extraordinary.

Last but not least the classification of Cir X-1 as a BeXB might have the potential to at least partially explain the ~ 30 yr transient flux behavior as shown by Parkinson et al. (2003) by invoking a precession period for the Be-star-disk system.

Such precession scenarios have already been suggested by Brandt & Podsiadlowski (1995) in terms of accretion disk precession and by Heinz et al. (2013) in terms of spin-orbit coupling effects between the neutron star spin and the binary orbit. Here we suggest a precession of a companion star disk. Super-orbital periods in accretion disks are not unusual in X-ray binaries as the examples of Her X-1, LMC X-4 and SMC X-1 show. Precessing Be-star disks are much more rare but not unheard of. Lau et al. (2016) recently reported on an apparent precessing helical outflow from the massive star WR102c. The interpretation is that the precessing outflow emerged from a previous evolutionary rapidly rotating phase of the star and attributed the precession to an unseen compact companion. In a sense this situation is not unusual to what we envision here. In the WR102c system the period of the unseen companion was constrained to between 800 and 1400 days, which is much larger than the period in Cir X-1, but the precession period of 1.4×10^4 yr is very close to the long term variation cycle in Cir X-1. This sets a precedent and it is no longer a question whether it can happen, but it calls for details of how it happens.

REFERENCES

- Bautista, M. A., & Kallman, T. R., 2000, *ApJ*, 544, 581
 Becker, P. A., & Wolff, M. T., 2007, *ApJ*, 654, 435
 Behrend, R., & Maeder, A., 2001, *A&A*, 373, 190
 Bhattacharya, D., & van den Heuvel, E. P. J., 1991, *Phys. Rep.*, 203, 1
 Bildsten, L., 1995, *ApJ*, 438, 852
 Bildsten, L., 1998, in *NATO Advanced Science Institutes (ASI) Series C*, ed. R. Buccheri, J. van Paradijs, A. Alpar, Vol. 515, 419
 Brandt, N., & Podsiadlowski, P., 1995, *MNRAS*, 274, 461
 Brandt, W. N., Fabian, A. C., Dotani, T., Nagase, F., Inoue, H., Kotani, T., & Segawa, Y., 1996, *MNRAS*, 283, 1071
 Brandt, W. N., & Schulz, N. S., 2000, *ApJ*, 544, L123
 Caballero, I., & Wilms, J., 2012, *Mem. Soc. Astron. Italiana*, 83, 230
 Canizares, C. R., et al., 2005, *PASP*, 117, 1144
 Cash, W., 1979, *ApJ*, 228, 939
 Clarkson, W. I., Charles, P. A., & Onyett, N., 2004, *MNRAS*, 348, 458
 Coburn, W., Kretschmar, P., Kreykenbohm, I., McBride, V. A., Rothschild, R. E., Staubert, R., & Wilms, J., 2006, *Advances in Space Research*, 38, 2747
 Cumming, A., 2008, in *American Institute of Physics Conference Series*, ed. R. Wijnands, D. Altamirano, P. Soleri, N. Degenaar, N. Rea, P. Casella, A. Patruno, M. Linares, Vol. 1068, 152
 D'Ai, A., et al., 2012, *A&A*, 543, A20
 DeCesar, M. E., Boyd, P. T., Markwardt, C. B., Pottschmidt, K., Miller, M. C., Strohmayer, T. E., Suchy, S., & Wilms, J., 2009, in *American Astronomical Society Meeting Abstracts #213*, Vol. 41, 299
 Degenaar, N., et al., 2013, *ApJ*, 775, 48
 Fender, R., Spencer, R., Tzioumis, T., Wu, K., van der Klis, M., van Paradijs, J., & Johnston, H., 1998, *ApJ*, 506, L121
 Fujimoto, M. Y., Hanawa, T., & Miyaji, S., 1981, *ApJ*, 247, 267
 Fürst, F., et al., 2011, *A&A*, 535, A9
 Gagné, M., Oksala, M. E., Cohen, D. H., Tonnesen, S. K., ud-Doula, A., Owocki, S. P., Townsend, R. H. D., & MacFarlane, J. J., 2005, *ApJ*, 628, 986
 Glass, I. S., 1994, *MNRAS*, 268, 742
 Gotthelf, E. V., & Halpern, J. P., 2007, *ApJ*, 664, L35
 Gotthelf, E. V., & Halpern, J. P., 2009, *ApJ*, 695, L35
 Gough, D. O., & Taylor, R. J., 1966, *MNRAS*, 133, 85
 Halpern, J. P., & Gotthelf, E. V., 2010, *ApJ*, 709, 436
 Halpern, J. P., Gotthelf, E. V., Camilo, F., & Seward, F. D., 2007, *ApJ*, 665, 1304
 Heinz, S., et al., 2015, *ApJ*, 806, 265
 Heinz, S., Schulz, N. S., Brandt, W. N., & Galloway, D. K., 2007, *ApJ*, 663, L93
 Heinz, S., et al., 2013, *ApJ*, 779, 171
 Homan, J., et al., 2010, *ApJ*, 719, 201
 Iaria, R., D'Ai, A., Lavagetto, G., Di Salvo, T., Robba, N. R., & Burderi, L., 2008, *ApJ*, 673, 1033
 Ji, L., Schulz, N., Nowak, M., Marshall, H. L., & Kallman, T., 2009, *ApJ*, 700, 977
 Ji, L., Schulz, N. S., Nowak, M. A., & Canizares, C. R., 2011, *ApJ*, 729, 102
 Jimenez-Garate, M. A., Raymond, J. C., & Liedahl, D. A., 2002, *ApJ*, 581, 1297
 Jonker, P. G., & Nelemans, G., 2004, *MNRAS*, 354, 355
 Jonker, P. G., Nelemans, G., & Bassa, C. G., 2007, *MNRAS*, 374, 999
 Kallman, T. R., Palmeri, P., Bautista, M. A., Mendoza, C., & Krolik, J. H., 2004, *ApJS*, 155, 675
 Kaluzienski, L. J., Holt, S. S., Boldt, E. A., & Serlemitsos, P. J., 1976, *ApJ*, 208, L71
 Kaper, L., van der Meer, A., & Najarro, F., 2006, *A&A*, 457, 595
 Kaspi, V. M., 2010, *Proceedings of the National Academy of Science*, 107, 7147
 Koh, D. T., et al., 1997, *ApJ*, 479, 933
 Lamb, F. K., Pethick, C. J., & Pines, D., 1973, *ApJ*, 184, 271
 Lamers, H. J. G. L. M., Snow, T. P., & Lindholm, D. M., 1995, *ApJ*, 455, 269
 Langer, N., Hegger, A., & Fliegner, J., 1997, in *IAU Symposium*, ed. T. R. Bedding, A. J. Booth, J. Davis, Vol. 189, 343
 Lau, R. M., Hankins, M. J., Herter, T. L., Morris, M. R., Mills, E. A. C., & Ressler, M. E., 2016, *ApJ*, 818, 117
 Linares, M., et al., 2010, *ApJ*, 719, L84
 Margon, B., Lampton, M., Bowyer, S., & Cruddace, R., 1971, *ApJ*, 169, L23
 Mirabel, I. F., 2001, *Astrophysics and Space Science Supplement*, 276, 319
 Orlandini, M., et al., 1998, *ApJ*, 500, L163
 Özel, F., & Freire, P., 2016, *ARA&A*, 54, 401
 Papitto, A., Riggio, A., di Salvo, T., Burderi, L., D'Ai, A., Iaria, R., Bozzo, E., & Menna, M. T., 2010, *MNRAS*, 407, 2575
 Parkinson, P. M. S., et al., 2003, *ApJ*, 595, 333
 Porquet, D., & Dubau, J., 2000, *A&AS*, 143, 495
 Prinja, R. K., & Massa, D. L., 1998, in *Properties of Hot Luminous Stars*, ed. I. Howarth, Vol. 131, 218
 Puls, J., Vink, J. S., & Najarro, F., 2008, *A&A Rev.*, 16, 209
 Reig, P., 2011, *Ap&SS*, 332, 1
 Rivinius, T., Carciofi, A. C., & Martayan, C., 2013, *A&A Rev.*, 21, 69
 Sakurai, S., et al., 2014, *PASJ*, 66, 10
 Sato, N., Nagase, F., Kawai, N., Kelley, R. L., Rappaport, S., & White, N. E., 1986, *ApJ*, 304, 241
 Schulz, N. S., & Brandt, W. N., 2002, *ApJ*, 572, 971
 Schulz, N. S., Chakrabarty, D., Marshall, H. L., Canizares, C. R., Lee, J. C., & Houck, J., 2001, *ApJ*, 563, 941
 Schulz, N. S., Kallman, T. E., Galloway, D. K., & Brandt, W. N., 2008, *ApJ*, 672, 1091
 Seifina, E., Titarchuk, L., & Shaposhnikov, N., 2016, *ApJ*, 821, 23
 Sell, P. H., et al., 2010, *ApJ*, 719, L194
 Shabaltas, N., & Lai, D., 2012, *ApJ*, 748, 148
 Shirey, R. E., Bradt, H. V., & Levine, A. M., 1999, *ApJ*, 517, 472
 Shirey, R. E., Bradt, H. V., Levine, A. M., & Morgan, E. H., 1998, *ApJ*, 506, 374
 Stewart, R. T., Caswell, J. L., Haynes, R. F., & Nelson, G. J., 1993, *MNRAS*, 261, 593
 Stewart, R. T., Nelson, G. J., Penninx, W., Kitamoto, S., Miyamoto, S., & Nicolson, G. D., 1991, *MNRAS*, 253, 212
 Tauris, T. M., Fender, R. P., van den Heuvel, E. P. J., Johnston, H. M., & Wu, K., 1999, *MNRAS*, 310, 1165
 Tauris, T. M., Sanyal, D., Yoon, S.-C., & Langer, N., 2013, *A&A*, 558, A39
 Tennant, A. F., 1987, *MNRAS*, 226, 971
 Tennant, A. F., Fabian, A. C., & Shafer, R. A., 1986, *MNRAS*, 221, 27P
 Watanabe, S., et al., 2003, *ApJ*, 597, L37
 Whelan, J. A. J., et al., 1977, *MNRAS*, 181, 259