BROAD COMPONENTS IN OPTICAL EMISSION LINES FROM THE ULTRA-LUMINOUS X-RAY SOURCE NGC 5408 X-1

D. Cseh1, F. Grisé2, S. Corbel1, and P. Kaaret2
1 Laboratoire Astrophysique des Interactions Multi-échelles (UMR 7158), CEA/DSM-CNRS-Université de Paris Diderot, CEA Saclay, F-91191 Gif sur Yvette, France; david.cseh@cea.fr
2 Department of Physics and Astronomy, University of Iowa, Van Allen Hall, Iowa City, IA 52242, USA

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ABSTRACT

High-resolution optical spectra of the ultra-luminous X-ray source (ULX) NGC 5408 X-1 show a broad component with a width of \( \sim 750 \) km s\(^{-1}\) in the He\(\text{ii}\) and H\(\beta\) lines in addition to the narrow component observed in these lines and [O\(\text{ii}\)]. Reanalysis of moderate-resolution spectra shows a similar broad component in the He\(\text{ii}\) line. The broad component likely originates in the ULX system itself, probably in the accretion disk. The central wavelength of the broad He\(\text{ii}\) line is shifted by \(252 \pm 47\) km s\(^{-1}\) between the two observations. If this shift represents motion of the compact object, then its mass is less than \(\sim 1800 M_\odot\).

Key words: black hole physics – galaxies: individual (NGC 5408) – X-rays: binaries

1. INTRODUCTION

Ultra-luminous X-ray sources (ULXs) are variable off-nuclear X-ray sources with luminosities exceeding the Eddington luminosity of a 20 \( M_\odot \) compact object, assuming isotropic emission (Colbert & Mushotzky 1999; Kaaret et al. 2001). Irregular variability, on timescales from seconds to years, suggests that ULXs contain accreting compact objects. Intermediate-mass black holes would be required to produce the inferred luminosities, but ULXs may, instead, accrete at super-Eddington rates or be beamed, mechanically or relativistically.

NGC 5408 X-1 is one of the best intermediate-mass black hole candidates because it powers a radio nebula requiring an extremely energetic outflow (Kaaret et al. 2003; Soria et al. 2006; Lang et al. 2007) and a photoionized nebula requiring an X-ray luminosity above \(3 \times 10^{39}\) erg s\(^{-1}\) (Kaaret & Corbel 2009). Also, quasi-periodic X-ray oscillations at low frequencies suggest a high compact object mass (Strohmayer et al. 2007).

The optical counterpart to NGC 5408 X-1 was identified by Lang et al. (2007) and optical spectra were obtained by Kaaret & Corbel (2009). The optical spectra had no absorption lines suggesting the emission is not dominated by the companion star. The observed continuum emission may arise from a nebula or reprocessing of X-rays in an accretion disk. The optical spectrum is dominated by emission lines, including forbidden lines that must be produced in a low-density environment such as a nebula. Several high excitation lines were detected indicating that the nebula is X-ray photoionized.

Kaaret & Corbel (2009) found that the He\(\text{ii}\) line from NGC 5408 X-1 was broader than the forbidden lines. Permitted lines produced in the high-density environment of an accretion disk can be broad, reflecting the distribution of velocities within the optical emitting regions of the disk. Furthermore, since the accretion disk moves with the compact object, the line velocity shifts may provide a means to constrain the compact object mass (Hutchings et al. 1987; Soria et al. 1998).

To study the He\(\text{ii}\) line profile of NGC 5408 X-1 in more detail, we obtained new observations using the FORS-2 spectrograph on the European Southern Observatory Very Large Telescope (VLT) with a high-resolution grism and reanalyzed our previous FORS-1 observations (Kaaret & Corbel 2009). The observations and data reduction are described in Section 2. The results are presented in Section 3 and discussed in Section 4.

2. OBSERVATIONS AND ANALYSIS

FORS-2 observations of NGC 5408 X-1 were obtained on 2010 April 12 using the GRIS\(_{1200B}\) and GRIS\(_{1200R}\) grisms with a slit width of 1'0 covering the spectral range 3600–5110 Å and 5750–7310 Å with dispersion 0.36 Å pixel\(^{-1}\) and 0.38 Å pixel\(^{-1}\) and spectral resolution \( \lambda/\Delta \lambda = 1420 \) and 2140 at the central wavelength, respectively. The observation block (OB) consisted of three 849 s exposures with a 12 pixel offset along the spatial axis between successive exposures. CCD pixels were binned for readout by two in both the spatial and spectral dimensions. We also reanalyzed all six OBs of the previous FORS-1 observations (Kaaret & Corbel 2009), hereafter the low-resolution data (LRD), taken using the GRIS\(_{600B}\) grism which has a spectral resolution of \( \lambda/\Delta \lambda = 780 \) at the central wavelength and with three shifted exposures per OB. The average seeing for our new observations were 0.72 and 0.62 arcsec for the blue and red spectra, respectively. The average seeing of the six OBs of the LRD were 0.87, 0.82, 0.96, 1.28, 0.64, and 0.57 arcsec, respectively.

Data reduction was carried out using the Image Reduction and Analysis Facility (IRAF\(^3\); Tody 1993). First, we created bias and flat-field images, then applied these to correct the spectrum images. The three exposures in each OB were aligned and then averaged to eliminate bad pixels and cosmic rays using the imcombine task with the ccdclassify rejection algorithm.

As the continuum emission of the ULX counterpart is faint, we could not trace its spectrum. Following Kaaret & Corbel (2009), we used the bright nearby star at Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) position \( \alpha_{2000} = 14^h03^m18.97^s, \delta_{2000} = -41^\circ22'56.6'' \) as a reference trace. The trace position on the spatial axis varied less than half a pixel along the whole length of the dispersion axis. The trace for the ULX counterpart was centered on the He\(\text{ii}\) \( \lambda 4686 \) emission line profile. The smallest possible trace width, 2 pixels.

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\(^{3}\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
corresponding to 0.5, was used to best isolate the ULX emission from the nebular emission. Background subtraction was done with a trace close by. The HgCdHeNeA lamp and standard star LTT7379 were used for wavelength and flux calibration. An atmospheric extinction correction was applied using the IRAF built-in Cerro Tololo Inter-American Observatory (CTIO) extinction tables. To estimate the reddening, we used the Balmer decrement of Hβ/Hα, we find E(B − V) = 0.08 ± 0.03 in agreement with Kaaret & Corbel (2009). We corrected for reddening using the extinction curve from Cardelli et al. (1989) with RV = 3.1.

To study the kinematics, we need to characterize the instrumental resolution in order to obtain intrinsic line widths. After applying the dispersion correction to the lamp spectrum, we measured the full width at half-maximum (FWHM) of several lines, excluding saturated ones, by fitting Gaussians with the IRAF splot subroutine. The instrumental FWHM was 2.24 Å and 5.08 Å for the high-resolution data (HRD) and LRD, respectively. The error on the instrumental FWHM was estimated by finding the standard deviation of the FWHM for several different lines.

For the HeII, Hβ, and [OIII] emission lines (see Figure 1 and Table 1) we first fitted the continuum with a second-order polynomial to a region around each line excluding the line itself by visual examination. We estimated the measurement errors by calculating the root mean square deviation of the data in the same region. Then, we performed a nonlinear least-squares fit using the LMFIT subroutine of the Interactive Data Language version 7.0 and based on “MRQMIN” (Press et al. 1992). We fitted the line profiles iteratively, first using one Gaussian which converged on the narrow component and then using a sum of two Gaussians with initial parameters adjusted to achieve convergence. All six parameters in the two-Gaussian fit were free to vary. The errors on the parameters were calculated by the fitting routine in a way that the uncertainty for the i-th parameter derives from the square root of the corresponding diagonal element of the covariance matrix. The intrinsic line width was calculated assuming the measured line width is the quadrature sum of the intrinsic and instrumental widths and the error on the intrinsic line width included a term for the uncertainty in the instrumental FWHM.

For the Hα line, we fitted the sum of four Gaussians, because the [NII] lines lie on the red and blue parts of the line wing. Initial fits to the HeII and red [NII] lines provided initial values for a fit with four Gaussians. Because the blue [NII] line has very low signal-to-noise ratio (S/N), the widths of the two [NII] lines were set equal, the wavelength offset was fixed at −35.44 Å, and the amplitude of the blue line was set to 1/3 of the red line (Osterbrock & Ferland 2006).

3. RESULTS

The improved resolution of the new data clearly resolves a broad component in the HeII line profile (see Figure 1 and Table 1). The centroid is shifted from the nebular component by +0.87 ± 0.26 Å in the red direction. We also searched for broad components in other lines. Hβ has a broad component with an FWHM similar to the HeII line but shifted by −0.52 ± 0.32 Å toward the blue, rather than the red. In contrast, a single Gaussian provides a good fit to the forbidden [OIII] line and there is no evidence for a broad component, as expected if the line is emitted only from the nebula.

Then we fitted the HeII line profiles of the six OBs of the LRD, see Figure 2 and Table 1. The flux variation of the overall line profiles correlates with the seeing, e.g., OB5 has the best seeing and the highest flux. We detected a broad component in the HeII line in OB3, OB5, and OB6. We did not significantly detect a broad component in OB1, OB2, and OB4. This may be due to seeing or variations in the flux of the broad component.

We note that Kaaret & Corbel (2009) reported lower fluxes for HeII, [Ne v], and the continuum emission for OB4 (with by far the worst seeing) as compared to the other OBs, while the other line fluxes remained relatively constant. Our new analysis suggests that this is due to changes in the seeing. If the emitting
region is smaller than the 0.51 slit used for the LRD, then poor seeing will decrease the flux through the spectrometer. If these emission components are enhanced close to the ULX system while the other line emission is uniform, then the poor seeing in OB4 would produce the observed changes in flux. Thus, there is no evidence for temporal variability of the continuum or line emission. However, the subtraction performed by Kaaret & Corbel (2009) to isolate continuum emission arising from near the ULX is still justified; the separation of components is spatial instead of temporal.

The He II line parameters are consistent between OB3, OB5, and OB6. The wavelength shifts of the He II broad component of OB3, OB5, and OB6 relative to the narrow component are $-1.82 \pm 0.78 \AA$, $-3.77 \pm 1.44 \AA$, and $-4.03 \pm 1.70 \AA$ into the blue direction instead of the red as in the HRD, and are consistent within 1σ. We averaged the spectrographs for these three observations and fit the resulting line profile. The fit results are listed as He II AVG in Table 1. The shift of average line profile is $-3.07 \pm 0.68 \AA$.

The He II broad component width is consistent between the new and old data. The narrow component is wider in the old data because we do not resolve the nebular lines. The line fluxes are higher in the new data, most likely due to the wider slit. The centroids of the narrow component are consistent, while the wavelength shift of the He II broad component between the old and new data is $\Delta \lambda = 3.94 \pm 0.73 \AA$.

Fitting the Hβ line of the LRD, we did not get a good fit due to the lack of spectral resolution and the low broad to narrow flux ratio. We could not fit the bluer Balmer lines because of their low S/Ns. We did fit the Hα line in the new data. Although we do not obtain a good fit ($\chi^2 = 4.9$) because of the complicated line profile (i.e., the two [N II] lines lie on the red and blue wings of the Hα line), we find that there is a broad component with a width of 19 Å, while the width of the nebular component is 2.7 Å. The [N II] lines are narrow, with a typical width of 3 Å, quantitatively supporting that the forbidden, nebular lines do not have broad components.

### 4. DISCUSSION

Our new, high-resolution spectra show narrow nebular lines and broad components in the He II, Hβ, and Hα lines. Our previous, moderate-resolution spectra show a broad component in the He II line. There is no broad component in the [O III] nebular lines in either the new or old spectra. There is still no sign of any absorption lines in the new spectra.

#### 4.1. The Line-emitting Region

The broad components of both He II and Hβ have widths $\sim 750 \text{ km s}^{-1}$, consistent with production in the accretion disk, and are roughly Gaussian, instead of having P-Cygni profiles that would indicate origin in a wind. Following Porter (2010), we estimate the size of the line-emitting region, $R_\text{e}$, by assuming the line-emitting gas is in Keplerian orbits around a compact object, thus $R_\text{e} \leq GM/v^2$. We find $R_\text{e} < 2.35 (\frac{M_\odot}{1500 M_\odot})$ AU, which for a mass of $10 M_\odot$ would give an upper limit of $3.4 R_\odot$. This is consistent with the origin of the broad He II line in the accretion disk.

The broad-line components are shifted relative to the narrow components. In the new data, the shifts are small compared to the line width, $+56 \pm 17 \text{ km s}^{-1}$ for He II and $-33 \pm 20 \text{ km s}^{-1}$ for Hβ. These shifts are consistent only at the 3σ level, which might indicate a difference in the spatial origin of the lines. However, this is still consistent with the production of both lines within the disk since random motions within the disk and variation between the emission regions could produce shifts that are small compared to the line widths, as observed.

The central wavelength of the He II broad component shifts markedly between the old and new data, $\Delta \lambda = 3.94 \pm 0.73 \AA$ or $\Delta v = 252 \pm 47 \text{ km s}^{-1}$. This shift is a substantial fraction of the line width. The shift could be due to random motion within the disk, differing viewing geometries (Roberts et al. 2010), or orbital motion of disk (and the compact object). If the shifts in the broad component of the He II line are due to orbital motion, then this would provide a means to determine the orbital period and would also provide a measurement of the mass function for the secondary star. Thus, a program of monitoring NGC 5408 X-1 with high-resolution optical spectroscopic observations will be important in extending our understanding of the physical nature of this system.
4.2. The Binary System

In this section, we make some speculations based on interpretation of the shift in the broad component of the He\textsc{ii} line as due to orbital motion. One can express the mass function and the compact object mass, $M_x$, in terms of the orbital period, $P$, the velocity excursion, $K_x$, and the companion mass, $M_c$, as

$$f_x = \frac{P K_x^3}{2 \pi G} = \frac{M_c \sin^3 i}{(1 + \frac{M_c}{M_x})^2} \leq M_c$$

where $i$ is the inclination angle and $G$ is the gravitational constant. From the shift of the He\textsc{ii} line quoted above, we constrain the semi-amplitude of the radial velocity $K_x \geq \Delta v/2 = 126 \pm 24$ km s$^{-1}$. Thus, if the maximum mass of the companion and the orbital period are known, then Equation (2) leads to an upper bound on the mass of the compact object.

The binary system has a visual magnitude $V_0 = 22.2$ that gives an upper limit on the absolute magnitude of the companion of $V_0 = -6.2$ at a distance of 4.8 Mpc (Karachentsev et al. 2002). Unfortunately, this places little restriction on the companion mass as even O3V stars, with masses of $120 M_\odot$, are allowed. However, very high mass stars are very short lived, no more than a few million years. There is no evidence of a dense stellar association near NGC 5408 X-1 and origin in the closest super-star cluster would require a transit time to the present location on the order of 30 Myr (Kaaret et al. 2003). Thus, the companion mass is likely significantly lower, near $20 M_\odot$ or less, similar to that found from studies of the stellar environments of other ULXs (Grisé et al. 2008, 2011). Figure 3 shows the upper bound on the compact object mass for donors of $120 M_\odot$ and $20 M_\odot$ as a function of orbital period. High black hole masses are excluded, except for very short periods. We note that the He\textsc{ii} line shift was the same in OB3 versus OB5 and OB6, taken one day apart, suggesting that the period is longer than a few days. Thus, the black hole mass is likely below $\sim 1800 M_\odot$. The more probable companion mass of $20 M_\odot$ or less would imply smaller black hole masses, less than $112 M_\odot$.

As a further constraint, we note that the orbital separation should be larger than the size of the emitting region calculated above. Assuming a circular orbit, the orbital separation of the compact object is $a = (\frac{(2GM_c)}{K_x^2})^{1/3}$. Figure 3 shows the orbital separation as a function of period. Also shown is the size of the line-emitting region, $R_{le}$, versus period. Both are calculated using the maximum black hole mass for each period assuming a
120 $M_\odot$ or 20 $M_\odot$ donor. The orbital separation is greater than the upper limit of the size of the line-emitting region when the compact object mass is below 875 $M_\odot$ for a 120 $M_\odot$ companion and below 128 $M_\odot$ for a 20 $M_\odot$ companion. These masses are reduced if the inclination is lowered. These results suggest that the most probable black hole mass is at most a factor of several above the usual stellar-mass black hole range.

Strohmayer (2009) proposed an orbital period of $P = 115.5 \pm 4.0$ days for NGC 5408 X-1, based on variations in the X-ray emission. With $P = 115.5$ days, the mass function is $f_t = 24.0 \pm 13.4 M_\odot$, implying a lower bound on the companion mass $M_c \geq 10.6 M_\odot$. It is interesting to determine if this period is consistent with other constraints on the system. An orbital period of $P = 115.5 \pm 4.0$ days would require a mean stellar density of $\rho = 1.5 \times 10^{-5}$ g cm$^{-3}$ and, thus, a supergiant companion if mass transfer proceeds via Roche lobe overflow (Strohmayer 2009; Kaaret et al. 2006). In particular, late F and early G supergiants have densities close to that required, although we caution that the high mass transfer rate needed to power the ULX may distort the spectral type of the star. Such stars have masses of 10–12 $M_\odot$, consistent with the minimum mass derived from the mass function, and absolute magnitudes close to or below the upper limit quoted above. The stellar radii are large, up to 0.7 AU, but smaller than the orbital separation for this period and mass. However, a companion mass so close to the lower bound on the mass function would require a very low mass compact object. For a companion mass of 10–12 $M_\odot$, the compact object would have to be below 1 $M_\odot$, which seems unlikely. For a 5 $M_\odot$ black hole, one would need a donor of about 17 $M_\odot$ if the system is edge on. A higher black hole mass or a less extreme inclination would require an even higher mass companion. These high companion masses contradict the required stellar density; there is no star with both $M_c \geq 17 M_\odot$ and $\rho \sim 1.5 \times 10^{-5}$ g cm$^{-3}$. Thus, either the orbital period is not near 115 days or mass transfer does not proceed via Roche lobe overflow. We note that Foster et al. (2010) have suggested that 115 day periodicity may, instead, indicate a super-orbital period.

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Facility: VLT: Antu

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