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Optical spectroscopy of (candidate) ultra-compact X-ray binaries: constraints on the composition of the donor stars

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ABSTRACT

We present optical spectroscopy of several (candidate) ultra-compact X-ray binaries (UCXBs) obtained with the ESO VLT and Gemini-North telescopes. In only one of five observed UCXB candidates did we find evidence for H in its spectrum (4U 1556-60). For XB 1905+00 the optical counterpart is not detected. For the known UCXBs 4U 1626-67 and XB 1916-05 we find spectra consistent with a C/O and a He/N accretion disc respectively, the latter is the first optical spectrum of a He-rich donor in an UCXB. Interestingly, the C/O spectrum of 4U1626-67 shows both similarities as well as marked differences from the optical C/O spectrum of 4U 0614+09. We obtained phase resolved spectroscopy of 4U 0614+09 and the 44 min transient XTE J0929-314. In neither object were we able to detect clear orbital periodicities, highlighting the difficulties of period determinations in UCXBs. We reanalysed the spectra of XTE J0929-314 that were taken close to the peak of its 2003 X-ray outburst and do not confirm the detection of Hα emission as was claimed in the literature. The peak spectra do show strong C or N emission around 4640Å, as has also been detected in other UCXBs. We discuss the implications of our findings for our understanding of the formation of UCXBs and the Galactic population of UCXBs. At the moment all studied systems are consistent with having white dwarf donors, the majority being C/O rich.

Key words: binaries: close – white dwarfs – X-ray: binaries

1 INTRODUCTION

Low-mass X-ray binaries are systems in which a neutron star or black hole accretes from a low-mass companion. Most systems have orbital periods of hours to days and are consistent with the scenario (van den Heuvel 1983) in which the donors are main sequence or evolved, hydrogen-rich, stars. A few ultra-compact X-ray binaries (UCXBs) have orbital periods below an hour and are so compact that the donor stars cannot be main sequence stars, but instead must be hydrogen poor (e.g. Nelson et al. 1986; Verbunt & van den Heuvel 1995). These systems have recently attracted attention for a number of reasons, such as the discovery of transient UCXBs which harbour millisecond X-ray pulsars (e.g. Remillard et al. 2002; Markwardt & Swank 2002) and the fact that such systems are strong sources of low-frequency gravitational wave radiation and will be guaranteed sources for the joint ESA/NASA mission LISA[1] (e.g. Phinney 2002; Nelemans 2003, 2005).

One of the distinguishing properties of UCXBs is their optical faintness in outburst, as expected for the small accretion discs in these systems (van Paradijs & McClintock 1994). Therefore it is only with the advent of 8m class telescopes that high-quality optical spectra have become available, and consequently much of our current knowledge is based on X-ray observations and photometry at different wavelengths. Due to the nature of the donor stars in UCXBs the disc material is expected to be hydrogen poor providing an opportunity to distinguish UCXBs from other low-mass X-ray binaries through optical or UV spectroscopy. There are 12 systems with known or suggested orbital periods, including systems in globular clusters. Six more systems are identified based on similarities with known systems in either their X-ray spectra (Juett et al. 2001) or as a result of their optical faintness (Bassa et al. 2006). For a short review of UCXBs see Nelemans & Jonker (2006).

⋆ E-mail: nelemans@astro.ru.nl, based on observations made with ESO Telescopes at the Paranal Observatories under programmes 269.D-5026 and 073.D-0486

[1] http://lisa.esa.int
http://lisa.jpl.nasa.gov

We have started a systematic program to obtain optical spectra of (candidate) UCXBs using the ESO Very Large Telescope and the Gemini-North telescope in order to test the proposed formation channels for UCXBs and probe the interior structure of the donor stars through determination of the chemical composition of the accretion discs in these systems. The result of the first part of this projects was the discovery of carbon-oxygen accretion discs in 4U 0614+09, 4U 1543-624 and possibly 2S 0918-549 (Nelemans et al. 2004). In this paper we report on the second set of observations, as well as on a collection of other spectra obtained from the ESO archive. In Sect. 2 we briefly describe the observations and the data reduction techniques. In Sect. 3 we will present the results of our observations for the individual systems. We end the paper with a discussion of the implications of our observations for our understanding of UCXBs (Sect. 4) and a summary of our conclusions (Sect. 5).

Table 1. Most prominent lines in the model spectrum for 4U 1916-05

lines (Å)	element
4097.36/ 4103.39	NIII
4195.74/ 4200.07	NIII
4471.68	HeI
4510.88/ 4510.96/ 4514.85/ 4518.14/ 4523.56	NIII
4634.13/ 4640.64/ 4641.85/ 4641.96	NIII
4686.75	HeII
4858.70/ 4858.98/ 4861.27/ 4867.12/ 4867.17	NIII
5015.68	HeI
5320.87/ 5327.19	NIII
5666.63/ 5679.56	NII
5875.62	He I
6559.71	He II
6610.56	N II
6678.15	He I
7065.19	He I

2 OBSERVATIONS AND REDUCTION

Spectroscopic observations of five (candidate) UCXBs
Spectra were taken with the FORS2 spectrograph on UT4 of the 8m Very Large Telescope on Paranal in Chile. For each object we took spectra both with the 600B and 600RI holographic grisms, with a 1" slit, using 2x2 on-chip binning. This setup resulted in coverage of 3326 – 6359 Å with mean dispersion of 1.48 Å/pix (resolution about 7Å) for the 600B spectra and 5290 – 8620 Å with mean dispersion of 1.63 Å/pix (resolution about 7Å) for the 600RI spectra. Exposure times were 2754 s. In addition VLT spectra of 4U1626-67, 4U 0614+09 and 4U 1556-60 were extracted from the ESO archive and reduced in the same way as the other spectra.
Spectroscopic DDT observations of XTE J0929-314
Spectra were taken first with the UVES spectrograph on the VLT . Unfortunately, the source had faded too much (cf. Fig. 5). The spectra of the individual exposures of 150 s could not be extracted so all 30 spectra were first combined before the spectrum was extracted. Additional spectra were taken with the FORS2 spectrograph with the 1200R and 1400V holographic grisms, with a 1" slit, using 2x2 on-chip binning (resolutions about 3Å) and exposure times of 150 s. This setup resulted in coverage of 4580 – 6154 Å with mean dispersion of 0.77 Å/pix for the 1400V spectra and 5869 – 7369 Å with mean dispersion of 0.73 Å/pix for the 1200R spectra. We also retrieved from the ESO archive the 3 spectra that were taken close to the peak of the X-ray outburst with the ESO 3.6m telescope using the EFOSC spectrograph (Castro-Tirado et al. 2002).
Spectroscopic observations of 4U 0614+09 with Gemini
Time resolved spectra were taken with the GMOS-North spectrograph on Gemini-North on Mauna Kea using the B1200 grating with a 0.75" slit (resolution about 2Å) with 4x4 on-chip binning and an integration time of 293 s. A total of 52 spectra were taken between 30/10/2003 and 22/11/2003.

For all of the above setups, data reduction was performed using standard IRAF[2] tasks. The bias was removed using the overscan region of the CCD, after which the images were flatfield corrected using the standard calibration plan flatfields. Spectra were extracted using optimal extraction (Horne 1986) with the `apall` task. Arc lamp spectra were extracted from the same place on the CCD. The 600B wavelength calibration was obtained using the positions of 14-17 lines, giving a root-mean-square scatter of less than 0.1 Å in fitting a cubic spline. The 600RI wavelength calibration uses typically 40 lines and gives a root-mean-square scatter of 0.15 Å. The GMOS-North spectra were calibrated with 40 lines, giving an scatter of less than 0.08 Å.

Because observations of spectroscopic standard stars were not obtained close in time to our observations, the spectra were not flux calibrated. The spectra of each object were averaged and the few remaining cosmics removed by hand. The reduced spectra were subsequently imported in the MOLLY package for further analysis. We normalised the spectra by fitting a second order cubic spline to the continuum at line-free regions of the spectrum.

[2] IRAF is distributed by the National Optical Astronomy Observatories

3 RESULTS

In the following sections we will discuss the results for the different objects in detail. Because there are very few optical spectra of UCXBs known, interpretation of these spectra generally is difficult. We found that simple LTE models are a good tool to identify lines from the different possible elements that the discs of UCXBs can contain, even though the LTE assumption is probably not justified (Nelemans et al. 2004). The LTE model that we use consists of a uniform slab of gas, with constant density and temperature. For more details of this model, see Marsh et al. (1991)and Nelemans et al. (2004). We discuss the interpretation of our results and the applicability of our LTE modeling in Sect. 4.

3.1 The known UCXB XB 1916-05

With the VLT we obtained spectra of the known UCXB 4U 1916-05, which has a 50 min orbital period (Walter et al. 1982; White & Swank 1982). The faint optical counterpart (V=21) has inhibited spectral studies until now. The discovery of 270 Hz burst oscillations (Galloway et al. 2001) shows the neutron star is spinning rapidly. Three spectra were taken with the 600RI grism, one with the 600B grism. In Fig. 1 we show the normalised, average spectrum, which on first sight looks similar to the spectrum of the C/O disc of 4U 0614+09 (Nelemans et al. 2004), but in addition broad emission around 4540Å is present. We found a good match with an LTE model consisting of pure helium plus overabundant nitrogen (see Fig. 1). The model has a temperature of 28,000 K, a particle density of 4×10^{13} cm^{-3} and a line of sight through the medium of 10^7 cm. The relative number of He and N atoms is 90:3, which is about 10 times higher than material of originally

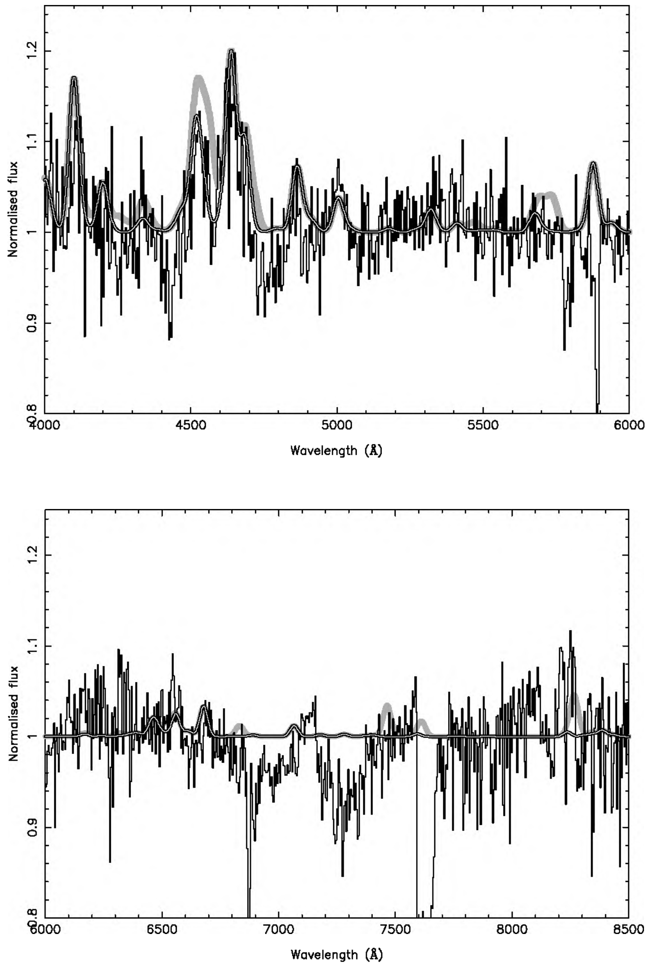

Figure 1. Normalised (and rebinned) spectrum of the known UCXB XB 1916-05, showing broad features, with a 30 kK LTE model consisting of pure helium plus nitrogen (thin black/white line) and a model including heavier elements at solar composition (thick grey line).

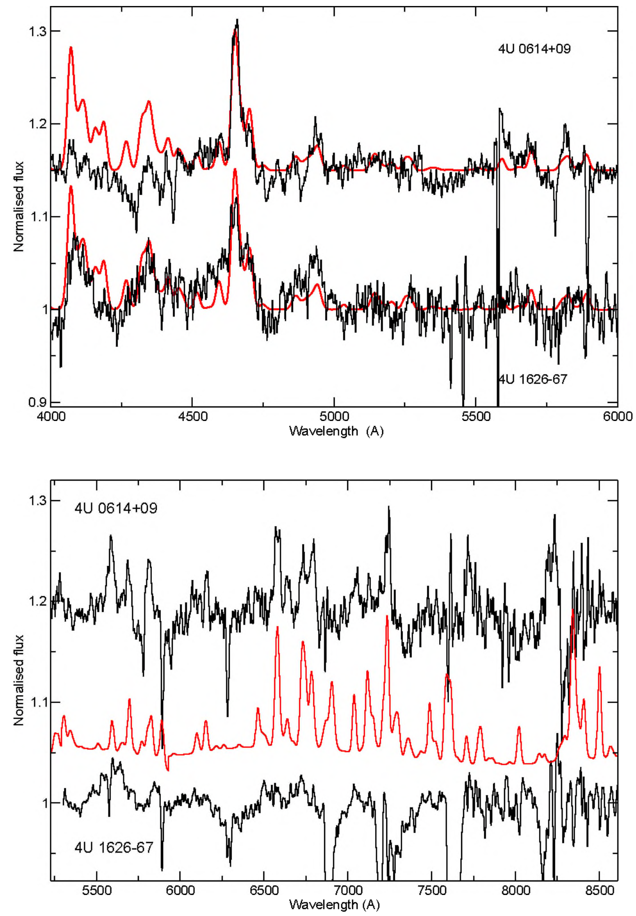

Figure 2. Normalised spectra of 4U 1626-67 and 4U 0614+09. Below 4500Å the spectrum of 4U 1626-67 follows the LTE model of a C/O disc that fitted our previous spectra of 4U 0614+09 (with wavelengths above 4600Å) much better than 4U 0614+09 itself. In the red part of the spectrum we plot the model which we used for the line identification of 4U 0614+09 in the middle. Most features are C features and are weaker in 4U 1626-67.

solar abundance which has been processed through the CNO cycle. The most prominent lines are from HeI, HeII, NII and NIII, and are listed in Table 1. In the figure we also plot a model with the same He and N abundance, but with the elements heavier than Ne at solar abundance. Although there are some small differences, it is not possible to determine the original metallicity of the donor. However, if the high N abundance is true, an initially high metallicity is likely.

We conclude that the detection of a He dominated accretion disk spectrum provides the first direct evidence for a helium donor in an UCXB.

3.2 The known UCXB 4U 1626-67 compared to 4U 0614-09

We obtained spectra of the 42 min. binary 4U 1626-67, which harbours a 7 s X-ray pulsar (Middleditch et al. 1981), making it a very different system to the other UCXBs, which all have old, low-field neutron stars as accretors. For a discussion of the formation of this system see Yungelson et al. (2002) and references therein. The system shows strong line emission in the X-ray spectrum, which has been identified with O and Ne lines (Schulz et al. 2001). Its UV spectrum shows strong carbon and oxygen lines (Homer et al. 2002). We therefore expect the optical spectrum to show C/O lines, just as the C/O disc of 4U 0614+09 (Nelemans et al. 2004).

Three spectra were taken with the 600RI grism, one with the 600B grism. In addition we retrieved two spectra taken with the 600B grism plus four spectra taken with the 600R grism (exposure time 1735 s), and three spectra taken with the 1400V grism (exposure time 1100 s) from the ESO archive. In Nelemans & Jonker (2005) we already showed a comparison between the spectrum of 4U 1626-67 and our earlier 4U 0614+09 spectrum which looked very much like each other, in agreement with the interpretation of the donors of both these systems being C/O rich. Indeed 4U 1626-67 follows the simple C/O LTE model that we made for 4U 0614+09 reasonably well even at bluer wavelengths than our 2003 4U 0614+09 spectrum reached. However, a second spectrum of 4U 0614+09, obtained with the VLT with the same setup and wavelength coverage as our 4U 1626-67 spectrum (that we extracted from the ESO archive, see also Werner et al. 2006) clearly does *not* follow the simple LTE model! (see Fig. 2). The blue part of the 4U 0614+09 spectrum does not show the prominent (OII) features (see also Werner et al. 2006). The small plateau just blue ward of the 4640Å feature in 4U 0614+09 seems a result of the continuum normalisation (cf. Fig. 3).

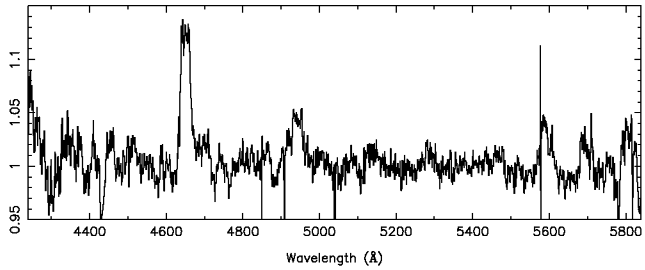

Figure 3. Average normalised spectrum of 4U 0614+09, taken with GMOS on Gemini-North.

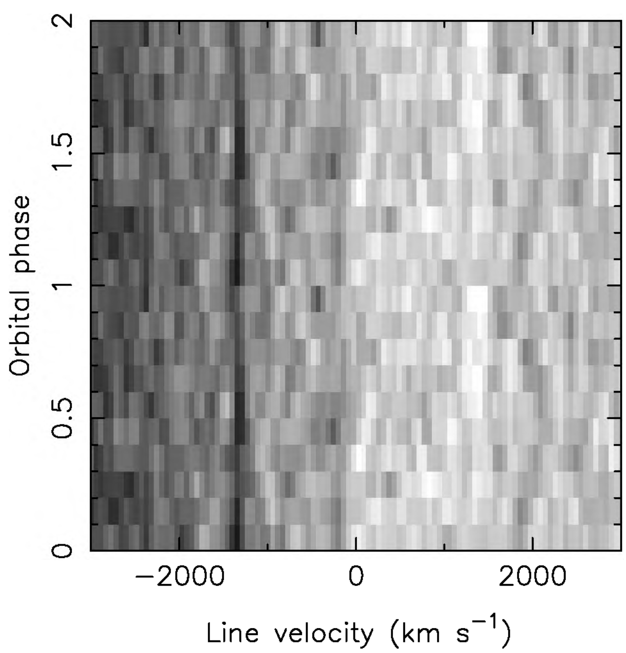

Figure 4. Trailed spectra of 4U 0614+09 around 4930Å folded on a period of 48.547 min., showing a sinusoidal velocity variation in weak line around 4960Å (CI 4959?) visible at ∼+2000 km s^{-1}. The amplitude of the variation is 190 km s^{-1}, which implies an inclination of about 15° for a neutron star mass of 1.4 $M_{\odot}$. The feature around −1700 km s^{-1} is the result of an artifact in the CCD.

In Fig. 3 we show the average spectrum of 4U 0614+09 from all 52 spectra taken with GMOS on Gemini-North. The spectrum shows the same features as the VLT spectra (Fig. 2). We used the GMOS spectra to look for variability in the line profiles on short timescales in order to search for signals of the orbital period. We produced periodograms of the data for the range of expected periods, but no periodic signals were found.

Another way to pick up coherent patterns in a variable environment is to search by eye. We used a utility (kindly provided to us by Gijs Roelofs) which shows movies of trailed spectrograms, folded at slowly varying periods. In this way we browsed through the data, without finding a clear periodic signature. The most convincing possible period is 48.547 min, which produces a rather nice sinusoidal pattern in a weak absorption line around 4960Å (possibly CI 4958.7Å), as shown in Fig. 4 (at velocity +2000 km s^{-1}). However, the significance of this "detection" is marginal at best and has been found after many hundreds of trial periods. Interestingly, this period fits in rather well with the period of 50 min. suggested recently based on photometric ULTRACAM data (O'Brien et al. 2005). If these periods are true the latter period would be a super-

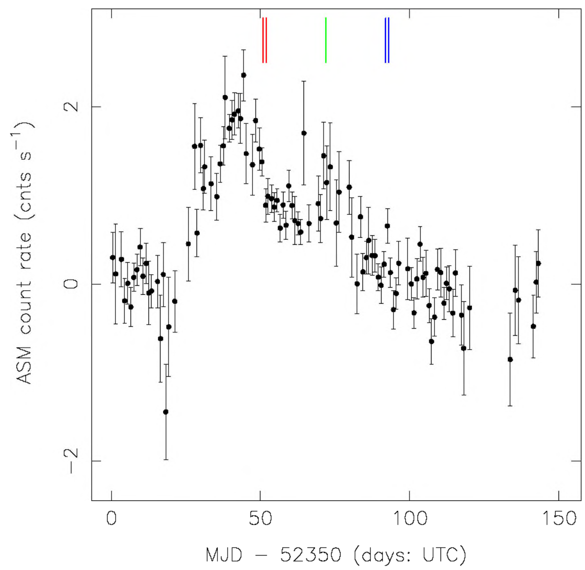

Figure 5. X-ray light curve of XTE J0929-314 from the RXTE All sky monitor. The dates of the optical observations are indicated at the top of the plot (left to right): ESO 3.6m EFOSC observations, VLT UVES observations and VLT FORS2 observations.

hump period, just above the orbital period. The amplitude of the velocity variation is 190 km s^{-1}, which if it originates in the donor and with the assumption of a ∼ 50 min orbital period gives a mass function of 0.025. Assuming a neutron star mass of 1.4 $M_{\odot}$ and a companion star that has a much lower mass, this implies an inclination of 15° which is rather low.

3.3 XTE J0929-314

XTE J0929-314 is one of the three transient UCXBs and was discovered in 2002 (Remillard et al. 2002). It has an orbital period of 44 min (Galloway et al. 2002). The X-ray lightcurve is shown in Fig. 5. The system showed X-ray pulsations at 185 Hz during the outburst (Remillard et al. 2002). Near the peak of the X-ray outburst a spectrum was taken with the ESO 3.6m telescope in which emission at Hα and around 4650Å was reported (Castro-Tirado et al. 2002). In particular the Hα emission is important, since this would clearly point to a donor which still has some hydrogen left (see Sect. 4). However, the evidence for Hα emission is rather weak as is shown in Fig. 6, where we display the spectra. The formal significance of the Hα emission is 3σ, but one has to keep in mind that there are many emission lines in the night sky around Hα that could lead to systematic errors. There is clearly significant emission around 4650Å as seen in Fig. 7. This is reminiscent of the strong emission seen in the spectrum of the C/O accretion disc of 4U 0614+09 (Nelemans et al. 2004), but also similar to the He + N spectrum of 4U 1916-05 discussed above. Because the peak spectra of XTE J0929-314 are not of very high quality it is difficult to distinguish, so as bracketing models, we plot in Fig. 7 LTE models of a C/O disc (with the same parameters as 4U 0614+09: a 27,000 K slab of 30 per cent C and 70 per cent O) and a disc consisting of He and N with the same parameters as 4U 1916-05 (3 per cent N by number). The spectrum is not good enough to determine the composition, although the lack of emission around 4500Å suggests a C/O donor. Between 4250 and 4400Å there are hints of emission, and possibly absorption around 4300Å. However, these features are not significant.

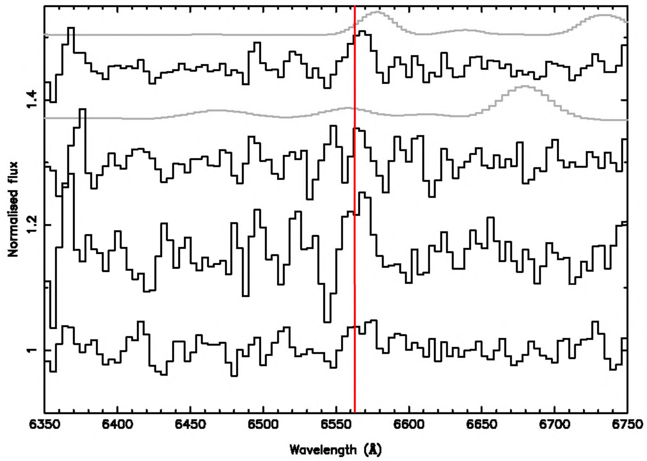

Figure 6. Region around Hα of the outburst spectrum of XTE J0929-314 on the basis of which Castro-Tirado et al. (2002) claim Hα emission which would contradict the interpretation of the donors as white dwarfs. The 3 individual spectra are shown at the bottom, the average as the top spectrum. The LTE models shown in Fig. 7 are shown in grey.

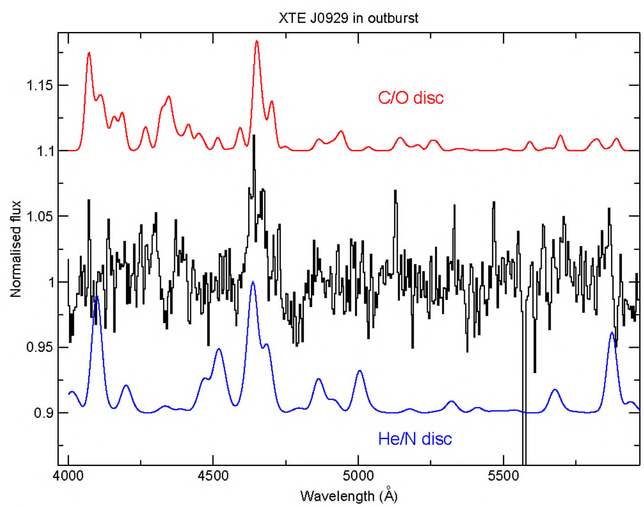

Figure 7. Spectrum of XTE J0929-314 taken close to the peak of the X-ray outburst. Also shown are LTE models for a C/O (top) and a He/N (bottom) disc are shown.

In order to see if a more quantitative criterion can be used we determined the equivalent widths (EWs) of the strongest line complex in our spectra: the range 4500-4700Å, which includes the strong NIII feature around 4515Å seen in 4U 1916-05. The EW of 4U 1916-05 is 15Å, while the EWs of the other systems are: 4U 0614+09, 4Å for the GMOS spectrum and 9Å for the VLT spectrum, 4U 1626-67 10 and 11 for the two VLT spectra and for XTE J0929-314 again 4Å. Formal errors on these measurements are all less than 0.5Å. Although 4U 1916-05 has the largest EW in the wide range, there is no clear gap between the EW values of C/O and He/N discs. And we note that close inspection of the three spectra we have of 4U 0614+09 show that differences in continuum normalisation cause large systematic errors on the obtained EWs, thus hampering this method. Despite all this, based on the EWs we again tentatively classify XTE J0929-314 as a C/O system.

After the discovery of XTE J0929-314 we requested VLT DDT observations to study the transient during the outburst (see Fig. 5 for the X-ray light curve with the times of our optical observations indicated). We first attempted UVES observations (on 27 May 2002), but it became soon clear that the target had faded too much. We therefore changed to FORS2 observations. Unfortunately when the observations were done (16/17 June 2002) the source again had faded and the spectra show no clear features. From Giles et al. (2005) we derive the I-band magnitudes on the dates of our observations as 18.5 (EFOSC), 19.5 (UVES), 20.1 (FORS2).

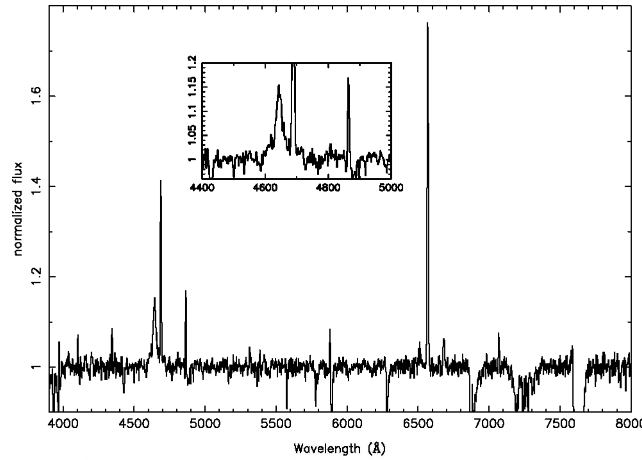

Figure 8. Normalised spectrum of 4U 1556-60, showing strong H and HeII emission, plus the Bowen blend at 4640Å.

3.4 4U 1556-60

The source 4U 1556-60 was selected as a candidate UCXB based on the suggested "Ne feature" in its X-ray spectrum (Farinelli et al. 2003). This feature was discussed in the context of finding UCXBs by Juett et al. (2001), who noted a similarity in the X-ray spectra of several X-ray binaries, among which the known 20 min UCXB 4U 1850-087. They interpreted this feature around 0.7 keV as an indication of enhanced Ne in the transferred material. In addition, earlier optical spectra of 4U 1556-60 (Cowley et al. 1988; Motch et al. 1989) show strong emission between 4600 and 4700Å, but no Hβ and only weak emission around Hα, similar to our spectrum of 4U 0614+09 (except of course for the Hα). We obtained four 600B and one 600RI spectra for this object. In Fig. 8 we show the normalised, averaged VLT spectrum of 4U 1556-60 which shows a classical low-mass X-ray binary spectrum with strong Balmer lines (4101, 4340, 4961 and 6563 Å) and lines from HeII (4686 (very strong), 5411 and 6678 Å). The equivalent width of the Hα line is 7.8Å and its FWHM is 540 km s^{-1}. There is also strong emission at the Bowen blend, a C and N complex around 4640Å that is driven by He fluorescence. This system thus probably is not an UCXB, suggesting that the "Ne feature" is not a unique property of UCXBs.

3.5 4U 1822-00

The optical counterpart of 4U 1822-000 is a V=22 object (Chevalier & Ilovaisky 1985). Due to its relatively high Galactic latitude (b=5.8 degrees) the extinction towards the source is low. Even for a distance of 20 kpc, the absolute magnitude would be 5.5. Such a faint absolute magnitude suggests a short orbital period, because the optical emission originates in an irradiated disc for which

Table 2. Overview of some properties of UCXB (candidates). Data from Nelemans & Jonker (2006) and references therein.

Name	Period (min)	Persistent/ Transient	Spec
4U 1543-624	18(?)	P	C/O
XTE J1807-294	40	T	-
4U 1626-67	42	P	C/O
XTE J1751-305	42	T	-
XTE J0929-314	44	T	C/O?
4U 1916-05	50	P	He/N
4U 0614+09	50?	P	C/O
2S 0918-549	?	P	He?
4U 1822-00	?	P	?
XB 1905+000	?	T	-

the brightness depends mainly on the *size* of the disc, which scales with the orbital period (van Paradijs & McClintock 1994). We obtained three 600B and four 600RI spectra, but due to the faintness of 4U 1822-00 its spectrum is of low quality. However, just as with 2S 0918-549 (Nelemans et al. 2004), the spectrum does not show hydrogen or helium lines, making it clearly different from the spectra of hydrogen rich systems. Provisionally we classify this system as an UCXB, but with the current results not more can be said about the nature of the donor.

3.6 XB 1905+00

With an optical counterpart of V=20.5 and distance of $\sim$8kpc, i.e. M_V= 4.9 (Chevalier & Ilovaisky 1985), this source is again at the faint end of the absolute magnitude distribution and thus a good candidate. The spectrum of XB 1905+00 shows the standard features of an early G star. As already discussed in Nelemans & Jonker (2005), this puzzling result is possibly due to a chance alignment. The acquisition image of the object obtained with a seeing of 0.6 arcsec suggest the source actually is a blend of two objects. A detailed discussion of recent X-ray and optical observations suggests that the optical counterpart has faded beyond detection and neither of the objects is the actual counterpart (Jonker et al. 2006).

4 DISCUSSION

We have, by now, collected spectra of seven UCXB (candidates) in the field, which we list in Table 2. We also list the chemical composition we have derived from these spectra. We obtained the first optical spectrum of a He transferring UCXB, XB 1916-05. However, the spectrum does not look at all like we had anticipated, i.e. with strong helium emission lines, like the spectra of AM CVn stars ES Cet and GP Com (e.g. Warner & Woudt 2002; Morales-Rueda et al. 2003). This means that really high S/N spectra are needed to determine the chemical composition of the donors and that our conclusion in Nelemans et al. (2004) that 2S 0918-549 most likely has a C/O donor due to the lack of strong helium emission lines was premature. Indeed, in't Zand et al. (2005) suggest a helium donor is more likely because of the properties of its X-ray bursts. It does show, however, that if there is He in the disc, it shows up in the lines, so we are rather confident that our earlier conclusions about the existence of pure C/O discs still hold. Indeed from the LTE models, but also from recent efforts modelling NLTE disc spectra (Werner et al. 2004, 2006) it is unlikely that H or He are hidden in these C/O discs.

In summary we have obtained spectra of 7 UCXB (candidates) and have found 3 cases of a C/O donor (plus one, possibly), one of a He/N donor (plus one, possibly), and two cases where we cannot determine the chemical composition. Before turning to the interpretation of these results we discuss some caveats in the determination of these compositions.

4.1 LTE modelling

Our chemical composition results are based on modelling of the accretion disc as very simple, single temperature, homogeneous, slabs of material for which we calculate the LTE spectrum. In real life these accretion discs are likely multi-temperature and NLTE effects almost certainly are important. Even worse, these discs are irradiated by the strong X-ray emission originating around the neutron star. Therefore it is surprising that the LTE models reproduce the observed spectra reasonably well. Indeed, contrary to what one would expect for these strongly irradiated discs, we see remarkably little evidence for highly ionised species of the elements which would be produced by photo-ionisation. Recently efforts have started to produce more realistic, NLTE spectral models of UCXBs (Werner et al. 2004, 2006). Unfortunately, the current models, although reproducing the observed spectra qualitatively do not provide quantitative results as it currently is not possible to fit all observed features simultaneously, either due to incompleteness in the radiation transfer physics or in the accretion disc physics. Until these discrepancies are resolved, we have to live with significant uncertainties in the derived chemical compositions.

4.2 Formation of UCXBs and their Galactic population

The main aim of this investigation is to use the determined chemical composition of the donor stars in UCXBs to constrain the possible formation channels and to come to a better understanding of the evolution of ultra-compact binaries and their Galactic population.

For a detailed discussion of the formation of ultra-compact binaries in the field we refer to Nelson et al. (1986); Nelemans et al. (2001); Podsiadlowski et al. (2002) and references therein. In short there are three routes, differentiated by the nature of the donor star: (i) a white dwarf donor when a detached binary with a white dwarf and a compact object comes into contact due to angular momentum losses via gravitational-wave radiation; (ii) a (semi-degenerate) helium star donor that evolved from a helium core burning star that filled its Roche lobe to a compact object and (iii) the core of a star that filled its Roche lobe to a compact object at the end of the main sequence and thus has a helium rich core (see also van der Sluys et al. 2005). In globular clusters the formation of X-ray binaries is probably dominated by dynamical interactions (see Verbunt 2005). Based on the inferred mass transfer rated of 4U 1626-67 and 4U 1916-05 Nelson et al. (1986) suggested evolved secondaries as donors in these systems.

These different formation scenarios result in principle in different chemical compositions which is one of the reasons for our study, but there is some overlap. The three formation scenarios will yield the following chemical composition:

- White dwarf donors: depending on the nature of the white dwarf the transferred material will be mainly He with CNO processed (i.e. mainly N) material for a He-core white dwarf, or a C/O mixture in case the donor is a C/O-core white dwarf.

- Helium star donor: He with little N, plus possibly helium burning products (i.e. C and O) depending on the amount of helium burning that has taken place before the donors fills its Roche lobe.
- Evolved secondaries: He plus CNO processed material and, depending on the exact evolutionary history and the phase of the evolution, some H.

In this light we can interpret the observed UCXBs. The possible presence of H in the peak spectrum of XTE J0929-314 is very important as only the third formation scenario can comfortable explain this. White dwarfs and helium stars do have a thin H envelope before they fill their Roche lobes, but this is typically expected to be at most 0.01 $M_{\odot}$ (likely less, but rather uncertain if the preceding evolution was through a common-envelope phase) and thus would only produce H in the very early phase of the mass transfer, unless it is mixed efficiently with the rest of the star which certainly for white dwarfs is not expected.

Apart maybe from XTE J0929-314 all observed spectra seem to be consistent with white dwarf donors, at odds with the conclusions of Nelson et al. (1986) and indeed with the inferred mass-transfer rates, *if these represent the average mass-transfer rate over an astronomical timescale*. In particular for the C/O spectra, where there is no hint of He, C/O white dwarf donors seem the only option. This is important, because according to this formation channel the systems first evolve to very short orbital periods (of a few min.) and then start mass transfer and evolve to longer periods again. The progenitors of the C/O donor systems are thus very strong gravitational wave sources for LISA (e.g. Nelemans 2003). The known UCXBs might already be guaranteed sources for LISA and thus be used as verification sources for the instrument (see Phinney 2002; Nelemans 2005). However, for many of the systems the orbital periods still have to be determined. This should therefore have a high priority.

A second ingredient that will become very important in disentangling the formation of UCXBs is the relative number of C/O vs He systems. Although for He systems the formation channel is uncertain, it is interesting to determine this ratio. For instance, it is telling that the fact that currently the majority of the systems with known chemical composition have C/O donors, while in the very related family of AM CVn stars (ultra-compact binaries which have white dwarf instead of neutron star accretors, see Nelemans 2005, for a recent review) only He donors are known. Based on the stability of mass transfer at the very short periods only low-mass donors are expected to be present (e.g. Nelemans et al. 2001; Yungelson et al. 2002) which would preferentially select He donors. Belczynski & Taam (2004) simulated the Galactic population of UCXBs and predict 60 per cent of the donors to be He rich. Apparently in UCXBs there is an evolutionary or an observational bias towards C/O donors. Only better statistics can tell. One of the important tools here will be optical spectroscopy of UCXB transients when they are in outburst.

Another important aspect of UCXBs is the distribution of persistent vs transient systems (see Table 2). Evolutionary calculations combined with disc instability models predicts that for UCXBs that have (semi) degenerate donors systems with periods longer than about 30 min are transient, while shorter period systems are persistent X-ray sources (see Deloye & Bildsten 2003). It is already clear that the observed systems do not follow this prediction (2 or 3 persistent systems have periods above 30 min), suggesting either incompleteness in the disc instability model or a different formation channel, which produces higher mass transfer rates at long periods. We note however, that the classical division between transient and persistent sources is beginning to be complicated by systems such as XB 1905+00 which after 11 years of "persistent" emission has returned to quiescence.

All UCXBs in the field for which we know the orbital period have periods between 40 and 50 min, except perhaps 4U 1543-624. On evolutionary grounds most systems are expected at long periods (e.g. Deloye & Bildsten 2003), but the mass transfer rates are also lower, making them fainter. In addition, the transient nature of longer period systems might make them easier to find. Still, the period distribution of UCXBs looks quite different from the distribution of periods in AM CVn systems, where 11 out of the 13 systems with known periods have periods below 40 min (see Nelemans 2005; Woudt et al. 2005; Anderson et al. 2005). However, the expected total active population of UCXBs in the field is small (e.g. Belczynski & Taam 2004), so small number statistics may dominate this discussion.

Finally, when it will be possible to obtain high quality spectra and obtain detailed, quantitative chemical compositions of the accretion disc through reliable spectral modelling we can use these to study the interior composition of the donor stars at different phases in their evolution which will open a new era in the study of stellar structure.

5 CONCLUSIONS

We have presented optical spectroscopy of (candidate) UCXBs and conclude that with the current (lack of) understanding of the spectra of hydrogen-poor accretion disc spectra we cannot make quantitative statements about the detailed chemical abundances of the donors stars in UCXBs, only determine the global chemical composition. We have obtained the first optical spectrum of a He dominated disc in an UCXB, XB 1916-05, implying a He-rich donor in this system. A simple LTE model suggests that the N abundance in this systems is strongly enhanced. We furthermore confirm the C/O nature of the donor stars in 4U 0614+09 and 4U 1626-67, and suggest the donor in XTE J0929-314 is a C/O white dwarf as well. Within the current sample the majority of the donors are C/O rich. This suggests that in UCXBs there is an evolutionary or observational bias towards C/O donors. Phase resolved spectroscopy of 4U 0614+09 does not reveal a clear periodicity, although there seem to be line variations at short time scales. We did not detect the optical counterpart of XB 1905+00 and found that the candidate UCXB 4U 1556-60 shows strong H emission and thus is not an UCXB but an ordinary low-mass X-ray binary.

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