Optical spectroscopy of (candidate) ultra-compact X-ray binaries

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Abstract. We present (preliminary) results of our systematic spectroscopic study of (candidate) ultra-compact X-ray binaries. Most candidates are confirmed and we found the first optical spectra of (pure) carbon-oxygen accretion discs.

INTRODUCTION

Ultra-compact X-ray binaries (UCXBs) are close binaries with periods less than about one hour, in which a neutron star (or possibly a black hole) accretes material from a companion star. Their short periods rule out ordinary hydrogen-rich companion stars, since these stars are too big; they do not fit in the Roche lobe [e.g. 1].

In recent years a renewed interest has developed in these systems for a number of reasons. Improved observing facilities (e.g. large optical telescopes and sensitive X-ray satellites) make it possible to study them in more detail. But more importantly the number of known systems has increased. In particular the discovery of three transient UCXBs [e.g. 2, 3, 4] in which the millisecond pulsations of the accreting neutron star were seen, has been an exciting development.

We have started a systematic spectroscopic study of known and candidate UCXBs (excluding systems in globular clusters) in order to confirm/reject the candidates, to constrain possible formation scenarios and to open the way to study the chemically peculiar accretion process that is expected to operate in these binaries.

CURRENT OPEN QUESTIONS

The formation of UCXBs has been proposed through three channels, in which the donor stars are either white dwarfs, helium stars, or the remnants of evolved main sequence stars [see 5, and references therein]. However, there are still many open questions about UCXBs. One of the first priorities is to increase the number of known systems and to find their orbital periods. Besides the orbital period there are a number of properties that indicate that a particular system could be an UCXB. Van Paradijs and McClintock [6] studied the absolute magnitudes of X-ray binaries and derived a relation between the absolute magnitude, the orbital period and the X-ray luminosity, based on the assumption...
that the absolute magnitude is dominated by the irradiated accretion disc, whose surface is determined by the size of the binary, i.e. the orbital period. They empirically gauged this relation. Systems with absolute magnitudes fainter than about $M_V = 4$ have a good chance to be UCXBs.

Juett et al. [8] found features in the X-ray spectrum of the 20 min UCXB 4U 1850-087, which they attributed to enhanced Ne in the system and found similar features in 3 other systems, making them good UCXB candidates. In Table 1 we list our selection of candidates, based either on their absolute magnitudes or the presence of the “Ne feature”.

Optical spectroscopy of UCXBs might also be a good way to study the formation of UCXBs, as the different formation scenarios will lead to different chemical composition of the transferred material and thus of the accretion disc. The first constraints on the chemical composition have come from the properties of the type I X-ray bursts observed from the 11 min globular cluster sources 4U 1820-30, suggesting helium rich material [9]. In the following section we will describe the results of our observations, which are already summarized in the last column of the table.

### OPTICAL SPECTROSCOPY: RESULTS

**The VLT and FORS2**

We used the FORS2 spectrograph on the 8.2m Very Large Telescope (VLT) of the European Southern Observatory at Paranal to obtain optical spectra of our candidate UCXBs. The observations were taken in the spring of 2003 and 2004. In 2003 we used the 1400V and 600RI holographic grisms, with a 1” slit, using 2x2 on-chip binning. This setup resulted in coverage of 4620 – 5930 Å with mean dispersion of 0.64 Å/pix for the 1400V spectra and 5290 – 8620 Å with mean dispersion of 1.63 Å/pix for the 600RI spectra. The 2004 spectra are taken with the 600B and 600RI grisms. The 600B grism covers the range 3325 – 6367Å with dispersion of 1.48 Å/pix. All spectra were reduced using standard IRAF tasks.

<table>
<thead>
<tr>
<th>Name</th>
<th>Period (min)</th>
<th>Ne</th>
<th>$M_V$ confirmed?</th>
</tr>
</thead>
<tbody>
<tr>
<td>4U 1543-624</td>
<td>18a</td>
<td>y</td>
<td>✓</td>
</tr>
<tr>
<td>4U 0614+09</td>
<td>?</td>
<td>y</td>
<td>5.4</td>
</tr>
<tr>
<td>2S 0918-549</td>
<td>?</td>
<td>y</td>
<td>6.9</td>
</tr>
<tr>
<td>4U 1822-00</td>
<td>?</td>
<td></td>
<td>5.5</td>
</tr>
<tr>
<td>4U 1556-605</td>
<td>?</td>
<td>y</td>
<td>4.9</td>
</tr>
<tr>
<td>XB 1905+000</td>
<td>?</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$a$ Wang and Chakrabarty [7]
Wavelength (Å)

**FIGURE 1.** VLT spectra of 4U 0614+09, 4U 1543-624 and 2S 0918-549, showing lines from a carbon-oxygen accretion disc. From Nelemans et al. [10]

The results of our 2003 programme are published in Nelemans et al. [10] and are summarized in Fig. 1. We identified the features in the spectrum of 4U 0614+09 as relatively low ionization states of carbon and oxygen. This clearly identifies this system as an UCXB and suggests the donor in this system is a carbon-oxygen white dwarf. The similarity of the spectrum of 4U 1543-624 suggests it is a similar system, while for 2S 0918-549 the spectrum didn’t have a high enough S/N ratio to draw firm conclusions, but is also consistent with being a similar system (and clearly does not show the characteristic strong hydrogen emission lines of low-mass X-ray binaries). We therefore concluded that all these systems are UCXBs.

**4U 0614+09, 4U 1543-624 and 2S 0918-549**

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

In Fig. 2 we compare the blue part of our 4U 0614+09 spectrum with the VLT spectrum of the 42 min. binary 4U 1626-67, which harbours a 7 sec X-ray pulsar [11]. The similarities are remarkable. This is interesting, as strong line emission in the X-ray spectrum of 4U 1626-67 has been identified with O and Ne lines [12].
The preliminary 2004 results

The results of the 2004 programme will be published in a forthcoming paper, but we will give some preliminary results here.

4U 1822-00

Due to the faintness of 4U 1822-00 its spectrum is of low quality. However, just as with 2S 0918-549, 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.

4U 1556-60

Based on its “Ne feature” 4U 1556-60 is a good UCXB candidate. However, its optical spectrum (Fig. 3) 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). 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.
FIGURE 3. Normalized spectrum of 4U 1556-60, showing strong H and HeII emission, plus the Bowen blend at 4640Å.

**XB 1905+00**

The spectrum of XB 1905+00 shows the standard features of an early G star. 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. In that case the optical counterpart of XB 1905+00 would be the fainter of the two stars. Note that this system was in quiescence at the time of our observation, making the counterpart much fainter than when it was found by Chevalier and Ilovaisky [13].

*The known UCXB XB 1916-05*

In Fig. 4 we show the spectrum of the 50 min UCXB XB 1916-05. Again it shows some features that are very similar to the spectra of 4U 0614+09 and 4U 1626-67, but in addition broad emission around 4540Å. A possible origin could be He, as there is a HeII line at 4541Å. Some of the other features also coincide roughly with positions of HeII lines, but these are very close (within a few Å) of the Balmer lines, making identification very difficult.

**CONCLUSIONS**

We have started a systematic study of the optical spectra of known and candidate UCXBs. The first results are both interesting and promising: we have confirmed the
FIGURE 4. Normalized (and rebinned) spectrum of the known UCXB XB 1916-05, showing broad features, like 4U 0614, but possibly also hints of He and H emission.

ultra-compact nature of many of the candidates and have uncovered a variety of optical spectra, from pure carbon-oxygen spectra to spectra probably still showing signs of helium (and possibly hydrogen). One candidate (4U 1556-60) shows a classical low-mass X-ray binary spectrum, making it unlikely that this system is an UCXB. The faintness of these systems makes spectroscopic period determination almost impossible, so that periods will have to be found photometrically, as was recently done with 4U 1543-624 [7].

REFERENCES