Hydrogen-Deficient Stars
ASP Conference Series, Vol. xxx, 2008
Werner & Rauch

Hydrogen deficient donors in low-mass X-ray binaries

Gijs Nelemans

Department of Astrophysics, IMAPP, Radboud University, Nijmegen, the Netherlands

Abstract. A number of X-ray binaries (neutron stars or black holes accreting from a companion star) have such short orbital periods that ordinary, hydrogen rich, stars do not fit in. Instead the mass-losing star must be a compact, evolved star, leading to the transfer of hydrogen deficient material to the neutron star. I discuss the current knowledge of these objects, with focus on optical spectroscopy.

1. Introduction: how to get hydrogen deficient donors

In low-mass X-ray binaries (LMXBs) a compact object (either a neutron star or a black hole) accretes material from a companion star. In the process, copious X-rays are produced, making these objects visible to large (many kpc) distances. Distinction based on the mass of the donor is made between high-mass and low-mass X-ray binaries (see various chapters in Lewin & van der Klis 2006). Combining Kepler's law and approximations to the maximum volume a star can occupy before starting to transfer mass to a companion (the Roche lobe), the following equality can be derived for stars that exactly fill their Roche lobe (e.g. Verbunt & van den Heuvel 1995)

$$P_{\rm orbital} \approx 9{\rm hr} \left(\frac{\rho}{\rho_{\odot}}\right)^{-1/2} \tag{1}$$

which together with the fact that the maximum density of hydrogen rich stars (around the hydrogen burning limit) is about 100 gr/cc, implies orbital periods for LMXBs with hydrogen rich donors larger than about 1 hour. Reversing the argument: any LMXB with a shorter orbital period necessarily has a donor star that is more compact that a main sequence star and thus (in view of the evolution of stellar cores) is hydrogen deficient (see Nelson et al. 1986). Therefore these short period LMXBs have a special status and are called Ultra-compact X-ray binaries (UCXBs). For a short review see Nelemans & Jonker (2006). The current known sample consists of 27 systems, 8 with known periods, 4 with tentative periods and 15 candidate systems (see in't Zand et al. 2007).

2. Formation of ultra-compact (X-ray) binaries

For a detailed discussion of the formation of UCXBs (and by analogy their cousins with white dwarf accretors, the AM CVn systems, see Marsh's contribution to this volume) I refer to Pringle & Webbink (1975); Nelson et al. (1986);

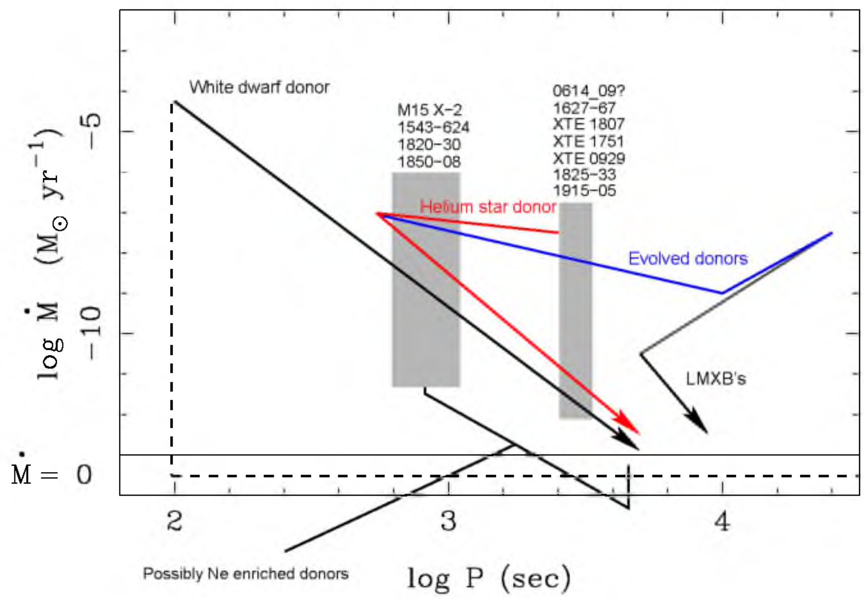

Figure 1. Formation paths of UCXBs stars (see text). The known systems are shown at their orbital period.

Savonije et al. (1986); Tutukov et al. (1987); Nelemans et al. (2001); Podsiadlowski et al. (2002); Yungelson et al. (2002); van der Sluys et al. (2005). There are three routes for the formation of ultra-compact systems (see Fig. 1): (i) via a phase in which a white dwarf – neutron stars binary or a double white dwarf loses angular momentum due to gravitational wave radiation and evolves to shorter and shorter periods to start mass transfer at periods of a few minutes after which it evolves to longer periods with ever dropping mass-transfer rate (e.g. Tutukov & Yungelson 1979). (ii) Via a phase in which a low-mass, non-degenerate helium star transfers matter to a neutron star or white dwarf accretor evolving through a period minimum of about ten minutes, when the helium star becomes semi-degenerate. After this minimum, the periods increase again with strongly decreasing mass-transfer rate (Savonije et al. 1986). (iii) From LMXBs (or cataclysmic variables) with evolved secondaries (Tutukov et al. 1987), which, after mass loss of the evolved star has uncovered the He-rich core, evolve rather similar to the helium star tracks. These formation paths are depicted in Fig. 1, together with the observed UCXBs at their orbital periods. It is clear that in order to distinguish between the different evolutionary scenarios, more information than the orbital period is needed and that for the currently observed systems all formation scenarios in principle are viable.

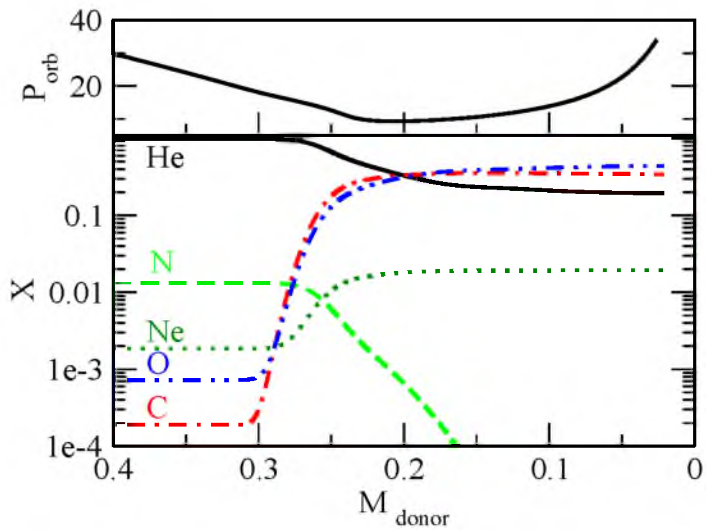

Figure 2. Orbital period (top) and chemical composition (bottom) as function of donor mass (and thus time, running from left to right) for a helium star donor that has burnt most of its helium before mass transfer starts. Solid line: He, dashed: N, dash-dot: C, dash-dot-dot: O, dotted: Ne.

3. Chemical composition of the donor

In order to distinguish the different formation channels, the chemical composition of the donor star is needed. For the three channels described above the expected chemical compositions are:

White dwarf channel 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 channel 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 order to asses the likelihood of helium burning products to show up in the transferred material in helium star donors, Lev Yungelson and I started a study of these stars. In Fig. 2 we show one example, for a case where the helium star has burnt most of its helium before the mass transfer starts. Rapidly the helium burning products (C, O Ne) become visible. Details will be presented elsewhere (Nelemans & Yungelson, in prep.) The question now is, whether observations can tell us the chemical composition of the donors.

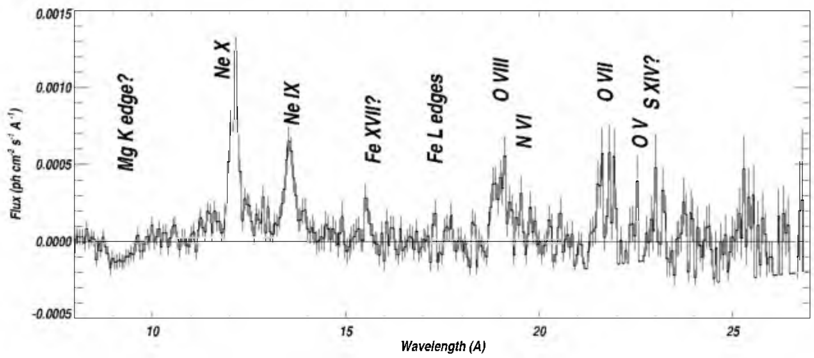

Figure 3. X-ray spectrum of 4U 1626-67 showing double peaked lines of O and Ne. From Schulz et al. (2001)

4. Observational results (optical/X-ray)

X-ray spectra

The X-ray spectra lacked resolution until recent observations obtained with the gratings on board the *Chandra* satellite. The X–ray spectra are difficult to interpret due to the lack of clear emission features (except in the 7s accreting pulsar 4U 1626-67 which shows strong O and Ne emission lines in its X-ray spectrum, Schulz et al. (2001) see Fig. 3) and contributions of interstellar absorption. A number of UCXBs have been (first) identified based on their X-ray spectra, when Juett et al. (2001) noted a similarity between the spectrum of 4U 1850-087 and three more LMXBs. The common feature in the X-ray spectra was suggested to be due to an enhancement of neon in these systems, however, this is uncertain (e.g. Juett & Chakrabarty 2003; Werner et al. 2006). These observations were interpreted as evidence for the donors being ONe, or more likely CO white dwarfs in which Ne has sunk to the core in an earlier evolutionary phase and is now exposed, after accretion has peeled–off the outer layers (Yungelson et al. 2002). Recently it has been noted that if it is really the O/Ne ratio that is anomalous, and not the Ne abundance itself, this points towards a He white dwarf donor, in which the O abundance is strongly reduced due to CNO processing (in't Zand et al. 2005). Interestingly, one system that shows a similar feature in its X-ray spectrum (4U 1556-605 Farinelli et al. 2003), shows strong hydrogen and helium emission in its optical spectrum, suggesting that it is not an UCXB (Nelemans et al. 2006).

Type I X-ray bursts

For a number of UCXBs type I X-ray bursts have been found, especially for the ones in globular clusters, but that may be a selection effect. The peculiar chemical composition of the accreting material will influence the burst properties and in principle can give an extra tool to study the chemical composition (e.g. Cumming & Bildsten 2001). Recently a number of peculiar bursts have been observed in 2S 0918-549 and 4U 0614+09 (in't Zand et al. 2005; Kuulkers 2005) which in't Zand et al. (2005) suggest are due to thick layers of He that are burned. It is clear that there is still uncertainty how we should interpret the

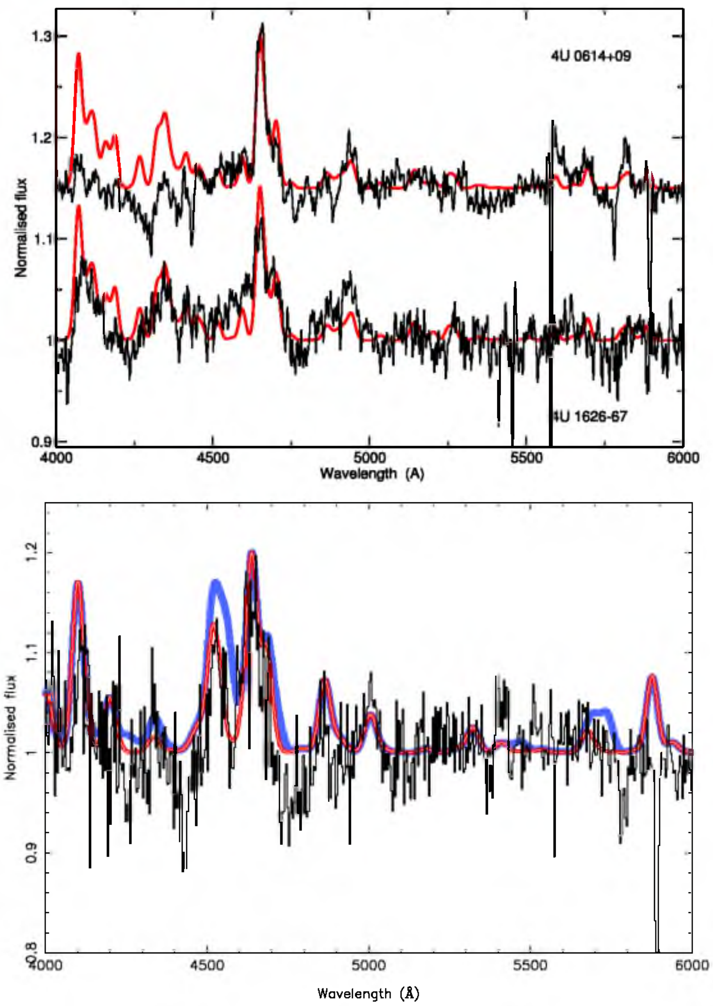

Figure 4. Optical spectra of 4U 0614+09 and 4U 1626-67 (top, with LTE C/O disc models) and 4U 1916-05 (bottom, with LTE He + N disc model). See Nelemans et al. (2006) for more details.

different pieces of information, because in some cases the bursts and the optical spectra suggest conflicting compositions as we will discuss below!

Spectra

With the advent of 8m class telescopes it has become possible to obtain optical spectra of some (candidate) UCXBs. We started a systematic spectroscopic study of (candidate) UCXBs using the VLT. The main aim was to confirm/reject candidates and to study the chemical composition of the donors stars in these systems. The first results are published in Nelemans et al. (2004) and can be summarised as follows. We identified the features in the spectrum of 4U 0614+09 as relatively low ionisation states of carbon and oxygen. This clearly identifies this system as an UCXB and suggests the donor in this system is a carbon-

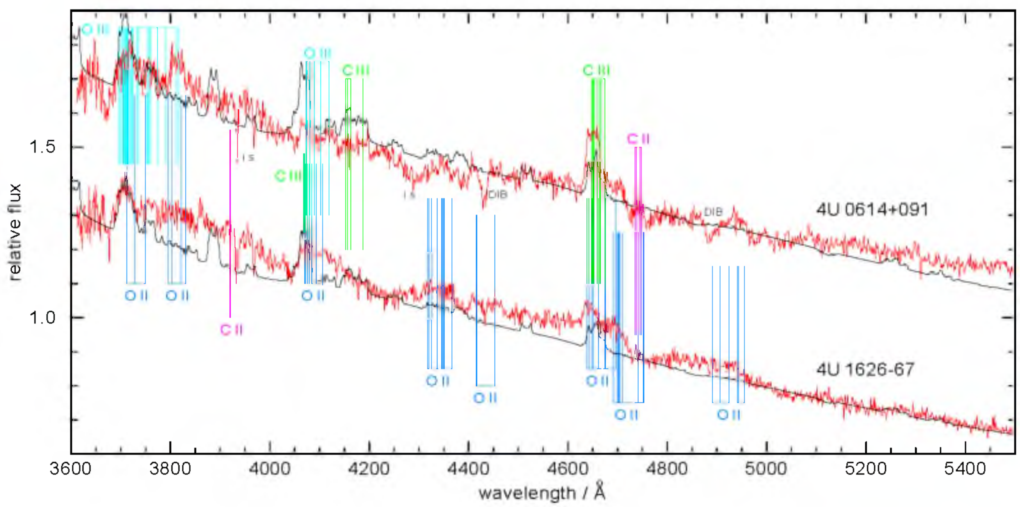

Figure 5. Optical spectra and detailed NLTE models for 4U 0614+09 and 4U 1626-67 from Werner et al. (2006).

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 it is also is 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. The second set of observations is presented in Nelemans & Jonker (2006) and Nelemans et al. (2006) and is briefly discussed here.

For two objects (4U 0614+09 and 4U 1626-67) the are clear indications that the discs are dominated by C and O (Figs. 4 (top) and 5). Werner et al. (2006) have also obtained VLT spectra of these sources and have compared these with detailed NLTE models for the spectra of UCXBs (Fig. 5). Unfortunately the NLTE models do not agree with the observed spectra in enough detail to be able to get quantitative abundances from this analysis. Surprisingly simple LTE models seem to fit better (Fig. 4), but can also not be used for quantitative measurements, as NLTE effects, mainly due to X-ray irradiation have to be important. Another surprise is that the interpretation of the donors being C and O rich is difficult to reconcile with the presence of type I X-ray bursts, as they seem to require H or He to be present (see in't Zand et al. 2005, and references therein). Either spallation of heavier elements (e.g. Bildsten et al. 1992) takes place, or there is He in addition to C and O which implies a helium star donor (see Fig. 2), or the X-ray bursts for some reason can be powered by C or O.

Another surprise came with the spectrum of 4U 1916-05, which shows similar weak lines as the other UCXBs (Fig. 4 bottom), but can best be fitted by a model consisting of He and overabundant N (again, because of the LTE nature of the model, no quantitative results can be obtained). Contrary to the He dominated spectra in AM CVn systems (see Marsh, this volume) that show very strong emission lines, the weakness of the lines makes distinction between He and C/O rich systems a matter of rather high signal-to-noise measurements.

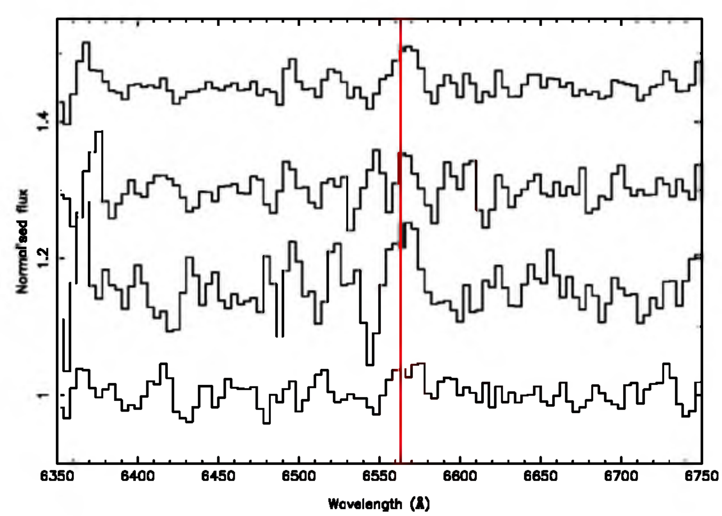

Figure 6. Optical spectra of XTE J0929-314, where the presence of Hα is claimed by Castro-Tirado et al. (2002). See Nelemans et al. (2006) for a detailed discussion.

The only object where possibly traces of hydrogen are detected is the transient XTE J0929-314 for which Castro-Tirado et al. (2002) claimed detection of Hα in spectra taken during the outburst. However, Fig. 6 shows these spectra (taken from the ESO archive) and the detection is at best marginal. This conclusion is strengthened by the fact that in the same spectra quite clear emission around 4600Å, which led us to tentatively conclude it is a C/O rich system (Nelemans et al. 2006).

5. Conclusions

Ultra-compact X-ray binaries are puzzling end products of binary evolution and despite substantial progress in recent years both in observational as well as theoretical work it is not yet clear how the observed systems are formed. The (detailed) chemical composition of the transferred material will be a key observable to distinguish different formation channels. In principle optical and X-ray spectroscopy in combination with detailed modelling of the donor stars and the disc spectra can provide this information. However of the currently 27 (candidate) systems that are know, for only 4 or 5 we know their (rough) chemical composition: 3 (or 4) C/O discs and 1 (or 2) He discs.

Acknowledgments. I wish to thank Lev Yungelson, Peter Jonker and Danny Steeghs for a lot of joint projects that form the basis of this article.

References

Bildsten, L., Salpeter, E. E., & Wasserman, I. 1992, ApJ, 384, 143
Castro-Tirado, A. J., Caccianiga, A., Gorosabel, J., et al. 2002, IAU Circ., 7895, 1
Cumming, A. & Bildsten, L. 2001, ApJ, 559, L127
Farinelli, R., Frontera, F., Masetti, N., et al. 2003, A&A, 402, 1021

in't Zand, J. J. M., Cumming, A., van der Sluys, M. V., Verbunt, F., & Pols, O. R. 2005, A&A, 441, 675
in't Zand, J. J. M., Jonker, P. G., & Markwardt, C. B. 2007, A&A, 465, 953
Juett, A. M. & Chakrabarty, D. 2003, ApJ, 499, 498
Juett, A. M., Psaltis, D., & Chakrabarty, D. 2001, ApJ, 560, L59
Kuulkers, E. 2005, The Astronomer's Telegram, 483
Lewin, W. H. G. & van der Klis, M., eds. 2006, Compact Stellar X-ray Sources (Cambridge: CUP)
Nelemans, G. & Jonker, P. 2006, New Ast. Rev., submitted, astro-ph/0605722
Nelemans, G., Jonker, P., & Steeghs, D. 2006, MNRAS, 370, 255
Nelemans, G., Jonker, P. G., Marsh, T. R., & van der Klis, M. 2004, MNRAS, 348, L7
Nelemans, G., Portegies Zwart, S. F., Verbunt, F., & Yungelson, L. R. 2001, A&A, 368, 939
Nelson, L. A., Rappaport, S. A., & Joss, P. C. 1986, ApJ, 304, 231
Podsiadlowski, P., Rappaport, S., & Pfahl, E. D. 2002, ApJ, 565, 1107
Pringle, J. E. & Webbink, R. F. 1975, MNRAS, 172, 493
Savonije, G. J., de Kool, M., & van den Heuvel, E. P. J. 1986, A&A, 155, 51
Schulz, N. S., Chakrabarty, D., Marshall, H. L., et al. 2001, ApJ, 563, 941
Tutukov, A. V., Fedorova, A. V., Ergma, E. V., & Yungelson, L. R. 1987, SvAL, 13, 328
Tutukov, A. V. & Yungelson, L. R. 1979, Acta Astron., 29, 665
van der Sluys, M. V., Verbunt, F., & Pols, O. R. 2005, A&A, 440, 973
Verbunt, F. & van den Heuvel, E. P. J. 1995, in X-ray Binaries, ed. W. H. G. Lewin, van Paradijs J., & van den Heuvel E. P. J. (Cambridge: Cambridge Univ. Press), 457–494
Werner, K., Nagel, T., Rauch, T., Hammer, N., & Dreizler, S. 2006, A&A, 450, 725
Yungelson, L. R., Nelemans, G., & van den Heuvel, E. P. J. 2002, A&A, 388, 546