On Possible Oxygen/Neon White Dwarfs: H1504+65 and the White Dwarf Donors in Ultracompact X-ray Binaries

K. Werner,¹ N.J. Hammer,¹ T. Nagel,¹ T. Rauch,¹² and S. Dreizler³

¹Institut für Astronomie und Astrophysik, Universität Tübingen, Sand 1, 72076 Tübingen, Germany
²Dr. Remeis-Sternwarte, Sternwartstr. 7, 96049 Bamberg, Germany
³Institut für Astrophysik, Universität Göttingen, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany

Abstract. We discuss the possibility to detect O/Ne white dwarfs by evidence for Ne overabundances. The hottest known WD, H1504+65, could be the only single WD for which we might be able to proof its O/Ne nature directly. Apart from this, strong Ne abundances are known or suspected only from binary systems, namely from a few novae, and from a handful of LMXBs. We try to verify the hypothesis that the latter might host strongly ablated O/Ne WD donors, by abundance analyses of the accretion disks in these systems. In any case, to conclude on O/Ne WDs just by strong Ne overabundances is problematic, because Ne enrichment also occurs by settling of this species into the core of C/O WDs.

1. Introduction

Stellar evolution theory predicts the existence of massive O/Ne white dwarfs as a result of carbon burning. WDs with masses exceeding 1 M⊙ should be such O/Ne WDs, but there are other ways to produce massive WDs, namely by binary merging or by mass accretion during close-binary evolution. The question is: Is there evidence for the existence of O/Ne WDs? A very useful overview about this topic has been given by Weidemann (2003) at the last WD workshop at Naples. We refer to his paper for a detailed discussion and references concerning stellar evolution scenarios, which we only briefly summarize here.

O/Ne WDs should have masses of 1–1.3 M⊙. Below a core mass of 1 M⊙ C burning cannot ignite. If the core mass exceeds 1.3 M⊙, an electron capture collapse will occur and probably result in a neutron star. There is a debate as to what initial-mass range this 1–1.3 M⊙ core-mass range corresponds. Depending on details in evolutionary models, the range of initial masses is between 9–11 M⊙ or between 7–9 M⊙ (for solar metallicity). In any case, in order to stop the O/Ne-core to grow (by C burning) beyond the 1.3 M⊙ limit, the star must loose mass, either by wind mass loss or by envelope removal in close binary systems. The WD mass distribution shows the existence of such massive WDs, however, their origin is not clear. It is possible that they are binary mergers.

If O/Ne WDs exist, then they have C/O envelopes and, thus, they are spectroscopically indiscernible from C/O WDs. Possible evidence, however, are observed neon overabundances in several cases: in neon novae, in some low-mass
X-ray binaries, and in one individual object (H1504+65). We will discuss here the LMXBs and H1504+65. In the case of neon novae, only those very few objects with extreme neon overabundances (over \( \approx 30 \) times solar, i.e. 3% mass fraction) suggest O/Ne WDs, because up to 3% \(^{22}\text{Ne}\) is expected in C/O WDs.

For the interpretation of Ne overabundances in novae or LMXBs it is important to consider gravitational settling of Ne into the core of a C/O WD. This problem is not yet solved theoretically. It could well be, that Ne overabundances observed in eroded WD cores are the result of this process and not the result of C burning.

2. **The hottest known white dwarf: H1504+65**

Spectroscopically, H1504+65 is an extreme member among the PG1159 stars, which are hot, H-deficient objects on or closely before the hot end of the WD cooling sequence. They are probably the result of a late He-shell flash that causes ingestion and burning of H, and the exposition of He/C/O-rich intershell matter on the surface (e.g. Werner 2001). H1504+65 is an extreme, and unique, PG1159 star because it is also He-deficient. The first quantitative analysis revealed that the photosphere is mainly composed of C and O, by equal parts (Werner 1991), and it has been discussed that H1504+65 is either a naked C/O core or that we see the C/O envelope of a O/Ne WD. The latter possibility is supported by the fact that H1504+65 is the most massive known PG1159 star, although the spectroscopic mass determination suggests a mass slightly below 1 M\(_\odot\). From the discovery of Ne lines in optical and EUV spectra (Werner & Wolff 1999) we found Ne=2–5%. This result is inconclusive concerning the nature of the star as a possible O/Ne WD.

Soft X-ray and FUV spectra of H1504+65 were taken by Chandra/LETG and FUSE, respectively, and the following atmospheric and stellar parameters were derived (Werner et al. 2004):

\[
T_{\text{eff}} = 200000 \text{ K} \pm 20000 \text{ K} \quad \log g = 8.0 \pm 0.5 \quad [\text{cgs}]
\]

\[
\begin{align*}
C &= 48 & O &= 48 & \text{Ne} &= 2 & \text{Mg} &= 2 & \text{He} &< 1 & \text{Na} &< 0.1 & \text{Al} &< 0.1 \\
M/M_\odot &= 0.836^{+0.13}_{-0.10} & \log L/L_\odot &= 2.45^{+0.6}_{-0.4} & d/\text{kpc} &= 0.67^{+0.3}_{-0.53}
\end{align*}
\]

Estimated errors for abundances are: ±20% for mass fraction of C and O, and a factor of 3 for Ne and Mg. One significant result is the detection of Mg in high amounts, which seems to confirm the O/Ne WD nature of H1504+65. However, a detailed discussion reveals that the abundance determinations of Ne and Mg still cannot decide if H1504+65 exposes a C/O core or a C/O envelope. The final answer to this problem was hoped to be accomplished by UV spectroscopy with HST. Planned observations during Cycle 13 aimed at the detection of Na which, if strongly overabundant, is a clear indicator for C burning. Unfortunately, the STIS spectrograph aboard HST died before the observations were carried out. It appears that this question will remain unanswered for many years to come. This is disappointing, because H1504+65 is the only object for which we can hope to proof that single O/Ne WDs do really exist.

Considering our mass determination, even if we stretch the result to the limit of our error bar, the mass of H1504+65 is slightly below 1 M\(_\odot\). However,
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we point out that the evolutionary tracks which we used to derive the mass, are those of post-AGB remnants that have lastly burned helium but – H1504+65 has no helium. There are no appropriate evolutionary tracks available. The main problem is that we have no idea what is the evolutionary history of this unique star: What event caused the helium-deficiency? We finally note that there is no indication that H1504+65 is in a binary system.

3. WDs in ultracompact low-mass X-ray binaries

It could be that AGB-like mass loss of single stars during carbon burning is not sufficient to stop the growth of the O/Ne core before the onset of electron-capture collapse. Hence, close binary systems in which mass is transferred from the C-burning star onto a companion might be the only places where O/Ne WDs are created. First evidence for the existence of such systems came from neon overabundances detected by line emission in (low resolution) ASCA spectra of the LMXB 4U 1626-67 (Angelini et al. 1995). Evidence for neon-rich absorbing circumstellar material was found in Chandra LETG spectra of 4U 0614+091 and three other LMXBs (Juett et al. 2001). The detection of double-lined emissions in the Chandra HETG spectrum of 4U 1626-67 (Schulz et al. 2001) suggests neon and oxygen overabundances in the accretion disk of this system.

In total there is now a group of five LMXBs, for which it is believed that they are ultracompact systems (orbital periods below 1 hour, i.e. separation of the order 1 light-s) in which a neutron star or a black hole accretes matter from a low-mass ($\approx 0.1 \, M_\odot$) degenerate star, the strongly ablated core of a WD. Mass transfer is driven by gravitational radiation.

The luminosity of these systems is dominated by the accretion disk. In the soft X-ray and UV spectral regions we see the hot (several 100 000 K) innermost parts of the disk, which can be X-ray heated by the neutron star. The optical light is dominated by cooler (about 10 000 K), outer parts of the disk. So we have the unique possibility to study the former WD interior composition by the determination of element abundances in the accretion disk.

For this purpose we have obtained optical medium-resolution spectra of two of these systems (4U 1626-67 and 4U 0614+091). We have used the FORS1 spectrograph attached to UT1 of ESO’s Very Large Telescope to record long-slit spectra. We used two grisms (600B and 600R) and obtained spectra in the regions 3450–5900Å and 5250–7450Å with a resolution of about 5Å. The B magnitude of both targets is near 18.7; exposure times for both binaries were 87 and 58 minutes for the red and the blue spectra, respectively. The observations were performed in service mode during Nov. 2003 and Mar. 2004. The spectra were reduced using standard IRAF procedures. They are presented in Fig.1, and show emission lines from CII/III and OII/III. They lack hydrogen and helium lines, apparently confirming the H- and He-deficiency of the donor stars. In the case of 4U 0614+091 we confirm the line identifications of Nelemans et al. (2004), who have obtained VLT/FORS2 spectra with slightly higher resolution.

In addition to these data, we also make use of archival HST/UV data of 4U 1626-67, kindly provided in reduced form by Homer et al. (2002). The HST spectrum is shown in Fig. 2. It shows emission lines from CIV, OV, and SiIV. It does not show HeII 1640Å.
Figure 1. VLT spectra of the probably H- and He-deficient disks in two ultracompact LMXBs. Some line features are identified. Overplotted are two models matching qualitatively some emission lines. One model (dashed line) includes trace hydrogen and shows a distinct H$\beta$ emission, which is not observed. The model emission lines at 3920 Å and 4310 Å, which are not seen in the observations, are from C II.
Figure 2. HST/STIS accretion disk spectrum of 4U 1626-67 and two model spectra, differing by their helium abundance. One is He-poor (0.2% by mass, full line), the other is He-rich (99%, dashed line). The observed lack of He II 1640Å obviously is no proof for He-deficiency of the disk. Note the broad absorption wings of the C IV resonance line in the He-poor model, which are not observed. This points at a stronger irradiation than assumed.

We have begun the construction of accretion disk models to calculate synthetic spectra and report here on the current state of our work. We use our accretion disk code AcDc, which is described in detail by Nagel et al. (2004). In essence, it assumes a radial $\alpha$-disk structure (Shakura & Sunyaev 1973). Then the disk is divided into concentric annuli. For each annulus we solve the radiation transfer equation (assuming plane-parallel geometry) together with the NLTE rate equations, plus energy- and hydrostatic equations, in order to calculate a detailed vertical structure. The integrated disk spectrum is then obtained by co-adding the spectra from the individual annuli. In comparison with the observed UV/optical spectra we present here first model spectra for particular, representative disk regions.

4U 1626-67 and 4U 0614+091

4U 1626-67 has an orbital period of 42 min (see e.g. Chakrabarty 1998, and references therein). The accretor is a 7.7s X-ray pulsar with a magnetic field strength of $3 \times 10^{12}$ G. The donor’s mass is smaller than 0.1 M$_\odot$. The system separation is 300 000 km. The inner disk edge is at the co-rotation radius, at R=6500 km from the pulsar, and the outer edge at the tidal truncation radius, near R=200 000 km. The mass transfer rate is roughly $2 \times 10^{-10}$ M$_\odot$/yr and the X-ray luminosity is about $2 \times 10^{36}$ erg/s.
Fig. 2 shows the UV spectrum of two disk models extending from R=6500–15000 km, seen under an inclination angle of 17°. They are irradiated by the neutron star, assuming the X-ray luminosity mentioned above and a blackbody energy distribution (T= 1.2 · 10^6 K). The two models differ by their chemical composition. One model is He-poor (dominated by C, O, Ne, Mg), the other is He-rich with abundances typical for He-rich disks in AM CVn systems. This comparison shows that neither model exhibits a clearly detectable He II 1640 Å line. Hence the lack of this line in the HST spectrum is no proof of He-deficiency. The situation is perhaps more favorable in the optical region. In Fig. 1 we have plotted two model spectra from C/O dominated disk regions at R=70000 km, one without H and the other with trace H (10^{-6} by number). A strong H β emission is seen in the second case, which is not present in the observed spectra. Although we have not yet performed this test with helium, we hope that we can derive a tight upper limit for the He abundance from the lack of He I lines.

The parameters of the system 4U 0614+091 are poorly known. No orbital period was measured. From X-ray bursts it is assumed that the accretor is a neutron star. From the similarity of the X-ray spectral characteristics with 4U 1626-67, Juett et al. (2001) suggest that this system is also ultracompact. The optical spectrum displays a number of C and O lines, as already identified by Nelemans et al. (2004). The lack of He I and HI lines supports the suggestion of Juett et al. (2001). The two C/O dominated models shown in Fig. 1 were computed for this system. Irradiation by the central object is not taken into account. They do show emission features, which qualitatively match some observed features. It appears that the disk in this region is optically thin.

Both LMXBs discussed here do not show neon lines in the optical spectra. Detailed modeling has to be performed to conclude what this means for the maximum possible neon abundance.

Acknowledgments. T.R. is supported by DLR under grant 50 OR 0201.

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