GALACTIC ULTRACOMPACT X-RAY BINARIES: DISK STABILITY AND EVOLUTION

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ABSTRACT

We study the mass-transfer rates and disk stability conditions of ultracompact X-ray binaries (UCXBs) using empirical time-averaged X-ray luminosities from Paper I and compiled information from the literature. The majority of UCXBs are consistent with evolutionary tracks for white dwarf donors. Three UCXBs with orbital periods longer than 40 minutes have mass-transfer rates above $10^{-10} \text{M}_\odot \text{yr}^{-1}$, inconsistent with white dwarf donor tracks. We show that if helium star donors can retain their initial high entropy, they can explain the observed mass-transfer rates of these UCXBs. Several UCXBs show persistent luminosities apparently below the disk instability limit for irradiated He accretion disks. We point out that a predominantly C and/or O disk (as observed in the optical spectra of several) lowers the disk instability limit, explaining this disagreement. The orbital period and low time-averaged mass-transfer rate of 2S 0918-549 provide evidence that the donor star is a low-entropy C/O white dwarf, consistent with optical spectra. We combine existing information to constrain the masses of the donors in 4U 1916-053 ($0.064 \pm 0.010 \text{M}_\odot$) and 4U 1626-67 ($<0.036 \text{M}_\odot$ for a 1.4 $\text{M}_\odot$ neutron star). We show that 4U 1626-67 is indeed persistent, and not undergoing a transient outburst, leaving He star models as the best explanation for the donor.

Key words: accretion, accretion disks – X-rays: binaries – X-rays: individual (4U 1916-053, 4U 1626-67, 4U 1728-34, 2S 0918-549)

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1. INTRODUCTION

Ultracompact X-ray binaries (UCXBs) contain a neutron star (or black hole; black hole systems have not yet been confirmed) accretor and a compact donor star, with an orbital period $P_{\text{orb}} < 80$ minutes. The donors must be hydrogen-deficient, partially or fully degenerate stars (e.g., Rappaport et al. 1982; Deloye & Bildsten 2003). UCXBs are preferentially produced in globular clusters (GCs), likely due to enhanced formation rates in such regions due to close dynamical interactions (Verbunt 1987; Deutsch et al. 2000; Ivanova et al. 2005, 2010).

Three major scenarios for the nature of UCXB donors have been extensively discussed (e.g., Nelemans & Jonker 2010); we briefly review them below. A binary of a low-mass white dwarf (WD) and neutron star (NS) will lose angular momentum by gravitational radiation, forcing the WD to eventually begin transferring mass to the NS (Pringle & Webbink 1975); we call this the WD evolution scenario. Mass transfer starting as the donor ascends the subgiant branch can lead to decreasing periods, down to below an hour, as the degenerate, hydrogen-poor core is exposed (Nelson et al. 1986); we call this the evolved main-sequence evolution scenario. Finally, the donor star may be a helium star, burning helium in its core, at the time of contact (Savonjé et al. 1986), known as the He star evolution scenario. Each scenario predicts different mass-transfer rates (due principally to the different entropies of the donor star) and different donor chemical compositions (see Nelemans et al. 2010 for a review). Thermonuclear X-ray bursts on NSs exhibit different characteristics depending on the nature of the fuel being burned (hydrogen or helium), and can therefore help constrain the composition of the accreted fuel (e.g., Cumming 2003; Galloway et al. 2008).

UCXB systems can be roughly categorized as persistent (over the ∼decades we have been observing them) or transient. Transient UCXBs spend the majority of the time in a quiescent state with little or no accretion, punctuated by occasional outbursts. Whether a UCXB will be persistent or transient depends upon the mass-transfer rate ($M$) of the system. A high $M$ and the resulting heating of the accretion disk through friction and X-ray irradiation, maintains the accretion disk in an ionized state with a high viscosity, which allows continued mass flow through the disk (Osaki 1974; White et al. 1984; Lasota 2001). If $M$ from the companion is below some critical rate $M_{\text{crit}}$, the mass transfer is unable to keep the entire accretion disk ionized. The viscosity decreases, stopping mass flow through the disk until enough mass builds up to re-ionize the disk; this leads to transient behavior.

The value of $M_{\text{crit}}$ depends on the orbital period, as smaller disks require smaller $M$ to maintain the entire disk in an ionized state (Smak 1983). It also depends upon the chemical composition of the disk, as lower-ionization-potential atoms allow faster ionization (Menou et al. 2002), and upon the effects of irradiation of the disk, which keeps it ionized to lower mass-transfer rates (Dubus et al. 1999). Dubus et al. stressed that the numerical calculation of the effects of irradiation is still significantly uncertain. Lasota et al. (2008) noted that several persistent UCXBs appeared to be below the critical mass-transfer rate for stability of He disks, and suggested that the donors may contain some hydrogen, which would lower the critical mass-transfer rate.

Juett et al. (2001) presented evidence that five X-ray binaries have unusual O/Ne ratios in their X-ray absorption spectra, suggesting that these donors were originally C/O or O/Ne/Mg WDs (though the Ne in many cases may be interstellar; Juett & Chakrabarty 2005; Krauss et al. 2007). 4U 1626-67 shows clear evidence of C, O, and Ne in X-ray (Schulz et al. 2001) and ultraviolet (Homer et al. 2002) spectroscopy, without evidence of helium. Nelemans et al. (2004, 2006) and Werner
et al. (2006) presented evidence from optical spectroscopy that two UCXBs (4U 1626-67, 4U 0614+09) clearly lack hydrogen and helium lines but exhibit carbon and oxygen lines, indicating that these systems have C/O WD donors. Nelemans et al. (2006) also showed that 4U 1543-624 & 2S 0918-549 show optical spectra similar to 4U 0614+09. Dieball et al. (2005) presented evidence from ultraviolet photometry requiring carbon in the disk of M15 X-2, and probably helium as well. Broad oxygen emission lines have been identified in high-resolution X-ray spectra of 4U 1543-624 and 4U 0614+091 (Madej et al. 2010; Schulz et al. 2010; Madej & Jonker 2011). Thus C/O donors are likely common in UCXBs, and the mass-transfer stability behavior of C/O disks is likely to be important.

This apparent lack of helium poses problems for our understanding of the observed X-ray bursts, as their properties indicate the presence of substantial amounts of helium (see, e.g., Juett et al. 2003; in’t Zand et al. 2007; Kuulkers et al. 2010). Spallation of heavy nuclei by accreting material to produce helium (Bildsten et al. 1992) has been repeatedly suggested as a possible solution, but suffers two well-recognized problems: the spallation requires infalling material of very different A/Z values, which is hard to understand in predominantly C/O accretion disks (in’t Zand et al. 2005a), and such spallation would also produce sufficient hydrogen to alter the characteristics of X-ray bursts, which in most UCXBs show no evidence of H (Cumming 2003; Galloway et al. 2008, 2010).

The overabundance of C/O disks among UCXBs has been widely discussed (e.g., Nelemans et al. 2010), but is not understood, since standard population syntheses tend to produce far more He WD systems than C/O WD systems (Nelemans et al. 2010; Belczynski & Taam 2004). Hybrid WDs of mass <0.45 M\(_\odot\) are thought to be required to explain the C/O disks (Yungelson et al. 2002). The reason is that high-mass donor WDs will produce extremely high (super-Eddington) mass-transfer rates when they make contact at small periods, and the accretor may be unable to expel the accreting material for >0.45 M\(_\odot\) donor WDs. It is unclear whether these hybrid WDs can also contain sufficient helium to produce X-ray bursts without substantial fine-tuning of the model.

In Paper I (Cartwright et al. 2013), we compiled a list of certain UCXBs, and used Rossi X-ray Timing Explorer (RXTE) bulge scan observations (Swank & Markwardt 2001) and Monitor of All-Sky X-ray Image (MAXI) monitoring light curves (Sugizaki et al. 2011), supplemented with Chandra observations, RXTE All-Sky Monitor (RXTE/ASM) data, and literature reports to construct histograms of the luminosities of these UCXBs. With these measurements, we constructed an empirical luminosity function for galactic UCXBs. Here we use the time-averaged luminosities from Paper I to interpret the behavior of individual UCXBs where the period is known (or suggested), reviewing a wide body of the literature to identify critical information. We give relevant information for these UCXBs in Table 1.

2. TIME-AVERAGED LUMINOSITIES VERSUS PERIOD

We construct a version of Lasota et al.’s (2008) plot of UCXB \(\dot{M}\) versus orbital period in Figure 1 using our time-averaged X-ray luminosity calculations (Table 1; see Paper I for details on the derivation) and a bolometric correction of 2.9 (in’t Zand et al. 2007). We estimate a <25% error associated with the bolometric correction factor and use distance errors as given in Table 1 (for 4U 1543-624, we estimate a distance uncertainty of <50%, see Paper I). These errors are combined in quadrature to produce upper and lower error estimates for \(\dot{M}\) (Table 1, Figure 1). In calculating \(\dot{M}\), we assume a 1.4 M\(_\odot\) NS with an 11.5 km radius (e.g., Steiner et al. 2013). (Predicted model mass-transfer rates vary linearly with the NS mass, while luminosity-inferred mass-transfer rates vary inversely with the NS mass. Nevertheless, the errors introduced by these choices are generally smaller than the other uncertainties.) We differ from many previous works regarding 4U 1626-67 as a persistent, rather than transient, source, considering its short orbital period (and thus small disk), 40 years of continuous activity (versus <month-long outbursts of transient UCXBs of similar periods), and currently increasing \(L_X\) (see below). \(\dot{M}\) values for four of the transient sources are very similar to previous literature estimates by Galloway (2006) for XTE J1807-294 and XTE J0929-314, Heinke et al. (2009) for XTE J1751-305, and Heinke et al. (2010) for NGC 6440 X-2. Our range for Swift J1756.9-2508 (rather wide, due principally to its distance uncertainty) is consistent with that of Patruno et al. (2010), although it still includes the lower estimate of Krimm et al. (2007). The general features of this plot are similar to the calculations by van Haarfen et al. (2012c), though we include an additional source (NGC 6440 X-2) and obtain smaller error bars for our fainter sources.

The timescales over which these average mass-transfer rates are calculated vary from 2.7 years (for the MAXI sources) to 15 years for the 2 sources where RXTE ASM data were used,
and is typically 12 years for the PCA bulge scan sources. The length the timescales used limits of our accuracy in determining the mass-transfer rate, as systems may go through cycles of enhanced mass transfer on timescales longer than our data sets (Kotze & Charles 2010). Evidence of such variations include the mass-transfer rate, as systems may go through cycles of lengths or recurrence times (individually), as the mass-transfer rate is typically 12 years for the PCA bulge scan sources. The nature of such cycles is not clear (especially for degenerate donors), but the possibility of such behavior must be considered as a caveat when interpreting our results.

2.1. Evolutionary Tracks

We first consider the evolution of WD UCXBs, as discussed in detail by Deloye & Bildsten (2003) and van Haften et al. (2012b). In Figure 1 we plot tracks for adiabatic UCXB evolution from C. Deloye, as shown in Lasota et al. (2008), for low-entropy or high-entropy He donors (dotted lines), and tracks for low-entropy C or O donors (dashed lines) from Deloye & Bildsten (2003). These tracks consider that WDs are not completely degenerate at the start of the mass transfer, and hence have some final entropy in the center, providing some range in possible mass-transfer rates for the same period (Deloye & Bildsten 2003). This effect decays for long periods, as the donor has time to thermally relax, explaining the return of the high-entropy track toward the low-entropy track (Deloye et al. 2007).

These tracks reasonably describe most of our UCXBs, apart from 4U 1728-34 (which does not yet have strong evidence for the suggested period) and three interesting long-period objects with high-mass-transfer rates (the period of 4U 0614+091 is not yet determined). Transient systems may not be detected because they show rare outbursts (e.g., XTE J0929-314) or more frequent outbursts that are too faint to be noted in most surveys (e.g., NGC 6440 X-2). Unfortunately, there does not seem to be any pattern to the changes in either outburst periods (see the next section). Transient systems may not be persistent beyond 25 minutes, with expected LX < 10^{36} erg s^{-1}, would be hard to detect and characterize, though they are unlikely to remain persistent at significantly longer periods (see the next section). Transient systems may not be detected because they show rare outbursts (e.g., XTE J0929-314) or more frequent outbursts that are too faint to be noted in most surveys (e.g., NGC 6440 X-2). Unfortunately, there does not seem to be any pattern to the changes in either outburst lengths or recurrence times (individually), as the mass-transfer rate decreases.

Alternatively, many of these systems may have stopped accreting mass, allowing the NSs to become radio millisecond

### Table 1

Key Properties and Mass Transfer Rates of UCXBs

| Source        | Location   | Distance (kpc) | Period (minutes) | \(N_M\) (10^{32} cm^{-2}) | Average Mass Transfer \(M_{\odot} \text{yr}^{-1}\) | Spectral Data | Bursts? (nature) |
|---------------|------------|----------------|-----------------|---------------------------|---------------------------------|--------------|------------------|
| 4U 1728-34    | Bulge      | 5.2 ± 0.8        | 10.8 ± 10       | 22.9 ± 8                  | 2.6 ± 1.6 \times 10^{-9}        | ...          | Yes; He^e        |
| 4U 1820-303   | GC         | 7.9 ± 0.4        | 14 ± 2          | 1.2 ± 0.8 \times 10^8     | 2.0 ± 0.6 \times 10^{-9}        | Yes; He^e    |
| 4U 0513-40    | GC         | 12.1 ± 0.6       | 17 ± 2          | 0.26 ± 0.6                | 2.0 ± 0.2 \times 10^{-9}        | Yes          |
| 2S 0918-549   | Field      | 5.4 ± 0.8       | 17.4 ± 3        | 3.0 ± 0.6                 | 2.6 ± 1.5 \times 10^{-10}       | C/O^m,^k    | Yes; He^e        |
| 4U 1543-624   | Field      | 7.0 ± 1.0       | 18.2 ± 3        | 3.5 ± 0.6                 | 1.3 ± 0.3 \times 10^{-9}        | C/O^m,^k    | No               |
| 4U 1850-087   | GC         | 6.9 ± 0.3       | 20.6 ± 3        | 3.9 ± 0.6                 | 2.8 ± 1.4 \times 10^{-10}       | ...          | Yes              |
| M15 X-2       | Field      | 10.4 ± 0.5       | 22.6 ± 3        | 0.67 ± 0.6                | 3.8 ± 1.9 \times 10^{-10}       | C, He^l     | Yes              |
| 4U 1626-67    | Field      | 8.3 ± 1.0       | 42 ± 3          | 1.4 ± 0.6                 | 8.1 ± 10^{-10}                   | C, O, Ne^m,^k,^l,^j | No       |
| 4U 1916-053   | Field      | 9.3 ± 1.4       | 50 ± 3          | 3.2 ± 0.6                 | 6.3 ± 3.7 \times 10^{-10}       | He, N^e     | Yes              |
| 4U 0614+091   | Field      | 3.2 ± 0.5       | 51 ± 3          | 3.0 ± 0.6                 | 3.9 ± 2.3 \times 10^{-10}       | C/O^m,^k,^e,^c, O^c,^e | Yes |

## Notes

UCXBs with known or suggested periods, with best estimates of their distance and \(N_M\), our estimate of their mass-transfer rate using the monitoring in Paper 1, and literature information on identification of spectra and properties of thermonuclear bursts (He means the accreted matter lacks H). Location in the Galactic field, (direction of the) bulge, or in a globular cluster (GC) is also specified. Distance errors are ranges from indirect estimates; 15% error so nx r s t s

### References

Galloway et al. 2010; Harris 2010; Stella et al. 1987; Zidov & Chakrabarty 2003; Wang & Chakrabarty 2004, distance estimate assumes \(M\) driven by GR; Homer et al. 1996; Dieball et al. 2005; White & Angelini 2001; Chakrabarty 1998; Krauss et al. 2007; Yoshida 1993; Walter et al. 1982; Church et al. 1998; Brandt et al. 1992; Shahbaz et al. 2008; Piraino et al. 1999; Galloway 2006; Markwardt et al. 2003; Falanga et al. 2005; Papiotto et al. 2008; Markwardt et al. 2002; Miller et al. 2003; Galloway et al. 2002; Jett et al. 2003; Krimm et al. 2007; Altamirano et al. 2010; Cumming 2003; Nelemans et al. 2004; Nelemans et al. 2006; Madej & Jonker 2011; Schulz et al. 2001; Homer et al. 2002; Werner et al. 2006; Schulz et al. 2010; Madej et al. 2010.
pulsars. It is difficult to identify the pulsar descendants of UCXBs, since most short-orbital-period millisecond pulsars have orbital periods longer than predicted (Deloye 2008; Ivanova et al. 2008). This has led to the suggestions that the donor stars are strongly heated and inflated, leading to longer periods (Rasio et al. 2000; Bailes et al. 2011) and/or complete donor destruction (Bildsten 2002; van Haften et al. 2012b), or to the possibility that many of these NSs are spun down as mass transfer decreases and never become pulsars (Jeffrey 1986; Deloye et al. 2008; but cf. Tauris 2012 who argues against this).

van Haften et al. (2012a) argue for enhanced UCXB angular momentum loss by donor wind mass loss to explain the companion of the millisecond pulsar PSR J1719-1438, which is a low-mass degenerate star in a 2.2 hr orbit (Bailes et al. 2011). This scenario offers the appeal of simultaneously explaining the long period of this system (too long for standard evolution to produce during a Hubble time), and perhaps of explaining the high-mass-transfer rates of several longer-period UCXBs (van Haften et al. 2012c). van Haften et al. (2012a) note that a similar wind mass loss is suggested to explain the orbital period derivative of SAX J1808.4-3658 (e.g., Burderi et al. 2009). This scenario, however, suffers some difficulties. The orbital period derivative of SAX J1808 is accelerating (Patruno et al. 2012), indicating that the orbital period evolution is probably driven by the exchange of angular momentum between the donor star and the orbit, as seen in many other binaries (e.g., PSR 1957+20; Arzoumanian et al. 1994). The suggested mass-loss rates may also be difficult to achieve at this stage of their evolution. “Black widow” radio-eclipsing millisecond pulsars such as PSR 1957+20 show ablative winds of only $10^{-12}$-$10^{-14} M_\odot$ yr$^{-1}$ (Fruchter & Goss 1992; Eichler & Gedalin 1995). (These companions are irradiated by pulsar winds rather than X-rays, which will alter the physics of heating, but they intercept similar energy fluxes from the primary.) However, those lower-density black widow companions have surface gravities that are factors of $\sim 10^4$ lower than similar-mass WDs, using the mass and radius values for the PSR 1957+20 companion, $M = 0.034 M_\odot$ and $R \geq 0.25 R_\odot$, from van Kerkwijk et al. (2011). (As we see below, this is roughly the appropriate mass for two high-mass-transfer long-period UCXBs.) A final concern is that it is difficult to understand how initially similar UCXBs with WD companions can evolve to the dramatically different mass-loss rates seen among UCXBs with periods beyond 40 minutes in our sample. Thus, we are skeptical that donor winds of the required magnitude are driven from UCXB companions, but the potential of this mechanism to solve several problems strongly motivates further study of this possibility.

2.2. High-$M$ Systems

There are two groups of UCXBs with periods of 40–60 minutes, well separated in their time-averaged mass-transfer rates; transient sources with low rates, $\lesssim 10^{-11} M_\odot$ yr$^{-1}$, versus persistent sources with average rates $\sim 100$ times higher for the same period range (4U 1626-67, 4U 1916-053, and 4U 0614+091). These persistent sources require an explanation other than simple WD evolution.

One alternative is to invoke an angular momentum loss mechanism that is stronger than gravitational wave radiation. Donor wind mass loss (van Haften et al. 2012c; see the discussion above) is one possibility. Alternatively, if an accretor does not accept all the donor’s material, a circumbinary disk (CBD) could form. A CBD, as it rotates slower than the binary orbits, provides a tidal torque on the binary, removing its orbital angular momentum (see Spruit & Taam 2001 for more details on a simple CBD model). The strength of that tidal torque depends on the physics of the CBD, mainly its viscosity and the scale height, as well as on what fraction of the donor’s mass loss ends up in the CBD, denoted as $\delta$. The physics of the CBD can be further simplified, as for a standard $\alpha$-viscosity disk the loss of angular momentum takes a simple form (Shao & Li 2012):

$$\dot{J}_{\text{CBD}} = A(GM)^{3/2} \delta \dot{M}_{\text{donor}}^{1/3}. \tag{1}$$

Here $A = (3\alpha\beta^2/4)^{1/3}$, where $\alpha$ is the viscosity parameter and $\beta$ is the ratio of the scale height of the disk to its radius; with values for a standard disk $\alpha = 0.01$ and $\beta = 0.03$, $A \approx 0.02$. $t$ is the time after the start of the mass transfer. Studies performed for cataclysmic variables suggested that $\delta \ll 1$, and its value is of the order of $10^{-4}$ to $10^{-3}$ (Taam et al. 2003). Further analysis showed that for a standard CBD in a binary system with an orbital period of about 1 hr, $\delta \sim 6 \times 10^{-4} t_0^{-1/3}$ (where $t_0 = t/10^3$ yr; Shao & Li 2012).

Using this formalism, a WD donor can drive a mass-transfer rate of $2 \times 10^{-10} M_\odot$ yr$^{-1}$ at a period $>40$ minutes (note that this is the minimum mass-transfer rate in the second group), if the CBD model has $\delta \gtrsim 0.0025$. This is several times larger than it should be for this evolutionary stage, typically $\delta \sim 3 \times 10^{-4}$.

See Figure 2 where we show an example WD track with a very strong CBD included.

A second option begins with an initially slightly evolved main-sequence donor with a helium-rich core, where the orbit shrinks due to magnetic braking, and can reach ultracompact periods (Nelson et al. 1986; Podsiadlowski et al. 2002). Such an evolutionary sequence can produce mass-transfer rates of $10^{-9} M_\odot$ yr$^{-1}$, and thus explain the second group of systems. This evolution requires rather finely tuned initial parameters to reach ultracompact orbits, producing very few systems with periods below 1 hr, and almost none below 30 minutes (van der Sluys et al. 2005). This evolutionary sequence may leave some hydrogen in the core, a clear observable difference with the other sequences (Nellemans et al. 2010).
For a third alternative, an He star can be produced by a common envelope event and inspiral via gravitational waves until it makes contact at short periods while still fusing He at its center (see Yungelson 2008; Nelemans et al. 2010; van Haften et al. 2012c). This avoids the fine-tuning difficulties with the evolved main-sequence star evolution. Naked He star donors generally have radii much larger than WDs of the same mass, where this radius is also a function of its final entropy (we demonstrate this dependence in Figures 3 and 4, where we show radius and central temperature $T_c$ evolution for a naked He core of a giant with initial mass of $5 M_\odot$ evolved with different mass-loss rates using the stellar code MESA$^3$). Once a naked He star is formed—through a common envelope event—it also may start He burning in the core (note that whether or not it burns depends on the naked He star mass). This burning may be fully completed (in the sense that the core is fully converted to a carbon–oxygen core) during the mass-loss sequence, depending on the initial post-common envelope binary separation, on how close to the giant tip the donor was before the common envelope event, and how fast the He star is losing mass (see Figure 5). As a result of this burning, a very low mass carbon–oxygen donor can be formed, although in some cases He fusion is simply stopped by the rapid expansion of the donor and drop of its central temperature. For example, we note that very rapid mass loss leads to donor expansion and cooling, hence burning is rapidly depleted and a C/O core might not form. Continued He burning is more likely to provide an inflated donor, versus a donor that had a composite He/C/O core before the mass transfer (see Figures 3 and 4). At some point, the He donor starts to expand with continued mass loss—note that this can happen due to various reasons, e.g., due to the core's conversion into a C/O core, or to adiabatic expansion due to rapid mass loss. The point where the nuclear burning turns off can also be roughly identified as where the He star tracks begin to expand outward to longer periods again (see Figure 6).

If an He star retained its entropy in the center due to either faster (in the past) mass transfer, or due to nuclear burning, tidal heating, or ongoing irradiation, it can provide the observed mass-transfer rates requiring only gravitational wave radiation without invoking a CBD. We tested this situation by applying a fast mass-loss rate to an He star model in MESA, and then checking what mass-transfer rate this star (which is out of thermal equilibrium) will have if it is in a binary evolving only under gravitational radiation (see Figure 2). Nondegenerate He star cores (appropriate for the intermediate-mass progenitors required) expand upon mass loss from the outer envelope (Deloye & Taam 2010; Ivanova 2011; Ivanova et al. 2013). Thus, they can continue to drive mass transfer as the orbit expands, giving mass-transfer rates up to $10^{-3} M_\odot$ yr$^{-1}$ for some fraction of the core. A fully self-consistent calculation of the evolution of He stars in binary systems has not yet been performed, and the stage where the core will stop expanding is not well established. MESA does not include tidal heating or donor irradiation, which could increase the inferred mass-loss rates.

If the donor is an (inflated) He star evolving under gravitational wave radiation only, then mass-transfer rates do not significantly exceed the Eddington rate during most of the mass-loss evolution, while still transferring $\sim 0.5 M_\odot$ (Figure 6). If an accretor accepts most of the transferred mass below the Eddington limit, then the NS in such a binary could grow significantly more massive than an NS with a WD donor, potentially forming an NS with $M \gtrsim 2 M_\odot$. This is in contrast with WD UCXB evolution; cold WDs more massive than 0.08 $M_\odot$ upon starting mass transfer, will exceed the Eddington limit (Bildsten & Deloye 2004), so cannot efficiently transfer more than $\sim 0.1 M_\odot$ to the NS.

$^3$ MESA (Modules for Experiments in Stellar Astrophysics) is a collection of libraries for computational stellar astrophysics that is relied upon by a natively implemented one-dimensional stellar evolution code capable of modeling stars at a wide range of evolutionary stages (Paxton et al. 2011, 2013).
He stars may show a wide range of surface abundances, depending on the initial post-common-envelope orbital period, which sets how long the star burns He before mass transfer stops fusion. Nelemans et al. (2010) present extensive calculations of the evolution and abundances of He stars. In the initial, rapid epoch of orbital shrinkage, the outer, unburnt helium layers are consumed (note that this epoch is very brief, \(<10^7\) years, and thus difficult to observe). After period minimum, the C/O fusion products are revealed, though some He is still available. Nelemans et al. (2010) show that wider initial orbital periods (e.g., 200 minutes) give primarily C and O chemical compositions at $P_{\text{orb}} > 30$ minutes, with reduced He. This matches the inferred compositions of 4U 1626-67 (substantial C, O, and Ne; Schulz et al. 2001; Werner et al. 2006) and 4U 0614+09 (C and O dominate; Nelemans et al. 2004; while X-ray bursts indicate the presence of He without H; Kuulkers et al. 2010). Schulz et al. (2001) claimed an overabundance of Ne in local absorbing material around 4U 1626-67, which would be hard to explain with an He star (or any star hot enough to provide this mass-transfer rate), since Ne can only sink to the core in a cold WD. However, the evidence for overabundant Ne in absorption seems to have disappeared, leaving only the strong Ne X-ray emission lines as more ambiguous evidence for Ne’s abundance (Krauss et al. 2007).

We note that the He star mechanism to create longer-period, high-mass-transfer systems cannot work in GCs due to the relatively high masses of the initial donors (>2.3 $M_\odot$) and short lifetimes of the systems (Yungelson 2008). This is consistent with the lack of UCXB systems with unusually high mass-transfer rates for their orbital period, like 4U 1626-67 or 4U 1916-053, in GCs. The lack of the He star mechanism in GCs can also explain part of the difference in the distribution of orbital periods between GC and field UCXBs (that field UCXBs have longer periods) which was noted by Zurek et al. (2009).

2.3. Critical Mass-transfer Rates of He versus C/O Accretion Disks

Deloye & Bildsten (2003) and Lasota et al. (2008) applied accretion disk stability calculations to understand the behavior of UCXBs. Deloye & Bildsten (2003) calculated the evolution of WD donors evolving to lower mass-transfer rates as they move outward, reaching mass-transfer rates prone to disk instability (for solar composition) as they reach orbital periods around 30 minutes and $M_{\text{crit}} = 3–6 \times 10^{-11} M_\odot \ yr^{-1}$. Lasota et al. (2008) pointed out that irradiated pure He disks require higher $M$ for stability, and thus become unstable earlier, at orbital periods around 20 minutes and $M_{\text{crit}} = 3–5 \times 10^{-10} M_\odot \ yr^{-1}$. Lasota et al. (2008) also noted that this stability criterion lies above three known persistent systems, and suggested that this can be resolved by the donors retaining a small fraction of H, e.g., by the evolutionary models of Podsiadlowski et al. (2002). These models have serious difficulties explaining the numbers of UCXBs at very short periods (van der Sluys et al. 2005). Here, we show that the possession of carbon and oxygen in the disks of most of these UCXBs solves the problem.

We take stability curves for He, C, O, and C/O disks from Menou et al. (2002), assuming $M_{\text{NS}} = 1.4 M_\odot$ and $\alpha = 0.1$. The stability curves for C and C/O disks lie below most of the lowest-luminosity persistent systems (Figure 7). We also plot the irradiated disk $M_{\text{crit}}$ lines from Lasota et al. (2008) for He and solar composition. Accurate $M_{\text{crit}}$ calculations for irradiated C and/or C/O disks have not yet been done, but are clearly needed. However, we might estimate from the drop in $M_{\text{crit}}$ for irradiated versus non-irradiated He disks that $M_{\text{crit}}$ for irradiated C/O disks will probably cross the Deloye helium UCXB tracks around $10^{-10} M_\odot \ yr^{-1}$, below all persistent UCXBs with known periods. Four of the six persistent UCXBs at or below the irradiated He stability line (4U 0614+091, 4U 1626-67, 2S 0918-549, and M15 X-2) show strong C or O lines in their optical or UV spectra (Nelemans et al. 2004, 2006; Dieball et al. 2005). Thus, C/O disks seem appropriate for them, and indicate they should be persistent, as observed. One of the other two persistent UCXBs below the helium stability line is 4U 1916-053, which shows He and N lines, but no C or O (the other, 4U 1850-087 in a GC, has no spectral information). We suspect that the nitrogen (a typical product of CNO cycle burning) could also lower the stability line, though to our knowledge no calculations for such disks have been performed.

3. INDIVIDUAL UCXBs

Here we consider the detailed properties of a few individual persistent systems, using all available information to constrain...
than unirradiated He disk stability limits, and that irradiation will lower them.

Figure 7. Stability limits for accretion disks of specified compositions and a radius equal to two-thirds the accretor’s Roche lobe radius are plotted. Helium in red (solid line for an unirradiated disk; dashed line for a irradiated disk), oxygen in blue, carbon in green, C/O also in blue, and solar metallicity material (irradiated) in magenta. Irradiated disk limits (dashed lines) are from Lasota et al. (2008) and others (solid lines) are from Menou et al. (2002). The lower-entropy helium WD evolution track (Deloye & Bildsten 2003) is plotted as in Figure 1. The meaning of the UCXB data points is as described in Figure 1. Note that the unirradiated disk stability limits for C/O disks are ~5 times lower than unirradiated He disk stability limits, and that irradiation will lower them further, thus reasonably explaining the persistence of the persistent UCXBs. (A color version of this figure is available in the online journal.)

their evolutionary history. These five systems do not lie on the standard He WD UCXB tracks, though two of them have rather uncertain orbital periods (4U 1728-34 and 4U 0614+091).

3.1. 2S 0918-549

One persistent UCXB with a well-determined period and distance, 2S 0918-549, has a mass-transfer rate significantly below the low-entropy helium UCXB track (Figure 1). Such a determination was suggested by Deloye & Bildsten (2003) as a method to securely identify a UCXB donor as C/O rather than He. This determination is supported by Nelemans et al. (2004), who identify 2S 0918-549’s optical spectrum as closely resembling the disk of 4U 0614+09, which shows only C and O lines without detectable H or He (though some He, perhaps 10%, might remain). The mass-transfer stability requirement (Yungelson et al. 2002; Nelemans et al. 2010) suggests that the donor is a hybrid WD of initial mass <0.45 M\(_{\odot}\). However, the helium mantle of such objects is generally lost at very short periods, so the observation of (likely helium-powered) X-ray bursts (in’t Zand et al. 2005b) from this system is hard to explain.

3.2. 4U 1728-34

4U 1728-34 has a suggested orbital period of 10.8 minutes (Galloway et al. 2010) from Chandra data. Its time-averaged luminosity indicates a mass-transfer rate a factor of 2–3 below the predictions of any UCXB evolutionary track for an 11 minute period. This time-averaged luminosity is consistent with all X-ray measurements over the 30 year history of X-ray astronomy. If the period is verified, we would not see any alternative to requiring substantial variations in its mass-transfer rate on timescales >30 years.

3.3. 4U 1916-053

4U 1916-053 shows strong He and N lines in its optical spectra, indicating a predominantly He donor with CNO-processed material (Nelemans et al. 2006). 4U 1916-053 shows evidence for precession of its accretion disk, by showing a “superhump” optical period 0.9% longer than its true binary period (Chou et al. 2001; Retter et al. 2002). An empirically calibrated relation between the mass ratio, q = M\(_d\)/M\(_1\), and the fractional excess, \(\epsilon = (P_{sh} - P_{orb})/P_{orb}\) (where \(P_{sh}\) is the (longer) superhump period), was shown for cataclysmic variables by Patterson et al. (2005; see also Pearson 2006; Patterson 2001), \(\epsilon = 0.18q + 0.29q^2\). Assuming that this relation also works for X-ray binaries (justified by the few low-mass X-ray binaries considered in Patterson 2001), we find q = 0.046, which for an NS mass of 1.4 ± 0.2 M\(_{\odot}\) (a range including the majority of well-measured NS masses) gives a companion mass of 0.064 ± 0.010 M\(_{\odot}\). Requiring the donor to fill its Roche lobe in a 50 minute orbit gives a radius of 0.082 ± 0.005 R\(_{\odot}\) (twice as large as a cold WD of this mass).

The assumption that mass transfer is driven only through gravitational radiation would then predict mass-transfer rates below 10\(^{-10}\) M\(_{\odot}\) yr\(^{-1}\) (Nelson et al. 1986), contrary to observations (Figure 1), proving that additional angular momentum loss must be driving mass transfer. This information does not clearly discriminate between the He star and evolved main-sequence star evolutionary channels, as both can produce tracks roughly matching the orbital period, mass, and mass-transfer rate of 4U 1916-053 (see Figures 2 and 6 for the He star channel, and Nelson & Rappaport’s 2003 track M\(_d\) = 0.0, or Podsiadlowski et al.’s 2002 Figure 15 for the latter channel). Alternatively, donor wind mass loss or CBDs could provide the required angular momentum loss in the WD scenario, but as discussed above we do not favor these possibilities.

4U 1916-053 is clearly below the irradiated helium disk stability line. Lasota et al. (2008) suggested that the presence of more than ~5% hydrogen in the disk would keep the disk stable and accretion persistent down to significantly lower mass-transfer rates. Would such a fraction be detectable, say, in studies of thermonuclear bursts? A small hydrogen fraction ~10% would not affect the durations of bursts (Cumming 2003), nor would it be detectable in current optical spectroscopy (Werner et al. 2006; Nelemans & Jonker 2010). However, due to hydrogen’s larger energy release per nucleon, it could significantly change the energy released. The energy released per nucleon is estimated at \(Q_{\text{nc}} = 1.6 + 4.0(X)\) MeV nucleon\(^{-1}\), where \(X\) is the mean hydrogen fraction (Cumming 2003; Fujimoto et al. 1987), which incorporates a 35% energy loss to neutrino emission. Galloway et al. (2008) measured the ratio of burst to persistent flux for 4U 1916-053, using a pair of bursts detected less than 10 hr apart with RXTE, as \(\alpha = 78.8 ± 0.3\). Using Galloway et al.’s (2008) relation between \(\alpha\) and \(Q_{\text{nc}}\),

\[
\alpha = 44 \frac{M}{1.4 M_{\odot}} \left(\frac{R}{10 \text{ km}}\right)^{-1} \left(\frac{Q_{\text{nc}}}{4.4 \text{ MeV nucleon}^{-1}}\right)^{-1},
\]

we find that a typical mass range of \(M = 1.4 ± 0.2 M_{\odot}\). R = 11.5 km gives estimates of \(X = 0.14 ± 0.08\). Thus, the energy release from burning hydrogen versus helium suggests that 10%–20% of the accreted material should be hydrogen. This matches the predictions of a 10%–20% abundance of...
hydrogen at the surface of an evolved secondary star of period 49 minutes (Nelemans et al. 2010; Nelson & Rappaport 2003). Such a fraction of hydrogen in the disk would nicely explain the persistence of this system. However, values of $\alpha$ may also be enhanced by incomplete burning of nuclear fuel, and often seem to vary with time in a single system, so further evidence of the existence of hydrogen should be sought.

A distinguishing characteristic between the He star and evolved main-sequence star tracks is that the He star tracks are evolving to longer periods, while the relevant evolved main-sequence star tracks are reaching their period minima at roughly this donor mass. Hu et al. (2008) show that the orbit of 4U 1916-053 is expanding at the fast rate of $P_{\text{orb}}/\dot{P}_{\text{orb}} = 1.62 \times 10^{-7}$ s$^{-1}$. This is $\sim 100$ times higher than the expected orbital period derivatives for the evolved main-sequence star scenario (Nelson & Rappaport 2003), and $\sim 5$ times higher than the expected orbital period derivative for its mass and mass-transfer rate, assuming conservative transfer where $P_{\text{orb}}/\dot{P}_{\text{orb}} = (3M_d/M_\text{accretor})^{-1}$. Orbital period derivatives orders of magnitude larger than expected, and/or with the wrong sign, are a common problem of XRBs (e.g., Wolff et al. 2009; Chou & Grindlay 2001; Burderi et al. 2009). They can often be explained by the transfer of angular momentum between the donor and orbit on timescales of years, as seen in several X-ray binary or millisecond pulsar systems with very low-mass donors (Arzoumanian et al. 1994; Patruno et al. 2012). However, it is unclear whether such an explanation can apply to partly degenerate donors such as 4U 1916-053. The other option is nonconservative mass transfer, as predicted by the van Haften et al. (2012c) scenario.

### 3.4. 4U 1626-67

The other persistent UCXB with a constraint on the donor mass is 4U 1626-67. An upper limit derived from searching for timing variations in the X-ray pulses at the known 41.4 minute orbital period constrains the projected semimajor axis of the NS to $<8$ lt-ms (Levine et al. 1988; Shinoda et al. 1990). This implies $i < 7.8 \times 10^{-3} q^{-1.5} (1 + q) 10^{13} M_{\text{NS},1.4} P_{\text{orb}}^{-2.3}$ (Chakrabarty 1998), where $q$ is the donor/NS mass ratio, and $i$ is the inclination, measured from $i = 0$ face-on. Schulz et al. (2001) found double-peaked emission lines in its spectrum, interpreted as the Keplerian Doppler shifts of the accretion disk. Krauss et al. (2007) measured disk line velocities of $v \sin i = 1700$ km s$^{-1}$, which, with the corotation radius of the NS at $6.5 \times 10^{8}$ cm (Coburn et al. 2002), allows a constraint on the inclination angle, $i > 22^\circ$. Combining this with the projected semimajor axis upper limit constrains the donor mass to $<0.036 M_\odot$ for a 1.4 $M_\odot$ NS. Requiring the donor to also fill its Roche lobe gives a radius of $<0.06 R_\odot$. 4U 1626-67 shows clear evidence of C, O, and Ne in its X-ray and optical spectra. Thus, the evolved main-sequence star track is ruled out. Its long-term accretion history has given a total fluence of 0.927 erg cm$^{-2}$ (Krauss et al. 2007), or $\sim 1.6 \times 10^{52}$ g (Lasota et al. 2008). The latter estimate depends on the poorly known viscosity, and was calculated for helium rather than C/O. Since C/O disks have lower instability limits (see Section 2.3), they will go into outburst at lower disk densities, and thus can store even less mass. Thus, it is very difficult to believe that 4U 1626-67 is undergoing a transient outburst; its mass transfer must indeed be persistent. This rules out the WD evolutionary track, which cannot evolve a WD donor from short periods (Deloye & Bildsten 2003).

He star tracks can possibly explain the nature of 4U 1626-67. Our He track with $M = 10^{-6} M_\odot$ yr$^{-1}$ passes nicely through its orbital period and most likely mass-transfer rate. However, we can also calculate the mass of our simulated donors at 42 minutes, finding that the $M = 10^{-6}$ track gives a mass that is too high (Figure 6). In addition, the inferred density of the donor seems too high for the $M = 10^{-4}$ track (mass and radius limits above, and Figure 3). The $M = 10^{-7}$ track is a more appropriate fit for both. If 4U 1626-67 is at the relatively nearby distance of $\sim 5$ kpc (barely allowed within the distance errors; see Figure 2, Table 1), its inferred luminosity and therefore $M$ would also be consistent with the $M = 10^{-7}$ track. Alternatively, the very high magnetic field of this NS ($3 \times 10^{12}$ G, Coburn et al. 2002) may provide additional magnetic braking in this system, which we do not attempt to model here. Finally, donor wind mass loss or CBDs with a WD donor are also possibilities.

To attain its current low-mass, high-entropy state, the donor star must have been fusing He when it started mass transfer, and thus must have transferred several tenth of a solar mass to the accretor. Yet the accretor has a magnetic field of $3 \times 10^{12}$ G, compared to typical magnetic fields of $10^{8}$ G for recycled NSs, which have likely been driven to field decay due to accretion of a few tenths of a solar mass (Bhattacharya & van den Heuvel 1991). It is difficult to understand why the magnetic field of the NS in 4U 1626-67 did not decay. This suggests either that the NS in 4U 1626-67 underwent accretion-induced collapse (Taam & van den Heuvel 1986; Yungelson et al. 2002), or that the progenitor NS had an originally much higher field strength, of magnetar levels. We cannot infer the age of this system from its spin period since its changes from spin-up to spin-down (e.g., Camero-Arranz et al. 2010) indicate that it is close to spin equilibrium. A difficulty with the accretion-induced collapse scenario is that mass transfer will stop after the collapse for a period of $\sim 10^8$ years (Verbunt et al. 1990), which should allow a low-mass donor to cool down and join the standard WD tracks (Deloye et al. 2007). As the analysis of Verbunt et al. (1990) assumed rapid magnetic field decay in NSs, a detailed reconsideration of this scenario could be rewarding.

### 3.5. 4U 0614+091

The orbital period of 4U 0614+091 is not well determined, although there are hints from both optical photometry and spectroscopy. O’Brien (2005), Shabaz et al. (2008), Hakala et al. (2011), and Zhang et al. (2012) have found photometric evidence for orbital periods of 50–51 minutes, although not consistently (for instance, Hakala et al. found a 50 minute periodic signal in only 1 of 12 data sets, and several of these papers found other possible periodicities). Weak evidence for a 48.5 minute orbital period was suggested by Nelemans et al. (2006) from Gemini/GMOS spectroscopic data, but Madej et al. (2013) find evidence for a 30 minute orbital period in the same Gemini/GMOS data as well as in VLT/X-Shooter spectra (and do not confirm the 48.5 minute period). No convincing evidence of the orbital period is seen in X-ray observations (Hakala et al. 2011; Madej et al. 2013).

If the suggested 50–51 minute orbital period of this system is correct, then the persistent nature of this system and the C/O composition of the accretion disk (Nelemans et al. 2006; Schulz et al. 2010; Madej et al. 2010) suggest an He star
donor, as for 4U 1626-67. A 30 minute orbital period would not change this conclusion, as the inferred mass-transfer rate would still be rather larger than can be supplied by standard WD evolution. However, the uncertainty in the orbital period means that conclusions about the nature of this object remain unclear. The clear evidence for He in the X-ray bursts, along with the lack of any evidence for He in optical spectra of this object, presents another mystery (Kuulkers et al. 2010).

4. CONCLUSIONS

We utilize the luminosity histograms calculated in Cartwright et al. (2013), new calculations of He star evolution, and a wide range of key facts from the literature to place constraints on the nature of various individual UCXBs.

We have calculated time-averaged mass-transfer rates for UCXBs with known (or suggested) periods and compared them with theoretical mass-transfer rates. Most agree very well with tracks for WD donors, supporting the idea that this is the primary route for UCXB production. A group of two or three systems with high (>10⁻¹⁰ M☉ yr⁻¹) mass-transfer rates and long (>40 minute) periods require alternative explanations, as standard WD evolution is incapable of reaching them. CBDs, while mathematically capable of providing the required angular momentum loss rates, require rather unfeasible physical conditions. Enhanced donor wind mass-loss rates (suggested by van Haften et al. 2012c) might explain these systems, but we identify some potential difficulties with this explanation. We show that stellar cores burning helium when mass transfer starts (He stars) are capable of reaching these mass-transfer rates at these periods due to their much higher initial entropy and continued strong irradiation, and could explain all three systems.

The disk instability line for helium accretion disks, even when irradiated by accretion X-rays, is too high to explain the persistent behavior of at least three, probably six, UCXB systems. We point out that C/O disks have lower disk instability lines (as calculated by Menou et al. 2002), which, when considering irradiation, can easily keep these systems persistent. As four of the six show evidence of carbon and/or oxygen in their optical, UV, and/or X-ray spectroscopy, this nicely explains their behavior. This provides a key physical explanation for the difference between the empirical UCXB luminosity function and current theoretical ones.

One system, 2S 0918-549, lies well below the lowest-entropy helium WD track. If its recent mass-transfer rate is representative, it must have a C/O WD; this is consistent with its optical spectroscopy, which suggests a C/O disk. A tentative 10.8 minute period for 4U 1728-34 would make this system’s mass-transfer rate impossible to explain by any evolutionary model, and require dramatic fluctuations in mass transfer on timescales >30 years.

Two unusual UCXBs have additional data to test evolutionary models. 4U 1916-053 shows positive and negative superhumps, due to its precessing accretion disk, which permits an estimate of the mass ratio and thus of the donor mass; we derive M_donor = 0.064 ± 0.010 M☉ (assuming a 1.4 M☉ NS). 4U 1916-053 shows helium and nitrogen in its optical spectra, which permits either an evolved main-sequence star or a slightly evolved He star as the initial donor. The large orbital period derivative suggests an He star for the donor, but is not conclusive.

4U 1626-67 shows 7.7 s X-ray pulsations, but no pulse frequency shifts. Combined with a constraint on the disk’s inclination from the velocity of X-ray lines in the disk, we can constrain M_donor < 0.036 M☉ (for a 1.4 M☉ NS). C, O, and Ne line emission has been observed in the optical, ultraviolet, and X-ray. Its time-integrated X-ray luminosity indicates a total mass transferred onto the NS during its history of continuous accretion that exceeds the mass that can be stored in a C/O disk in a 42 minute orbit, proving that this system is not experiencing a transient disk-instability outburst, but is truly a persistent system. The chemical composition and mass-transfer requirements strongly suggest an He star donor. The unusually high magnetic field of the NS indicates a past history of substantially stronger, magnetar-strength fields or recent accretion-induced collapse of a WD.

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Note added in proof. van Haften et al. (2013) have recently performed a UCXB population synthesis, finding similar numbers of UCXBs with C/O and He composition in the range of observed UCXB periods.

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