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AM CVn stars

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Abstract.   I review our observational and theoretical knowledge of AM CVn stars, focusing on recent developments. These include newly discovered systems, the possibility that two recently discovered extremely short period objects are AM CVn stars and an update on X-ray, UV an optical studies. Theoretical advances include the study of the details of both the donor and accretor, and the physics of the helium accretion discs. I review our (limited) knowledge of the formation of AM CVn stars and the apparent success of the now more than 25 year old suggestion that in these objects the mass transfer is driven by gravitational wave radiation losses. The exciting prospect of directly detecting these gravitational waves and the possibilities this brings conclude this contribution.

1.   Introduction

AM CVn stars are binary systems that have very short orbital periods (less than about one hour) and helium dominated spectra. The prototype, with an orbital period of 17 min. was discovered in 1967 (Smak 1967). Paczyński (1967) quickly proposed that this object was a very short period binary with a degenerate, helium-rich donor and that the mass transfer is driven by angular momentum loss due to gravitational wave radiation (GWR). Because GWR depends very strongly on orbital period, this interpretation suggests a rapidly dropping mass-transfer rate as function of orbital period. Since 1967 another ten objects have been discovered with periods up to 65 minutes. Four of them were found in the last few years, as well as two extremely short period objects that are possibly also AM CVn stars. In this review I'll first give a description of the properties of AM CVn stars, followed by a short overview of our understanding of their formation and evolution, recent observational developments, and highlight some interesting questions and their possible answers. Finally I discuss AM CVn stars as GWR sources. For earlier reviews see Warner (1995); Solheim (1995, 2003).

1.1.   Fundamental properties of AM CVn stars

The known AM CVn stars and two candidate systems are listed in Table 1. The table gives a very short overview of the observational properties of the systems, with recent references (for earlier work, see the previous reviews). As function of increasing orbital period (and thus also as function of time as they evolve to longer periods) they go through three distinct phases: (i) A high-state phase (AM CVn and HP Lib, with $P \lesssim 20$ min), with low-amplitude photometric variations on various periods, among which the orbital period and

Table 1.   Overview of observational properties of AM CVn stars

Name	P_{orb}^a (s)		P_{sh}^a (s)	Spectrum	Phot. var^b	dist (pc)	X-ray^c	UV^d
ES Cet	621	(p/s)		Em[1,2]	orb		C[3]X	GI
AM CVn	1029	(s/p)	1051	Abs	orb	235[4]	RX	HI
HP Lib	1103	(p)	1119	Abs	orb		X	HI
CR Boo	1471	(p)	1487	Abs/Em?	OB/orb		ARX	I
KL Dra	1500	(p)	1530	Abs/Em?	OB/orb			
V803 Cen	1612	(p)	1618	Abs/Em?	OB/orb		Rx	FHI
CP Eri	1701	(p)	1716	Abs/Em	OB/orb			H
2003aw	?		2042	Em/Abs?	OB/orb			
SDSSJ1240-01	2242[5]	(s)		Em	n			
GP Com	2794	(s)		Em	n	70[6]	ARX[7]	H[8]I
CE315	3906	(s)		Em	n	77[9]	R(?)[e]X	H[10]
Candidates								
RXJ0806+15	321	(X/p)		He/H?[11]	"orb"		[12–15]CRX	
V407 Vul	569	(X/p)		K-star[16]	"orb"		[17–19]ARCRxX	

a orb = orbital, sh = superhump, periods from Woudt & Warner (2003a), see references therein, (p)/(s)/(X) for photometric, spectroscopic, X-ray period.
b orb = orbital, OB = outburst
c A = ASCA, C = Chandra, R = ROSAT, Rx = RXTE, X = XMM-Newton (see Kuulkers et al. 2004, for a short review and references)
d F = FUSE, G = GALEX, H = HST, I = IUE (see Solheim 1995; Warner 1995, for references)
e 1RXS J131246.8-232118
References: 1 Warner & Woudt (2002), 2 Steeghs et al, in prep., 3 Strohmayer (2004a), 4 C. Dahn, private communication, 5 Roelofs et al. in prep. 6 Thorstensen (2003), 7 Strohmayer (2004c), 8 Morales-Rueda et al. (2003), 9 Thorstensen, this conference, 10 Gänsicke et al. (2003), 11 Israel et al. (2002), 12 Israel et al. (2003), 13 Strohmayer (2003), 14 Israel et al. (2002), 15 Ramsay et al. (2002a), 16 Steeghs et al. in prep., 17 Cropper et al. (1998), 18 Strohmayer (2002), 19 Strohmayer (2004b)

a slightly longer one, called the superhump period (see Warner 1995). The latter is the result of the fact that the accretion disc becomes eccentric and starts to precess due to the extreme mass ratio (Whitehurst 1988). For AM CVn, the absorption lines show variations on the beat frequency between orbital and superhump frequencies. (ii) An outbursting phase, in which large optical variability (up to 4 magnitudes) is seen (CR Boo, KL Dra, V803 Cen, CP Eri, 2003aw with periods $20 \lesssim P \lesssim 40$ min). During the bright phases these systems resemble the the high-state absorption line systems, whereas emission lines are visible during the quiescent phases (as far as we have seen these spectra, e.g. Groot et al. 2001).. These systems are thought to have unstable discs, in analogy with the hydrogen-rich dwarf novae (Tsugawa & Osaki 1997). (iii) The longest period systems (SDSSJ1240-01, GP Com and CE315, with $P \gtrsim 40$ min) show no optical photometric continuum variability, but their orbital periods are determined spectroscopically. SDSSJ1240-01 also shows the He absorption lines
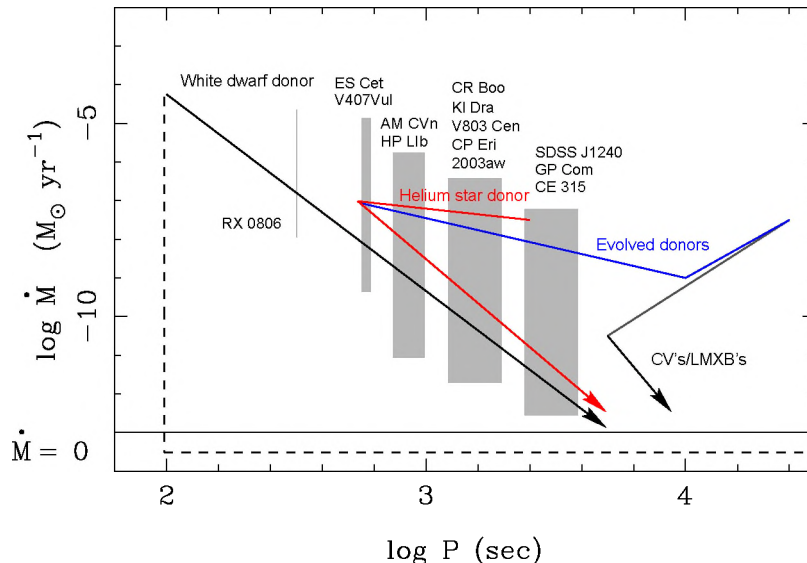
Figure 1.   Formation paths of AM CVn stars (see text). The known systems (including the two candidates) are shown at their orbital period.

of the accreting white dwarf (Roelofs et al. 2004), while the continuum emission of GP Com and CE315 is also shown to come from the white dwarf (Bildsten et al., in prep). In these cases, however, the effective temperature of the accreting white dwarf is too low to show He absorption. The low-state systems probably have stable cool accretion discs.

1.2.   Formation and evolution of AM CVn stars

For a detailed discussion of the formation of AM CVn systems I refer to Nelemans et al. (2001a), and references therein.   There are three routes for the formation of AM CVn systems (see Fig. 1): (i) via a phase in which 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. Paczyński 1967).   In order for the mass transfer to be stable and below the Eddington limit, the mass of the donor must be small (e.g. Nelemans et al. 2001a). (ii) Via a phase in which a low-mass, non-degenerate helium star transfers matter to a 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 (Iben & Tutukov 1991).   (iii) From cataclysmic variables with evolved secondaries (Podsiadlowski et al. 2003), 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 systems 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 (except for RXJ0806+15).

1.3.   Direct impact

A special situation occurs at the onset of mass transfer between two white dwarfs. The two objects are so close together that there is no room for an accretion disc in the system and the stream of gas that falls from the inner Lagrangian point towards the accreting white dwarf impacts directly onto its surface (Webbink 1984; Nelemans et al. 2001a, see Fig. 2). This has has important consequences for the

Figure 2. Schematic picture of the direct impact phase of accretion between two white dwarfs.

stability of the mass transfer and the AM CVn stars formed from detached double white dwarfs (Nelemans et al. 2001a; Marsh et al. 2004).

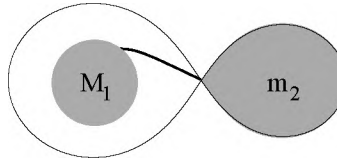## 2.   Recent observational developments

2.1.   Low state systems

The low state systems are dominated by strong HeI emission lines, with a weak continuum. In 2001 a new system was discovered, CE315 (V396 Hya, Ruiz et al. 2001). It is virtually identical to GP Com in terms of its optical spectrum. Recent work on GP Com shows that the mysterious central spike seen in the middle of the double peaked emission lines indeed originates on the accreting white dwarf (Morales-Rueda et al. 2003, Steeghs et al., in prep). This yields a radial velocity amplitude of the accretor of GP Com of 11.7 ± 0.3 km/s and for CE315 of 5.8 ± 0.3 km/s. Together with the hot spot velocity this yield $q \approx 0.018$ for GP Com and $q \approx 0.0125$ for CE315. The peculiar chemical abundance of GP Com, with low abundances of heavy metals suggesting a low-metallicity origin and highly over-abundant N (even compared to CNO processed material) possibly accreted from an AGB companion (Marsh et al. 1991) is confirmed by further UV and X-ray studies (Morales-Rueda et al. 2003; Strohmayer 2004c, see Fig. 3).
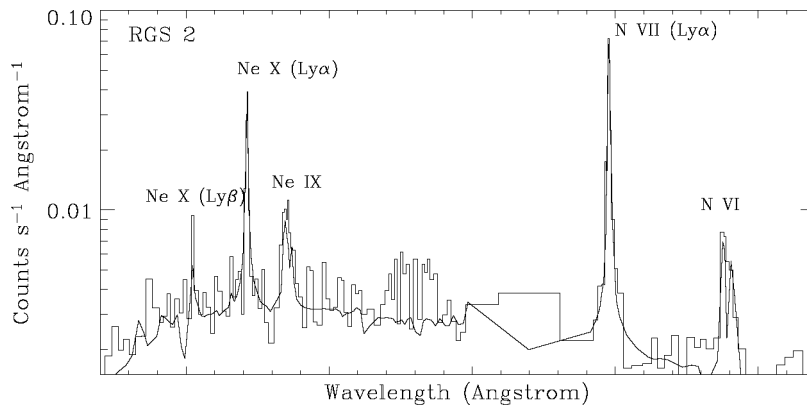

Figure 3.   XMM/Newton spectrum of GP Com, showing clear detection of N and Ne lines, confirming the peculiar chemical abundances. From Strohmayer (2004c)

A new system was found in the first data release of the Sloan Digital Sky Survey: SDSSJ1240-01 (Roelofs et al. 2004). It shows the strong HeI emission lines, but the continuum shows the DB spectrum of the accreting white dwarf. Follow-up spectroscopy yields an orbital period of 2242 s (Roelofs et al., in prep.). No outburst have (yet) been seen. A completely new feature is the presence of a quite strong line at 5169Å, probably from Fe.

2.2. Outbursting systems

The outbursting systems are viewed as being in the mass-transfer regime where the He accretion disc is unstable (Tsugawa & Osaki 1997). In their bright phase they should behave similar to the high state systems and in quiescence similar to the low state systems. Indeed in their bright phase they look very much like the high state systems, but very few quiescent spectra are available. The recent quiescent spectrum of CP Eri (Groot et al. 2001), confirms the similarity with the spectra of the low-state systems, however with distinct differences. There is no sign of a central spike and the presence of Si lines suggest much higher metallicity than GP Com and CE315. Two new objects are found recently, interestingly, both in supernova searches. The first (SN 1998di, now called KL Dra, Jha et al. 1998) showed a high state spectrum in outburst and shows a photometric period of 1530 s., which is interpreted as a superhump period suggesting an orbital period of about 1500 s (Wood et al. 2002). The other object, SN 2003aw, (Chornock & Filippenko 2003) interestingly in the discovery spectrum showed emission lines, but seems to be discovered in a state of intermediate brightness, as in May 2004 it reached $V \sim 15$, about 1.5 mags brighter than at its discovery (Woudt, private communication). Follow-up photometry resulted in the discovery of a 2042 s. period (Woudt & Warner 2003b), again interpreted as a superhump period. VLT spectra of this object show a spectrum that is very similar to that of SDSSJ1240-01 (Roelofs et al., in prep). Recent papers on photometry of outbursting superhump systems are Patterson et al. (1997); Patterson et al. (2000); Kato et al. (2000, 2004)

2.3. High state systems

The two high state systems, AM CVn and HP Lib are characterised by broad, shallow helium absorption lines. Relatively recently the orbital period of AM CVn was confirmed spectroscopically (Nelemans et al. 2001b). A similar study for HP Lib has not (yet) yielded results. Extensive photometric campaigns of AM CVn and HP Lib have shown a complex system of periodicities (Skillman et al. 1999; Patterson et al. 2002; Seetha et al. 2000). For a detailed discussion of the many types of variability in AM CVn stars (and CVs in general) see Warner (2004) and Warner & Woudt, these proceedings.

2.4. ES Cet

ES Cet (KUV 01584-0939) was discovered as a strong emission line system in the KISO survey, but in 2002 Brian Warner realized the "H" lines present in the spectrum of this peculiar CV were lines of the HeII Pickering series (see Fig. 4). Warner & Woudt (2002) discovered a 620 s. period in their photometry, which is interpreted as the orbital period, making ES Cet the shortest period binary known to day. Phase resolved spectroscopy clearly reveals the period in
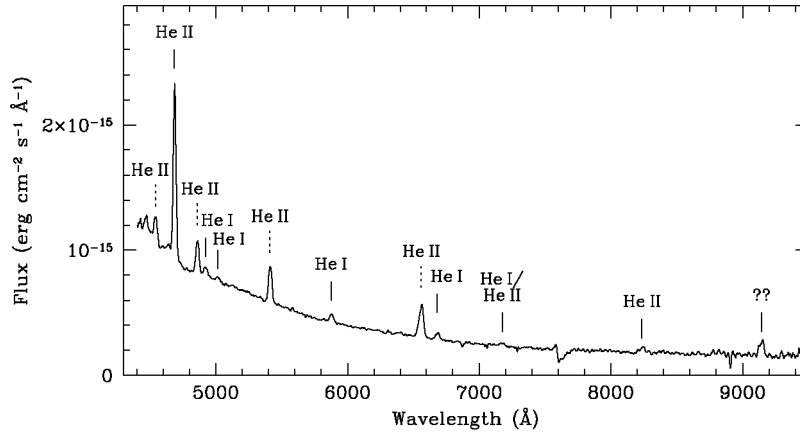
Figure 4.   Average spectrum of ES Cet. From Warner & Woudt (2002)

the changing line profiles (Steeghs et al. in prep). Its period is on the edge of the period range where direct impact accretion is expected (see Fig. 4 of Nelemans et al. 2004).

2.5.   Ultra-short period candidates

In the last few years a lot of attention has focused on two candidate AM CVn stars: V407 Vul (RXJ1914.4+2456 Cropper et al. 1998) and RXJ0806.3+1527 (Israel et al. 2002; Ramsay et al. 2002a) which were discovered as *ROSAT* X-ray sources (Motch et al. 1996; Israel et al. 1999). They show an on-off X-ray light curve with periods of 9.5 and 5.4 minutes and very soft X-ray spectra. These periods are also found in the optical, but out of phase (Ramsay et al. 2000; Israel et al. 2003). No other periods are found in their light curves. The optical spectra are peculiar. Israel et al. (2002) showed a spectrum of RXJ0806+15 with very weak emission lines, which they interpreted as HeII lines (see Fig. 5). The fact that the even lines of the series (which are very close to the Balmer lines) are stronger than the odd lines can also be interpreted as evidence for the presence of some H. In the optical and IR the spectral energy distribution is consistent with a single hot black body (Reinsch et al. 2004). The optical spectrum of V407 Vul shows the spectrum of a late G-star (Steeghs et al., in prep.). If not the same object the G-star is very close to the object (within 0.03", Marsh et al., these proceedings), the lack of any detectable radial velocity and emission lines appears at odds with the observed X-ray emission. Israel et al. (2004) have reported detection of linear polarisation from RXJ0806+15. A very interesting development is that for both objects it has become clear that the periods are getting shorter (Strohmayer 2002; Hakala et al. 2003; Strohmayer 2004b, Israel et al. in prep), in contradiction with the expectation for the secular evolution of AM CVn stars.

2.6.   Distances and Surveys

Distances to AM CVn stars have been unknown for long. This is currently changing (rapidly). John Thorstensen has determined 2: 70 pc for GP Com (Thorstensen 2003) and 77 pc for CE315 (Thorstensen, this proceedings). The
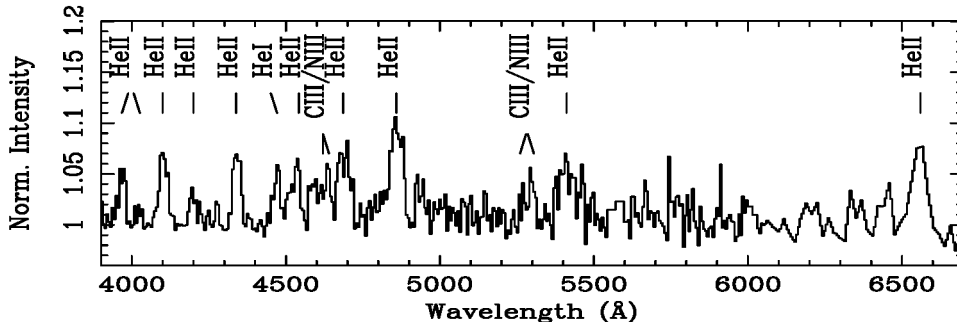
Figure 5.   VLT spectrum of RXJ0806+15. From Israel et al. (2002)

USNO parallax team (C. Dahn, private communication) has measured the distance to AM CVn to be 235 pc. Distances to AM CVn, HP Lib, CR Boo, V803 Cen and GP Com will be determined (confirmed) by HST FGS parallaxes (Groot et al., in prep).

Another promising area of development for AM CVn stars are surveys. Both general purpose surveys (in particular the Sloan survey) and dedicated surveys to find more AM CVn stars. As a pilot project, a survey was done of ~40 square degrees at Galactic latitude ~15 degrees with imaging in two broad band filters (B and R) and two narrow band filters (one on Hα and one on the 6678 Å He emission line). The already known emission line systems (GP Com and CE315) were clearly detected. However, among the few candidates no new AM CVns were discovered (Groot et al., in prep). A larger, lower Galactic latitude survey, including variability information will be performed with the OmegaCam wide field imager on the VLT Survey Telescope, the OmegaWhite survey (PI Paul Groot). The RApid Time Survey looking for short-period photometric variables with the WFC on the INT (Ramsay & Hakala, in prep.) is another promising survey.

3.   Questions and partial answers

AM CVn stars are interesting objects for a number of reasons, mainly related to their short periods and the fact that the donor stars in these systems have peculiar chemical composition. This makes it possible to study some astrophysical processes in rather unusual and extreme conditions. At the same time many questions regarding AM CVn stars are unanswered. Below I list some of the outstanding questions, their importance and sometimes their (partial) answers.

3.1.   Interpretation of V407 Vul, RXJ0806+15

One of the main questions that people have tried to answer in the recent years is what the nature of the two short-period candidates is. They have been proposed to be either double degenerate polars (Cropper et al. 1998), direct impact accretors (Marsh & Steeghs 2002; Ramsay et al. 2002b, see below), double white dwarfs with an electrical interaction like the Jupiter-Io system (Wu et al. 2002), or face-on stream-fed intermediate polars (Norton et al. 2004). In the last two cases they would not belong to the AM CVn stars. See for a discussion

Cropper et al. (2004), who conclude that the electrical star is the most viable model. Since then the period derivatives have been confirmed and detection of linear polarisation for RXJ0806+15 has been reported (Israel et al. 2004).

If the measured period derivative reflect the secular evolution of these systems (which it tends not to do in interacting binaries) it strongly argues against an AM CVn star interpretation. The period derivatives are roughly in agreement with what is expected for detached double white dwarfs spiralling together due to GWR. However, the inferred masses for V407 Vul (Strohmayer 2002) are too low for a detached double white dwarf (see Fig 1 in Nelemans et al. 2001a). Furthermore, for a dipole magnetic field, the necessary geometry to make the electrical star fit the observed X-ray light curve seems to be very contrived (Barros et al., these proceedings).

For the intermediate polar model, the absence of emission lines, the very soft X-ray spectrum and the absence of any cool component in the optical and IR spectral shape of RXJ0806+15 (limiting any donor star to spectral types later than L6 or later Reinsch et al. 2004) are serious problems. The apparent support for this model by the presence of a G-star in the spectrum of V407 Vul is hampered by the fact that the star does not show radial velocity variations more than ~ 10 km s^{-1}, limiting the inclination to $< 4°$ for the system parameters given in Norton et al. (2004), and even smaller if a more realistic mass for the G9V star is taken.

In summary all proposed models seem to have problems explaining these systems, and it is not clear yet if any of these models will be the right one.

3.2.   Physics of the He accretion disc

A unique property of AM CVn stars are their He dominated accretion discs. Furthermore, the GWR driven mass transfer is expected to drop by at least five orders of magnitude over the observed period range (see Fig. 1), allowing in principle the study of He accretion discs as function of mass-transfer rate. Tsugawa & Osaki (1997) studied the stability of He discs and concluded that for increasing orbital period the AM CVn stars should go through a phase with a stable hot discs (identified with the high-state systems), a phase with an unstable disc (identified with the outbursting systems) and settle down in a phase with a cool (neutral) stable disc (identified with the low-state systems). The stability lines as given by Tsugawa & Osaki (1997) actually match the then known observed properties well. The new systems follow the trend and if SDSSJ1240-01 does indeed not show outbursts, the transition to the stable cool discs happens between 34 and 39 minutes. In Fig. 6 I plot the expected visible population of AM CVn stars, the stability criteria and the periods of the observed systems (after Nelemans et al. 2001a).

In recent years a number of groups have attempted to construct model disc spectra in order to constrain the system parameters of the observed objects. Nasser et al. (2001) found relatively high mass transfer rates of a few times 10^{-9} M$_\odot$ yr^{-1} for AM CVn, HP Lib, CR Boo and V803 Cen. El-Khoury & Wickramasinghe (2000) modelled AM CVn and CR Boo and find somewhat lower mass transfer rates ($\sim 10^{-9}$ M$_\odot$ yr^{-1}). Nagel et al. (2003) modelled the spectrum of AM CVn with the parameters of Nasser et al. (2001) but do not reproduce the relative strengths of the HeI 4026 and 4143 Å lines.
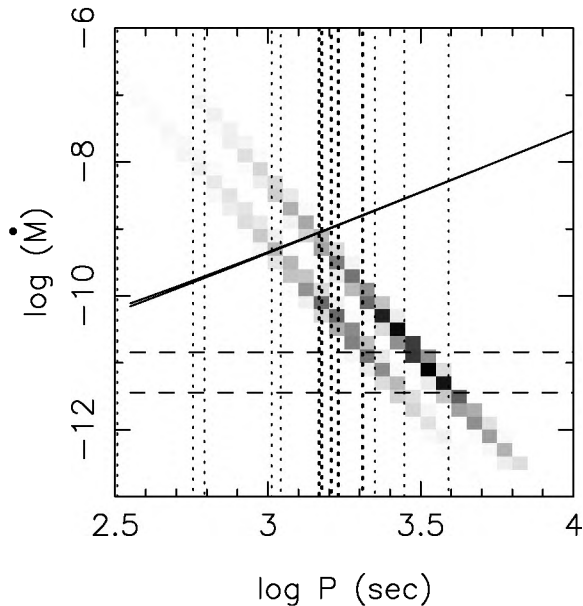
Figure 6. Period mass transfer plot with the two tracks of the different formation scenarios and the stability criteria of Tsugawa & Osaki (1997) plotted. Above the solid lines the discs should be hot and stable, below the dashed lines (upper for an accretor mass of 0.5 $M_\odot$, the lower for 1.0 $M_\odot$). The periods of the known systems are plotted as the dotted lines (thicker for outbursting systems). From Nelemans et al. (2001a) with updates.

Finally, there have been a number of recent SPH calculations reported that are relevant for AM CVn stars (Wood et al. 2000; Kunze et al. 2001; Pearson 2003), coupling their results to the observed (negative) superhumps. Pearson (2003) suggests that AM CVn has a relatively high donor mass with a modest magnetic field.

3.3. Evolution and system parameters

One of the promising ways to distinguish between the different possible formation scenarios for the currently observed systems is to study the chemical composition of the donor star (Nelemans & Tout 2003). This reveals itself through the chemical composition of the accretion disc which dominates the light (except for the low-state systems, see below). In case the donor is a white dwarf, its composition should be that of a helium white dwarf or a carbon/oxygen white dwarf. The descendants of the helium star channel should (at some point) show produces of helium burning (i.e. carbon) in their spectrum, although the theoretical models suggest most went though very little helium burning Nelemans et al. (2001a). Lastly, the systems formed from CVs with evolved donors can show traces of H (Podsiadlowski et al. 2003).

In none of the confirmed AM CVn systems is there any sign of H. The spectral models suggest that only a tiny fraction of H (10^{-5} by number) would be detectable in the spectrum. On the other hand, the spectrum of GP Com shows a large overabundance of N (Marsh et al. 1991), as is expected for a helium white dwarf donor or possibly a remnant from an evolved CV donor if all the H is

lost. CE315 shows a similar effect. However, as is discussed above Marsh et al. (1991) suggest additional N is accreted when its companion was an AGB star. The low-state spectrum of CP Eri does show Si lines, suggesting it had higher initial metallicity.

Recent XMM observations confirm the high N abundance and show Ne lines in GP Com (Strohmayer 2004c), while spectra of AM CVn, HP Lib and CR Boo seem to show evidence for enhanced N, in case of AM CVn and HP Lib again above the expected value of CNO processed material (Ramsay et al., in prep). Finally, the newly discovered systems in which both lines from the disc and lines from the accreting white dwarf are seen, both show the Fe 5169 Å line in the disc (and again no sign of H in the absorption lines of the accreting white dwarf).

It is generally assumed that the white dwarf donors obey the mass – radius relation for zero-temperature white dwarfs (e.g. Nelemans et al. 2001a) which is an extreme simplification. Recent calculations have become available of finite entropy low-mass white dwarfs as donors in ultra-compact X-ray binaries (Deloye & Bildsten 2003) and AM CVn stars (Deloye et al. in prep) will fill in the gap in our knowledge here. Another very interesting recent development is the application of the calculations of compressional heating of accreting white dwarfs in CVs (Townsley & Bildsten 2004) to the accreting white dwarfs in AM CVn systems (see Bildsten, these proceedings). The result is that at late times (long orbital periods) the accreting white dwarf will dominate the light from the system. This is clearly the case in the newly discovered systems showing the accreting white dwarf absorption lines, but is also the case for GP Com and CE315. For the latter two, this can be directly inferred from the effective temperature of the continuum and the absolute magnitude (Bildsten et al., in prep).

3.4. Population

At present the extent of the Galactic population of AM CVn stars is not (well) known. Theoretical calculations predict between $\sim 10^7$ to more than 10^8 in the Galaxy (e.g. Tutukov & Yungelson 1996; Nelemans et al. 2001a; Hurley et al. 2002) but the uncertainties in both the efficiencies of the formation scenarios and the selection effects are very large (Nelemans et al. 2001a). In any case the vast majority of the systems in the Galaxy should be at the long period end, where the systems pile up at very low mass-transfer rate. Also, estimates based on the observed systems (e.g. Warner 1995) are heavily affected by selection effects, both with regard to the brightness of the objects as well as the fact that almost all known sources have been found serendipitously. Only recently, with the large surveys like the Sloan survey and the dedicated AM CVn surveys will the latter point be remedied. The increasing number of systems with distance determinations will greatly help the question of the brightness of the systems as function of orbital period.

We recently started looking in more detail at the selection effects and calculated the expected number of detectable short-period AM CVn systems, in particular to address the question of how likely it would be to have two direct impact accretors in the Galaxy that are currently visible. We found that in order to expect a few of these systems, we need to adopt one of the most optimistic models about the total population in the Galaxy (Nelemans et al. 2004). That
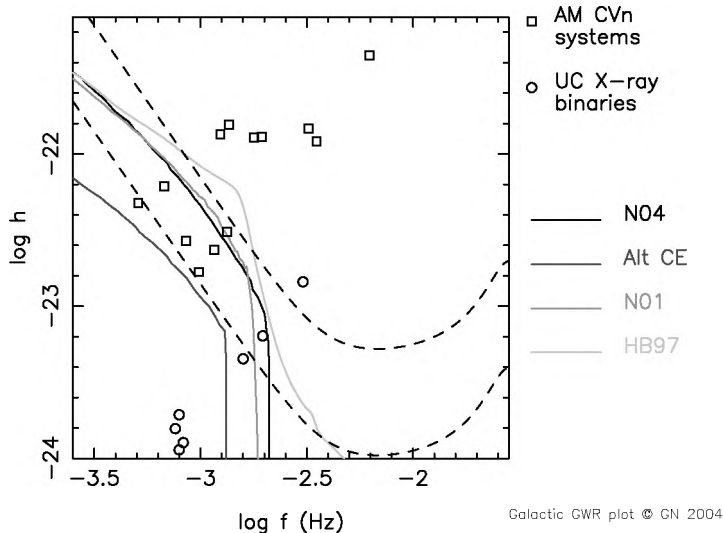
Figure 7.   Known AM CVn stars (open squares) and Ultra-compact X-ray binaries (open circles) in the GWR frequency - GWR strain amplitude plain. The dashed lines show the *LISA* sensitivity for a one year mission giving a signal-to-noise ratio of 1 and 5 respectively. The Solid curves are different estimates of the average confusion limited double white dwarf background. Black: Nelemans et al. (2004) (N04), dark grey: the same with the alternative common-envelope (Nelemans et al. 2000) applied in all cases, lighter grey: Nelemans et al. (2001c) (N01) and lightest grey: Bender & Hils (1997) (HB97).

would suggest there should still be many more relatively bright longer period systems undetected.

4.   AM CVn stars as GWR sources

AM CVn stars are important sources of low-frequency GWR (e.g. Nelemans 2003), a frequency range that will be probed by the ESA/NASA *LISA* mission[1]. They hardly contribute to the noise background (Hils & Bender 2000), but they are the only *known* sources in this frequency band (although many exotic sources like massive black hole mergers, compact objects spiralling into massive black holes etc. are expected). Fig. 7 shows the known and candidate AM CVn stars and the *LISA* sensitivity. It is clear that even if the two candidates are not AM CVn stars there are still seven objects that will be easily detected (with the caveat that except for AM CVn the distances are not well known).

A more detailed discussion of AM CVn stars as sources of GWR is given in Nelemans et al. (2004), in particular the promising possibility to combine GWR and electro-magnetic observations to study AM CVn stars. The expected number of AM CVn stars that *LISA* will detect individually is many thousands (although the data reduction problem of how exactly all these signals

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[1]http://sci.esa.int/science-e/www/area/index.cfm?fareaid=27
http://lisa.jpl.nasa.gov/

are recovered from the data is far from solved, e.g. Cornish & Larson 2003;
Vecchio & Wickham 2004).

5.   Conclusions and outlook

In this concluding section I summarise some of the questions that I find interesting and briefly discuss (near) future developments.

Formation and properties of AM CVn stars The properties of the observed
systems seem to be in rough agreement with having a strongly decreasing mass transfer rate as function of orbital period. The details of the mass transfer rate as orbital period are currently studied in more detail, through more realistic models of the donor stars. At the same time, predictions made by calculating the effective temperature and brightness of the accreting white dwarfs agree with the observations. The question of which of the three different formation channels led to the observed systems will hopefully be answered in the relatively near future by detailed studies of the chemical composition of the accreted material, both theoretically as function of formation history (including possible accretion in a previous mass transfer phase) and initial metallicity and observationally by higher signal-to-noise ratio spectra. Current preliminary conclusions are that there seems to be a quite large range in initial metallicities (some quite low). Secondly, there currently is no evidence for H in any system, but there is a lot of evidence for enhanced N, indicating CNO processing in the progenitors, i.e. either helium white dwarfs or evolved secondaries in CVs.

AM CVn stars as astrophysical laboratories The use of AM CVn stars as
astrophysical laboratories is hampered by our lack of understanding both of the formation and population of systems in the Galaxy. Upcoming surveys (and hopefully theoretical developments that will allow us to compare the survey results directly with population studies) will probably greatly help sort out at least the population question. The fact that a number of distance estimates are available makes that questions like the brightness of the accretion discs and the accreting white dwarf (and thus their sizes) can be addressed. The disc instability model applied to helium discs has been mentioned above and the discovery of more systems will enable much more strict tests of this model than was previously possible. Finally, binary evolution constraints, in particular on the common envelope phase, which determines the mass ratios of the detached double white dwarfs (Nelemans et al. 2001c) which in turn determines the number of possible AM CVn progenitors. This is also relevant in the search for the progenitors of type Ia supernovae. Finally, the direct impact phase, which must exist, regardless of the identification of the two candidate AM CVn stars as direct impact accretors, will be an interesting aspect.

AM CVn stars as GWR sources AM CVn stars are currently the only known
sources for the space based GWR detector *LISA*. The expected number of

individually detected sources is many thousands and the *LISA* measurements will be mainly sensitive to the relatively rare short period systems that are difficult to access with classical observational techniques.

The nature of V407 Vul and RXJ0806+15 The nature of the two candidate short-period AM CVn systems is unclear. All proposed models seem to have problems explaining the observations. They are very interesting objects in any case and the observations scheduled in the near future will keep them in the spotlight. Hopefully either observational or theoretical advances will solve this puzzle soon. If not, *LISA* will certainly do so.

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