Detached white-dwarf close-binary stars – CV’s extended family

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Abstract

I review detached binaries consisting of white dwarfs with either other white dwarfs or low mass main-sequence stars in tight orbits around them. Orbital periods have been measured for 15 white dwarf/white dwarf systems and 22 white dwarf/M dwarf systems. While small compared to the number of periods known for CVs (> 300), I argue that each variety of detached system has a space density an order of magnitude higher that of CVs. While theory matches the observed distribution of orbital periods of the white dwarf/white dwarf binaries, it predicts white dwarfs of much lower mass than observed. Amongst both types of binary are clear examples of helium core white dwarfs, as opposed to the usual CO composition; similar systems must exist amongst the CVs. White dwarf/M dwarf binaries suffer from selection effects which diminish the numbers seen at long and short periods. They are useful for the study of irradiation; I discuss evidence to suggest that Balmer emission is broadened by optical depth effects to an extent which limits its usefulness for imaging the secondary stars in CVs.

1. Introduction

Cataclysmic variable stars (CVs) have not always been as we see them today. They evolve from pairs of main-sequence stars in relatively long period orbits. We know this because the white dwarf components of CVs were once the cores of giant stars much larger than the CVs are now. The standard explanation for this invokes a phase during which both stars orbit within a single envelope (derived from the giant star). As the stars orbit they lose angular momentum to the envelope which is ejected, leaving a much tighter binary star.

This so-called “common-envelope phase” does not produce a CV: some other angular momentum loss, such as magnetic braking, is required to further whittle down the orbit before mass transfer from the still-unevolved secondary star can get underway. Clearly we must expect to find binary stars which have gone through common-envelope evolution, but have yet to become CVs. These stars, which for simplicity we will call pre-CVs – although they will not always manage to become CVs – should consist of white dwarf stars with low mass companions, typically M dwarf stars. I will look at examples of these stars in section 3. They are of direct interest to evolutionary models of CVs and give us clean examples of irradiated stellar atmospheres.

After the common-envelope phase, the binary may still be of sufficiently large separation that it cannot become a CV before the secondary star has itself evolved. If this occurs one can expect a second common-envelope phase. If the binary survives this, a pair of white dwarfs or a “double-degenerate” may emerge; such systems may also be produced from the remnants of Algols. I will refer to them as DDs. There has been much interest in DDs mainly because they are a possible progenitor system of Type Ia supernovae.
Table 1
Detached white-dwarf/sub-dwarf + white-dwarf/M-dwarf binaries of known orbital period.

| Name             | Period (days) | Type  | Ref  | Name      | Period (days) | Type  | Ref  |
|------------------|---------------|-------|------|-----------|---------------|-------|------|
| WD 0957-666      | 0.061         | WD/WD |      | GD 448    | 0.103         | WD/M | 6    |
| KPD 0422+5421    | 0.090         | sdB/WD | 1    | MT Ser    | 0.113         | sdO/M |      |
| WD 1704+481A     | 0.14          | WD/WD | 2    | HW Vir    | 0.117         | sdB/M |      |
| PG 1101+364      | 0.145         | WD/WD |      | NN Ser    | 0.130         | WD/M  |      |
| WD 2331+290      | 0.166         | WD/WD |      | EC 13471-1258 | 0.151       | WD/M  |      |
| PG 1432+159      | 0.225         | sdB/? | 3    | GD 245    | 0.174         | WD/M  |      |
| PG 2345+318      | 0.241         | sdB/? | 3    | BPM 71214 | 0.202         | WD/M  | 7    |
| PG 1101+249      | 0.354         | sdB/? | 3, 4 | PG 1224+309 | 0.259       | WD/M  | 8    |
| PG 0101+039      | 0.570         | sdB/? | 3    | AA Dor    | 0.261         | sdO/M |      |
| WD 1713+332      | 1.123         | WD/WD |      | CC Cet    | 0.287         | WD/M  |      |
| WD 1428+373      | 1.143         | WD/WD | 2    | RR Cae    | 0.304         | WD/M  | 9    |
| WD 1022+050      | 1.157         | WD/WD | 5    | TW Crv    | 0.328         | sdO/M |      |
| WD 0136+768      | 1.407         | WD/WD | 5    | WD 1042-690 | 0.336       | WD/M  | 5    |
| Feige 55         | 1.493         | WD/WD |      | GK Vir    | 0.344         | WD/M  |      |
| L870-2           | 1.556         | WD/WD |      | KV Vel    | 0.357         | WD/M  |      |
| WD 1204+450      | 1.603         | WD/WD | 5    | UU Sge    | 0.465         | WD/M  |      |
| PG 1538+269      | 2.50          | sdB/? |      | V477 Lyr  | 0.472         | sdO/M |      |
| WD 1241-010      | 3.347         | WD/WD | 5    | Gi 781A   | 0.497         | M/WD  | 10   |
| WD 1317+453      | 4.872         | WD/WD |      | HZ 9      | 0.564         | WD/M  |      |
| WD 2032+188      | 5.084         | WD/WD | 5    | PG 1026+002 | 0.597       | WD/M  | 11   |
| WD 1824+040      | 6.266         | WD/WD | 5    | EG Uma    | 0.668         | WD/M  |      |
| WD 0940+068      | 8.33          | sdB/? | 2    | RE J2013+400 | 0.706       | WD/M  | 11   |
|                  |               |       |      | WD 2009+622 | 0.741       | WD/M  | 5    |
|                  |               |       |      | RE J1016-0520 | 0.789     | WD/M  | 11   |
|                  |               |       |      | IN CMa    | 1.263         | WD/M  |      |
|                  |               |       |      | Feige 24  | 4.232         | WD/M  |      |
|                  |               |       |      | G 203-047 ab | 14.71     | M/WD  | 12   |

a Types defined as primary/secondary with code: WD= white dwarf; M= M dwarf; sdO/sdB= O/B sub-dwarfs; ?= uncertain.

b References are only given if they cannot be traced from the compilation of [Ritter & Kolb 1998].
1. [Koen et al., 1998], 2. [Maxted et al., in prep], 3. [Moran et al., 1999], 4. [Saffer et al., 1998], 5. [Moran et al., in prep], 6. [Maxted et al., 1998], 7. [Krzeminski, priv comm], 8. [Drosz et al., 1999], 9. [Bruch & Diaz, 1998], 10. [Gizis, 1998], 11. [Wood et al., 1999], 12. [Delfosse et al., 1999]
The idea here is that as gravitational wave radiation shortens their orbital periods, DDs will eventually start mass transfer at orbital periods of order 100 seconds. While they may survive this (and then emerge as AM CVn stars), it is likely instead that they will merge. If the merged product exceeds the Chandrasekhar limit, collapse will occur which might ignite fusion violently enough to give a Type Ia supernova, with no remnant. The biggest problem with this model appears to be whether explosions occur as opposed to much more gentle collapses leaving neutron stars; this is largely a matter for theoretical models. However, a different aspect is directly testable: if DDs are Type Ia progenitors then there should be a population of DDs with total masses above the Chandrasekhar limit and with periods short enough to merge within the lifetime of the Galaxy, which works out at about 10 hours. I now turn to what is known about DDs.

2. Double-Degenerates

The first double-degenerate discovered, L870-2 \cite{saffer1988}, consists of two cool (\( \sim 7,000 \) K) white dwarfs in a 1.56 day period orbit. Around the same time as this discovery, there were three surveys to find the short period population relevant to Type Ia supernovae \cite{robinson1987, bragaglia1990, foss1991}. These were mostly unsuccessful, although a system called 0957-666 was found to have a 1.18 day period \cite{bragaglia1990}. Soon after this work, model atmosphere and evolutionary model fits to the spectra of white dwarfs revealed a population of low mass (\(< 0.45 \, M_\odot\) objects \cite{bergeron1992, bragaglia1995}. On the other hand, white dwarfs which evolve from single stars within the age of the Galaxy are expected to have a minimum mass of around \(0.55 \, M_\odot\). The models are dependent upon the uncertainties of mass loss on the AGB, but some white dwarfs have masses as low as \(0.33 \, M_\odot\), which is too low for them even to have reached the AGB. These must be the helium cores of stars which failed to advance beyond the RGB, perhaps as a result of mass loss within a binary. This suggested that concentrating on the low mass white dwarfs might be an effective method for finding close binaries, as indeed proved to be the case \cite{marsh1995, marsh1997}. This has raised the number of DDs with measured periods to 15, with another 7 sdB binaries that probably have white dwarf companions (see table 1). During this work it was also found that the original period determination for 0957-666 was in error; the revised value of 0.66 days remains the shortest known for these systems \cite{moran1997}.

The observed periods are compared to the results of binary “population synthesis” \cite{iben1997} in Fig. 1. I have assumed that all the sdB stars in the left column of Table 1 have white dwarf companions and that they will emerge as DDs with little alteration in period; this remains to be proved. The essential result of the comparison is that theory and observation match fairly well, although there is perhaps a hint that there may be a dearth of DDs with periods around 0.5 days.

Things become more interesting when one looks at the 2-dimensional distribution of mass and period (Fig. 2): the relative reliability of mass determination for non-accreting white dwarfs is a significant advantage compared to the normal case for CVs. Fig 2 shows a significant discrepancy between theory and observation. Theory predicts the existence of a large fraction of very low mass white dwarfs (\(< 0.25 \, M_\odot\) which are not observed; I can think of no plausible observational selection effect to side-step this discrepancy. Reinforcing this problem, particular systems, such as 0957-666 (the left-most point), lie in regions of near-zero probability according to theory. While the theory has many free parameters that can be adjusted to produce a better fit, the absence of very low mass white dwarfs is a puzzle as it suggests that for some reason we never see the results of mass loss early on the RGB.

2.1. Numbers of DDs

With only 15 bona-fide DDs with measured periods, compared to over 300 CVs \cite{ritter1998}, it may seem that they are relatively rare. In fact the reverse is the case: my best guess at the space density...
The period distribution of WD+WD and sdB+WD binaries is compared to theoretical distribution at birth and after 10^8 yr of erosion by gravitational waves [Iben et al., 1997]. (Solid = WD+WD only; hatched includes sdB+WD too.)

The mass versus period distribution of WD+WD (solid circles) and sdB+WD (asterisks) binaries is compared to theory. Update of Saffer et al., 1998.

The number density of DDs is 5 × 10^{-4} pc^{-3}, of order 20 times that of CVs, including the very faint and so far undetected CVs presumed to have “bounced” at 80 mins orbital period [Politano 1996]. The estimate for DDs is based on the relatively well determined space density for all white dwarfs [Knox et al., 1999] and the roughly 10% of white dwarfs that are DDs [Saffer et al., 1998, Maxted & Marsh, 1999]. The difference in observed numbers is down to ease of detection. This means that there are some 250 million DDs in the Galaxy, with perhaps 1 million systems with periods of less than an hour; they are likely to be the dominant source of low frequency gravitational waves in the Galaxy [Hils et al., 1990].

Can DDs be the progenitors of Type Ia supernovae? We have now found systems of short enough period, and one, KPD 0422+5421 [Koen et al., 1998], may even have enough mass. In terms of numbers, and leaving aside the issue of whether they really explode on merging, the answer would appear to be yes, they remain a viable progenitor. While we have not found convincing examples of systems with enough mass, these are probably just rare; only about 1 in 40 of DDs is expected to be such a system [Iben et al., 1997] and we have been concentrating specifically on low mass systems.

3. Pre-CVs

When one searches for DDs, one also finds pre-CVs. I define these as binaries containing a white dwarf (or sub-dwarf which will evolve into a white dwarf) and an M dwarf companion. Higher mass companions are excluded because (a) it becomes hard to see the white dwarf if the companion is too bright and (b) theoretically, CVs are descended from systems with mass ratio q = M_{MS}/M_{WD} < 0.28 [Politano 1996], and since white dwarfs are usually below a solar mass, this implies M dwarf companions. There are 27 pre-CVs known: 22 are white dwarf/M dwarf systems, and 5 are sub-dwarf/M dwarf systems. The observed periods are compared to theory in Fig. 3. Observations and theory do not compare well. In this case however, I think it is likely that observational selection could be to blame for the lack of systems at both long and short periods. At long periods, the radial velocity of the white dwarf is relatively low and irradiation-induced emission from the M dwarf will be weak. There are a good number
of white dwarf/M dwarf pairs known which don’t have measured orbital periods, and the long period systems may well be lurking amongst them. At short periods only very low mass M stars can remain inside their Roche lobe; for example the shortest period system listed, GD 448, has a mass of 0.09 M⊙, barely above the brown dwarf limit [Maxted et al., 1998]. It is difficult to see any sign of the M dwarf in GD 448, with only weak emission at Hα; we may well be missing still shorter period systems.

The masses of the white dwarfs in pre-CVs are not as well determined as they are for DDs because the line profiles are often filled in by emission from the M dwarf. However, there are enough known to be certain that helium core white dwarfs exist in some numbers. I define helium-core white dwarfs as those with masses < 0.5 M⊙; some are borderline, but there is little doubt for systems such as GD 448 (MWD = 0.41 ± 0.01 M⊙) and RR Cae (0.36 ± 0.04 M⊙). Therefore there must be helium-core white dwarfs amongst the CVs too, as expected theoretically [Politano 1996], although observational selection effects which favour high masses may count against their detection.

There are four eclipsing white dwarf/M dwarf systems known (GK Vir, RR Cae, NN Ser and EC 1347-1258). Observations of these have the potential to provide accurate system parameters and to detect orbital period changes as may be caused by solar-type magnetic cycles. These systems cover a range of M dwarf mass, and it would be particularly interesting, for example, to see if the period of RR Cae, which has a very low mass M dwarf (0.09 M⊙), changes since the standard disrupted magnetic braking model would suggest a low level of magnetic activity in such a star.

The numbers of pre-CVs are comparable to DDs i.e. they are intrinsically much more common than CVs. It may prove difficult to detect potential period-gap-crossing systems against this background.

3.1. Irradiation in pre-CVs

The pre-CVs provide clean systems for the study of irradiation of stars. A result of interest for CV studies is that the Balmer emission lines induced by irradiation are significantly broadened by optical
depth effects (Fig. 3, Maxted et al., 1998; Wood et al., 1999). The broadening is of order 40 km s\(^{-1}\), which is enough to severely limit their usefulness for imaging the secondary star in CVs; the CaII lines seem to be a better option (Fig. 4). The same broadening is seen in chromospherically active stars, which is perhaps surprising given the rather different mechanisms producing the lines.

4. Conclusions

Over the last ten years the number of double-degenerate binaries has gone from 1 to 15 and it is apparent that they are intrinsically extremely common within our Galaxy, with a space density of order \(5 \times 10^{-4} \text{ pc}^{-3}\). Their short periods, which range from 1.5 hours to a few days, are a testament to the orbital shrinkage involved in ejecting the envelopes of the two white dwarfs. In terms of numbers, they remain a viable progenitor class for Type Ia supernovae.

The pre-CVs have grown similarly in number, although observational selection affects detection at periods above a day or so and below two hours. Amongst them are helium core white dwarfs, and presumably this must be the case for CVs too. Irradiation-induced Balmer emission is broadened by radiative transfer effects, and should be avoided in favour of CaII for imaging the secondary stars in CVs.

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