Pre-Cataclysmic Variables: Their Past, Future, and Minimum Orbital Period

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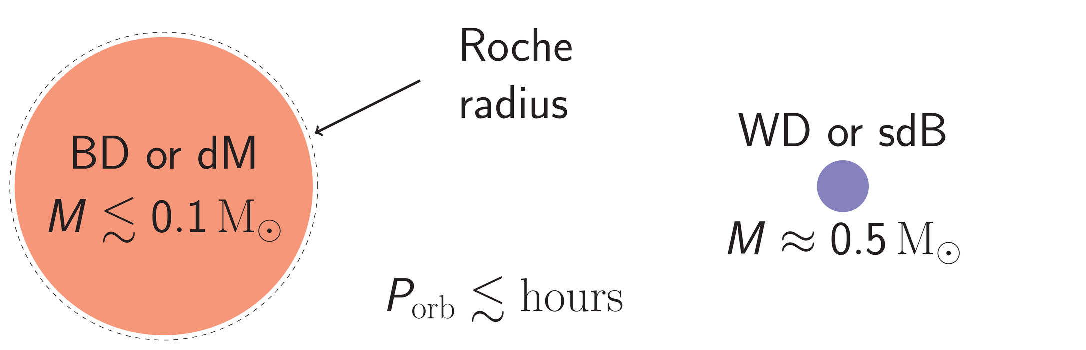
What is a Pre-CV?

We define a pre-cataclysmic variable (pre-CV) to be a system consisting of a white dwarf (WD) or hot subdwarf (sdB) primary with a low-mass unevolved companion star, either a brown dwarf (BD) or low-mass main sequence star (dM). The companion star has successfully ejected the envelope of the primary progenitor (through a common envelope phase), but mass transfer from the companion star back to the primary has not yet commenced.

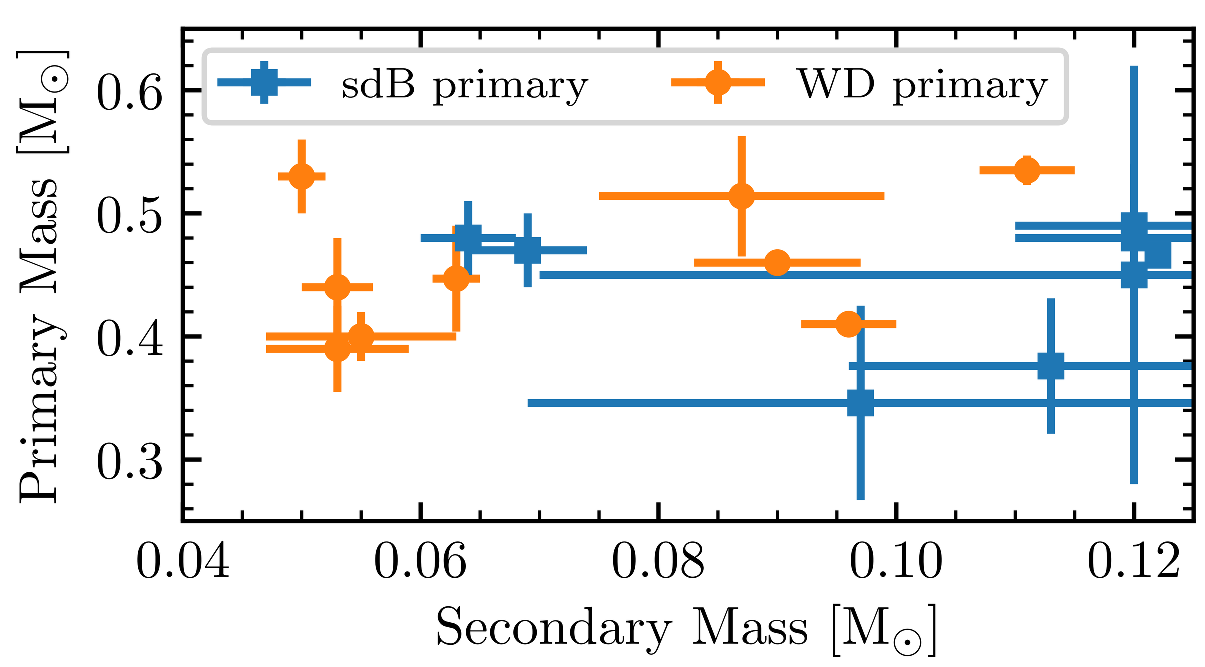


(system to scale for EPIC 212235321; Casewell et al. 2018)

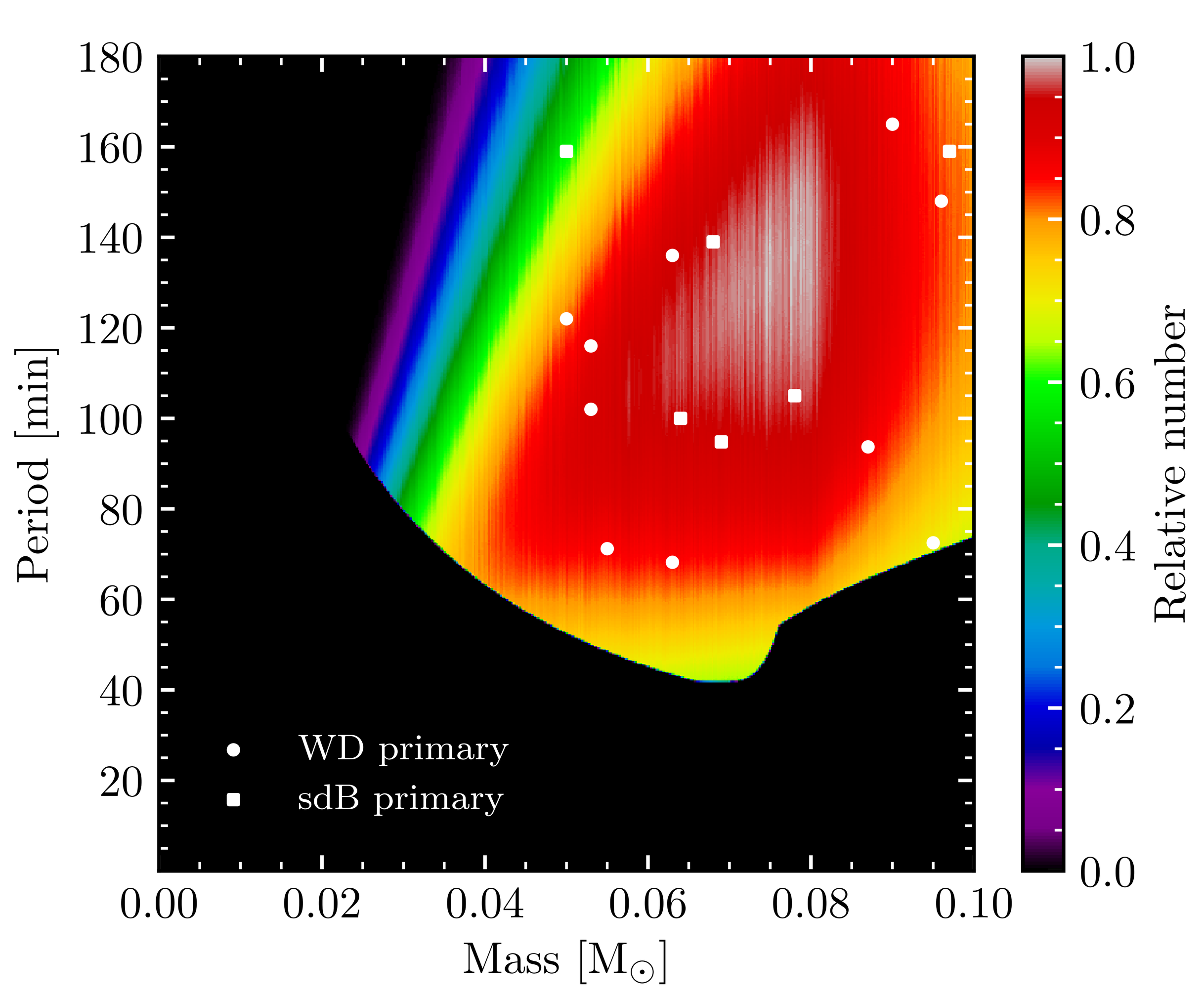
More than twenty pre-CV systems have been discovered with orbital periods ranging from 250 minutes down to 68 minutes.

Their Past

The observed systems with relatively well-measured component masses are shown in the figure below. The fact that the WDs in these systems are generally $\approx 0.5\,\mathrm{M}_\odot$ implies that most of the current WD+BD systems could have had sdB primaries when they exited the common envelope (see also Schaffenroth et al. 2018).



To better understand the formation of these systems, we have carried out a rudimentary binary population synthesis, the results of which are shown in the figure below. It seems qualitatively reasonable to believe that there exist BD+WD systems with periods between 40 and 68 minutes that simply have not yet been found. More quantitatively, we can show from the simulated data that only about 11% of all the systems with masses between 0.05 and 0.075 $\mathrm{M}_\odot$ are expected to have periods in the range of 40-68 minutes. The known systems shown in the figure include none with masses $\lesssim 0.05\,\mathrm{M}_\odot$. The location of the "cutoff" at the upper left of the plot depends sensitively on the choice of $\alpha\lambda$ when modeling the common envelope phase. The observed systems match reasonably well with the predictions for $\alpha\lambda = 0.15$, though it is not clear if ultra-low mass secondaries do exist but have not yet been discovered.



Minimum Orbital Period

There is a minimum orbital period below which the BD will fill its Roche lobe. For small mass ratios, this does not depend on the mass of the primary star, but only on the mass and radius of the BD. This relation is

$$P_\mathrm{min} \approx 8.85 \left(\frac{R_\mathrm{bd}}{R_\odot}\right)^{3/2} \left(\frac{M_\odot}{M_\mathrm{bd}}\right)^{1/2} \mathrm{hr}\ .$$

In order to evaluate this equation, we require BD cooling models for all masses of interest. To this end, we used MESA to evolve a suite of BD and low-mass MS star models ranging from 0.002 to 0.1 $\mathrm{M}_\odot$ in steps of 0.0002 $\mathrm{M}_\odot$ out to an age of 20 Gyr.

The shortest allowed orbital period occurs for the highest mass BD at the oldest evolutionary ages (where R_bd is a minimum). As can be seen in the figure below, this occurs near a mass of $\simeq 0.072\,\mathrm{M}_\odot$. The minimum orbital period for such BDs is 40 minutes at an age equal to a Hubble time. This then is the absolute minimum period allowed for these pre-CV binaries.

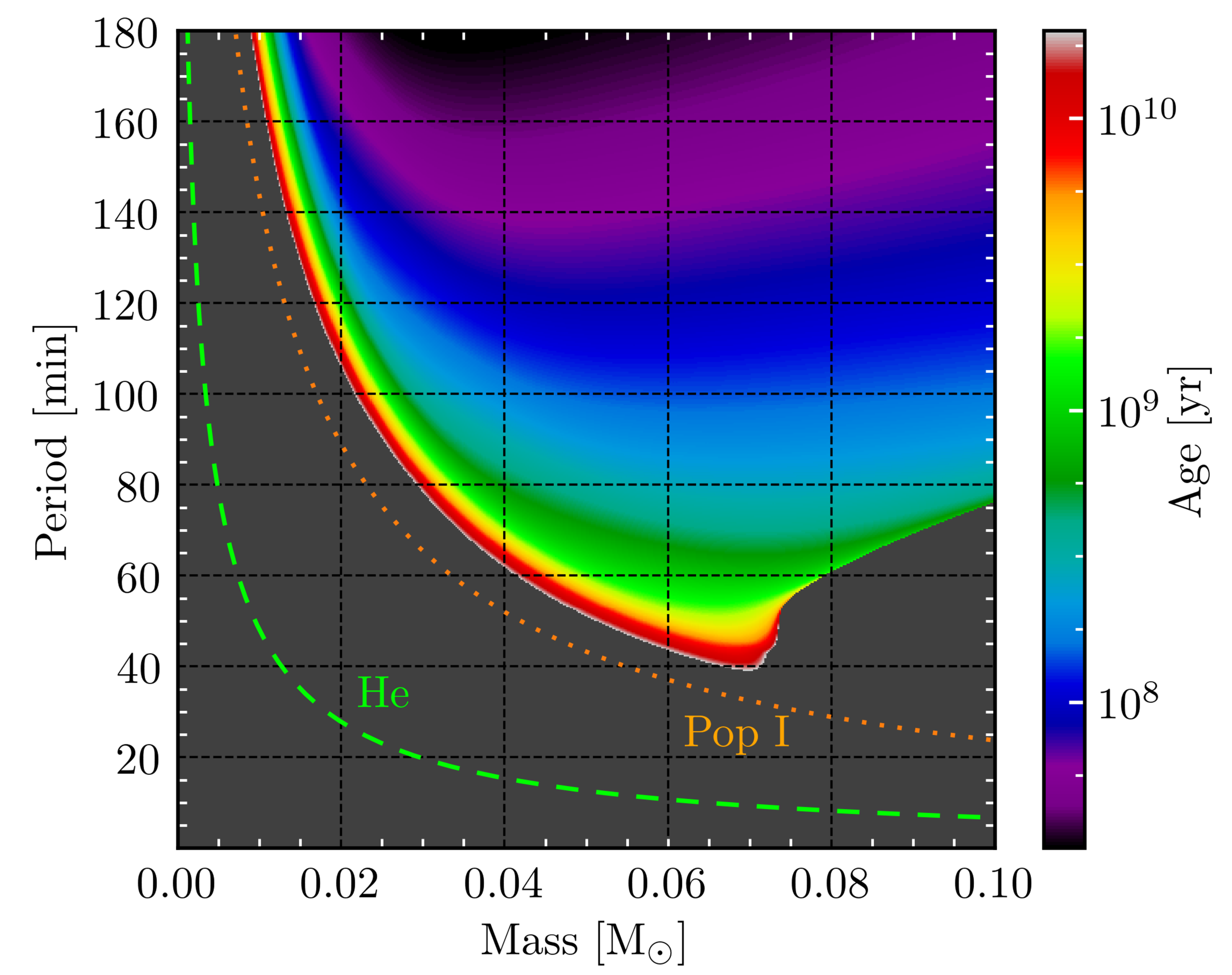


Figure: The plane of minimum allowed orbital period vs. stellar mass (for solar metallicity models). The diagram is color-coded according to the logarithm of the age of the star. The dark grey background indicates the region where there are no models. For reference, we show a set of "zero temperature" models for the indicated compositions.

For a conventional (unevolved) CV system, a low-mass star ($\lesssim 1\,\mathrm{M}_\odot$) is brought into contact with the WD accretor as a result of orbital decay due to angular momentum losses from gravitational wave radiation and/or magnetic braking. Once the donor overfills its Roche lobe, mass transfer drives the orbital evolution from periods of several hours down to an observed orbital period minimum ($P_\mathrm{CV,min}$) of about 80 minutes. The typical donor-star mass at this juncture is $\approx 0.06\,\mathrm{M}_\odot$ and then subsequently the donor continues to lose mass with a concomitant increase in the period.

When the pre-CV systems start mass transfer they will have orbital periods shorter than $P_\mathrm{CV,min}$ even though the masses of the donors are comparable. The reason is that the donors in conventional CVs at $P_\mathrm{CV,min}$ are already in the process of losing mass and this causes them to depart from thermal equilibrium. The 'thermal bloating' that they experience causes them to be considerably larger in radius than the low-mass companions in pre-CVs. The above figure shows that pre-CV systems with companion masses $0.03\,\mathrm{M}_\odot \lesssim M \lesssim 0.10\,\mathrm{M}_\odot$ can exist below $P_\mathrm{CV,min}$. Indeed, systems at 72, 71, and 68 minutes have been recently discovered (Parsons et al. 2017, Rappaport et al. 2017, Casewell et al. 2018).

Acknowledgments

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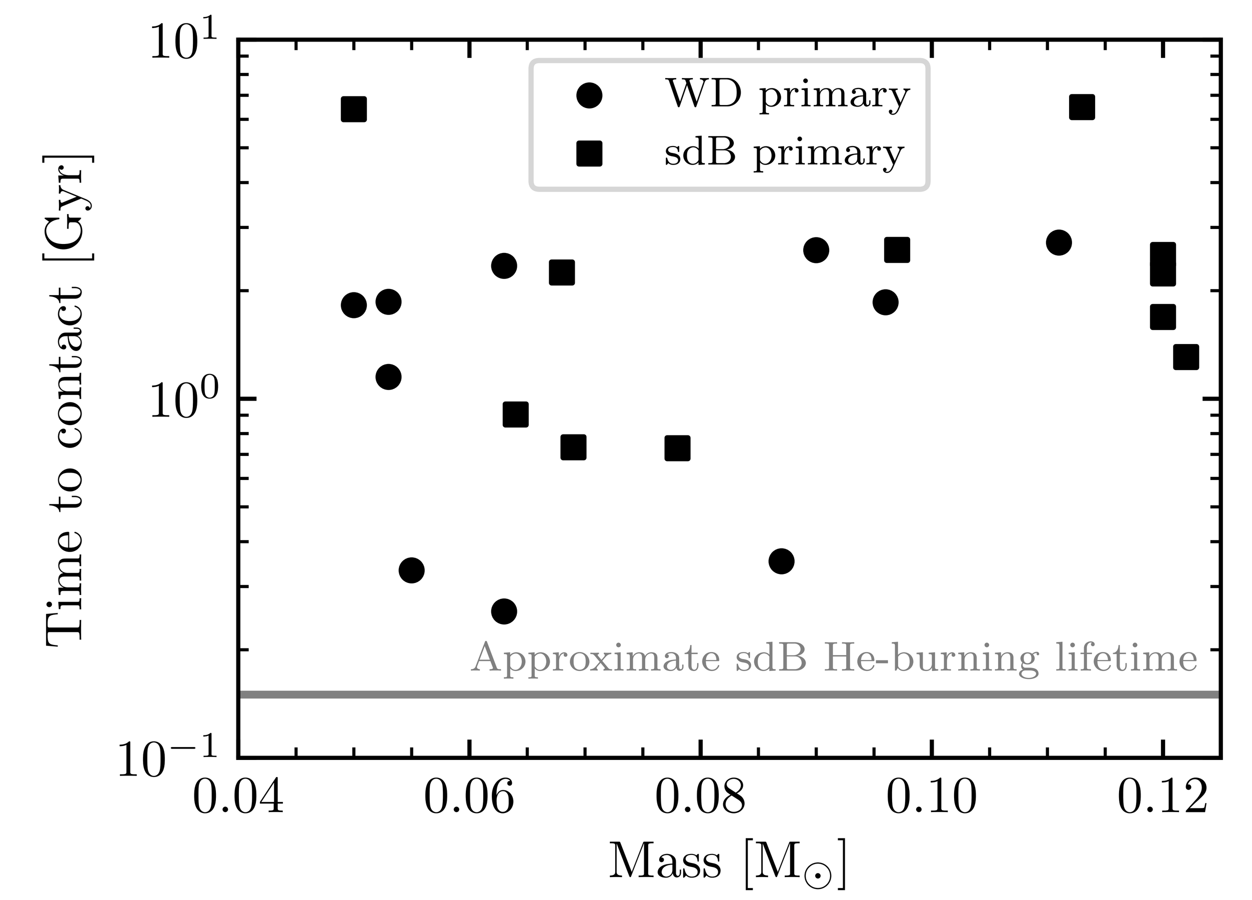
Their Future

These WD+BD and sdB+BD binaries will become mass-transferring CVs once the orbit shrinks to the point where the BD fills its Roche lobe. As shown in the figure below, under the assumption that the orbit shrinks at a rate set by gravitational wave radiation, the sdB primaries will have evolved to become WDs by the time mass transfer begins (see also Kupfer et al. 2015).



When the low mass pre-CV companions overfill their Roche lobes, they do so at periods $\approx$ 40-80 minutes (so long as their radii are consistent with models having cooling ages $\gtrsim$ Gyr). Therefore, they can produce CVs below $P_\mathrm{CV,min}$ (e.g., Politano 2004). One CV thought to have been possibly formed via this channel is SDSS J150722.30+523039.8 (Littlefair et al. 2007), which has an orbital period of only 66 minutes and no helium observed in its spectrum (implying that the donor is not chemically evolved).

After mass begins to be transferred from the BD to the WD, the system might be detected as a faint dwarf nova with very long intervals between outbursts (Howell et al. 1997). As mass transfer proceeds, the period of the binary will begin to increase. Using expressions for the evolution of Roche-lobe overflowing binaries (Faulkner 1971), one can write a characteristic timescale for the orbital evolution of

$$\mathcal{T} = 145 \left(\frac{P_0}{1\,\mathrm{hr}}\right)^{8/3} \left(\frac{M_\odot}{M_\mathrm{bd} + M_\mathrm{wd}}\right)^{5/3} \left(\frac{0.1}{\mu_0}\right)\ \mathrm{Myr}.$$

where $\mu = M_\mathrm{bd}/(M_\mathrm{bd} + M_\mathrm{wd})$.

Thus, once Roche-lobe contact has been established, the timescale for the binary to increase its period from as short as 40 minutes back up to $\approx$ 70-80 minutes is $\sim$ 100 Myr. After this time, it would presumably resemble any normal CV that had evolved from a much longer period and an initially much more massive donor star.

Conclusions

- The minimum possible period for a pre-CV system is 40 minutes.
- Population synthesis suggests there should be pre-CV systems with periods in the 40-68 minute range.
- The observed sdB+BD binaries will spend most of their lives as WD+BD binaries before coming into contact.
- Most of the observed WD+BD binaries have low WD masses ($\approx 0.5\,\mathrm{M}_\odot$) consistent with the systems having exited the common envelope as sdB+BD binaries.
- Mass transferring CV systems formed from pre-CVs will spend $\sim$ 100 Myr below the conventional CV period minimum.

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