140. Cataclysmic variables

Cataclysmic variables are compact interacting binaries containing a white dwarf accreting from a donor star overflowing its Roche-lobe. In most systems, the companions are low-mass, late-type stars. As a class, they allow for the study of (non-)equilibrium accretion disks, themselves relevant for the understanding of X-ray binaries, black holes and active galactic nuclei.

If the white dwarf is non-magnetic, the outflowing donor material forms an accretion disk around it. For larger magnetic fields, the accretion flow follows the field lines and accretes onto the white dwarf at its magnetic poles, resulting either in 'intermediate polars' with truncated disks ($B \sim 10^2 - 10^3$ T), or in 'polars' in which the accretion disk is fully suppressed ($B \gtrsim 10^3$ T).

As in many area of astronomy, complete samples to well-defined observational limits provide an important foundation for detailed studies. The space density of cataclysmic variables, for example, places strong constraints on models of their formation and evolution.

Early binary population synthesis studies (e.g. de Kool, 1992; Politano, 1996) suggested space densities of $\rho = 0.2 - 2.0 \times 10^{-4}\,\mathrm{pc}^{-3}$. More recent models (e.g. Goliasch & Nelson, 2015; Belloni et al., 2018) have yielded comparable estimates of $\rho \sim 1 - 2 \times 10^{-5}\,\mathrm{pc}^{-3}$.

These predicted values are systematically larger than those inferred from observations, a result often taken as suggesting significant shortcomings in theoretical models. However, the determination of accurate space densities has also been greatly hampered, observationally, both by the limited number of X-ray detected objects defining the samples, as well as by the lack of accurate parallax distances quantifying their spatial distribution.

At the time of Gaia Data Release 2, in 2018, the most extensive X-ray selected samples were drawn from the ROSAT Bright Survey, yielding 15 or so non-magnetic cataclysmic variables (with typical distances in the range 100–500 pc), and from the 70-month Swift/BAT(Burst Alert Telescope) yielding a similar number of intermediate polars (with slightly larger typical distances in the range 500–1000 pc).

Based on the distances of these small sample members from Gaia DR2, almost all with distance accuracies better than 5%, Schwope (2018) concluded that most of the distances to the intermediate polars (in particular) had been somewhat under-estimated in the past. He gave revised upper limits for their space densities of $\rho < 1.1 \times 10^{-6}\,\mathrm{pc}^{-3}$ for the non-magnetic objects (assuming a Galactic scale height of 260 pc), and $\rho < 1.3 \times 10^{-7}\,\mathrm{pc}^{-3}$ for the long-period intermediate polars (assuming a scale height of 120 pc), even lower than the previous estimates.

Larger X-ray samples are today becoming available with the Spektrum-X-Gamma mission's eROSITA all-sky survey, operational 2019–2022 (Predehl et al., 2021). Compared to ROSAT, this provides a factor 25 sensitivity improvement at low X-ray energies, broader energy coverage (0.3–10 keV), and better spatial resolution. Spectroscopic identification, classification and detailed follow-up to determine orbital periods, are ongoing.

Meanwhile, Pala et al. (2020) presented a volume-limited sample, defined using their Gaia DR2 parallaxes, composed of 42 objects within 150 pc, which they estimated as ~80% complete. Their sample includes two new systems discovered using the Gaia data.

Amongst their findings was the very high fraction of *magnetic* cataclysmic variables, at 36%. This is in contrast with the absence of magnetic white dwarfs in the detached population of cataclysmic variable *progenitors*, underlining the fact that the evolution of magnetic systems has to be included in the next generation of population models. Their resulting space density, $\rho = 4.8 \pm 0.7 \times 10^{-6}\,\mathrm{pc}^{-3}$, is (again) significantly lower than predicted by binary population synthesis studies.

Let me provide more of the details of the accretion process, as summarised by Pala et al. (2020), to explain the sorts of insights that are now becoming available.

Since mass accretion results in compressional heating of the white dwarfs, it follows that the effective temperature of the white dwarf provides a direct indication of its mean accretion rate.

The different efficiencies of magnetic wind braking and gravitational wave radiation in removing angular momentum from the binary orbit cause long-period cataclysmic variables to have mean accretion rates about a factor 10 higher compared to those of short period. Consequently, long-period systems should host hotter white dwarfs compared to short-period systems, and hence effective temperature measurements provide a direct insight into the system's evolutionary stage.

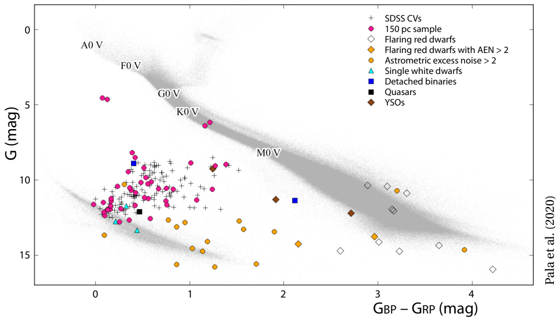
The masses of 14 white dwarfs in their 150 pc sample were available in the literature. From these, they found an average white dwarf mass of $0.83 \pm 0.17 M_\odot$. They conclude that the higher mass of these cataclysmic variable white dwarfs compared to that of single white dwarfs and their detached progenitors, $\sim 0.6 M_\odot$, supports the idea of additional mechanisms of angular momentum loss, beyond magnetic wind braking and gravitational wave radiation, needed to explain the increased accretion rate inferred from the larger final mass.

The physical insights that can be gained from these complete samples is quite remarkable, and to delve a little further into this involves mention of the phenomena of the 'period gap', the 'period minimum', and the 'period bounce', explained in more detail by, for example, Pala et al. (2020) and Belloni et al. (2020).

The evolution of cataclysmic variables is, as for all interacting binaries, dictated by orbital angular momentum loss, and by the internal structure of the donor star. The timescale on which the secondary star loses mass is, it turns out, comparable to its thermal timescale, resulting in a donor which is slightly out of thermal equilibrium, and therefore hotter and more bloated compared to an isolated main sequence star of the same mass. This deviation from thermal equilibrium is thought to be the cause of the 'period gap' and the 'period minimum'.

As angular momentum is removed from the system, the orbital separation decreases and, consequently cataclysmic variables evolve from long to short orbital periods. At long orbital periods ($\gtrsim$ 3 h) their evolution is driven by magnetic wind braking and gravitational wave radiation. The mass transfer systematically erodes the secondary star which, at around 3 h orbital period, becomes fully convective. In the standard framework of evolutionary models, it is assumed that a reconfiguration of the magnetic fields on the donor results in a greatly reduced efficiency of magnetic wind braking from that point onwards, and the secondary star detaches from its Roche lobe.

In the period range 2–3 h, the so-called period gap, the system evolves as a detached binary whilst still losing angular momentum through gravitational wave radiation. At orbital periods of around 2 h, the orbital separation is such that the donor fills its Roche lobe again, and the accretion process resumes.



Below the period gap, cataclysmic variables continue to evolve towards shorter orbital periods until they reach the period minimum, of around 80 min. At this stage, the timescale on which the secondary star loses mass becomes much shorter compared to its thermal timescale. The donor is driven out of thermal equilibrium, and stops shrinking in response to this mass loss. Consequently, the system starts evolving back towards longer orbital periods, becoming a 'period bouncer'.

In this context, Pala et al. (2020) found a very low fraction, ~7%, of period bounce systems. Being an order of magnitude below theoretical predictions, it remains one of the open problems in the understanding of their evolution (Belloni et al., 2020).

From a much larger sample of 1587 cataclysmic variables, many from the AAVSO database, along with distances from Gaia DR3, Canbay et al. (2023) derived local space densities of all objects, and magnetic systems, of $6.8 \pm 1.2 \times 10^{-6}$ and $2.1 \pm 0.5 \times 10^{-6}\,\mathrm{pc}^{-3}$ respectively, broadly confirming the previous estimates. They suggest that the ongoing discrepancy with population synthesis models arises from cataclysmic variables which remain undetected so far, notably systems with very low mass-loss rate, as well as those in the period gap.

They derived the exponential scale heights of all CVs, and the magnetic systems, of 375 ± 2 pc and 281 ± 3 pc, respectively, considerably larger than those suggested in previous observational studies. And they found that a simple scaling, of ~500, relates the luminosity function of all cataclysmic variables with that of white dwarfs.

Further insights on the occurrence and evolution of cataclysmic variables continue to build on the photometry and distances from Gaia DR2 and DR3, and the location of the various sub-types in the Hertzsprung–Russell diagram (e.g. Abril et al., 2020; Abrahams et al., 2022).

Application of Gaia data to the understanding of cataclysmic variables is at an early stage. The discrepancies between the observations and population synthesis models is catalysing both further theoretical studies of their evolution, as well as observational studies to discover the large number of systems in the solar neighbourhood which apparently remain undetected so far.