Mem. S.A.It. Vol. 90, 126

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Magnetic cataclysmic variables discovered in hard X-rays

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Abstract. Among hard X-ray galactic sources detected by *INTEGRAL* and *Swift* surveys, those discovered as accreting white dwarfs have surprisingly boosted in number, representing 20% of the galactic sample. The majority are identified as magnetic cataclysmic variabiles of the intermediate polar type suggesting this subclass as an important constituent of galactic population of X-ray sources. In this conference-proceeding, we review the X-ray emission properties as observed with our ongoing *XMM-Newton* programme of newly discovered *INTEGRAL* and/or *Swift* sources that enlarged almost by a factor of two, identifying cataclysmic variabiles commonalities and outliers.

Key words. novae, cataclysmic variables – white dwarfs – X-rays: binaries – populations

1. Introduction

Cataclysmic variables (CVs) are close binary systems composed by a white dwarf (WD) that accretes matter from a Roche-lobe filling, late-type companion star. Although CVs can be classified into several groups, depending on their observational characteristics, we can distinguish between two main classes: magnetic and non-magnetic CVs. In magnetic cataclysmic variables (mCVs) the accretion of matter onto the compact object is dominated by the magnetic field of the WD. Depending of the field strength, B, mCVs can be further divided into two types: polar mCVs have $B \sim 10^7 - 10^8$ G and, in these systems, the matter outflow from the companion star is immediately funnelled along the field lines and accreted onto the WD polar caps, hence no accretion disk is formed. The strong field also causes the WD spin rate to be locked with the binary orbital period, i.e., syncronismus ($P_{\omega=\Omega}$ ~hrs). On the contrary, intermediate polar mCVs are believed to harbour weakly magnetized accreting WDs with $B \lesssim 5 \times 10^6$ G. This allows for a fast rotation of the WD (i.e., asynchronous WD rotation, P_ω ~mins) and for the formation of an accretion disk. The latter is disrupted at the

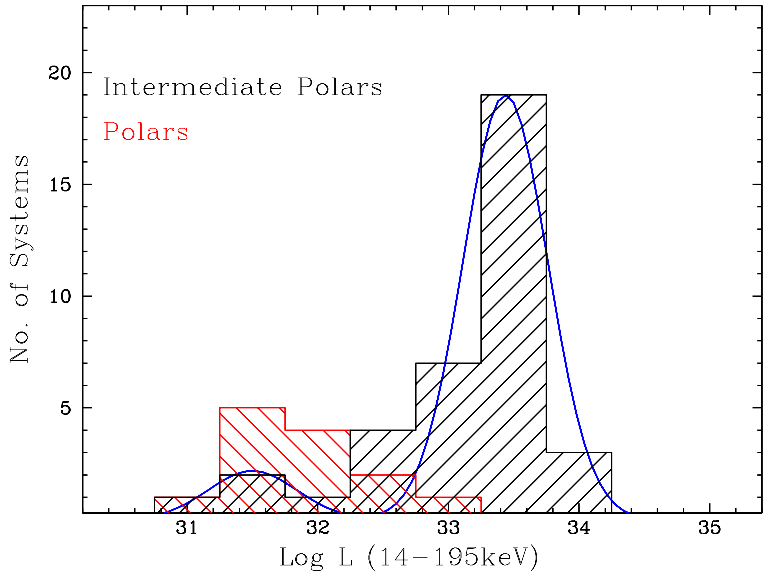

Fig. 1. The 14–195 keV luminosity distribution of confirmed IPs and polars in the *Swift*/BAT catalogue with *Gaia* distance accurate better than 10%. A bimodal distribution (blue line) in the IP sample is suggested with 4 low-luminosity systems overlapping the polar sample (in red). Figure provided by D. De Martino

magnetospheric radius, due to the strong WD magnetic pressure.

From that point, the matter attaches to the magnetic field lines and follows them almost radially at free-fall velocity towards the WD magnetic poles surface (see e.g., Aizu 1973). Magnetic accretion produces a strong shock above the WD magnetic poles, so-called post-shock region (PSR), hard optically thin emission, where temperatures can reach $kT_{\rm brem.} \sim 20 - 40$ keV, below the flow cools by bremsstrahlung (hard X-rays) and cyclotron (optical) radiation that are partially thermalized and re-emitted in the soft X-rays and/or EUV/UV domains. The efficiency of the two cooling mechanisms depends on the magnetic field strength: cyclotron is increasingly efficient in high field systems ($>$ 10MG, the Polars) and is able to suppress high temperatures. It is then likely that the low-field systems (IPs) preferentially emit in the hard X-rays, being bremsstrahlung dominated, as indeed observed. This actually explains, why we were used to observe the CVs as bright soft X-rays sources during the ROSAT era (Beuermann et al. 1995). We note, that among 13 hard Polars identified so far (see Bernardini et al. 2014, 2017; Gabdeev et al. 2017; Mukai 2017, Bernardini 2019b, in prep). Those few with determined magnetic fields (up to 40×10^6 G) challenge our knowledge of emission properties in mCVs. Since three hard X-ray Polars are also slightly desynchronised, asynchronism seemed a common characteristics of hard mCVs. Other processes, such as Compton scattering, turn out to be much less important for low mass accretion rates or low WD masses (Suleimanov et al. 2008). Substantial reviews on CVs can be found by Warner (1995); Norton et al. (2004); Ferrario et al. (2015); Mukai (2017), and references therein.

2. The hard X-ray cataclysmic variables surveys

Our view of the hard X-ray sky dramatically changed thanks to the deep *INTEGRAL*/ISGRI and *Swift*/BAT surveys with more than 1000 sources detected above 20 keV (Bird et al.

2016; Krivonos et al. 2010; Cusumano et al. 2010; Baumgartner et al. 2013; Oh et al. 2018).

These surveys have surprisingly shown a large number of CVs, the majority, $\sim$ 70%, being magnetic of the intermediate polar type. mCVs, in particular the IPs, are claimed as important contributors to the galactic X-ray source population above $\sim 10^{31}\,\mathrm{erg\,s^{-1}}$ from surveys of the galactic centre with *Chandra*, *XMM-Newton*, and *NuSTAR* (Muno et al. 2004; Heard & Warwick 2013; Perez et al. 2015; Hailey et al. 2016), respectively.

Whether IPs also dominate the galactic ridge emission is still disputed (see e.g., Revnivtsev et al. 2009). Our knowledge of X-ray binary populations is also crucial to understand close binary evolution. The high ($\sim$ 20 − 25%) incidence of magnetism in CVs with respect to that in single WDs ($\sim$ 10%) (Ferrario et al. 2015), would either imply CV formation is favoured by magnetism or CV production enhances magnetism (Tout et al. 2008).

The negligible absorption in the hard X-rays makes these surveys unique for population studies. In particular the *INTEGRAL*/ISGRI and specially *Swift*/BAT survey, with a more uniform exposure over the sky was used to estimate the mCV space densities but with large uncertainties (Pretorius & Mukai 2014, and references therein). The hard X-ray BAT and ISGRI catalogues surveys, however, still carry tentative new CV identifications, with many claimed as magnetic, based on optical follow-ups and thus subject of revisions. However, the magnetic nature can only be inferred through the detection or non-detection of Xray pulses at the WD spin period that imply magnetically channeled accretion and through the study of broad-band spectra.

The *Gaia* DR2 release in April 2018 now offers the opportunity of assessing the true space densities. Using the shallow flux-limits of the 70-month*Swift*/BAT sample of Pretorius & Mukai (2014) and the *Gaia* parallaxes, the IP space density appears to be lower than previously estimated $< 1.3 \times 10^{-7}\,\mathrm{pc^{-3}}$ Schwope (2018). The release of the 105-month *Swift*/BAT catalogue reaching flux levels down to $\sim$ 7 and $8 \times 10^{-12}\mathrm{erg\,cm^{-2}\,s^{-1}}$ over 50% and 90% of the sky gives the opportunity to confirm this finding and to unveil a putative still-hidden low-luminosity IP population from hints of bimodality in the luminosity distribution (see Fig. 1).

3. The spin-orbit period plane of confirmed IPs

One of the most challenging open question in the context of CVs is the lack of observations of systems with periods between $\sim$ 2 and $\sim$ 3 hours, known as the period gap. The orbital evolution of CVs with periods shorter than those in the gap is dominated by gravitational radiation while for periods exceeding those of the gap it is dominated by magnetic braking of the secondary star. The magnetic complexity might then explain the period gap, as well as different population. The low-luminosity IP population are found below the 2–3h CV orbital period gap and thus they are low-rate accretors (see Fig. 2). The number of IPs below the 2–3 h CV orbital period gap has surprisingly increased to 10 members. This is challenging since short period mCVs should have already reached synchronism Norton et al. (2008). The large spread in spin-to-orbit period ratios of short period IPs may suggest they represent a different population of old, possibly, low-field systems. Clearly the mechanisms driving mCV evolution are still to be understood.

4. The mass distribution of hard X-ray IPs

The majority of all stars born in the Galaxy will one day evolve into WDs. WDs are supported against collapse by electron degeneracy pressure and as such show the remarkable property that the more massive they are, the smaller their radius. Moreover, this mass-radius relationship sets an upper limit to the mass of a WD (Chandrasekhar 1931) above which electron degeneracy can no longer support them, a result that underpins our understanding of type Ia supernovae and hence the expansion of the Universe. The mass-radius relationship forms an essential part of many studies of WD,

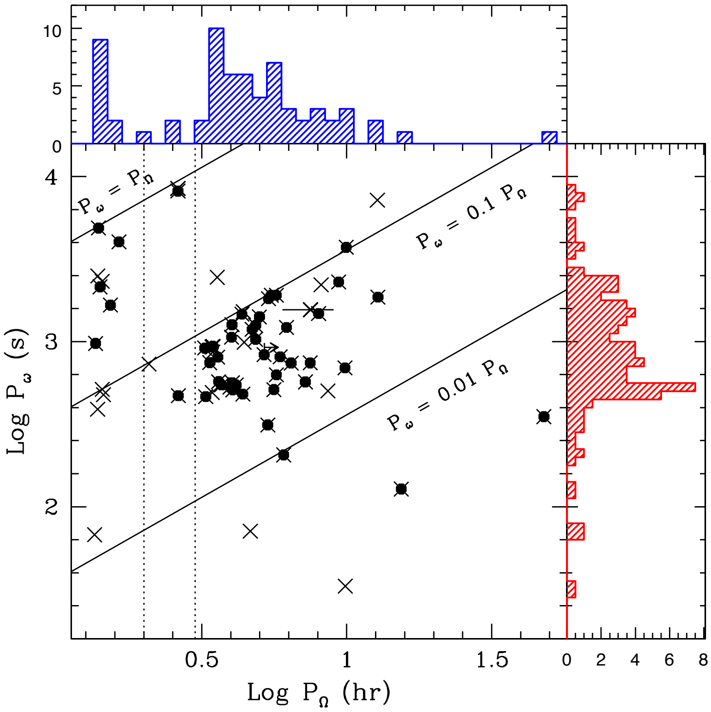

Fig. 2. The spin-orbit period plane of confirmed IPs (crosses). Hard X-ray detected sources are also shown as filled circles. Solid lines mark synchronism and two levels of asynchronism (0.1 and 0.01). Vertical lines mark the orbital CV gap, where mass transfer is expected to stop at the upper bound and to be resumed at the lower bound. The spin (right panel) and orbital (upper panel) period distributions are reported as from (Bernardini et al. 2017, 2018, 2019).

such as the initial-final mass relationship, stellar evolution, WD population i.e., mass measurements for white dwarfs in interacting binary systems or isolated WDs, WD mergers masses cousing gravitational waves, WD equation of states, i.e., matter composition, the WD luminosity function etc... Despite its huge importance to a wide range of astrophysical topics, the WD mass-radius relationship remains poorly tested observationally.

The fact, that IPs are mainly discovered in the *INTEGRAL*/*Swift* hard X-ray broadband energy band, allow us to estimate the IPs masses by measuring the maximum temperature of the post-shock plasma (see e.g., Suleimanov et al. 2005; Falanga et al. 2005; de Martino et al. 2008; Anzolin et al. 2009; Bernardini et al. 2012, 2013, 2015, 2017, 2018, 2019), (see Fig. 3). We note, the IP radius can be calculated from the Nauenberg (1972) WD mass-radius relation. Using mass determinations from our combined *XMM-Newton*/*INTEGRAL*/*Swift* observations and those from Brunschweiger et al. (2009); Suleimanov et al. (2005); Tomsick et al. (2016); Shaw et al. (2018) very massive WDs are not favoured although the majority is found above 0.7 $M_\odot$ (Fig. 3). Other parameters as the local accretion rate and the effects of reflection are to be included. However, IP masses do not appear much different from other CVs. The mean WD mass among CVs is $\langle M_{\rm WD}\rangle = 0.83 \pm 0.19\ M_\odot$, much larger than that found for pre-CVs, $\langle M_{\rm WD}\rangle = 0.67 \pm 0.21\ M_\odot$. It may indicate, that either most CVs have formed above the orbital-period gap (which requires

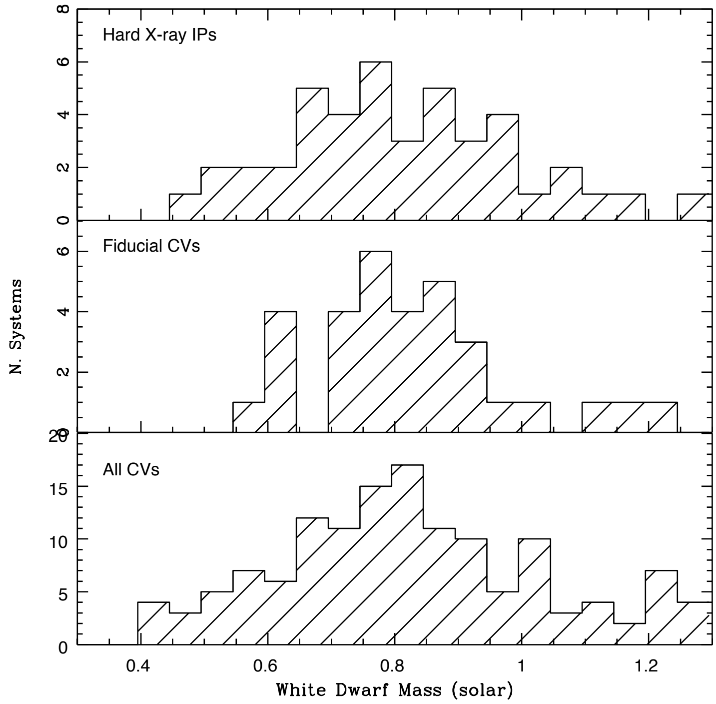

Fig. 3. The mass distribution of hard X-ray IPs (top) as derived by us and by Brunschweiger et al. (2009), giving $< M >= 0.80 \pm 0.16\,M_{\odot}$, compared with those of "fiducial" CVs (Zorotovic et al. 2011), giving $< M >= 0.82 \pm 0.15\,M_{\odot}$ (centre) and those of CVs from the Ritter & Kolb, 7.20v CV Catalogue (bottom), giving $< M >= 0.82 \pm 0.24\,M_{\odot}$. Figure provided by D. De Martino.

a high WD mass to initiate stable mass transfer or a previous phase of thermal-timescale mass transfer), or the mass of the WDs in CVs grows through accretion (which strongly disagrees with the predictions of classical nova models). Both options may imply that CVs contribute to the single-degenerate progenitors of type Ia supernovae.

5. Conclusions

The number of hard X-ray emitting CVs has been boosted in the recent years, unveiling the dominance of asynchronously rotating, magnetic accreting white dwarf primaries - the Intermediate Polars. These systems are disputed to be important contributors to the galactic population of low-luminosity X-ray sources. We have been carrying out a systematic identification programme of new optically discovered hard X-ray CV candidates with the unique potential of *XMM-Newton* to securely assess their purported magnetic nature by detecting X-ray spin pulses and characterizing their spectral properties. We aim at obtaining a CV flux-limited sample with *Gaia* distances finally making statistical studies possible and uncover the true population of low luminosity sources. Up to date 70 confirmed IPs are known, 26 of them identified by us (see e.g., Bonnet-Bidaud et al. 2007; de Martino et al. 2008; Anzolin et al. 2009; Bernardini et al. 2012, 2013, 2015, 2017, 2018, 2019). The polar group, instead, amounts to ∼130 systems with 13 identified as hard X-ray sources, 3 of them found by us (see e.g., Bernardini et al. 2014, 2017, 2019b in prep.). This suggests that hard Polars are not as rare as previously thought. We also disproved the magnetic nature for 6 candidates (see e.g., Bernardini et al.

2014; de Martino et al. 2010, 2013). Therefore, secure identifications are needed to construct true samples.

Acknowledgements. DdM acknowledges financial suport from INAF-ASI agreements I/037/12/0 and ASI-INAF n.2017-14-H.0 and INAF-PRIN SKA/CTA Presidential Decree 70/2016. FB is founded by the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement n. 664931.

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