



## **X-ray emission from magnetic cataclysmic variables**

K. P. Singh\*

<sup>1</sup>Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400 005, India

**Abstract.** I present a brief review of the present status of X-ray emission from Magnetic Cataclysmic Variables (MCVs). A short introduction to the types of Cataclysmic Variables (CVs) is followed by a presentation of some of the properties of the two types of MCVs - Polars and Intermediate Polars (IPs) as seen in X-rays. Finally X-ray spectra of MCVs and future prospects of their studies are discussed.

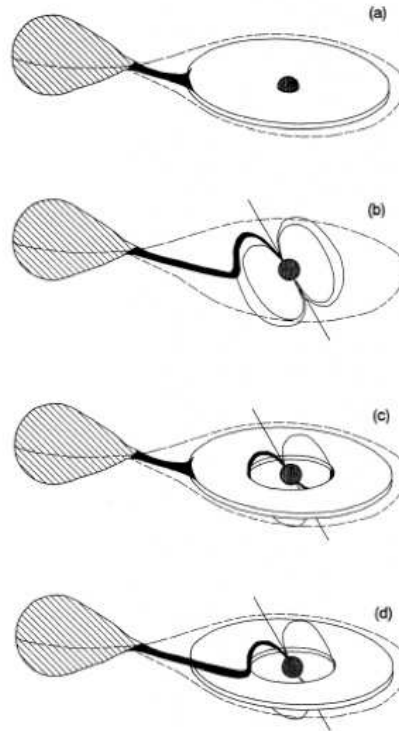
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### **1. Introduction**

Cataclysmic Variables (CVs) are semi-detached binary star systems with very short periods ( $\sim 10$  min to 10 hrs) containing a red dwarf main-sequence-like secondary star and a more massive white dwarf (WD) primary star. The secondary star fills its Roche Lobe and the matter overflows the lobe and is accreted by the primary white dwarf star. CVs have been classified into various types based on their observational characteristics. These characteristics are in turn believed to depend on the nature of the primary star and the accretion process. Systems in which the white dwarf surface magnetic field is  $< 10^7$  Gauss are called non-magnetic CVs and these systems display a variety of observational characteristics leading to further sub-types like: (a) Novae which show large eruptions of  $\sim 6$ – $9$  magnitudes in the optical, (b) Recurrent Novae that are previous novae seen to re-erupt, (c) Dwarf Novae (DN) that show regular outbursts of  $\sim 2$ – $5$  magnitudes and are further classified into SU UMa stars showing occasional super-outbursts, Z Cam stars that show protracted standstills between outbursts, and U Gem stars that are basically all other DN, (d) Nova-like variables consisting of VY Scl stars which show occasional drops in brightness and UX UMa stars consisting of all other non-eruptive variables. CVs in which the white dwarf surface magnetic field is very high, i.e.,  $\geq 10^7$  Gauss, are called Magnetic CVs (MCVs). MCVs come in two varieties known as the Intermediate Polars (IPs) or DQ Her stars, and the Polars or AM Her stars. The white dwarfs in the Polars have a higher magnetic field than in the IPs. In the non-magnetic CVs the accretion takes place via an accretion disk produced

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\*email: [Kulinderpal.Singh@tifr.res.in](mailto:Kulinderpal.Singh@tifr.res.in)



**Figure 1.** Schematic diagram of accretion in CVs. (a) Non-magnetic CV with no disruption of the accretion disk. (b) Stream-fed magnetic CV in which the formation of an accretion disk is prevented. (c) Disk-fed MCV in which the accretion disk is disrupted at the magnetospheric boundary. (d) MCV with non-accretion disk in which the disrupted disk exists, but in which (some of) the accreting material skims over the surface to impact the magnetosphere directly as in (b). [Reproduced from Norton (1993)].

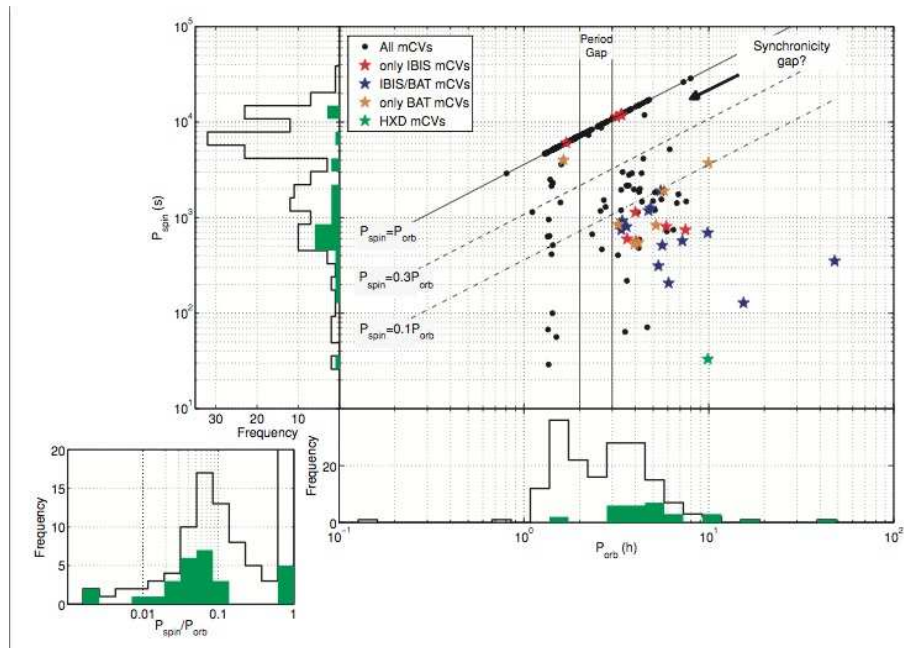
to conserve the angular momentum of the accreting material. In the MCVs, however, the pressure of the magnetic field disrupts completely or partially the accretion disk depending on the strength of the magnetic field and the accreting material is guided along the magnetic field lines to the poles of the white dwarf in an accretion stream or an accretion curtain (Hameury, King & Lasota, 1986; Norton, 1993; Warner, 2003). The different types of accretion processes are shown in Fig. 1.

Large levels of circular polarization are seen in the optical emission from the MCVs thus implying that the radiation process is largely cyclotron emission. For the polarized emission to be in the optical (or UV) requires high values of magnetic field strength,  $\geq 3 \times 10^7 \text{G}$  (3000 Tesla), which disrupts the accretion disk completely in Polars (Fig. 1(b)). Slightly lower magnetic field leads to a partial disruption of the accretion disk seen in the IPs (Fig. 1(c) & (d)). The magnetically controlled accretion in MCVs is reflected in their eclipse light curves which show very sharp (seconds)

drop and rise in the brightness, consistent with a small spot on the white dwarf surface. During the eclipses, different parts of the system are successively eclipsed and uncovered, and in some systems one can also infer the presence of accretion stream between stars that can be very bright, and can see faint light from the secondary star (see e.g., Bridge et al. (2002)). As the material falling towards the WD is accreted it is de-accelerated and a shock is produced in the flow. Gas which is initially in free-fall then encounters the shock front where the shock converts the kinetic energy into thermal energy (bulk motion into random motion). In this standard model of accretion onto a magnetic white dwarf most of the gravitational energy is released in the post-shock region. The resulting shock temperature is given by  $T_s = 3GM\dot{m}_i/8kR$ , which is of the order of 10 to 50 keV ( $M$  and  $R$  being the WD mass and radius respectively). The corresponding X-ray luminosity,  $L_X = GMM_\odot/R$ , is  $\sim 10^{31} - 10^{33}$  erg  $s^{-1}$  ( $M_\odot$  being the accretion rate). Corresponding hard X-rays are emitted mainly via the bremsstrahlung process and multi-temperature plasma are also observed with characteristic atomic lines from ionized plasma. Below the shock, bremsstrahlung and cyclotron radiation are the two main competitive cooling processes and broad cyclotron lines are seen in the optical/UV. Hard X-rays ( $E > 2$  keV) are radiated from the post-shock plasma. The same material also radiates in IR–UV by cyclotron process. The accreting matter gradually settles down on the surface of the white dwarf. Half of the accreting luminosity illuminates the polar caps and is reprocessed as soft X-ray blackbody emission ( $E < 2$  keV) with a temperature,  $T_{bb} = (L_{acc}/8f\pi R^2\sigma)^{1/4}$ ,  $\sim 10-50$  eV ( $f$  being the irradiated fractional area of the stellar surface).

## 2. Periods, luminosities and catalogues of MCVs

In Polars, the white dwarf and the red dwarf stars are locked into the same orientation and their rotation and binary periods are synchronized. Consequently all the short-term variability seen in a) the orbital period radial velocity curves of the secondary, b) X-ray light curves from the primary, and c) optical polarization, occurs at a single period. The mechanism for synchronization is believed to be the dissipation due to the magnetic field of the primary being dragged through the secondary. As the relative spin rate of the primary decreases, locking can occur due to the dipole-dipole magneto-static interaction between primary and (weaker) secondary magnetic field. Polars, therefore, show only one period in their light curves or a single peak in their Fourier power spectra if the variations are sinusoidal. Some Polars are slightly out of synchronism, and in these systems, it typically takes 5–50 days for the white dwarf orientation to repeat itself (Mouchet et al. 1999, Rana et al. 2005). The reason for asynchronism is not known, but one suggestion is that these systems are Polars which have had a recent nova event, kicking them slightly out of synchronization (Warner 2003). Only four such systems are known and these can be very useful to study the effect of orientation of magnetic field on the accretion process. The radiations from the IPs, however, show a number of periods as these systems are not synchronized and the effects of the binary rotation can be seen directly or indirectly through several peaks in their Fourier power spectral densities (Norton 1993, Norton, Beardmore



**Figure 2.** Orbital period versus spin period for MCVs taken from RKcat. Stars indicate MCVs detected at hard X-ray energies. Also plotted are the period gap and Synchronicity lines. For reference, the orbital, spin and synchronicity distributions are also displayed. The shaded green areas represent hard X-ray-selected MCVs. [Reproduced from Scaringi et al. 2010]

& Taylor 1996, Beardmore et al. 1998, Rana et al. 2004, Girish & Singh 2012 and references therein). Wynn & King (1992) computed theoretical power spectra of the X-ray modulations expected from IPs in various accretion geometries, and showed that disk less accretion models show strong spin modulations and absence of spin-orbit beat modulations.

Both Polars and IPs are expected to emit high-energy photons, however, an excess of soft X-rays is observed in Polars (Lamb 1985). Chanmugam, Ray & Singh (1991) and others have reported that the total X-ray luminosities of IPs are greater than those of Polars by a factor of  $\sim 10$ , attributed mainly to the higher accretion rates. Moreover, it has been proposed that strong magnetic fields in Polars produce a more blobby flow than in IPs (Warner 2003). These high-density blobs are then able to penetrate within the post-shock region, emitting fewer bremsstrahlung photons and contributing more to the soft X-ray blackbody component, thought to be produced at the base of the post-shock region. In recent years, an increasing number of IPs have been detected and discovered by hard X-ray telescopes such as INTEGRAL/IBIS (Barlow et al. 2006; Landi et al. 2009), Swift/BAT (Brunschweiler et al. 2009) and SUZAKU/HXD (Terada et al. 2008). Scaringi et al. (2010) have compiled a new list of IBIS MCVs, forming part of a larger compilation of hard X-ray-selected

IPs from all three telescopes mentioned above, to help study the general properties of this hard X-ray-selected sample. Scaringi et al. (2010) used two well known Catalogues of the CVs: 1) the Catalogue and Atlas of Cataclysmic Variables (Downes et al. 2005, or DWScat) and the Catalogue of Cataclysmic Binaries (Ritter & Kolb 2003, or RKcat). DWScat contains 1830 CVs, whereas RKcat contains 731. Scaringi et al (2010), merged both the catalogues and found that 656 CVs are common to both the catalogs. The principal reason for RKcat having fewer objects is that only CVs with known orbital periods are included in the sample; however, RKcat also includes a few CVs that DWScat does not report (Scaringi et al 2010). Their final known CV set therefore contains 1905 CVs (hereafter DRKcat). Fewer than  $\approx 9\%$  of the total number of CVs within DRKcat are known to be magnetic in nature (Polars and IPs), and only  $\approx 3\%$  (56 sources) are IPs. Compared to IPs, only 4 Polars are detected at high energies with INTEGRAL, including the two asynchronous systems BY Cam and V1432 Aql (Landi et al. 2009, Scaringi et al. 2010). Thus, though optically selected samples favour Polars, with the number of known Polars being twice that of IPs, in the hard X-ray-selected sample,  $\sim 90\%$  of the MCVs detected are IPs. This is not unexpected since the IPs are seen to produce 10 times more hard X-rays than Polars due to their higher mass transfer and intrinsically harder spectrum (see Warner 2003). The distribution of the orbital and spin periods in this expanded sample of MCVs is shown in Fig. 2 reproduced from Scaringi et al. (2010). They find that most hard X-ray-detected MCVs have  $P_{spin}/P_{orb} < 0.1$  above the period gap, and that there are very low number of detected systems in any band between  $P_{spin}/P_{orb} = 0.3$  and  $P_{spin}/P_{orb} = 1$  and the apparent peak of the  $P_{spin}/P_{orb}$  distribution at about 0.1.

### 3. X-ray spectra of MCVs

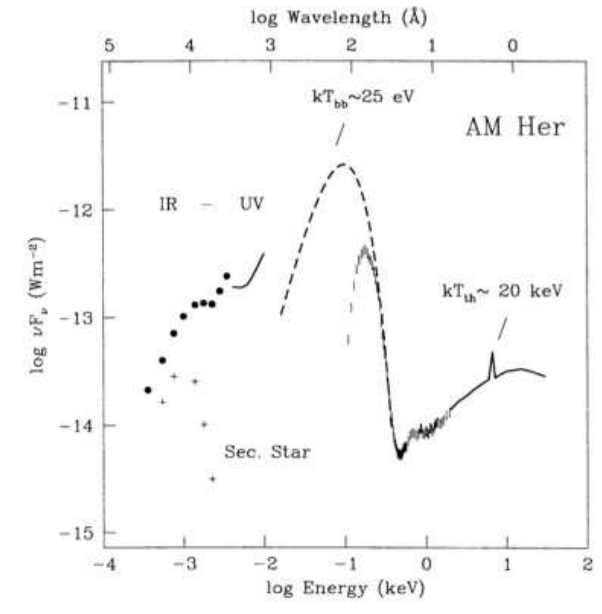
Broad-band (IR to UV) spectrum observed from a Polar - AM Her is shown in Fig. 3 taken from Beuermann (1999). Apart from the photospheric emission from the white dwarf seen in UV, emission seen in the IR-Optical-UV bands is from cyclotron radiation from accretion column. The dominating soft X-ray emission is seen as a blackbody emission from the heated surface of the WD in Polars. The absence of the blackbody emission in the IPs, in the early observations, was interpreted as due to either strong absorption in the accretion curtain or to a lower temperature EUV emission from a larger irradiated zone. The number of IPs detected in soft X-rays ( $E < 2\text{keV}$ ) has recently increased significantly (Evans & Hellier 2007, Anzolin et al. 2008, Girish & Singh 2012). The black-body soft-X-ray component in the IPs has temperatures ( $\sim 50\text{-}120\text{ eV}$ ) that are higher than those usually found in Polars ( $20\text{-}60\text{ eV}$ ) and with a lower soft/hard flux ratio. The higher temperatures found in IPs indicate higher accretion rates, in line with higher luminosities. Multiple and partial absorption is also seen in the soft X-ray spectra of IPs (e.g., see Girish & Singh 2012) indicating the presence of complicated patterns of absorption by accretion curtains in the line of sight. The maximum temperature of the system seen in the hard X-ray continuum provides an estimate of the mass of the accreting magnetic white dwarf (see §1).

A prominent emission line, presumably from ionized Fe in hot plasma can be seen in almost all CVs. The Fe line complex is resolved in very high energy resolution spectra taken with Chandra High Energy Transmission Gratings (HETG), and an example is shown in Fig. 4 taken from Girish, Rana & Singh (2007). The intensity of the He-like triplets seen at 6.7002 keV (r: resonance line), two inter combination lines at 6.6821 keV and 6.6673 keV (i=i1+i2) (unresolved), and 6.6364 keV (f: forbidden) line provide a powerful diagnostics of the ionized plasma in the hot or highly ionized plasma. For example, assuming a thin plasma, as in the solar corona, G-ratio = (f+i)/r can be used to get the electron temperature, and R-ratio = f/i to obtain the electron density of the plasma, Similarly, H-like doublets at 6.973 keV and 6.952 keV indicate the highest temperature regions. The X-ray spectrum actually contains H-like and He-like lines of many other elements as well: S, Si, Mg, Ne and O with several Fe L-shell emission lines. The forbidden lines in the spectrum are generally weak whereas the H-like lines are stronger suggesting that emission from a multi-temperature, collisionally ionized plasma dominates in AM Her. A line-by-line fitting analysis of all the available spectra on all CVs obtained using the Chandra HETG has been reported by Schlegel et al. (2013), who report the existence of broad ionization and electron temperatures ranging from  $\sim 0.4$  keV to  $\sim 5-10$  keV, thus confirming the previous results based on a global analysis of HETG data by Hellier & Mukai (2004). Number densities are also found to cover a broad range, from  $10^{12}$  to  $> 10^{16}$   $\text{cm}^{-3}$  (Singh et al. 2006, Rana et al. 2006, Schlegel et al. 2013). Much of the plasma is probably in a non-equilibrium state; the Fe emission, however, may arise from plasma in ionization equilibrium (Schlegel et al. 2013).

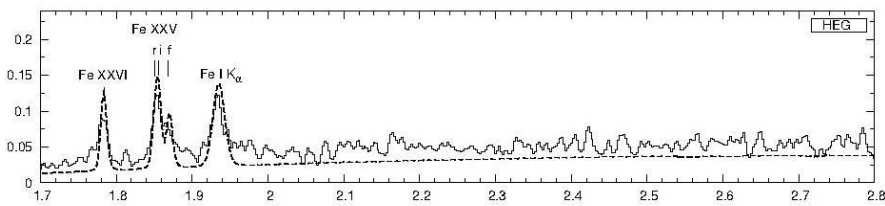
Phase resolved spectroscopy of AM Her has shown that the line centres of Mg XII, S XVI, resonance line of Fe XXV, and Fe XXVI emission are modulated by a few hundred to 1000  $\text{km s}^{-1}$  from the theoretically expected values, indicating bulk motion of ionized matter in the accretion column of AM Her (Girish, Rana & Singh 2007). The observed velocities of Fe XXVI ions are close to the expected shock velocity for a  $\sim 1M_{\odot}$  white dwarf. The observed velocity modulation is consistent with that expected from a single pole accreting binary system (Girish et al. 2007). Almost all CVs (including the MCVs) show most of these lines from ionized species, and also show a line due to fluorescence of Fe (Fe I  $K_{\alpha}$ ) at 6.4 keV, thus indicating the presence of cold (un-ionized) material and reflection in both the disk and diskless systems (Ezuka & Ishida 1999, Rana et al. 2006; Girish et al. 2007; Girish & Singh 2012).

#### 4. Future

Simultaneous multi-wavelength studies in optical, UV, soft and hard X-rays with ASTROSAT of the newly discovered population of IPs (INTEGRAL sources), would be of great help in elucidating the nature of these sources. Broad-band hard X-rays continuum observations of MCVs with ASTROSAT will provide better estimates of the mass of the accreting WDs. High spectral resolution studies with X-ray calorimeter on board Astro-H will provide the ionization structure of the accretion column and the



**Figure 3.** Multi-wavelength spectral energy distribution of the Polar AM Her [Reproduced from K. Beuermann, 1999].



**Figure 4.** Chandra HETG spectrum of AM Her. A section of the spectrum near the Fe line complex is shown. [Reproduced from Girish, Rana & Singh (2007)]

properties of the hot multi-temperature plasma behind the shock front in the accretion column.

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