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Magnetic cataclysmic variable accretion flows

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Abstract. We have used a magnetic accretion model to investigate the accretion flows of magnetic cataclysmic variables (mCVs) throughout a range of parameter space. The results of our numerical simulations demonstrate that broadly four types of flow are possible: discs, streams, rings and propellers. We show that the equilibrium spin periods in asynchronous mCVs, for a given orbital period and magnetic moment, occur where the flow changes from a type characterised by spin-up (i.e. disc or stream) to one characterised by spin-down (i.e. propeller or ring). 'Triple points' occur in the plane of spin-to-orbital period ratio versus magnetic moment, at which stream-disc-propeller flows or stream-ring-propeller flows can co-exist. The first of these is identified as corresponding to when the corotation radius is equal to the circularisation radius, and the second as where the corotation radius is equal to the distance from white dwarf to the L1 point. If mCVs are accreting at their equilibrium spin rates, then for a mass ratio of 0.5, those with $P_{\rm spin}/P_{\rm orb} \lesssim 0.10$ will be disc-like, those with $0.10 \lesssim P_{\rm spin}/P_{\rm orb} \lesssim 0.55$ will be stream-like, and those with $P_{\rm spin}/P_{\rm orb} \sim 0.55$ will be ring-like. In each case, some material is also lost from the binary in order to maintain angular momentum balance. The spin to orbital period ratio at which the systems transition between these flow types decreases as the mass ratio of the stellar components increases, and vice versa.

Keywords: stars: cataclysmic variables – X-rays: stars – stars: magnetic fields – stars: binaries
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INTRODUCTION

Magnetic cataclysmic variable stars (mCVs) provide an excellent probe of the accretion process under extreme astrophysical conditions. They are interacting binary stars in which a magnetic white dwarf (WD) accretes material from a late-type companion star via Roche lobe overflow. The WD has a large magnetic moment ($\mu_1 \sim 10^{32} - 10^{36}$ G cm^3) which has a wide ranging influence on the dynamics of the accretion flow. The mCVs fall into two distinct classes: the AM Herculis stars (or polars) and the intermediate polars (IPs or DQ Herculis stars); a comprehensive review may be found in Warner (1995). The rotational periods of the WDs ($P_{\rm spin}$) in polars are generally locked to the orbital period ($P_{\rm orb}$), whereas the WDs in IPs are asynchronous with $P_{\rm spin}/P_{\rm orb} \approx 0.01 - 0.2$. Polars contain the most strongly magnetic WDs and their synchronism is thought to come about due to the interaction between the magnetic fields of the two stars which is able to overcome the spin-up torque of the accreting matter (see e.g. King, Frank and Whitehurst 1991). IPs fill the parameter space between the strongly magnetic polars and the non-magnetic CVs. The accretion flows within IPs are known to take on a wide variety of forms, from magnetized accretion streams to extended accretion discs. This variety has constantly perplexed efforts to understand these objects and is the subject of this work.

In an earlier paper (Norton, Wynn & Somerscales 2004; hereafter NWS) we used a model of magnetic accretion to investigate the rotational equilibria of mCVs. We showed that there is a range of parameter space in the $P_{\rm spin}/P_{\rm orb}$ versus μ_1 plane at which rotational equilibrium occurs. This allowed us to infer approximate values for the magnetic moments of all known IPs. In that paper we noted that the spin equilibria correspond to a variety of different types of accretion flow; in this paper we investigate these flows in a more systematic manner and present our conclusions.

A MODEL FOR MAGNETIC ACCRETION FLOWS

Full details of how the magnetic accretion flow may be characterized and how we model this may be found in NWS. Briefly, we assume that material moving within the binary system interacts with the local WD magnetic field via a shear velocity-dependent acceleration. This is analogous to the assumption that the magnetic stresses are dominated by the magnetic tension rather than the magnetic pressure, which will be valid in all but the innermost regions of the flow, close to the white dwarf surface. We thus write the magnetic acceleration as a coefficient (k) multiplied by the difference in velocity between the accreting material and the field lines ($\mathbf{v}_\perp$).

$$k(r)\mathbf{v}_\perp = \frac{1}{\rho(r)R_{\rm c}(r)}\frac{B^2(r)}{4\pi}\hat{\mathbf{n}} \tag{1}$$

where $\rho(r)$ is the local density of plasma and $R_{\rm c}(r)$ is the local radius of curvature of the field lines. k therefore contains the details of the plasma-magnetic field interaction. We also assume a dipole field structure, so $B(r) = B_{\rm wd}(r/r_{\rm wd})^{-3}$ where $B_{\rm wd}$ is the magnetic field strength at the surface of the white dwarf, of radius $r_{\rm wd}$. In order to account for the variation in plasma density and field curvature throughout the system, we further assume that $\rho(r)R_{\rm c}(r) \propto r^{-3}$. Hence the k parameter itself scales as $k(r) = k_0(r/r_{\rm wd})^{-3}$ where k_0 is the parameter which is input to the modelling code and represents the magnetic field strength at the white dwarf surface. The results we present here were obtained with a three-dimensional particle hydrodynamics code known as HyDisc, using an implementation of the model described fully in NWS. The calculations are carried out in the full binary potential and include a simple treatment of the gas viscosity.

TRIPLE POINTS IN THE $P_{\rm spin}/P_{\rm orb}$ VS. μ_1 PLANE

In NWS we reported the accretion flows corresponding only to the equilibrium spin periods, as a function of orbital period and magnetic field strength. Although we expect mCVs to remain close to equilibrium when considered on long timescales, at a given instant a particular system may not be at its equilibrium spin period. This is evidenced by the fact that many intermediate polars are observed to be either spinning up or spinning down. In order to explore the accretion flows corresponding to the full range of mCV parameter space, the magnetic model was run for each combination of parameters in a grid defined by the orbital period ($P_{\rm orb} = 80$min to 9h), spin period ($P_{\rm spin} = 100$s to 5h) and magnetic field strength ($k = (10^2 - 10^8)(2\pi/P_{\rm orb})\rm s^{-1}$). Initially, the mass ratio of the two stellar components ($q = M_2/M_1$) was set at 0.5. A model based on each combination of parameters was allowed to run for several orbital periods before the nature of the resulting accretion was examined. An atlas of these flows may be found in the PhD thesis by Parker (2005). Broadly speaking, each of the flows may be characterized as one of:

propellers in which most of the material transferred from the secondary star is magnetically propelled away from the system by the rapidly spinning magnetosphere of the WD.

discs in which most of the material forms a circulating flattened structure around the WD, truncated at its inner edge by the WD magnetosphere where material attaches to the magnetic field lines before accreting on the WD surface.

streams in which most of the material latches onto the field lines immediately and follows these on a direct path down to the WD.

rings in which most of the material forms a narrow annulus circling the WD at the outer edge of its Roche lobe, with material stripped from its inner edge by the magnetic field lines before being channelled down to the WD surface.

We show in Figure 1 the results of analysing where the various flow types occur, for systems with a mass ratio of $q = 0.5$. Each panel is for a particular orbital period, and the $P_{\rm spin}$ vs. μ_1 plane is divided according to where each flow pattern is observed. The bold line in the plane is roughly the locus of the equilibrium spin period in each case, as derived in NWS. Clearly this marks the boundary between accretion flow types that will generally spin-up the WD (discs or streams) and accretion flow types that will generally spin-down the WD (propellers or rings). As noted in NWS, at equilibrium in the ring-like flow, angular momentum from the WD is passed back to the accreting material, some of which is lost from the outer edge of the ring to maintain equilibrium. Elsewhere in the parameter space at equilibrium, combinations of disc/propeller and stream/propeller are seen. As shown in Figure 2, close to the stream-disc-propeller triple point and the stream-ring-propeller triple point, the equilibrium flows are a combination of the various flow types. In each case at equilibrium the angular momentum accreted by the WD is balanced by an equal amount lost from the system via material which is magnetically propelled away from the WD. This, after all, is the definition of the equilibrium spin period. If real IPs sit at their equilibria they will exhibit accretion flows that are apparently disc-like, stream-like or ring-like, each with a component of the flow that is propelled away.

As can be seen in Figure 1, at equilibrium for this mass ratio, the dividing point between disc-like and stream-like flows is close to $P_{\rm spin}/P_{\rm orb} \sim 0.10$ for all orbital periods; whilst the dividing point between stream-like and ring-like flows is close to $P_{\rm spin}/P_{\rm orb} \sim 0.55$. Hence, for a mass ratio of 0.5, if IPs are accreting at their equilibrium spin rates, those with $P_{\rm spin}/P_{\rm orb} \lesssim 0.10$ will be disk-like, those with $0.10 \lesssim P_{\rm spin}/P_{\rm orb} \lesssim 0.55$ will be stream-like, and those with $P_{\rm spin}/P_{\rm orb} \sim 0.55$ will be ring-like. Equilibrium is not possible for $P_{\rm spin}/P_{\rm orb} \gtrsim 0.55$, until a system reaches synchronism (and is therefore a polar, exhibiting stream-fed accretion once more).

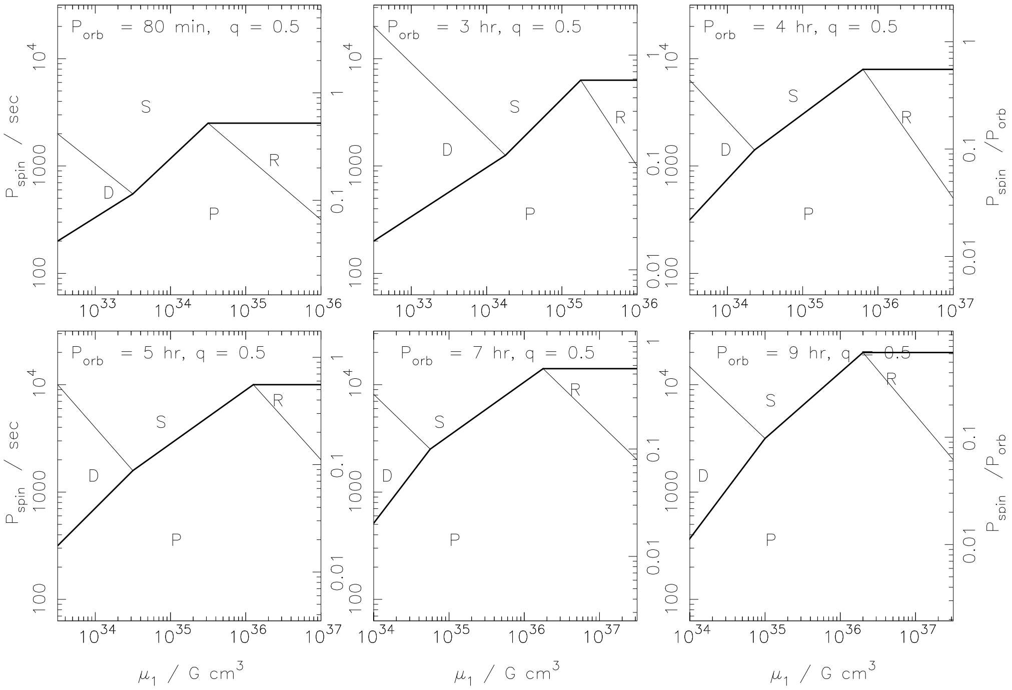

FIGURE 1. The distribution of accretion flow types as a function of orbital period, in the spin period vs. magnetic moment plane, at a mass ratio of $q = 0.5$. The right hand axes show the spin to orbital period ratio in each case. 'D' stands for disc accretion, 'S' for stream accretion, 'R' for ring accretion and 'P' for propeller flow. The thick line shows the locus of the equilibrium spin period in each case and marks the boundary between accretion flows that spin-up the WD and those which cause it to spin-down. Note that the horizontal scale shifts between each row of panels to enable us to plot the parameter space investigated at each orbital period.

CHANGING THE MASS RATIO

Changing the mass ratio of the stars in the system changes where the equilibrium spin period occurs. To investigate this, we have rerun the model accretion flows for mass ratios of $q = 0.2$ and $q = 0.9$ for the case of a 4 hour orbital period. The same pattern of accretion flow behaviours is seen, but the 'triple points' move to smaller $P_{\rm spin}/P_{\rm orb}$ ratios and larger white dwarf magnetic moments as the mass ratio increases. Conversely, at smaller mass ratios, the triple points move to larger $P_{\rm spin}/P_{\rm orb}$ ratios and smaller white dwarf magnetic moments.

King & Wynn (1999) noted that mCVs have an equilibrium condition specified by the condition $R_{\rm co} \sim R_{\rm circ}$. Here $R_{\rm co}$ is the corotation radius, namely that at which matter in local Keplerian rotation corotates with the magnetic field of the white dwarf, and $R_{\rm circ}$ is the circularisation radius, namely that at which the specific angular momentum equals that of matter at the inner Lagrangian point. This in turn yields the condition $P_{\rm spin}/P_{\rm orb} \sim (1+q)^2(0.500 - 0.227\log q)^6$. We identify this equilibrium with the lower 'triple point' in Figure 1. For the three mass ratios examined here (i.e. $q = 0.2$, 0.5 and 0.9), this predicts spin to orbital period ratios of 0.12, 0.076 and 0.064 respectively.

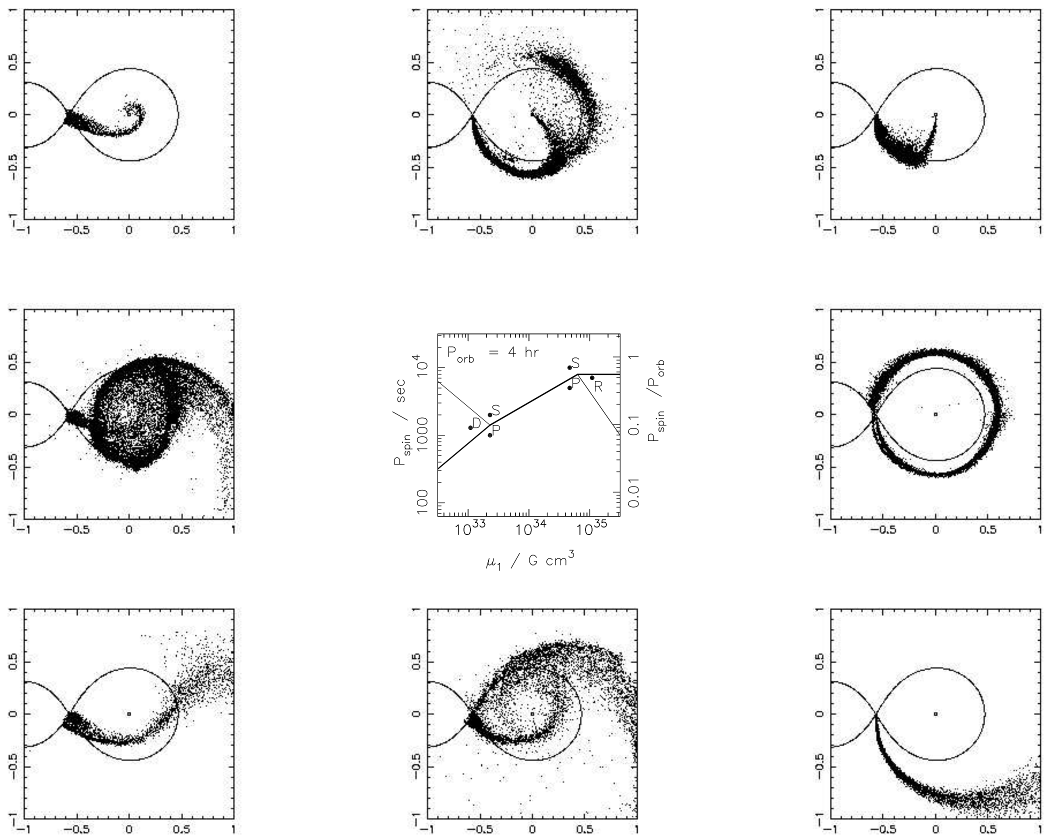

FIGURE 2. Illustration showing how the accretion flow varies in the vicinity of the boundaries between the different flow types. The models shown are all for $P_{\rm orb}$ = 4h and $q = 0.5$. The panels on the left show flows in the vicinity of the stream-disc-propeller triple point, indicated by 'S', 'D' and 'P' on the central panel, whilst the panels on the right show flows in the vicinity of the stream-ring-propeller triple point, indicated by 'S', 'R' and 'P' on the central panel. The panel at the bottom, centre is the accretion flow *at* the stream-disc-propeller triple point and shows characteristics of all three flows at an equilibrium spin period of 1450s for $\mu_1 = 2.3 \times 10^{33}$ G cm^3. The panel at the top, centre is the accretion flow *at* the stream-ring-propeller triple point and shows characteristics of all three flows at an equilibrium spin period of 8000s for $\mu_1 = 5.7 \times 10^{34}$ G cm^3.

From our simulations, the triple points are at spin-to-orbital period ratios of 0.14, 0.08 and 0.06, in good agreement with the predictions.

King & Wynn (1999) also noted another possible equilibrium, where $R_{\rm co} \sim b$, i.e. the distance from the white dwarf to the inner Lagrangian point. This yields the condition $P_{\rm spin}/P_{\rm orb} \sim (0.500 - 0.227 \log q)^{3/2}$. We identify this equilibrium with the upper 'triple point' in Figure 1, as it indicates ring-like accretion flow confined to the outer edge of the white dwarf's Roche lobe. For the three mass ratios examined here (i.e. $q = 0.2$, 0.5 and 0.9), this predicts spin to orbital period ratios of 0.53, 0.43 and 0.36 respectively. From our simulations, the triple points are at spin-to-orbital period ratios slightly higher than these, which probably reflects the fact that we observe ring-like structures to form just outside the white dwarf's Roche lobe, rather than at the edge of the lobe itself.

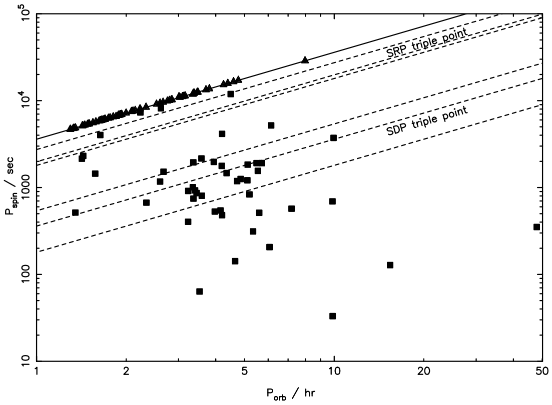

FIGURE 3. The known mCVs distributed throughout $P_{\rm spin}$ vs $P_{\rm orb}$ parameter space. Polars are indicated by triangles, and IPs by squares. The lower set of three diagonal lines correpsonds to the spin-to-orbital period ratio of the stream-disc-propeller triple point at mass ratios of 0.2, 0.5 and 0.9. The upper set of three diagonal lines correspond to the stream-ring-propeller triple point for the same mass ratios.

CONFRONTING REALITY

Figure 3 shows the distribution of currently known mCVs in the $P_{\rm spin}$ vs. $P_{\rm orb}$ plane. The diagonal lines represent loci of constant $P_{\rm spin}/P_{\rm orb}$, and hence divide the plane into regions where different accretion flows may be expected to occur. Regions below any of the three lines corresponding to the stream-disc-propeller triple points for $q = 0.2$, 0.5 and 0.9 indicate where disc-like flows can occur; regions between any of these three lines and the three lines corresponding to the stream-ring-propeller triple points for $q = 0.2$, 0.5 and 0.9 indicate where stream-like flows can occur; and the region around these upper three lines indicate where ring-like flows will be most likely to occur.

As can be seen, at least half of the IPs cluster around the region where $0.05 \lesssim P_{\rm spin}/P_{\rm orb} \lesssim 0.15$ which characterises the stream-disc-propeller triple point for plausible mass ratios. Assuming these systems are accreting close to their equilibrium spin period, they are all therefore likely to exhibit accretion flows which resemble the combination disc-like/stream-like flow shown in the lower, centre panel of Figure 2. The few ‘EX Hya-like’ systems below the period gap (which is rapidly becoming more populated by mCVs) generally have higher $P_{\rm spin}/P_{\rm orb}$ ratios, and as noted in NWS may be characterised by stream-like or ring-like accretion if they are at equilibrium. The systems at very small $P_{\rm spin}/P_{\rm orb}$ ratios ($\lesssim 0.01$) are likely to be either disc-like accretors or, if they are out of equilibrium like AE Aqr, strong magnetic propellers.

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