THE ACCRETION FLOWS AND EVOLUTION OF MAGNETIC CATACLYSMIC VARIABLES

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ABSTRACT

We have used a model of magnetic accretion to investigate the accretion flows of magnetic cataclysmic variables (mCVs). Numerical simulations demonstrate that four types of flow are possible: disks, streams, rings, and propellers. The fundamental observable determining the accretion flow, for a given mass ratio, is the spin-to-orbital–period ratio of the system. If intermediate polars (IPs) are accreting at their equilibrium spin rates, then for a mass ratio of 0.5, those with $P_{\text{spin}}/P_{\text{orb}} \leq 0.1$ will be disklike, those with $0.1 \leq P_{\text{spin}}/P_{\text{orb}} \leq 0.6$ will be streamlike, and those with $P_{\text{spin}}/P_{\text{orb}} \geq 0.6$ will be ringlike. The spin-to-orbital–period ratio at which the systems transition between these flow types increases as the mass ratio of the stellar components decreases. For the first time we present evolutionary tracks of mCVs, which make it possible to investigate how their accretion flow changes with time. As systems evolve to shorter orbital periods and smaller mass ratios, in order to maintain spin equilibrium their spin-to-orbital–period ratio will generally increase. As a result, the relative occurrence of ringlike flows will increase, and the occurrence of disklike flows will decrease, at short orbital periods. The growing number of systems observed at high spin-to-orbital–period ratios with orbital periods below 2 hr and the observational evidence for ringlike accretion in EX Hya are fully consistent with this picture.

Subject headings: accretion, accretion disks — binaries: close — stars: magnetic fields

1. 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 ($\mu_{1} \sim 10^{32}-10^{35}$ G cm$^2$), 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 ($P_{\text{spin}}$) in IPs are generally locked to the orbital period ($P_{\text{orb}}$), whereas the WDs in IPs are asynchronous with $P_{\text{spin}}/P_{\text{orb}} \approx 0.01-0.6$. 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 et al. 1991). IPs fill the parameter space between the strongly magnetic polars and the nonmagnetic CVs. The accretion flows within IPs are known to take on a wide variety of forms, from magnetically confined accretion streams to extended accretion disks, similar to nonmagnetic CVs. This variety has constantly perplexed efforts to understand these objects and is the subject of this work.

In an earlier paper (Norton et al. 2004; hereafter Paper I) 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 $P_{\text{spin}}/P_{\text{orb}}$ versus $\mu_{1}$ plane at which rotational equilibrium occurs. This finding allowed us to infer approximate values for the magnetic moments of all known intermediate polars. As a result we established that the number of systems as a function of the WD magnetic moment is distributed approximately according to $N(\mu_{1})d\mu_{1} \propto \mu_{1}^{-1}d\mu_{1}$. In that paper we noted that the spin equilibria correspond to a variety of different types of accretion flow, including disklike accretion at small $P_{\text{spin}}/P_{\text{orb}}$ values, streamlike accretion at intermediate $P_{\text{spin}}/P_{\text{orb}}$ values, and accretion fed from a ring at the outer edge of the WD Roche lobe at higher $P_{\text{spin}}/P_{\text{orb}}$ values. In this paper we investigate these flows in a more systematic manner and examine how the accretion flow varies as a system evolves. In particular, for the first time we determine the evolutionary tracks of IPs at a range of magnetic field strengths and compare these with the observed distribution of IPs.

2. MAGNETIC ACCRETION FLOWS AND THE MAGNETIC MODEL

Full details of how the magnetic accretion flow may be characterized and how we model this may be found in Paper I. 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 WD 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 ($v_{\perp}$): \begin{equation} k(r)v_{\perp} = \frac{1}{\rho(r)}\frac{B^2(r)}{4\pi}n, \end{equation} where the unit vector $n$ is perpendicular to field lines, $\rho(r)$ is the local density of plasma, and $R_{c}(r)$ is the local radius of curvature.
of the field lines. The coefficient \( k \) therefore contains the details of the plasma-magnetic field interaction and, as shown in Paper I, it scales as

\[
k(r) = k_0 \left( \frac{r}{r_{WD}} \right)^{-3},
\]

where \( k_0 \) is the parameter that is input to the modeling code and encodes both the magnetic field strength at the WD surface and the plasma density at the L1 point. A Gaussian distribution of \( k_0 \) is used in the model, with typically a standard deviation of 1% around the mean value to represent the range of plasma densities in the flow. Larger values of this Gaussian width result in more “blurred” boundaries between regions displaying different accretion flows (see below) but do not alter the WD equilibrium spin period for a given \( k_0 \).

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 Paper I. The calculations are carried out in the full binary potential and include a simple treatment of the gas viscosity. Previous results obtained with HyDisc are described in King & Wynn (1999), Wynn et al. (1997), and Wynn & King (1995). The HyDisc code uses “packets” of plasma injected at the L1 point. The density and size scale of these packets change as they travel toward the white dwarf and they interact individually with the magnetic field lines. This structure mimics the “blobby” accretion seen in (e.g.) AM Her (Heise et al. 1985; Hameury & King 1988), which gives rise to large variations in the density of the flow at the WD surface.

3. FLOW RESULTS

3.1. Triple Points in the \( P_{\text{spin}}/P_{\text{orb}} \) versus Magnetic Moment Plane

In Paper I we reported the accretion flows corresponding only to the equilibrium spin periods as a function of orbital period and magnetic field strength. Although mCVs are expected to remain close to equilibrium when considered on long timescales, at a given instant a particular system may be spinning up or spinning down. Indeed, Patterson (1994) predicted that the period derivative of an IP in equilibrium will not be steady. The observed spin-up and spin-down rates in IPs typically correspond to much longer timescales \((\sim 10^9 \text{ yr})\) than the timescale to reach spin equilibrium \((\sim 10^7 \text{ yr})\), indicating that systems are only exhibiting random excursions away from equilibrium, probably driven by mass transfer fluctuations.

In order to explore the accretion flows corresponding to the full range of mCV parameter space, including behavior away from spin equilibrium, the magnetic model was run for each combination of parameters in a grid defined by the orbital period \((P_{\text{orb}} = 80 \text{ min to 9 hr})\), spin period \((P_{\text{spin}} = 100 \text{ s to 5 hr})\), magnetic field strength \([k = (10^2 - 10^7)(2\pi/\omega_{\text{orb}}) \text{ s}^{-1}]\), and the mass ratio of the two stellar components \((q = M_2/M_1 = 0.2, 0.5, 0.9)\). This corresponds to a range of WD magnetic moments from about \(10^{32}\) to \(10^{36} \text{ G cm}^3\). The secular mass transfer rate appropriate to the particular orbital period was assumed in each case. A model based on each combination of parameters was allowed to run to steady state.
before the nature of the resulting accretion was examined. An atlas of these flows may be found in the Ph.D. thesis by Parker (2005).

Broadly speaking, each of the flows may be characterized as one of the following:

1. **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;

2. **disks**: 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;

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

4. **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 channeled down to the WD surface.

We show in Figure 1 the results of analyzing 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 $P_{\text{spin}}$ versus $\mu_1$ plane is divided according to where each flow pattern is observed. We emphasize that the boundaries between the flow types are generally rather blurred, and this blurring increases a little as the Gaussian spread of input $k_0$ values is increased. Nonetheless, the plane divides into the regions shown, with the bold line marking roughly the locus of the equilibrium spin period in each case, as derived in Paper I. Clearly this marks the boundary between accretion flow types that will generally spin up the WD (streams) and accretion flow types that will generally spin down the WD (propellers). Broadly speaking, if an asynchronous mCV finds itself in a region of parameter space where it is fed by a stream, this will spin up the white dwarf and so shift it downward in the plane of Figure 1 toward the equilibrium line. Similarly, if an asynchronous mCV finds itself in a region of parameter space where the flow takes the form of a propeller, this will spin down the white dwarf and so shift it upward in the plane of Figure 1, again toward
the equilibrium line. We note that the accretion flow in the (possibly) magnetic system WZ Sge was modeled by Matthews et al. (2007) who derived a ringlike flow with a strong magnetic propeller in that case. This system contains a rapidly spinning white dwarf \((P_{\text{spin}} = 28 \text{ s})\) and shows that other solutions are possible in non-equilibrium situations such as this.

We note that the disk- and ringlike flows we see can each maintain the white dwarf close to spin equilibrium through a combination of accretion and ejection of material. As noted in Paper I, at equilibrium in the disk- and ringlike flows, angular momentum from the WD is passed back to the accreting material, some of which is lost from the outer edge of the ring or disk to maintain equilibrium. Elsewhere in the parameter space at equilibrium, a stream-propeller combination is seen, which we have previously referred to as a “weak propeller.” As shown in Figure 2, close to the stream-disk-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 that is magnetically propelled away from the WD. This, after all, is the definition of the equilibrium spin period. Hence, if real IPs sit at their equilibria they will exhibit accretion flows that are disk-, stream-, or ringlike, each with a component of the flow that is propelled away.

As can be seen in Figure 1, both triple points move to smaller magnetic moments as the orbital period decreases. However, for this mass ratio, the triple points occur at the same spin-to-orbital—period ratio at all orbital periods. In particular, the lower triple point is always close to \(P_{\text{spin}} / P_{\text{orb}} \approx 0.1\), while the upper triple point is always close to \(P_{\text{spin}} / P_{\text{orb}} \approx 0.6\). Hence, for a mass ratio of 0.5, if IPs are accreting at their equilibrium spin rates, those with \(P_{\text{spin}} / P_{\text{orb}} \approx 0.1\) will be disklike, those with \(0.1 \leq P_{\text{spin}} / P_{\text{orb}} \leq 0.6\) will be streamlike, and those with \(P_{\text{spin}} / P_{\text{orb}} \approx 0.6\) will be ringlike. Equilibrium is not possible for \(P_{\text{spin}} / P_{\text{orb}} \approx 0.6\), until a system reaches synchronism (and is therefore a polar, exhibiting stream-fed accretion once more). Details of the synchronization condition are given in Paper I.

3.2. Changing the Range of Plasma Density

Changing the spread in the input \(k_0\) value mimics changing the range of plasma density throughout the flow. For the simulations described above, the \(k_0\) values had a Gaussian distribution with a standard deviation of 1% of the mean value. Increasing this width to 10% or 100% results in the changes to the flow shown in Figure 3. These simulations each correspond to a system with \(P_{\text{orb}} = 4 \text{ hr}\) and \(q = 0.5\) and sit in the four regions of the \(P_{\text{spin}} / P_{\text{orb}}\) versus \(\mu_1\) plane identified above. In this case, the disklike flow corresponds to a magnetic moment of \(\approx 10^{33} \text{ G cm}^3\).
and a spin period of 1000 s, the streamlike flow to $\sim 10^{34}$ G cm$^{-3}$ and 5000 s, the propeller-like flow to $\sim 10^{35}$ G cm$^{-3}$ and 1000 s, and the ringlike flow to $\sim 2 \times 10^{36}$ G cm$^{-2}$ and 5000 s. As can be seen, the four types of flow are still readily classified, and the effect of broadening the range of plasma densities in each model is minimal.

3.3. Changing the Mass Ratio

Changing the mass ratio of the stars in the system changes where the equilibrium spin period occurs. Figure 4 shows representative diagrams for mass ratios of $q = 0.2, 0.5,$ and 0.9 for the case of a 4 hr orbital period. The same pattern of accretion flow behaviors is seen, but the triple points move to larger $P_{\text{spin}}/P_{\text{orb}}$ ratios and larger WD magnetic moments as the mass ratio decreases.

King & Wynn (1999) noted that mCVs have an equilibrium condition specified by $R_{\text{co}} \sim R_{\text{circ}}$. Here $R_{\text{co}}$ is the corotation radius, namely, that at which matter in local Keplerian rotation corotates with the magnetic field of the white dwarf, and $R_{\text{circ}}$ is the circularization radius, namely, that at which the specific angular momentum equals that of matter at the inner Lagrangian point. This, in turn, yields the condition

$$\frac{P_{\text{spin}}}{P_{\text{orb}}} \sim (1 + q)^2 (0.500 - 0.227 \log q)^6. \quad (3)$$

We identify this equilibrium with the lower triple point in Figures 1 and 4. For the three mass ratios examined here (i.e., $q = 0.2, 0.5,$ and 0.9), equation (3) predicts spin-to-orbital–period ratios of 0.118, 0.076, and 0.064, respectively. From our simulations, the triple points are at spin-to-orbital–period ratios of 0.69, 0.56, and 0.49. The slightly higher ratios observed probably reflect the fact that we observe ringlike structures to form just outside the WD’s Roche lobe, rather than at the edge of the lobe itself.

4. DISCUSSION

4.1. The Observed Distribution of Intermediate Polars

Figure 5 shows the distribution of currently known mCVs in the $P_{\text{spin}}$ versus $P_{\text{orb}}$ plane. The diagonal lines represent loci of constant spin-to-orbital–period ratio corresponding to the triple points at each of three mass ratio values. They therefore 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-disk-propeller triple points for mass ratios of 0.2, 0.5, and 0.9 indicate where disklike flows can occur; regions between any of these three lines and the three lines corresponding to the stream-ring-propeller triple points for mass ratios of 0.2, 0.5, and 0.9 indicate where streamlike flows can occur; and the region around these upper three lines indicate where ringlike flows will be most likely to occur.

As can be seen, at least half of the IPs cluster around the region where the spin-to-orbit–period ratio is in the range $0.05 \lesssim \frac{P_{\text{spin}}}{P_{\text{orb}}} \lesssim 0.15$, which characterizes the stream-disk-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 that resemble the combination disk-stream-propeller–like flow shown in the bottom center panel of Figure 2.

There is a growing number of “EX Hya–like” systems below a 2 hr orbital period. Many of these (e.g., SDSS J233226.61+05050.5 [Southworth et al. 2006], SDSS J23325.92+15222.1 [Southworth et al. 2007], DW Cnc [Patterson et al. 2004], V1025 Cen [Heller et al. 2002], as well as EX Hya itself) have high $P_{\text{spin}}/P_{\text{orb}}$ ratios in the range 0.4–0.7. As noted in Paper I, they are likely to be characterized by ringlike accretion if they are at equilibrium. We note that this suggestion has recently received considerable support from the spectroscopic observations of EX Hya presented by Mhlahlo et al. (2007). The velocities they observed (in the range $500–600 \text{ km s}^{-1}$) suggested that in this system material circulates the WD near to its Roche lobe and that accretion curtains are fed from a ring at this radius. This is exactly as predicted by our simulations.

Finally, the systems at very small $P_{\text{spin}}/P_{\text{orb}}$ ratios ($\lesssim 0.01$) are likely to be either disklike accretors or, if they are out of equilibrium like AE Aqr, strong magnetic propellers.
Given that there are likely to be roughly equal numbers of magnetic CVs per decade of magnetic field strength (as derived in Paper I), we can comment on the expected distribution of accretion flows among the observed population of IPs. Examining the distribution of accretion flow types in Figure 1, and assuming that all IPs are close to their spin equilibria at all times, we can expect there to be relatively more disklike accretors at long orbital periods and relatively more ringlike accretors at short orbital periods. The number of streamlike accretors is likely to be roughly constant at all orbital periods, as the region between the two triple points occupies about one and a half decades of magnetic moment in each panel of Figure 1.

4.2. The Evolution of Intermediate Polars

The observed distribution of IPs in the spin-period–orbital-period plane is a result of observing systems with a range of magnetic field strengths at different stages in their evolution. Assuming that they remain close to their equilibrium spin periods at all times, we can investigate how the observed distribution may be understood in terms of our results.

As IPs evolve, like all CVs, their mass ratio \( q = M_2/M_1 \) will decrease and they will move to shorter orbital periods as they lose angular momentum via a combination of magnetic braking and gravitational radiation. As a system evolves in this way, if the magnetic locking torque \( \propto \mu_1 \mu_2 / a^3 \) exceeds the accretion torque, it may synchronize and emerge as a polar. As noted in Paper I, the reason we see several intermediate polars at short orbital periods may be because their secondary stars have weak magnetic field strengths and so the magnetic locking torque is ineffective. Alternatively, the magnetic fields of the two stars may be misaligned in some way so as to minimize the effectiveness of this mechanism.

In order to investigate the variation in spin period and accretion flow as intermediate polars evolve, we took a typical theoretical evolutionary track of a cataclysmic variable, and followed this as it evolves to the orbital period minimum. In this evolutionary track, the WD had a constant mass of 1.0 M\(_\odot\) and the mass ratio decreased from \( q = 1.18 \) at \( P_{\text{orb}} = 9 \) hr to \( q = 0.11 \) at \( P_{\text{orb}} = 80 \) minutes. The mass accretion rate at each instant was determined from the evolutionary model. We ran accretion flow simulations for three different WD magnetic moments, namely, \( \mu_1 = 10^{32} \) G cm\(^3\) (i.e., \( B_{\text{WD}} = 0.6 \) MG), \( \mu_1 = 10^{33} \) G cm\(^3\) (i.e., \( B_{\text{WD}} = 6 \) MG), and \( \mu_1 = 10^{34} \) G cm\(^3\) (i.e., \( B_{\text{WD}} = 60 \) MG). For each field value, we determined the equilibrium spin period of the white dwarf, following the same method as the one used in Paper I, at a range of orbital periods along the evolutionary track.

The results of this, assuming that the systems under study do not synchronize, are shown in Figure 6. In order to maintain spin equilibrium as a system evolves to shorter orbital periods, the WD spin period will generally change in the manner shown. Note that since both the mass ratio and orbital period of the system vary continuously as the system evolves, the progress of the system cannot be easily tracked across the panels of Figure 1 or 4. In particular, since a decrease in orbital period causes the triple points to move to smaller magnetic moments, while a decrease in mass ratio causes the triple points to move to larger magnetic moments, the behavior of a given system is not easy to predict. Nevertheless, it is apparent from our simulations that as systems evolve, their spin-to-orbital–period ratios will generally increase and their accretion flows will become less disklike and more streamlike. By the time they have crossed the period gap, the accretion flows are likely to be ringlike, and systems (if not synchronized) will appear similar to EX Hya with a large spin-to-orbital–period ratio. As noted above, this has

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**Fig. 5.** Known mCVs distributed throughout \( P_{\text{spin}} \) vs. \( P_{\text{orb}} \) parameter space. Polars are indicated by triangles, and IPs by squares. The lower set of three diagonal lines corresponds to the spin-to-orbital–period ratio of the stream-disk-propeller triple point at mass ratios of 0.2, 0.5, and 0.9 (top to bottom). The top set of three diagonal lines corresponds to the stream-ring-propeller triple point for the same mass ratios.
been supported by the recent observations of EX Hya presented by Mhlahlo et al. (2007), which show evidence for a ringlike accretion flow. Furthermore, the growing number of systems discovered with high spin-to-orbital–period ratios at short orbital periods, as noted earlier, provides additional support for the picture we have outlined.

We also note that Cumming (2002) has suggested that the relatively high accretion rates in IPs may overcome ohmic diffusion, such that magnetic flux is advected into the interior of the white dwarf, reducing the surface magnetic field strength. This effective burying of the WD magnetic field would make IPs appear less magnetic than they really are. Under this scenario, when IPs emerge below the period gap after magnetic braking has presumably turned off, their accretion rates will be substantially lower, and their “true” magnetic field strengths might be expected to emerge. With a higher effective magnetic moment, at a shorter orbital period, systems will be in spin equilibrium farther to the right along the tracks in Figure 1 or 4, thus making a ringlike accretion flow even more likely for those systems that have not synchronized to become polars. In terms of Figure 6, one can imagine a system jumping from a lower magnetic field track to one corresponding to a higher magnetic field strength, as it emerges below an orbital period of 2 hr. However, we also note that Cumming’s suggestion, which was extrapolated from the case of accreting neutron stars, must be treated with caution, as the timescale of the Rayleigh-Taylor instability in the upper layers of an accreting WD differs substantially from that in neutron stars (Romani 1990). This may mean that the flows in WDs are not so easily buried after all. Furthermore, nova outbursts in accreting WDs will clear away much of the accreted layer, thus helping to restore the field of the WD.

5. CONCLUSIONS

Using a three-dimensional particle hydrodynamical model of magnetic accretion, we have demonstrated that broadly four types of accretion flow are possible in mCVs: disks, streams, rings, and propellers. We have shown that the equilibrium spin periods in asynchronous mCVs, for a given orbital period and magnetic moment, occur where the flow changes from a type characterized by spin up (i.e., streamlike) to one characterized by spin down (i.e., propeller-like). As a result, the plane of WD spin period versus WD magnetic moment divides into four regions, one for each type of accretion flow, and contains a pair of triple points at which stream-disk-propeller and stream-ring-propeller flows coexist. The first of these corresponds to when the corotation radius is equal to the circularization radius, and the second is when the corotation radius is equal to the distance from white dwarf to the L1 point. Changing the orbital period does not alter the spin-to-orbital–period ratios at which these triple points occur, although they do move to smaller WD magnetic moments as the orbital period decreases. If IPs are accreting at their equilibrium spin rates, then for a mass ratio of 0.5, those with $P_{\text{spin}}/P_{\text{orb}} \leq 0.1$ will be disklike, those with $0.1 \leq P_{\text{spin}}/P_{\text{orb}} \leq 0.6$ will be streamlike, and those with $P_{\text{spin}}/P_{\text{orb}} \sim 0.6$ will be ringlike. In each case, at equilibrium some material is also expelled away from the system to maintain angular momentum balance. Decreasing the mass ratio increases the $P_{\text{spin}}/P_{\text{orb}}$ ratio at the stream-disk-propeller and stream-ring-propeller triple points and also increases the WD magnetic moments at which they occur.

At long orbital periods dislikelike accretion flows are likely to be predominant, while at short orbital periods the number of systems displaying ringlike accretion flows will increase. The relative number of systems displaying streamlike accretion flows is predicted to be roughly constant at all orbital periods. As IPs evolve to shorter orbital periods and smaller mass ratios, in order to maintain spin equilibrium their spin-to-orbital–period ratios will generally increase. Those systems at short orbital periods that avoid synchronization are likely to appear similar to EX Hya, with a large spin-to-orbital–period ratio and a ringlike accretion flow, as recently seen by Mhlahlo et al. (2007).

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