MASS AND ANGULAR MOMENTUM FLOWS IN MAGNETIC CVS

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Abstract. I review recent progress in understanding the accretion geometry and angular momentum flows in magnetic CVs. The recent discovery that AE Aqr is an ejector demonstrates that the criterion for disc formation depends on the spin rate of the white dwarf, in addition to the strength of its magnetic field. It seems likely that AE Aqr represents one phase of a cyclic evolution followed by magnetic CVs. An important consequence is that an observed white dwarf spin rate is not uniquely determined by current properties of the system (e.g. magnetic field and instantaneous accretion rate), but also by its history.

1. Introduction

Among all CVs, magnetic systems have a particular interest because one can directly measure the white dwarf spin and thus make statements about angular momentum transport within the binary. Accordingly, one of the main goals in studying these systems is to explain their observed spin rates in terms of other properties. The fact that no convincing explanation currently exists shows that present theories of the angular momentum flows in these binaries are deficient. This is hardly surprising, given the many idealizations that these theories are forced to adopt in order to give tractable results. These simplifying assumptions may include those of infinite conductivity, flow along field lines, or other ingredients. At bottom however, it appears that the most fundamental of these is the (often implicit) assumption that the accretion flow is very smooth, and thus homogeneously penetrated by the magnetic field. In fact there is ample observational evidence to the contrary; I shall mention here just three examples of such evidence, but there are many more.

A. Evans and J. H. Wood (eds.), Cataclysmic Variables and Related Objects, 153–160.

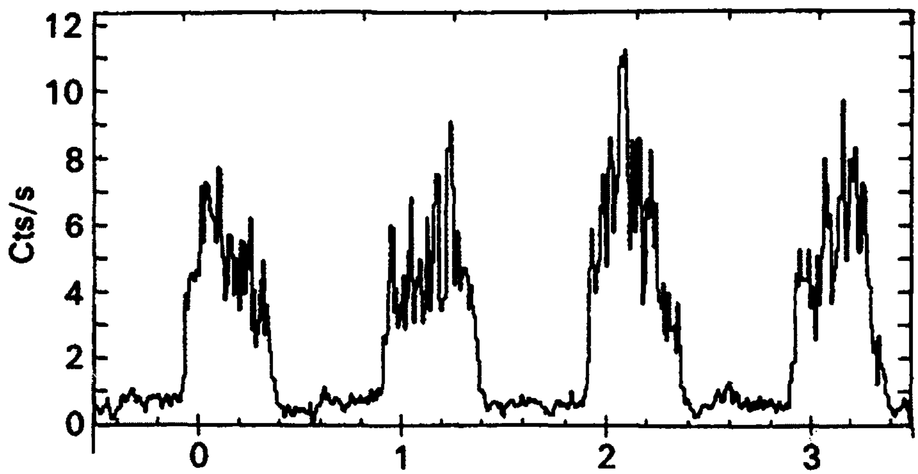

Figure 1. Soft X-ray light curve of AM Her in an anomalous state (Heise et al. 1985).

X–ray light curves: these are strikingly noisy in both non-synchronous and synchronous systems (cf. Fig. 1). In the so-called anomalous states of the latter one can directly simulate the light curves as the arrival of rather small numbers ($\sim$ 15) of blobs of gas at the accretion region (Hameury & King 1988).

X-ray/IR dips: Fig. 2 shows an observation of the synchronously-rotating system EF Eri through an X-ray dip. These dips have long been understood (King & Williams 1985) as photoelectric absorption in the accretion stream as it crosses the line of sight to the accretion region, once per orbital period in synchronous systems (similar dips are seen in the *spin* cycle of the non-synchronous system PQ Gem). The accompanying IR dips were supposed by King & Williams (1985) to result from free-free absorption in the stream, as a homogeneous stream capable of absorbing the X-rays should give such an effect. Yet detailed observation in the J and K infrared bands does not show the expected λ^2 wavelength dependence of this absorption: the process appears to be 'grey'. The explanation (Watson et al. 1989) is that the gas stream is not the simple homogeneous structure envisaged by King & Williams (1985) and subsequent authors, but contains dense filaments or blobs whose optical depths are very large, so that they are effectively opaque. The material between these blobs is diffuse and thus

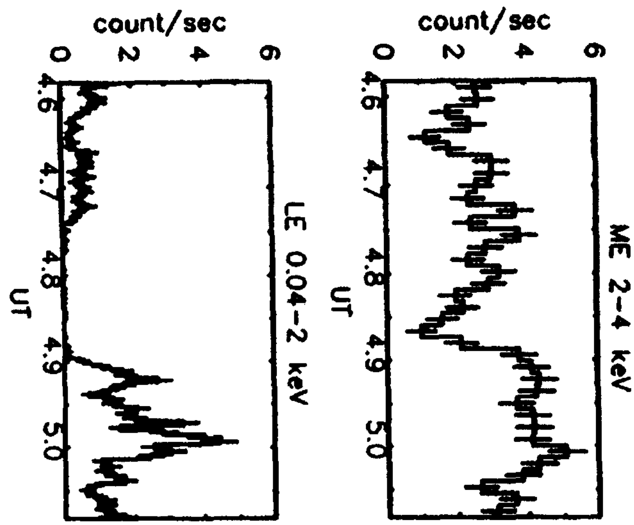

Figure 2. Profiles of an absorption dip in EF Eri in the soft X-ray (LE: 0.04. . . 2 keV) and hard X-ray (ME: 2. . . 4 keV) bands (Watson et al. 1989).

transparent, so that the opacity of the stream is essentially geometrical, i.e. given by the relative area filled by the dense blobs as seen in projection.

The soft X-ray excess: It is now well established that most of the luminosity of the synchronous systems emerges at soft X-ray energies; a similar picture may well be emerging for the non-synchronous systems. The commonly-accepted explanation is that the accretion is mainly in the form of separated blobs of gas, which are able to penetrate the white dwarf photosphere before releasing their infall energy to radiation.

All this evidence suggests that the accretion flow in magnetic CVs is very inhomogeneous. This is of fundamental importance in understanding the gas-field interaction, because the length-scale, l, of a gas element controls the time-scale for the magnetic field to diffuse into it as

$$t_{\rm diff} = l^2 \sigma, \tag{1}$$

where σ is the conductivity. The gas leaving the secondary star at the inner Lagrange point is probably not threaded by the white dwarf magnetic field, so if the flow is in the form of large gas blobs it is likely that these will behave diamagnetically. This is in direct contrast to many theoretical treatments which assume that the gas will flow along field lines as soon as the magnetic stresses ($\sim B^2/8\pi$) exceed material ones ($\sim \rho v^2$).

2. Inhomogeneous diamagnetic accretion.

Of course an inhomogeneous flow is more complicated than a smooth one; we might then think that the description of accretion flows in magnetic CVs should be even more complex than current MHD treatments. However, it appears that a rather simple phenomenological treatment of the inhomogeneous case is possible. Arons & Lea (1976) already suggested that one should treat the interactions of diamagnetic blobs with the field through a surface drag term. Drell, Foley & Ruderman (1965) showed that the drag time-scale is

$$t_{\rm drag} = \frac{c_{\rm A} m}{B^2 l^2} \qquad (2)$$

for a blob of mass m and length-scale l. Here $c_{\rm A}$ is the Alfvén speed in the plasma between the blobs (in practice this is usually very diffuse, so that $c_{\rm A} \sim c$). This drag will predominate over viscous interactions between blobs if $t_{\rm drag}$ is smaller than the viscous time-scale, $t_{\rm visc}$. For the neutron star systems studied by Arons & Lea (1976) the drag force is probably never important, as the gas passes rapidly from a regime with $t_{\rm visc} < t_{\rm drag}$ to one in which the blobs are quickly penetrated by the field and flow along it. For typical conditions in magnetic CVs however, King (1993) showed that

$$t_{\rm dyn} \lesssim t_{\rm drag} < t_{\rm visc} \qquad (3)$$

where $t_{\rm dyn}$ is the dynamical ($\sim$ free-fall, Keplerian) time-scale of a gas blob. Under these conditions the gas blobs will behave as independent particles influenced by gravity and the drag force. Per unit mass, this can be written as

$$\mathbf{f}_{\rm drag} = k[\mathbf{v} - \mathbf{v}(\text{field})]_{\perp}, \qquad (4)$$

where $k = t_{\rm drag}^{-1}$, $\mathbf{v}, \mathbf{v}(\text{field})$ are the blob and field velocities, and the suffix on the square bracket denotes that only the component of this velocity difference perpendicular to field lines is taken into account. The form of (4) immediately shows that if k becomes large, i.e. $t_{\rm drag}$ becomes small compared with $t_{\rm dyn}$, the blobs will try to reduce the square bracket to zero. Thus (4) naturally describes the tendency of gas to flow along field lines in cases where the field becomes very strong. Of course we do not in general have easy ways of discovering the values of the quantities entering (2), so in practice k is usually regarded as a parameter rather like the viscosity parameter α used in accretion disc theory. On quite general grounds we expect k to fall off with radial distance, r, from the white dwarf, probably

https://doi.org/10.1017/S0252921100038495 Published online by Cambridge University Press

as $k \sim r^{-2}$. However the normalization inevitably differs for different blobs [cf. (2)], so it is important in simulations to allow a range of normalizations.

The simple form of (4) makes it extremely easy to add it to particle codes. However, because the blobs are almost independent of each other, a simple analytic treatment of the effects of the force (4) can be given (King 1993). Clearly the blobs can exchange their orbital energies and angular momenta with the spinning white dwarf by interacting with its field through (4). The most important result is the existence of a critical specific orbital energy

$$E_{\rm E} \simeq -\frac{\omega J}{2} \tag{5}$$

for the blobs, where J is the specific angular momentum and ω the white dwarf spin rate. Blobs with $E > E_{\rm E}$ gain energy by interacting with the field, while those with $E < E_{\rm E}$ lose energy. For fixed ω, low-energy blobs lose more energy to the white dwarf and ultimately accrete to it, while high-energy blobs ultimately gain enough energy from the white dwarf that their E becomes positive and they are expelled. Numerical simulations using (4) in a particle code (Wynn & King 1995) qualitatively show precisely this behaviour. Often the expelled blobs are simply caught by the secondary star's gravity and re-accreted rather than being expelled to infinity.

We can use (5) to understand the equilibrium spin rate of a white dwarf accreting in this way. Clearly if ω is close to zero $E_{\rm E}$ will be near zero and thus much larger than the typical value E_1 for blobs leaving the inner Lagrange point L_1 with specific angular momentum J_1. Thus all blobs will be accreted, spinning up the white dwarf, raising ω and lowering $E_{\rm E}$. The process continues until $E_{\rm E}$ becomes of order the typical specific orbital energy of a blob at L_1: clearly ω cannot increase significantly beyond the value $\omega_{\rm eq} \simeq -2E_1/J_1$ since no accretion would be possible. This defines an equilibrium spin rate which is proportional to the orbital rotation rate, the constant of proportionality depending somewhat on the binary mass ratio. For typical parameters one finds the connection

$$P_{\rm spin} \simeq 0.1 P_{\rm orb} \tag{6}$$

between spin and orbital periods (King 1993; Wynn & King 1995).

As the white dwarf is at least potentially a sink of orbital angular momentum, thus tending to shrink the binary, there is the real possibility of dynamical instability, i.e. that the Roche lobe could shrink faster than the stellar radius, causing very rapid mass transfer. Wynn & King (1995) show that spin-up to the 'discless' or 'intermediate polar' (IP) equilibrium (6) always involves dynamical instability, and is therefore likely to be very rapid. Systems with spin periods longer than given by (6), such as EX Hya, thus presumably have accretion discs (spin-up via a disc is always stable, and therefore slow). By contrast, spin-*down* to (6) is always stable: further, once (6) is achieved it is stable, provided that the mass ratio $M_2/M_1 \lesssim 0.7$. Because of the connection $M_2 \sim 0.1 P_{\rm orb}({\rm h})\ {\rm M}_\odot$ this limits the orbital periods of systems accreting in this way to $P_{\rm orb} \lesssim 5$ h. It is also possible to have a perfectly stable system in which all of the mass transferred from the secondary is expelled and returned to it by the white dwarf, particularly if the drag coefficient, k, is large.

3. AE Aqr: an ejector system.

The ideas discussed above have recently received strong support from observations of AE Aqr. This magnetic CV has $P_{\rm orb} = 9.88\,{\rm h}$, $P_{\rm spin} = 33\,{\rm s}$. For many years it was straightforwardly interpreted in terms of a magnetic white dwarf accreting from an extensive accretion disc which was disrupted close to the white dwarf (e.g. Patterson 1994). Difficulties with this idea began with the discovery that the white dwarf is spinning down on a timescale of a few $\times 10^6$ yr (de Jager et al. 1994). The rapid spin rate means that the implied spin-down luminosity is $\sim 6\,10^{33}$ erg s^{-1}, far larger than the observed radiative output of the system. The true nature of AE Aqr is revealed by Doppler tomography performed by Welsh, Horne & Gomer (1996). This shows that, far from possessing a fully developed disc, AE Aqr is actually ejecting most of the matter being transferred from the secondary star. The tomograms show the unmistakable signature of matter being violently accelerated near the white dwarf and flung out of the system by centrifugal force. This is of course where most of the spin-down luminosity is going.

AE Aqr is thus a clear example of a magnetic CV spinning down and ejecting most of the mass transferred to it, just as envisaged in Sect. 2. Using the drag prescription (4) it is straightforward to reproduce the Doppler tomogram from particle simulations of the flow (Wynn & King 1995; Wynn, King & Horne 1995, 1996). These simulations also reproduce the observed spin-down rate. One can use the simulations to produce a pictorial representation of the system (Fig. 3).

The success of the simulations should not obscure the fact that it is extremely surprising that AE Aqr does not have a disc. Indeed in many ways one would regard it as the best *a priori* candidate for such a system. The short spin period must mean that the magnetic field is fairly weak ($\lesssim 10^6$ G), as otherwise the system could never have accreted and spun up to this period. Combined with this, the very long (for a CV) orbital period should make disc formation very easy, as the circularization radius is large, and one would imagine the magnetosphere to be very small, thus presenting no obstacle to the self-intersection of the gas stream and the

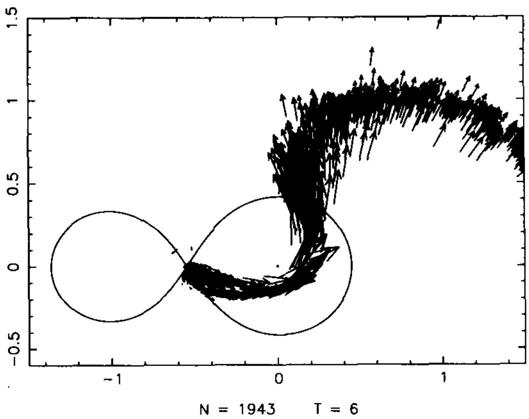

Figure 3. Simulated ejection stream in AE Aqr. The plot shows the Roche lobes of the primary and secondary, with orbital motion being in a clockwise direction. Inertial velocity vectors are plotted for each particle.

consequent disc formation. Yet this argument is clearly wrong. The reason is that the criterion for disc formation evidently depends not just on the magnetic field strength and the accretion rate, but also on the spin rate of the white dwarf. The form (4) of the drag force embodies precisely this connection, and the example of AE Aqr is powerful evidence for such a formulation.

4. What determines the spin rates of magnetic CVs?

The obvious question to ask is how AE Aqr ever got into its present state. The discussion above shows that it would have had no difficulty forming a disc if the spin rate were low. If this was true in the past, the disc would have spun the white dwarf up to $P_{\rm spin} \leq 33\,{\rm s}$ in about $10^7\,{\rm yr}$. Presumably as long as the disc remained stable, accretion could proceed quite normally. But if accretion was interrupted for a few viscous times, i.e. long enough for the disc to disappear (a few weeks at most), it is evident that it could not re-form. The system would thus have reached something like its present state. There are two possibilities for the future spin behaviour. One is that the white dwarf will spin all the way down to the equilibrium (6), i.e. with $P_{\rm spin} \sim 1\,{\rm h}$. A more likely eventuality is that the spin-down will proceed until the drag time-scale at the circularization radius becomes longer than the viscous time there, allowing a disc to re-form with $P_{\rm spin}$ much smaller than this. Disc accretion will spin the white dwarf up again, possibly to an equilibrium value ≤ 33 s, but any further interruption in mass transfer will allow the system to become an ejector once more. AE Aqr thus seems destined to spend its lifetime moving between disc accretion, ejection, and possibly the IP equilibrium (6), at essentially random intervals determined by the vagaries of the mass transfer rate. Something similar is clearly true for all magnetic CVs, depending on their precise parameters. The important result is that the current observed value of $P_{\rm spin}$ is not simply fixed by short-term conditions in the system, such as the relationship of the accretion rate to the white dwarf magnetic moment μ; on the contrary, we have seen that it must depend on the previous history of the system. The implicit belief in a simple relationship between $P_{\rm spin}, P_{\rm orb}$ and μ, which has characterized research in this field up to now, must be abandoned.

Acknowledgements. Much of the work reported here was performed with Graham Wynn. I thank him for many discussions, and much help in the preparation of this article.

References

Arons J., Lea S. M., 1976, Ap. J., **207**, 914
de Jager, O. C., Meintjes, P. J., O'Donoghue, D., Robinson, E. L., 1994, MNRAS, **267**, 577
Drell, S. D., Foley, H. M., Ruderman, M. A., 1965, J. Geophys. Res., **70**, 3131
Hameury, J.M., King, A.R., 1988, MNRAS, **235**, 433
Heise, J., Brinkman, A. C., Gronenschild, E., et al., 1985, A&A, **148**, L14
King, A. R., 1993, MNRAS, **261**, 144
King, A. R., Williams, G. A., 1985, MNRAS, **215**, 1P
Patterson J., 1994, PASP, **106**, 209
Watson, M. G., King A. R., Jones, M. H., Motch, C., 1989, MNRAS, **237**, 299
Welsh, W.F., Horne, K., Gomer, R., 1996, in preparation
Wynn, G. A., King, A. R., 1995, MNRAS, **275**, 9
Wynn, G. A., King, A. R., Horne, K., 1995, in "Magnetic Cataclysmic Variables", eds D. Buckley, B. Warner, ASP Conf. Ser. **85**, 196
Wynn, G. A., King, A. R., Horne, K., 1996, in preparation