ACCRETION DISC FORMATION IN INTERMEDIATE POLARS

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1. Introduction

The large-scale accretion flow in the intermediate polars (IPs) is still a matter of vigorous debate. It is known that the magnetic field of the white dwarf (WD) controls the accretion flow close to the surface, channeling the plasma onto the polecaps and giving rise to X-ray emission modulated at the WD spin period ($P_{\rm spin}$). After their discovery it was assumed that IPs were the WD analogues of the pulsing X-ray binaries, where a magnetic neutron star accretes from a disrupted accretion disc. However, a number of authors have pointed out that the criteria for disc formation in IPs are less certain than those for the X-ray binaries.

The simplest possible criterion for disc formation in a binary is that the accretion flow should be able to orbit freely about the primary star (see Frank, King & Raine 1991 for a review). In non-magnetic systems this is merely the condition that the minimum approach distance of the free stream ($R_{\rm min}$) should exceed the radius of the primary. The situation in magnetic systems is more complex, as the magnetic field of the primary presents an obstacle to the infalling accretion stream. In many treatments of IPs it is assumed that the plasma stream is able to orbit freely about the WD until the ram pressure of the stream is of the same order as the magnetic pressure $\rho v^2 \sim B^2/8\pi$, where ρ is the stream density, v the stream velocity and B the local magnetic field strength. This condition fixes the magnetospheric radius, $R_{\rm mag}$, inside which the magnetic field is assumed to thread the stream material and direct the accretion flow along the fieldlines. The criterion for disc formation in these treatments is then

$$R_{\rm min} > R_{\rm mag}. \tag{1}$$

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The radius $R_{\rm mag}$ is a difficult quantity to estimate in general, but is usually written as a fraction of the spherical Alfvén radius (eg. Frank, King & Raine 1991) such that $R_{\rm mag} \propto \mu^{4/7}\dot{M}^{-2/7}$, where μ is the magnetic moment of the white dwarf and $\dot{M}$ is the accretion rate.

If a disc forms, the WD will tend to spin up as it accretes the Keplerian angular momentum of material at the inner edge of the disc. An equilibrium spin period ($P_{\rm eq}$) will be reached at which the WD is able to centrifugally expel as much angular momentum as it accretes. This equilibrium spin period depends on the complex global interaction between the field and the accretion disc and, as yet, there remains no consensus on the actual spin evolution of the primary in the disc case. However a number of models (eg. Ghosh & Lamb 1979) predict that this equilibrium will occur when the co-rotation radius $R_{\rm co} = (GM_1P_{\rm spin}^2/4\pi^2)^{1/3}$, where the field lines move with the local Keplerian speed, is of order $R_{\rm mag}$. This gives $P_{\rm eq} \propto R_{\rm mag}^{3/2} \propto \mu^{6/7}\dot{M}^{-3/7}$, and leads to an equilibrium with

$$P_{\rm eq} \ll P_{\rm orb}, \tag{2}$$

in general, where $P_{\rm orb}$ is the orbital period of the binary.

2. Inhomogeneous, diamagnetic accretion in IPs

In contrast to the picture presented above, a recent treatment (King 1993; Wynn & King 1995; see also King 1996 for a review) considered the accretion flow in IPs to consist of a number of diamagnetic blobs. Applying the work of Arons & Lea (1980) and Drell, Foley & Ruderman (1965) to conditions typical of IPs, shows that the blobs orbit the WD and interact with the magnetic field via a surface drag force, which can be written, per unit mass, as

$$\mathbf{f}_{\rm drag} = -k\mathbf{v}_{\rm r}. \tag{3}$$

Here $\mathbf{v}_{\rm r}$ is the relative velocity between the field and the blob across the field lines, and $k \propto \mu^2(\rho_{\rm b}l_{\rm b})^{-1}$ is the drag coefficient, where $\rho_{\rm b}$ is the blob density and $l_{\rm b}$ is the blob length-scale. The blobs are able to exchange orbital energy and angular momentum with the field, allowing a particular blob to be accreted or ejected depending upon the WD spin rate (King 1993). So, in contrast to the previous treatment, $P_{\rm spin}$ has a direct influence on the dynamics of the plasma flow, and therefore must affect disc formation. The diamagnetic blob model predicts a longer $P_{\rm eq}$ than the disc equilibrium (2), with $P_{\rm eq} \sim 0.1P_{\rm orb}$ (King 1993; Wynn & King 1995), a position at which a number of IPs have been noted to cluster (eg. Barrett, O'Donoghue & Warner 1988).

A recent application of the diamagnetic blob model to the long period ($P_{\rm orb} = 9.88\,$h) cataclysmic variable AE Aqr, has shown this system to be

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in an ejector state (Wynn, King & Horne 1995). The observation that the rapidly spinning WD ($P_{\rm spin} = 33$ s) is spinning down with an implied spin down power exceeding the X-ray and UV luminosities (de Jager et al. 1994), as well as the unusual Doppler tomogram (Welsh, Horne & Gomer 1996) can be explained if the system is ejecting $\sim$ 99% of the mass overflowing the L_1 point. By independently fitting the simulated flow pattern with the tomogram and the observed and predicted spin down rates, it is possible to estimate μ and the mass overflow rate ($\dot{M}_{\rm ov}$) as

$$\begin{aligned} \mu &\sim 10^{32}(l_9\,\rho_{-8})^{1/2}\ {\rm G\,cm^3} \\ \dot{M}_{\rm ov} &\sim 5\,10^{17}\ {\rm g\,s^{-1}}, \end{aligned} \tag{4}$$

where ρ_{-8} is $\rho_{\rm b}$ in units of 10^{-8} g cm^{-3}, and l_9 is $l_{\rm b}$ in units of 10^9 cm. Note that the more recent $\dot{M}_{\rm ov}$ estimate presented here is higher than that of Wynn, King & Horne (1995).

3. Discussion: a possible accretion history for AE Aqr

A dramatic example of the differences between the treatments of the accretion flow in IPs outlined in Sect. 1 and 2, when considering the question of disc formation, can be illustrated by the following possible accretion history of AE Aqr.

If, at the onset of mass transfer, we assume AE Aqr to have an initial orbital period $\gtrsim 10$ h, and a μ and $\dot{M}$ in line with the estimates (4), it is possible to consider the disc formation criteria in both treatments discussed above. In the case of a homogeneous stream, ram and magnetic pressure balance leads us to condition (1). It is possible to estimate these radii as $R_{\rm mag} \sim 10^9$ cm, and $R_{\rm min} \sim 0.5 R_{\rm circ} \sim 10^{10}$ cm where $R_{\rm mag}$ is taken as half the spherical Alfvén radius, and $R_{\rm min}$ is calculated from the stream circularization radius $R_{\rm circ}$. From this we can see that condition (1) is satisfied and an accretion disc is expected to form. For the case of diamagnetic blob accretion we must further take into account the spin rate of the WD. It is probable that the initial $P_{\rm spin}$ of the WD was much longer than the current value of 33 s; if we consider $P_{\rm spin} \sim$ hours initially the combination of a low μ and $\mathbf{v}_{\rm r}$ in (3) (at $r \sim R_{\rm min}$) allows the blobs to orbit freely about the white dwarf. So again we expect the formation of an accretion disc at the onset of mass transfer.

Once the accretion disc has formed the WD will spin up to the disc $P_{\rm eq}$ as in (2). It is interesting to note that $P_{\rm eq} \simeq 33$ s gives an estimate of μ (cf. Ghosh & Lamb 1979, with a fastness parameter of unity) as $5\,10^{31} \lesssim \mu$ (in G cm^3) $\lesssim 3\,10^{32}$ for accretion rates in the range $10^{17} \lesssim \dot{M}$ (in g s^{-1}) $\lesssim 10^{18}$. This independent estimate is encouraging in that it is in agreement with the diamagnetic blob model result (4).

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Once the WD has been spun up, the evolution of the system depends on short-term fluctuations of $\dot{M}$. If we assume that $\dot{M}$ drops to a value low enough to allow the accretion disc to be eroded (typically only a few weeks), then on the resumption of mass transfer the accretion flow will now interact with a rapidly rotating magnetosphere ($P_{\rm spin} \sim 33$ s). As far as the pressure balance condition is concerned the situation is unchanged if $\dot{M}$ increases to its previous value, and an accretion disc reforms (in fact we would expect accretion disc formation even for much lower $\dot{M} \lesssim 10^{16}$ g s^{-1}). However, in the framework of the diamagnetic model, $\mathbf{f}_{\rm drag}$ has increased by 2...3 orders of magnitude because of the increased value of $\mathbf{v}_{\rm r}$, which is now governed by $P_{\rm spin}$. In this case we expect the blobs to gain angular momentum and to be rapidly expelled from the system as they approach $R_{\rm min}$, as confirmed by numerical simulations (cf. Wynn, King & Horne 1995).

So it can be seen that the two prescriptions for the disc formation criteria in IPs give very different results for the same μ and $\dot{M}$; the difference being that $P_{\rm spin}$ plays a central role in determining the dynamics of the plasma flow when the flow is inhomogeneous and diamagnetic. Under the homogeneous stream treatment outlined in Sect. 1, AE Aqr would be an ideal system for an accretion disc to form, having long $P_{\rm orb}$ (and thus large $R_{\rm min}$) and low μ. However, once a disc has formed and spun up the WD, any interruption of mass transfer causes the system to enter an ejector state, as currently observed. So it is probable that the IPs are a mixed bag of systems, which show disc accretion, blob accretion and ejection phases determined by μ and the evolution of $\dot{M}$ and $P_{\rm spin}$ in the system. This fact may well account for the failure of any single model to explain the observational properties of IPs (cf. Hellier 1996).

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