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Properties of Magnetic Accretion Curtains: Magnetic CVs and T Tauri Stars

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Abstract. In this paper, I present a review on the properties of accretion curtains in magnetic Cataclysmic Variables and T Tauri stars. In particular, I will show that magnetically confined accretion curtains that are heated by hard, soft x-rays or UV radiation originating from the accretion shocks at the surface of the accreting star can give rise to the observed complex emission line profiles.

1. Introduction

The main aim of this review is to discuss the properties of magnetically channelled material in two very distinct classes of objects: the magnetic Cataclysmic Variables (mCVs) and the T Tauri stars.

The Intermediate Polars (IPs) and the AM Herculis systems (AM Hers) form a subclass of cataclysmic variables in which the white dwarf is highly magnetic. In the more strongly magnetic (7–60 MegaGauss) and synchronously rotating AM Hers, the accreting material is channelled along the field lines towards the white dwarf without the formation of the usual CV accretion disc. In the less magnetic ($\lesssim 7$ MG) and asynchronous IPs, accretion usually occurs via a disc which is truncated in its inner regions by the magnetic field, except in some of the most strongly magnetic IPs where accretion may occur directly from the stream (e.g. RE 0751+14, Piirola et al. 1993; and RX J1712-242, Buckley et al. 1995).

The spectra of mCVs are characterized by prominent emission lines which are highly modulated at the spin period of the white dwarf. The line profiles are generally very broad and complex, characterised by velocities that are too large to be associated with the binary motion and must therefore originate in the accretion flow close to the white dwarf.

Ferrario, et al. (1993) and Ferrario & Wickramasinghe (1993) argued that the large velocities observed in mCVs originate from magnetically confined accretion curtains. In particular, in disced IPs these curtains are formed by material that couples onto field lines at the inner edge of an accretion disc.

In contrast to the mCVs, where the accreting object is the end product of the stellar evolution of a low-mass star, the T Tauri stars are fully convective, pre-main sequence stars of about one solar mass which accrete matter from a protoplanetary accretion disc. The strong magnetic activities observed in T Tauri stars are believed to originate from fields of about 100 – 1,000 Gauss (Hartmann et al. 1982; Lago 1984). The observed line profiles are very broad and, similarly to the disced IPs, can be explained by large infall velocities from matter frozen on to magnetic field lines and funnelled towards the central star (e.g. Königl 1991; Calvet, & Hartmann 1992; Guenther & Hessman 1993; Hartmann et al. 1994).

2. Models for Accretion Curtains

In this section, I will draw a parallel between magnetic accretion in disced IPs and T Tauri stars.

In IPs, the radiation consists of two main components. The first originates from matter that flows towards the white dwarf via an accretion disc and is then chanelled along magnetic field lines to impact onto the white dwarf's surface. The second comes from matter at the impact regions and from the white dwarf itself. If we indicate with M and R the mass and radius of the white dwarf, then the regions of impact are heated to shock temperatures of the order of

$$T_s = 3.0 \times 10^8 \left(\frac{M}{0.8M_\odot}\right)\left(\frac{10^9\ \mathrm{cm}}{R}\right) \quad \mathrm{K}$$

and produce the observed thermal bremsstrahlung hard X-ray emission. If we assume that roughly half of the hard X-ray photons are directed downward and thermalise in the stellar photosphere, then a soft X-ray emission component of black body origin is also expected in IPs with an estimated temperature of

$$T_e = 2.5 \times 10^5 \left(\frac{\dot{M}}{10^{16}\ \mathrm{g\ s^{-1}}}\right)^{\frac{1}{4}}\left(\frac{10^{-3}}{f}\right)^{\frac{1}{4}}\left(\frac{M}{0.8M_\odot}\right)^{\frac{1}{4}}\left(\frac{10^9\ \mathrm{cm}}{R}\right)^{\frac{3}{4}} \quad \mathrm{K}$$

where $\dot{M}$ is the mass accretion rate and f is the fractional area of the star which is heated by the hard X-rays.

If the dipole axis is not aligned with the rotation axis of the system, the hot arc-like emission regions will give rise to the observed X-ray to optical periodic oscillations.

Similarly in T Tauri stars, the accreting material is also expected to be shocked to temperatures

$$T_s = 1.7 \times 10^6 \left(\frac{M}{0.8M_\odot}\right)\left(\frac{2.5R_\odot}{R}\right) \quad \mathrm{K.}$$

And a black body component of temperature

$$T_e = 1.2 \times 10^4 \left(\frac{\dot{M}}{10^{19}\mathrm{gs^{-1}}}\right)^{\frac{1}{4}}\left(\frac{10^{-2}}{f}\right)^{\frac{1}{4}}\left(\frac{M}{0.8M_\odot}\right)^{\frac{1}{4}}\left(\frac{2.5R_\odot\ \mathrm{cm}}{R}\right)^{\frac{3}{4}} \quad \mathrm{K}$$

is expected. In this picture, the emission from the accretion shocks in T Tauri stars is also expected to exhibit periodic oscillations. This can explain the 8.5 day period in the light curve of objects such as DF Tau (Bouvier & Bertout 1989).

Given a certain stellar angular velocity Ω, if we assume that the central star is in spin equilibrium with the inner edge of the accretion disc R_{in}, then for typical parameters found in IPs we have:

$$B = 9.5 \times 10^5 \left(\frac{M}{0.8M_\odot}\right)^{\frac{5}{6}} \left(\frac{\dot{M}}{10^{17}\mathrm{gs}^{-1}}\right)^{\frac{1}{2}} \left(\frac{R}{10^9\mathrm{cm}}\right)^{-3} \left(\frac{\Omega}{10^{-2}}\right)^{-\frac{7}{6}} \quad \mathrm{Gauss}$$

and

$$R_{in} = 5.0 \times 10^9 \left(\frac{M}{0.8M_\odot}\right)^{\frac{1}{3}} \left(\frac{\Omega}{10^{-2}}\right)^{-\frac{2}{3}} \quad \mathrm{cm}$$

where B is the polar field strength for an assumed dipolar field distribution. These estimates are consistent with the observed properties of IPs. The absence of circular polarisation in most IPs excludes the presence of fields greater than a few MegaGauss (Wickramasinghe et al. 1991). Likewise, the inner coupling radii agree with the values deduced through emission line modelling of disced IPs by Ferrario et al. (1993) and Ferrario & Wickramasinghe (1993).

If we now apply similar considerations to accretion on to T Tauri stars, we find:

$$B = 10^3 \left(\frac{M}{0.8M_\odot}\right)^{\frac{5}{6}} \left(\frac{\dot{M}}{10^{19}\mathrm{gs}^{-1}}\right)^{\frac{1}{2}} \left(\frac{R}{2.5\mathrm{R}_\odot}\right)^{-3} \left(\frac{\Omega}{1.7 \times 10^{-5}}\right)^{-\frac{7}{6}} \quad \mathrm{Gauss}$$

and

$$R_{in} = 3.6 \times 10^{11} \left(\frac{M}{0.8M_\odot}\right)^{\frac{1}{3}} \left(\frac{\Omega}{1.7 \times 10^{-5}}\right)^{-\frac{2}{3}} \quad \mathrm{cm.}$$

The above field strength values agree with the Zeeman split line measurements of the T Tauri star RU Lup (Johnstone & Penstone 1986, 1987). Some indications from IR spectroscopy that the inner disc radius is greater than the stellar radius also point to the presence of truncated accretion discs (Hessman 1995).

A summary of the key accretion parameters in disced IPs and T Tauri stars is given in Table 1.

Table 1. Typical accretion parameters in disced IPs and T Tauri stars

Parameter	IPs	T Tauri stars
Magnetic field strength (Gauss)	$\sim 10^5 - 7 \times 10^6$	$\sim 10^2 - 10^3$
Accretion rate (g s^{-1})	$10^{16} - 10^{17}$	$10^{18} - 10^{19}$
Inner accretion radius	$\sim 6 - 9$ R_{wd}	$\sim 2 - 5$ R_*
Number density in curtain (cm^{-3})	$10^{13} - 10^{14}$	$10^{12} - 10^{13}$
Shock temperature (K)	few × 10^8	few × 10^6
Heated photosphere temperature (K)	few × 10^5	few × 10^4
Main heating mechanisms	Hard/Soft X-rays	Soft X-rays/UV

3. Properties of Accretion Curtains

Ferrario et al. (1993) and Ferrario & Wickramasinghe (1993) argued that the emission lines in disced IPs originate from two "accretion curtains", one above and the other below the orbital plane formed by material that couples onto field lines from a truncated accretion disc. Each of the curtains extend over 180° in magnetic (and rotational) longitude and consists of "downhill" field lines connecting the accretion disc to the surface of the white dwarf. They assumed that the inner edge of the accretion disc R_{in} and the size of the region over which the material threads on to the magnetic field lines, $\Delta R_{acc} = R_{out} - R_{in}$ are free parameters which are determined from fits to observational data. They showed that the size and location of the accretion regions dramatically change the values of the calculated radial velocity and velocity dispersion. In particular, as the distance of the accretion region from the star is increased, both the velocity and the velocity dispersion decrease since the emitting volume is shifted away from the white dwarf to regions of lower infall velocities. In addition, large values of R_{in} and R_{out} make the curtains extend to greater heights above and below the orbital plane so that a larger fraction of the curtain that is located below the accretion disc also becomes visible. As a result, the radial velocity averaged over the emitting volume decreases, while the velocity dispersion remains large (typically a few thousand km s^{-1}), in close agreement with the observations of most IPs.

Based on the above accretion pattern, Ferrario & Wickramasinghe (1993) presented detailed calculations of the thermal structure and Balmer line and optical continuum emission arising from accretion curtains in IPs. The gas was assumed to be in local thermodynamical equilibrium (LTE). The models showed that the flux of soft and hard X-rays that impinges on the curtains is sufficient to heat the gas to temperatures $\sim$ 10,000−40,000 K, necessary to produce strong Balmer lines. Typical line profiles obtained through these calculations are shown in Figure 1 at different spin phases (Ferrario 1995). The model corresponds to a magnetosphere intersecting the accretion disc between $R_{in} = 9R_{wd}$ and $R_{out} = 15R_{wd}$.

Similar work in the non-LTE regime was carried out by Hartmann et al. (1994) to explain the Balmer line profiles in T Tauri stars. The observed line profiles are broad with inflow velocities of a few hundred km s^{-1}. These values are inconsistent by several orders of magnitude with the small radial velocities predicted by boundary layer models. In their calculations, the emission line modelling suggested that the accretion disc is disrupted at several stellar radii from the central object and that the magnetosphere extends over several stellar radii above the stellar photosphere. In general, they found that their calculations were in good agreement with the observations of emission lines in T Tauri stars and could explain the complex line profiles of UY Aur and BP Tan. Examples of H_α line profiles from Hartmann et al. (1994) are shown in Figure 2. The models correspond to a magnetosphere with field lines intersecting the disc between $R_{in} = 4R_*$ and $R_{out} = 6R_*$ and viewed at different angles to the magnetic axis.

Although detailed calculations are not yet available for T Tauri stars, some conclusions may be drawn on the so-called "optical veiling" which is present in some of these objects. This effect consists of an additional featureless continuum which is modulated with the rotational period of the star and correlated with the

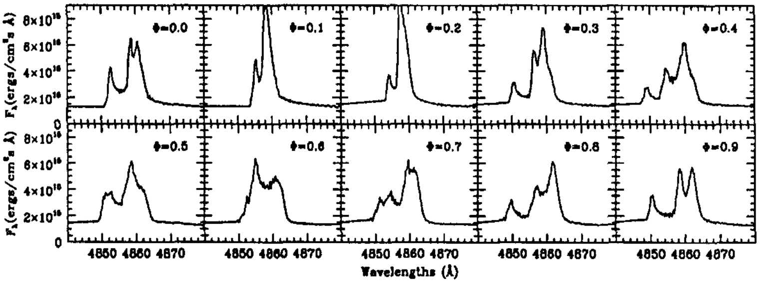

Figure 1. Hβ profile variations as a function of the spin cycle. The model corresponds to a magnetosphere intersecting the accretion disc between $R_{in} = 9R_{wd}$ and $R_{out} = 15R_{wd}$ (Ferrario 1995).

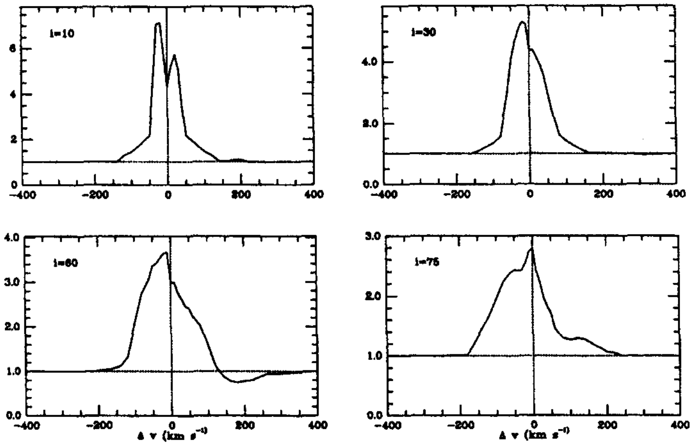

Figure 2. H$_\alpha$ line profiles for a magnetosphere with field lines coupling on to the disc between R_{in}=4R_* and R_{out}=6R_* (figure from Hartmann et al. 1994)

emission line strengths (Guenther & Hessman 1993). According to the accretion curtain model, such a continuum could arise either from the curtains themselves (as in the case of IPs) or from the accretion shocks on the stellar surface, or both.

4. Conclusions

Although mCVs and T Tauri stars are completely different astrophysical objects, they seem to share the same accretion pattern. Therefore, through the comparison of the accretion physics of mCVs and T Tauri stars as well as their accretion environment and their scaling properties (in terms of the balance between the gravitational and centrifugal forces and the magnetic field pressure), important inferences can be made regarding the interaction between matter and magnetic field and on mechanisms that drive the transfer of matter and angular momentum on to the central star.

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Discussion

A. Königl: In connection with your thermal structure calculations for magnetic accretion curtains in CVs, I would like to advertise the analogous calculations for T Tauri stars done by S. Martin (poster in this meeting). He found that adiabatic compression dominates the heating near the base of the column, whereas closer to the stellar surface the CaII and MgII ions act as a powerful thermostat that regulates the gas temperature.