MRI-DRIVEN X-RAY DISC CORONAE IN CATACLYSMIC VARIABLES

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ABSTRACT

A prediction of the magneto-rotational instability (MRI) model for angular momentum transport in accretion discs is that high-state discs should have X-ray coronae. This is because magnetic flux is buoyant in the disc, and floats to high scale heights and low optical depths before depositing energy through reconnection. However, the best observed accretion discs, i.e. those in cataclysmic variables, have not supported the presence of a disc corona until now. I show that observations of high-state accretion discs with XMM-Newton and Chandra are now revealing a new X-ray emission component that may arise from an MRI-driven corona.

Key words: Eclipse, Accretion Disc Corona, X-rays.

1. INTRODUCTION

In order for accretion to proceed through an accretion disc, in-falling matter must lose energy and angular momentum. In general, energy can be lost quite easily, as it can be thermalised in shocks and then radiated. Angular momentum is more difficult to shed, and its transport in accretion discs tends to limit the rate of accretion by the central object.

Until relatively recently the mechanism of angular momentum transport in accretion discs remained a mystery. However, there is now a consensus that the most likely origin is the magneto-rotational instability (MRI; Balbus & Hawley, 1991). In this process, magnetic fields with radial components allow neighbouring disc annuli to communicate. A net drag is applied to the inner annulus, which causes material to fall in-wards, but also to orbit with a higher velocity. Since this stretches the magnetic field lines further, the drag is increased, and the process is unstable. The effect is to drive MHD turbulence that results in net angular momentum transport and amplification of the magnetic field.

The magnetic pressure associated with MRI-driven magnetic flux in the accretion disc causes the flux to be buoyant in the accretion disc, and so it tends to float to higher scale heights in the disc. This effect has been reproduced in numerical simulations (Miller & Stone, 2000). The result is a highly magnetised corona above a weakly magnetised accretion disc. Reconnection of the magnetic field is likely to heat the corona, leading to an observable optically-thin X-ray corona, much like that of the Sun (Balbus & Hawley, 1998).

This hot disc corona is often invoked to explain the hard X-ray spectra of active galactic nuclei (AGN) and Galactic black-hole X-ray binaries (BHXRBs), but in practise it is difficult to test this association. This is partly because the X-ray emission in black hole system is dominated by the extreme luminosity of the very inner-most region, whereas the MRI is a global disc phenomenon. It is also because the accretion discs in BHXRBs and particularly AGN do not evolve on accessible timescales. Ideally we would like to observe the global disc corona switch on and off as the accretion disc switched between high and low states of angular momentum transport.

Fortunately, just such an opportunity it provided by the accretion discs in cataclysmic variables. Dwarf nova outbursts allow us to observe their accretion discs in both high and low states within a few days (e.g. Wheatley et al., 2003). The global disc is visible because it is not out-shined by the inner most regions (because white dwarfs are less compact than black holes and their gravitational potential wells are less deep). And the location of any X-ray emission can be pinned down through eclipse observations of highly-inclined systems (e.g. Wheatley & West, 2003).

In this paper I discuss the observational evidence for MRI-driven X-ray corona in cataclysmic variables. Unambiguous detection of such a corona in the high-state, and its absence in the low-state, would provide rare observational evidence for MRI model as the source of angular momentum transport in accretion discs.

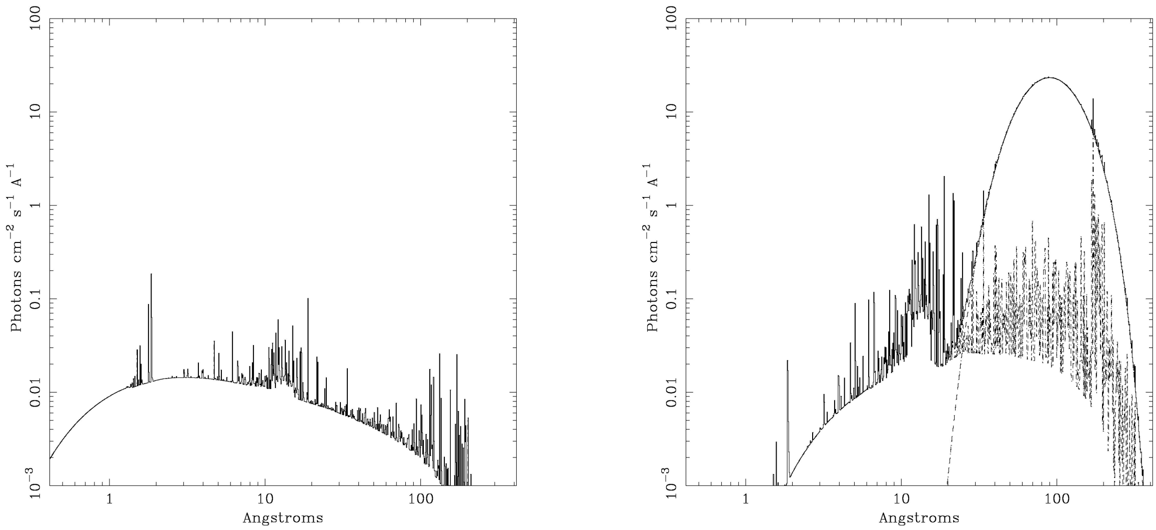

Figure 1. Schematic X-ray spectra of non-magnetic cataclysmic variables in the low state (left) and the high state (right).

2. THE X-RAY EMISSION OF CATACLYSMIC VARIABLES

The X-ray spectrum of non-magnetic cataclysmic variables changes dramatically between the low accretion rate state (or quiescence) and the high state (outburst). This is shown schematically in Fig. 1.

In quiescence the X-ray emission is hard, with characteristic temperatures around 10 keV. XMM-Newton observations of eclipsing systems show that this X-ray emission arises very close to the accretion object, in fact the X-ray emitting region as been constrained to be no larger than the white dwarf itself (Wheatley & West, 2003). This is usually interpreted as emission due to shock heating in the boundary layer between the accretion disc and white dwarf.

These observations essentially rule out significant X-ray emission from the accretion disc. Certainly there is no energetically important disc corona in the low state. This is expected, however, because the accretion rate is very low in the low state, angular momentum transport must be inefficient, and the MRI should not operating.

In outburst the accretion rate rises dramatically, by about four orders of magnitude, and this must be due to increased angular momentum transport in the disc. It is in this state that the MRI should be operating and in which we might expect to detect an accretion disc corona.

Observations in outburst show that the hard X-ray emission is suppressed, and that it is replaced by intense extreme-ultraviolet emission (e.g. Wheatley et al., 2003). This is usually interpreted as the boundary layer becoming optically-thick to its own emission and suffering a cooling catastrophe (due to the increased mass transfer rate through this region). The X-ray emission does not disappear entirely however, and the residual X-ray emission is seen to be softer than in quiescence (e.g. Baskill et al., 2005).

Eclipse observations in outburst have caused confusion because no eclipse is seen in the intense extreme-ultraviolet emission (e.g. Naylor et al., 1988). At first sight this seems inconsistent with the interpretation of this component arising from the boundary layer, which clearly is eclipsed in quiescence. The solution is that a significant fraction of the extreme-ultraviolet boundary layer emission is resonantly scattered in the outflowing accretion-disc wind, which is also a feature of high-state accretion discs. Observations with *EUVE* showed that the spectra of the low-inclination systems are dominated by optically-thick boundary-layer emission, whereas the spectra of highly inclined systems are dominated by strong and broad low-excitation resonance lines, i.e. boundary layer photons scattered by the wind (Mauche & Raymond, 2000).

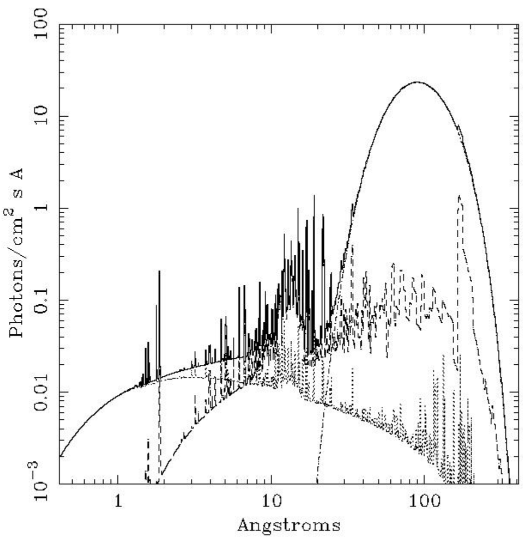

Figure 2. Revised schematic of the X-ray spectra of high-state cataclysmic variables showing the newly discovered two-component nature of the X-ray emission component. The hard emission is eclipsed in UX UMa, the soft emission is not.

3. EVIDENCE FOR A HIGH-STATE X-RAY CORONA

The standard picture of the X-ray emission of cataclysmic variables (above) leaves no room for a high-state MRI-driven accretion disc corona. All the high-energy emission is accounted for. However, this situation changed with the remarkable XMM-Newton observation of UX UMa (Pratt et al., 2004). UX UMa is a member of the *nova-like* class of cataclysmic variable, i.e. high-state cataclysmic variables that are commonly thought of as systems in permanent outburst. It is also an eclipsing system, and the XMM-Newton light curve revealed an X-ray eclipse for the first time in any high-state cataclysmic variable. The eclipsed emission is hard and must arise from the boundary layer, as in quiescence. Remarkably, this XMM-Newton observation also revealed the presence of a second, softer, X-ray component that is not eclipsed. This must be in addition to any extreme-ultraviolet component, which would lie softwards of the XMM-Newton bandpass. This new three-component picture of the high-energy emission of cataclysmic variables is illustrated by the schematic diagram in Fig. 2.

Pratt et al. (2004) interpret the uneclipsed soft X-ray emission of UX UMa as arising from resonant scattering, just like the extreme-ultraviolet emission. However, this interpretation is problematic because there is no evidence from low-inclination systems for intense continuum emission from the boundary layer in this wavelength range ($\sim 10-20\AA$). Consequently there are insufficient photons available to the wind to scatter into the line of sight of the observer.

Instead, I suggest that this newly discovered intermediate/soft energy emission component may arise in an MRI-driven accretion disc corona. If this can be confirmed it would provide evidence in support of the MRI model as the source of angular momentum transport in accretion discs. This is because this emission has all the characteristics of the reconnection-heated corona predicted by that model (i.e. its extent and temperature), and also because we know that this component is present only in the high state, just as expected for the MRI.

In search of additional supporting evidence for this interpretation I turn to the Chandra observations of WZ Sge in outburst presented by Wheatley & Mauche (2005). WZ Sge is not an eclipsing cataclysmic variable, but it is highly inclined and Wheatley & Mauche (2005) found that the extreme-ultraviolet emission is dominated by strong low-excitation resonance lines, just as is seen in the eclipsing systems. The X-ray spectrum of WZ Sge is clearly separated into distinct hard and soft components, just as in UX UMa, although the lack of eclipses means that we have to assume that the softer component arises from the extended emission region (by analogy with UX UMa).

The properties of the soft X-ray component of WZ Sge, described by Wheatley & Mauche (2005), are clearly inconsistent with the wind-scattering interpretation proposed by Pratt et al. (2004) for UX UMa. First, the emission line are from highly excited on species, and the line ratios are consistent with thermal emission (rather than resonant scattering). Second, the emission lines are relatively narrow: $\sim$800 km s^{-1} compared with 3000 km s^{-1} for the resonantly-scattered extreme-ultraviolet lines. This velocity rules out not only resonant scattering, but also shock-heating in the wind, which should still carry the imprint of the high velocity outflow. In contrast, it *is* consistent with emission from material frozen to magnetic field lines that are rooted in the accretion disc. A velocity of 800 km s^{-1} corresponds to a Keplerian radius of $\sim 2\times10^{10}$ cm which is characteristic of the accretion discs of cataclysmic variables.

4. CONCLUSIONS

I conclude that the properties of the soft-X-ray emission of UX UMa and WZ Sge, taken together, provide strong evidence in favour of the presence of an X-ray disc corona in these systems in their high state. This component is absent in WZ Sge in the low-state, as would be expected for a component driven by the MRI.

Further observations of eclipsing cataclysmic variables in the high state have the potential to prove the presence of global disc coronae, which would provide rare observational evidence in support of the MRI model of angular momentum transport in accretion discs.

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