Accretion onto Magnetic White Dwarfs

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Abstract. Recent developments in the accretion onto magnetic white dwarfs are reviewed. Accreting magnetic white dwarfs display many of the characteristics of accreting systems of a galactic scale, with the advantage that in these systems the accreting material is collimated into a relatively well-determined 1-dimensional flow.

INTRODUCTION

Accreting magnetic white dwarfs occur in binary systems in which the companion secondary star is (at least approximately) on the main sequence. In this guise they are called magnetic cataclysmic variables (mCVs) (see Cropper 1990 [1], Patterson 1994 [2] and Warner 1995 [3] for reviews). CVs exist with degenerate companions, and it is likely that the first mCV with a degenerate companion has been recently been found (Cropper et al 1998 [4]). There are other classes of accreting white dwarfs, in which the secondary is evolved (such as the recurrent novae and some symbiotic stars): however, so far no magnetic examples of such systems have been identified. There is no reason for such systems not to exist, and their apparent dearth is probably because few predictions for their behaviour have been made and no significant searches carried out. A probable further class of accreting white dwarfs, the Super-Soft Sources, also have no known magnetic analogs, although a few suggestions for candidates have been made (Kahabka 1995 [5]).

Of course MCVs are of interest intrinsically: they are even more so when viewed in the wider context of accreting astrophysical systems. They show many of the characteristics of accreting systems of a galactic scale – for example they have cooling flows with hard X-ray spectra, Compton reflection and fluoresence components, partially ionised absorbers, plasmas with different ion and electron temperatures, magnetic fields and cyclotron radiation. They have the advantage that in these systems the accreting material is collimated into a relatively well-determined 1-dimensional flow, the physical processes are relatively tractable, and the variability timescales are more accessible. MCVs are therefore prime targets for the study of accretion physics.

MCVs are broadly divisible into those in which the dipole magnetic moment on the white dwarf is sufficient ($\mu > 10^{34}$ G cm^3, $B > 10$ MG) to force synchronous rotation or near synchronous rotation with the binary rotation (the Polars or AM Her systems) and those with magnetic fields down to a factor of 10 lower (the Intermediate Polars – IPs – or DQ Her systems). It should be noted that these magnetic moments are orders of magnitude larger than those for accreting neutron stars such as those in LMXBs and HMXBs ($\mu \sim 10^{26}$ and $\mu \sim 10^{30}$ G cm^3). In the Polars, the field is sufficient to prevent the formation of an accretion disk, so that accretion takes place directly via the stream from the secondary after threading onto the magnetic field. In IPs, there is evidence for an accretion disk, so that quasi-radial accretion occurs from magnetic field lines threading the inner edge of the disk.

This paper reviews the current status of accretion onto magnetic white dwarfs. It begins with the region in which the accretion flow threads onto the magnetic field in both IPs and Polars, then concentrates on the region at the surface of the white dwarf. It concludes with a view on those areas which may be the most productive to explore in the near future.

THE THREADING REGION

Much of the structure of the accretion region in Polars depends on how the accreting material is threaded by the magnetic field. This is a difficult region to treat theoretically, with a number of physical processes and instabilities competing (Liebert & Stockman 1985 [6] and Lamb 1985 [7]). Although there has been some subsequent theoretical work (eg King 1993 [8]) a clear picture has yet to emerge. Observationally one approach has been to use the velocity flows (see eg Schwope, Mantel & Horne 1997 [9]) in eclipsing systems, since in these it is easier to deal with the out-of-plane velocities. These confirm the picture of a stream in two parts, a ballistic stream and a magnetically funnelled stream after the threading region. There is no strong evidence for a strongly emitting threading region of large extent. In another approach Hakala (1995) [10] and Harrop-Allin et al (1998) [11] use the eclipses to reconstruct the luminosity profile along the stream assuming a fixed ballistic-magnetic trajectory. These track both the line and continuum emission, rather than only the line emission and give compatible results, except that rather more emission is detected from the stream closer to the accretion shock.

In IPs, the magnetically-confined accretion takes place from the inner edge of the accretion disk. As with the Polars, the interactions in this region are complex, and treatments are usually based on the work of Ghosh & Lamb (1979) [12]. More recent work has refined this (eg Li, Wickramasinghe & Rüdiger, 1996 [13]) and this problem is now being addressed with numerical MHD calculations (Stone, this conference). Accretion is expected to occur over a wide range of azimuths, leading to more extended accretion structures, with a wider range of shock heights (see below) than for Polars: this led to the accretion curtain model developed by Rosen, Mason

& Córdova (1988) [14] based on the IP EX Hya. From the equilibrium spin period of this short period IP there are indications that the disk may be non-Keplarian and that threading of the material is described by the inhomogeneous diamagnetic accretion model of Wynn & King (1995) [15]. In this model diamagnetic clumps of material experience a surface drag via Alven waves from the magnetic field at the Alven radius, and can subsequently be accreted or ejected. The model has been extended to explain the spin behaviour of the IP AE Aqr in which the rapidly spinning white dwarf acts as a magentic propellor (Wynn, King & Horne 1997) [16], ejecting material from the system. The nature of the interactions between the inner edge of the disk and the magnetic field in IPs is therefore at an early stage.

THE ACCRETION REGION

Background

The paradigm for the accretion region in mCVs was laid down before their discovery as a class (only DQ Her was recognised) by Fabian, Pringle & Rees (1976, FPR) [17]. This built on the calculations by Hoshi (1973) [18] for spherical flows and Aizu (1973) [19] for 1-D planar flows. It predicted the X-ray luminosities and temperatures and incorporated the magnetic field, the cyclotron cooling and reprocessing of the hard X-ray emission by the white dwarf surface. It also recognised the regime where cyclotron cooling could be dominant, and the possibility that the ion and electron populations could decouple thermally when this cooling was particularly fierce. Other stable solutions in which the accretion energy is thermalised directly by the white dwarf photosphere were also mentioned.

The discovery of highly magnetised mCVs, the Polars, in 1976 provided new impetus and led Masters (1978) [20], Lamb & Masters (1979) [21] and King & Lasota (1979) [22] to develop a three component model (bremsstrahlung and cyclotron from the post-shock region and reprocessed soft X-rays from the heated photosphere) of the emission from the accretion region. The overall view is shown in Fig. 1. The postshock flow is mostly optically thin to X-rays so the accretion energy is emitted at a temperature corresponding to randomised ion and electron velocities a quarter of the free-fall velocity (because of the strong shock), mostly as bremsstrahlung and line emission. Thus $kT_s \simeq 3\mu G M_{wd} m_p / 8 R_{wd}$ (where T_s is the temperature of the shock). For typical white dwarf parameters, $kT_s \sim 30$ keV. The gravitational potential wells of more massive WDs, which have smaller radii, are deeper, so the corresponding shock temperatures are higher.

The hard X-ray component

The postshock flow is confined by the magnetic field, so that it builds up to a height above the white dwarf surface set by the cooling rate in the postshock flow.

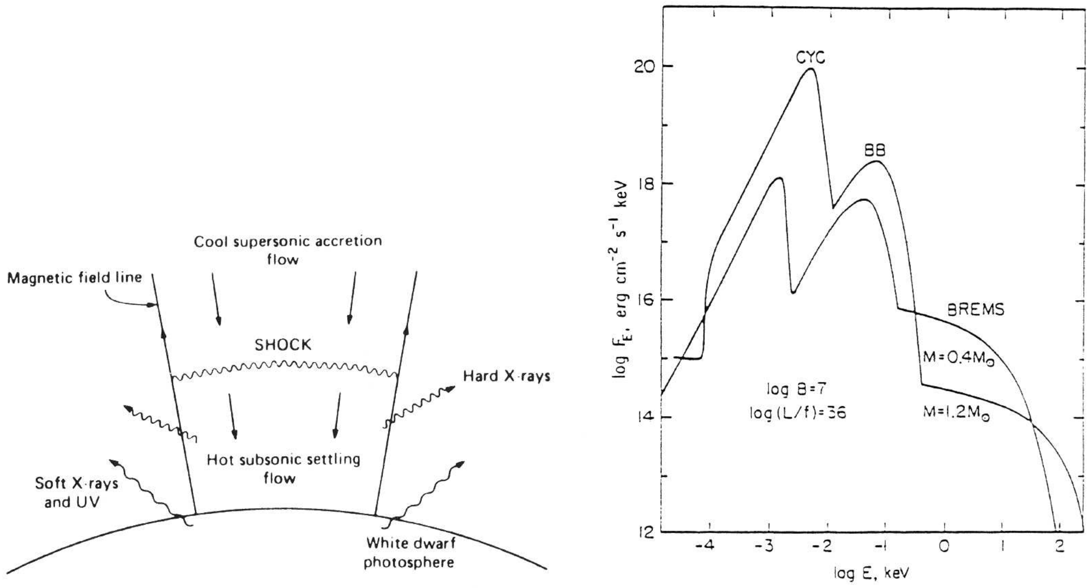

FIGURE 1. (a-left) Schematic of the accretion flow onto the surface of the white dwarf in the FPR formulation. Note that this diagram omits the cyclotron radiation from the postshock flow. From Watson (1986). (b-right) The emitted spectrum where cyc and brems are the cyclotron and bremsstrahlung components from the postshock flow and bb is the blackbody reprocessed radiation from the surface of the heated white dwarf. From Lamb & Masters (1979).

The height also depends on the inflow rate across the shock into the postshock region: higher accretion rates cause higher densities in the post-shock flow, and because the cooling rate for bremsstrahlung dominated cooling scales with the square of the density, such postshock flows radiate more effectively than those with lower accretion rates. The shock height is therefore lower for higher accretion rates. If there is a gradient in accretion rate across the surface of the white dwarf then the shock height will rise in regions of low accretion rate.

The postshock flow is hottest at the shock front and coolest and most dense near the surface of the white dwarf. The temperature and density profile as a function of shock height in the postshock flow was first calculated by Aizu (1973) [19] for the case of bremsstrahlung cooling. The X-ray emission therefore occurs from plasma at a range of temperatures and densities. This is often neglected when fits are made to X-ray data (eg. Rothschild et al. 1981 [24], Ishida 1991 [25]), but will lead to systematic errors. When the additional cooling from cyclotron radiation is included, the shock is lower than that for the bremsstrahlung case, and since the cyclotron cooling can be parametrised as varying as $T^{2.5}$ with only a weak density dependence (Wu 1994 [26]), this emission takes place at the top of the postshock flow where it is hottest. An even softer X-ray spectrum is the result. Wu (1994) [26] has noted that all postshock flows are bremsstrahlung dominated at the base of the flow, even if cyclotron cooling dominates near the shock.

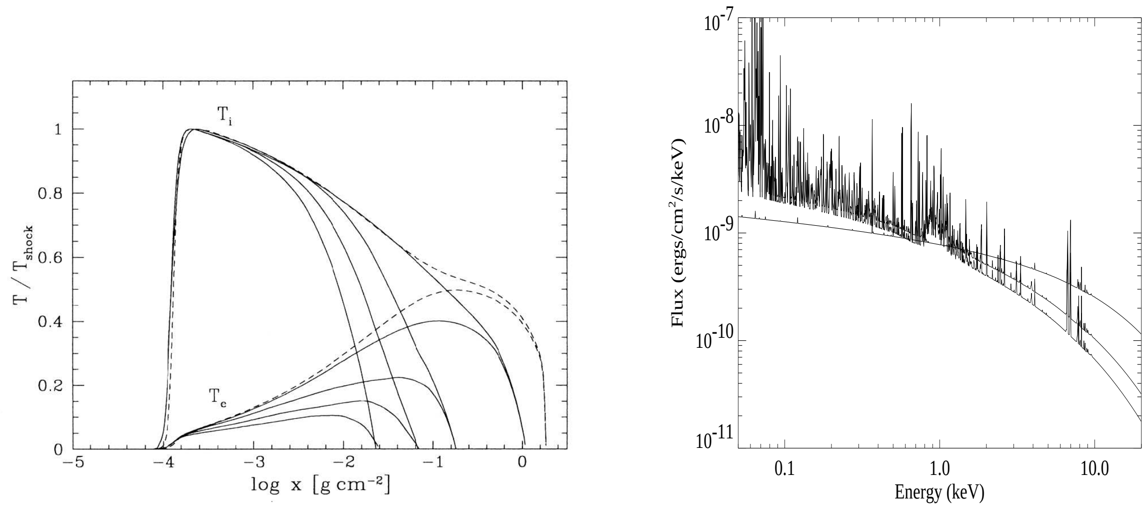

FIGURE 2. (a-left) The ion and electron temperatures as a function of height within the accretion flow for magnetic fields of 0 MG (dotted line) to 70 MG. The X-axis is plotted on a mass scale and relates to the geometric height z though the density ρ where $dz = dx/\rho$, so that this compresses the length scale at the bottom of the flow (the right hand side of the figure). The sharp increase in ion temperature marks the location of the shock. (From Woelk & Beuermann 1996.) (b-right) Optically thin X-ray spectra from the postshock flow in which the flattest spectrum is that characterised by the plasma at the shock temperature and density, the next steepest is that from a multi-temperature flow as in Cropper et al (1997) assuming bremsstrahlung cooling alone, and the steepest spectrum includes the cyclotron cooling from a 40 MG field.

Fig. 2a shows the result of numerical calculations by Woelk & Beuermann (1996) [27] on the temperature structure of the shock. The calculations include the effect of cyclotron cooling, so that the electron population has decoupled from the ions because the cyclotron cooling timescale is shorter than the electron-ion collision timescale. The shock structure in this case is set by the ions, so that the electrons and ions are heated in a precursor by conduction (not included in Fig. 2a). Separate populations are important only where the magnetic field is strong, as in the Polars, but it is clear that in such cases these effects should be included in predictions of the X-ray spectrum.

Cropper, Ramsay & Wu (1997) [28] have constructed the optically thin spectra from the post-shock flow. These include cyclotron cooling and the line emission which becomes more significant at energies below 2 keV, but assume the ion and electron temperatures are the same. Examples are shown in Fig. 2b. The prominent low energy lines will be unresolved at the resolution of typical CCD or PSPC X-ray spectra. The lines from these post-shock flows are emitted from the base of the flow near the white dwarf: for example the line emissivity for the Lyman-α (the most highly ionised) lines of Si XIV, Fe XXVI and Ni XXVIII peak at 10^{-3}, 0.3 and 0.5 of the height of the postshock flow for a 0.5 $M_{\odot}$white dwarf (Wu, Cropper

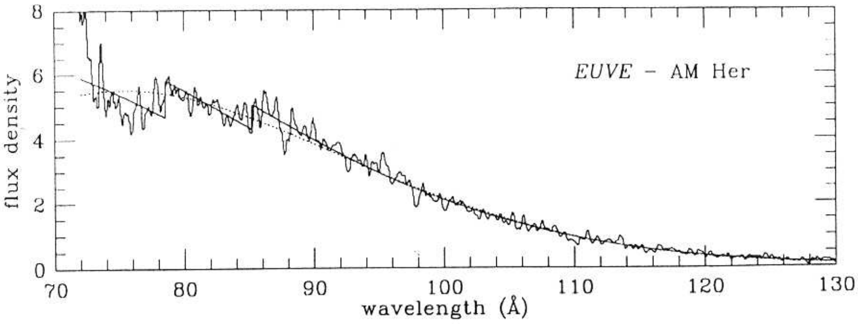

FIGURE 3. The EUVE spectrum of AM Her in the bright phase showing only absorption edges and none of the optically thin emission lines shown in fig 2b (from Mauche et al, 1995).

& Ramsay 1998 [29]). For a 1.0 $M_{\odot}$white dwarf even the Ni XXVIII Lyman-α line emissivity peaks only at 0.01 of the height of the postshock flow. None of these lines therefore sample the plasma near the shock directly, and good models of the temperature and density structure in the postshock flow will be required to extract information about it (and hence fundamental parameters such as the mass of the white dwarf and the accretion rate) from the line emission. Unfortunately the best candidates are compromised in practise – the Ni lines will generally be too faint to detect even with the next generation of X-ray satellites, and the Fe emission is contaminated (and largely swamped) by fluorescence from the heated white dwarf atmosphere (see below).

Progress in interpreting both bremsstrahlung continuum and line emission from the postshock flow will therefore depend on reliable models. In particular, because the line emission is predominantly from the lowest few percent of the postshock flow, the interface between the flow and the white dwarf photosphere will need to be more carefully modelled. Present models based on the FPR paradigm assume that the white dwarf photosphere is cold and that the velocity drops to zero at the base of the flow. However, the energy liberated from the accretion causes local heating of the photosphere which becomes bloated and more tenuous as a result (Litchfield & King 1990 [30] and, in a slightly different context, Frank, King & Lasota 1988 [31]). At this height, the ram pressure of the postshock flow will exceed that of the atmosphere, so that part of the flow will punch through it. At some level in the photosphere the mean infall velocity of the flow will be zero, essentially the base of the postshock flow. The lower boundary conditions should therefore be the pressure and temperature at this level. How much of the base of this flow is visible will depend on the optical depth – at softer X-ray wavelengths much of it will be shrouded by the bloated, partially photoionised atmosphere. This means that the lines will be optically thick, which is indeed as is observed by EUVE (see Fig. 3). A further result is that the heated photosphere will be seen as a raised region: this gives rise to the characteristically rapid rises in EUV flux seen as the region rotates into view over the limb (see for example Warren, Sirk & Vallerga, 1995 [32]).

The strength of the Fe line suggests that it is dominated by fluorescence, indicating that it is necessary to include the Compton reflection of hard X-rays from the irradiated white dwarf photosphere. Such calculations have been made by van Teeseling, Kaastra & Heise (1996) [34]). The albedo peaks at ~ 0.5 depending on scattered angle, at ~ 25 keV. This treatment assumes angle averaged illumination: for the grazing angles from the low postshock flows in mCVs the component may be more significant.

The reprocessed soft X-ray component

The FPR paradigm predicted that approximately half of the X-ray flux from the post-shock flow would be intercepted by the white dwarf, causing heating of the photosphere, and the emission of blackbody radiation with a characteristic temperature of ~ 25 eV. Of course, the emission is from a heated atmosphere (Williams, King & Brooker 1987 [35]), so the term blackbody is approximate. A long-standing difficulty was the relative lack of hard X-ray emission by comparison with this soft reprocessed component. This has been tested with data from different satellites and sources, and after initial controversy is now well established (see eg Ramsay et al 1994 [36]). Kuijpers & Pringle (1982) [37] pointed out that rapid increase in luminosity frequently seen in these systems suggested that there were density inhomogeneities in the flow and that these could easily be the origin of the discrepancy. This explanation is generally accepted. Such a deposition of the accretion energy directly into the photosphere was investigated by Frank et al (1988) [31] and Litchfield & King (1990) [30]. These denser parts of the flow ("blobs") will be threaded by the magnetic field later in their trajectory, so that they may accrete in a somewhat separate region from the more finely divided material. This led King (see eg King 1995 [38]) to propose that the accretion region in Polars may be highly inhomogeneous, with three characteristic scales: the area over which a blob accretes, f_{acc}, the area over which the photosphere around each accreting blob emits in soft X-rays, f_{eff}, and the region of the white dwarf surface over which the the blobs accrete, f_{zone}, with $f_{acc} << f_{eff} < f_{zone}$ (see Fig. 4a). Depending on the spatial extent of f_{zone} the temperature of the soft X-rays may be significantly less than ~ 25 eV and the radiation may appear at UV wavelengths (Gänsicke, Beuermann & de Martino 1995 [39]).

The IPs have an unresolved soft X-ray problem of their own: a lack of soft X-ray flux. Even if the flow in IPs is more finely divided than in Polars, a significant soft X-ray flux would be expected. The standard explanation of its absence is that this is due largely to greater absorption both within the system and in the intervening line of sight, high mass transfer rates and a large accretion area, rendering the soft component less visible (King & Lasota 1990) [42]. Recently a group of "soft-IPs" (Haberl & Motch 1995 [43]) have been identified; these are no closer than the classical IPs, and there is apparently no particularly favourable presentation of these systems to the line of sight.

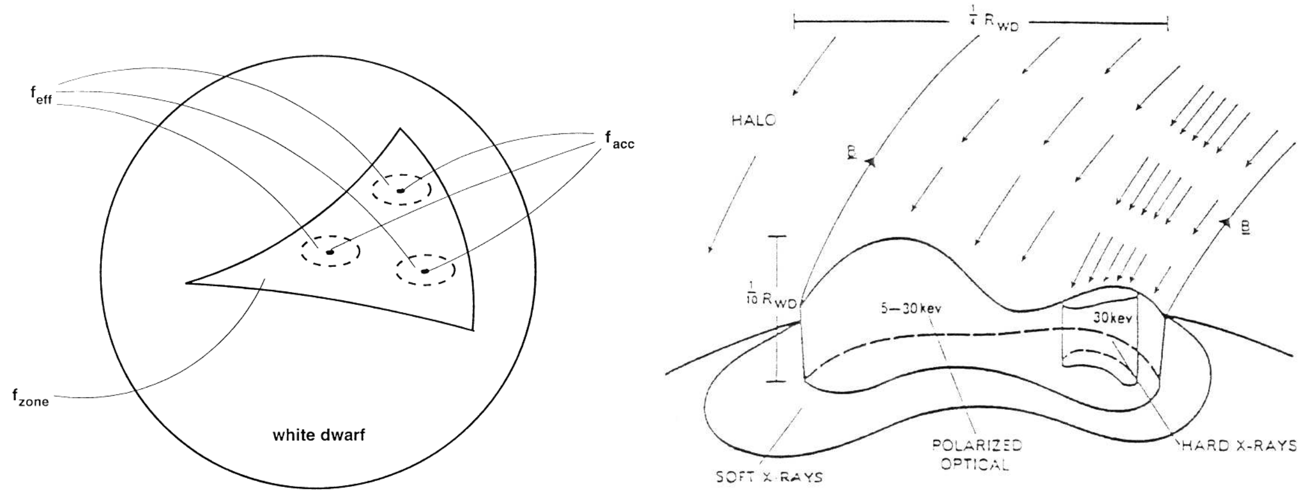

FIGURE 4. (a-left) The accretion region assuming highly inhomogeneous accretion (from King 1995). (b-right) The accretion region assuming finely divided accretion flows (from Wickramasinghe, 1988).

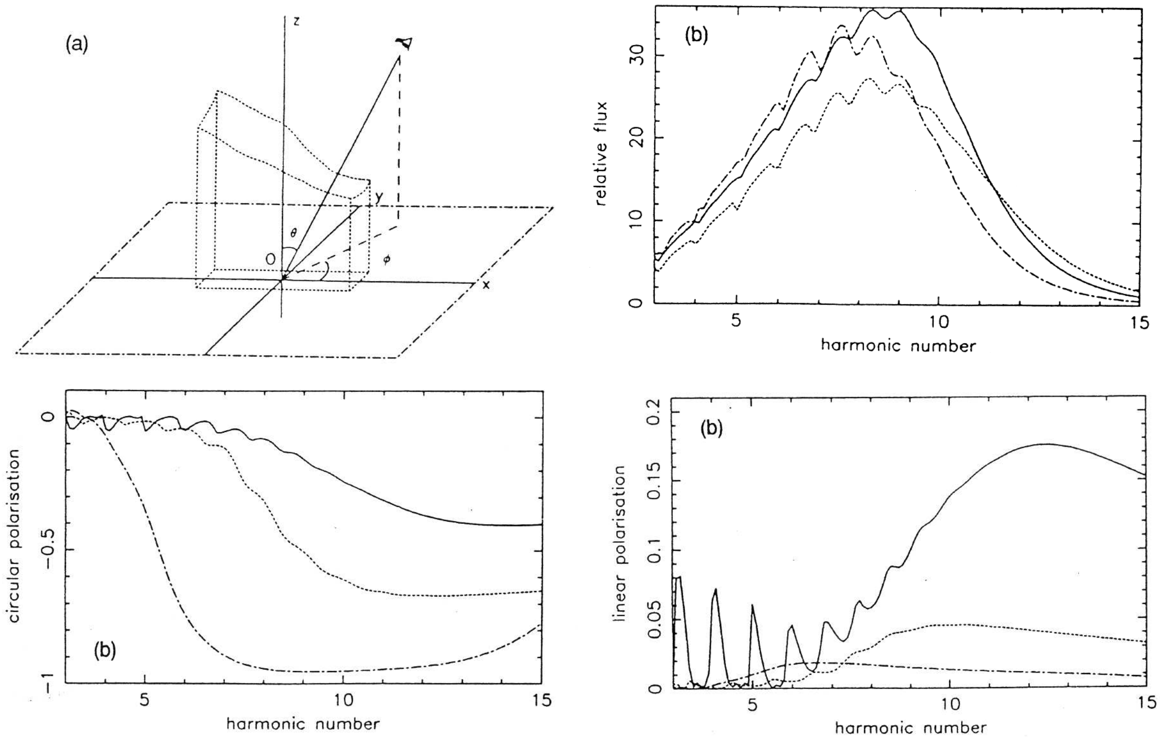

FIGURE 5. The cyclotron emission from an inhomogeneous postshock accretion flow from Wu & Wickramasinghe (1992). (top left) the structure of the postshock flow, (top right) the relative flux, (bottom left) the fractional circular polarisation and (bottom right) the fractional linear polarisation for 3 different viewing angles.

Depending on the range of blob densities, some fraction of the bolometric luminosity will be the result of thermalisation of the blobs deep in the photosphere, but this should not be taken too far. If there is hard X-ray emission, there must be an optically thin standoff shock as in the FPR paradigm, and some of the soft X-ray emission will still be reprocessed. The temperature and density profiles within the postshock region are amenable to calculation, and thus the line and continuum diagnostics are still available. Moreover, one of the defining characteristics of the Polars is polarised radiation, and from the breadth of the cyclotron lines at optical wavelengths (see eg Visvanathan & Wickramasinghe 1979 [44]), this is observed to be emitted from a hot plasma co-located with the postshock region.

Cyclotron Emission

The polarised cyclotron emission originates broadly from the same region as the hard X-rays, and is therefore optically thin in the high harmonics for the magnetic fields of relevance. At low harmonics, however, Lamb & Masters (1979) [21] noted that the cyclotron emission would exceed the Raleigh-Jeans tail of the blackbody envelope appropriate to the $\sim$ 30keV postshock flow so that it is optically thick and thus limited by the envelope at low harmonics. The excess flux is absorbed.

The cyclotron emission has been one of the most valuable characteristics of mCVs because the polarised fractions depend sensitively on the viewing angle to the field line: it therefore carries very detailed information on the structure of accretion region. Several groups (Chanmugam 1980 [45], Meggitt & Wickramasinghe 1982 [46] are early references) have calculated the polarised emission from the postshock region. A major difficulty at this stage (but later opportunity, as it becomes possible to perform these calculations more easily) is the 3-dimensional nature of the shock structure. This requires a full 3-D polarised radiative transfer treatment such as that in Fig. 5. by Wu & Wickramasinghe (1992) [41]. Such calculations have been used with polarisation data to model the structure of the accretion region (see eg Cropper, 1985 [47], Ferrario & Wickramasinghe 1990 [48], Potter et al 1997 [49], Potter, Hakala & Cropper 1998 [50]). The polarisation data tend to require more extended, arc-shaped regions than required by the hard X-ray data, as shown in Fig. 4b, which, however, does not include any blob accretion.

The spacing of the harmonics in the cyclotron spectrum provides a direct measurement of the magnetic field in the accretion region. This can also in principle be obtained from the slope of the bremsstrahlung X-ray spectra themselves, as a result of the different temperature gradients in the postshock flow, though in practice this may be difficult. It should be noted that on longer timescales than the cooling timescale at the base of the postshock region, material will diffuse transverse to the fieldlines. Over the lifetime of the system some displacement of the field in the accretion region may result. In addition, magnetic flux from the threading region may be entrained in the flow, and added to the accretion region.

Instabilities

Langer, Chanmugam & Shaviv (1981) [51] found that the accretion shock was unstable, and that the shock should oscillate in height on the cooling timescale, typically 1–100 sec. Quasi-periodic oscillations in the 1–3 sec range were observed by Middleditch (1982) [52] and more widely by Larsson (eg Larsson 1995) [53]. It has been found (eg Saxton, Wu & Pongracic 1997) [54] that cyclotron cooling damps the instability, so that it is thought that these QPOs are from infalling blobs exciting the instability. Currently, only some Polars display such high frequency QPOs, and none have been seen in the IPs, perhaps surprisingly given the absence of cyclotron damping. The greater range of local accretion rate expected for IPs may wash out the QPO peak in the power spectra into a broader range of frequencies. This may be the origin of the excess in high frequency noise power seen in the IPs AO Psc and V1223 Sgr by Warner, O'Donoghue & Fairall (1981) [55] and Warner & Cropper (1984) [56], although they may have their origin in the instabilities in the threading region at the inner edge of the disk (see above).

CONCLUDING REMARKS

The field stands on the brink of a new phase driven by the next generation of X-ray observatories, XMM, AXAF, Spektrum-X-Γ and Astro-E. Phase-resolved multiwavelength data of improved spectral resolution from these facilities will propel all aspects of the development of improved models of the accretion region. Areas in which there is likely to be particlar activity include the slightly asynchronous group of Polars such as BY Cam, because they provide the key to the effect on the accretion region of the changing orientation of the field to the incoming accretion stream; high field Polars such as AR UMa, which provide the opportunity to explore the accretion physics in the case of intense cyclotron cooling (for example the effects of separate ion and electron temperatures in the postshock flow); double-degenerate mCVs and accreting magnetic white dwarfs with evolved companions; and the interaction of the inner edge of the disk with the magnetic field, giving rise to mass ejection in IPs such as AE Aqr. Finally, the link between the IPs and the non-magnetic CVs may be the Dwarf Nova Oscillations as proposed by Warner (1995) [3].

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