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# Accretion Processes in Magnetic Binaries*

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**Abstract:** In this paper, we give a brief summary of the talks on accretion processes in AM Herculis systems which were presented at the ANU Astrophysical Theory Centre workshop on 'Magnetic Fields and Accretion'. One of the topics to be discussed was the mechanism that leads to the formation of magnetically funnelled accretion flows in close interacting magnetic binaries. New solutions to the Bernoulli integral indicate that the field lines must be twisted and have a strong toroidal component at the base of the funnel in order for channelled flow to be possible. The magnetic field pressure of these toroidal fields first lifts the material out of the orbital plane allowing it to 'levitate' before freely falling along magnetic field lines towards the stellar surface. Results of recent calculations of the thermal structure and radiation properties of accretion funnels were also presented. These new 3D calculations allow for heating by the soft X-rays originating from the accretion shock, and by magnetic heating at the base of the funnel, and determine self-consistently the thermal structure, and the continuum and line emissions, allowing for both transfer of the external radiation field and the trapping of radiation within the funnel. Calculations were also presented of the expected properties of H- and He-like Fe lines originating from the accretion shock itself at the stellar surface. These lines are predicted to be rather strong and can be used as diagnostics of the accretion flow. Finally, the stability of the accretion shock was also addressed. In particular, it was shown that radiative cooling may cause thermal instability and an oscillatory behaviour, with two competing processes coming into play: bremsstrahlung cooling, which promotes instability, and cyclotron cooling, which tends to dampen the oscillations.

**Keywords:** stars: binaries — stars: cataclysmic variables — magnetic fields — white dwarfs

## 1 Introduction

In the magnetic cataclysmic variables (mCVs), the accreting white dwarf has a strong enough magnetic field (1–250 MG) to channel material along field lines, either directly from the accretion stream AM Hers and some intermediate polars (IPs) or from the inner regions of a truncated accretion disk (disk-fed IPs and DQ Hers). In the mCVs, the gas in the resulting field-channelled flow (the accretion curtains or funnel) is heated by radiation from shocks at the white dwarf surface, and produces continua and emission lines that have a significant impact on the observed properties of these systems.

This paper summarises the results of some aspects of the accretion phenomena occurring in mCVs which were presented in November 1998 at the ANU Astrophysical Theory Centre workshop on 'Magnetic Fields and Accretion'. The theoretical modelling of the optical line spectrum and X-ray light curves requires a proper physical treatment of the accretion flow, and in this workshop we saw some of these important problems addressed.

The range of topics covered varied from the theoretical interpretation of the so-called 'magnetic levitation' which gives an explanation, in terms of ideal MHD, of the reason why material escaping from the secondary star via the inner Lagrangian point becomes threaded by magnetic field lines and is channelled by the super-strong primary's magnetic field towards the stellar surface (see Section 2). The subsequent paper, presented in Section 3, deals with the radiation properties of the material forming the

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accretion funnel, allowing for a full 3D radiation transfer treatment to reproduce the observed optical spectra. Finally, we present in Sections 4 and 5 results concerning some of the fundamental properties of the accretion shock at the base of the accretion funnel, where the material finally settles onto the white dwarf surface and cools down via thermal bremsstrahlung and cyclotron radiation.

## 2 Magnetohydrodynamics of Accretion: Magnetic Levitation

A stellar magnetic field tends to be a closed configuration, which, from a theoretical viewpoint, seems to prevent accretion. On the other hand, it is observationally indisputable that magnetic stars do accrete matter from their surroundings, either from a protoplanetary accretion disk, as in the classic T Tauri stars, or from a companion star losing mass via Roche overflow, as in low-mass X-ray binaries, where the primary star is a neutron star, or in the mCVs, where the accreting object is a magnetic white dwarf. The mechanisms that lead to field channelled accretion flow remain substantially unresolved due to the complicated nonlinear effects arising from the interaction between the magnetic field and matter.

The current picture on field matter interaction may be that the accreting matter entering the magnetosphere consists of diamagnetic blobs that are continuously stripped, as their surface layers become magnetised, by reconnection processes. Therefore, during their penetration into the magnetosphere, they feed the curtains, or funnels, of material until they are slowly depleted of all their matter and finally disappear.

Once threading has occurred, the accreting material behaves like a magnetised fluid, and the conditions for ideal MHD are thus satisfied.

In magnetically confined accretion flows the toroidal dynamics is only weakly coupled to the poloidal dynamics, and thus the velocity and magnetic field can be separated into toroidal and poloidal components. In a steady-state, axisymmetrical, magnetically channelled flow, the Bernoulli integral along a poloidal magnetic field line can then be written as (Li & Wilson 1999 and references therein)

$$\mu = \tfrac{1}{2}v_p^2 + \int \frac{dP}{\rho} - \frac{GM}{r} + \tfrac{1}{2}\Omega^2\varpi^2 - \alpha\Omega\varpi^2\,, \quad (1)$$

where $v_p$ is the poloidal flow velocity, $\rho$ is the plasma density, $\varpi$ is the cylindrical radius, $\Omega$ is the angular velocity, $M$ is the stellar mass, $r$ is the radius, $G$ is the gravitational constant, $P$ is the pressure and $\mu$ is the total energy per unit mass in the rotating frame, which has angular velocity $\alpha$. The quantities $\mu$ and $\alpha$ are constant along a given poloidal field line.

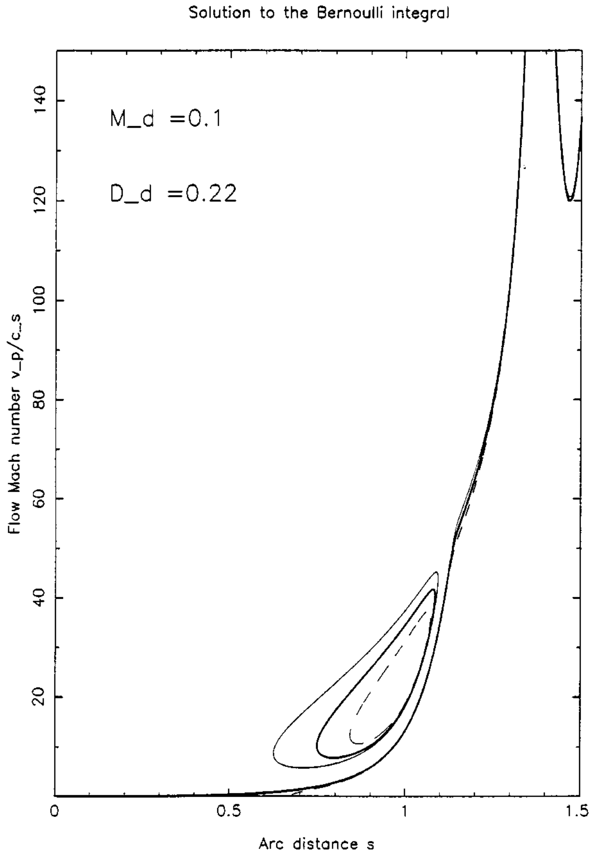


**Figure 1**—Solution of the Bernoulli integral. The horizontal axis denotes the dimensionless arc distance $s$, and the vertical distance is the Mach number $u = v_p/c_s$. Here the initial Mach number $M_d$ is set equal to $0{\cdot}1$. The lower initial limit is $D = v_p^2/V_A^2 = 0{\cdot}22$ and the upper limit $D = 0{\cdot}7$.

Li & Wilson (1999) have shown that it is possible to find solutions to the above Bernoulli integral of the funnel flow, but only under certain conditions. Their conclusion is that while solutions do not exist if $v_p \ll V_A$, where $V_A$ is the Alfvén velocity (defined by the poloidal magnetic field), solutions can be found if $v_p$ is initially *near-Alfvénic*, that is when $D = v_p^2/V_A^2$ is in the range $0{\cdot}22 - 0{\cdot}7$, for an initial Mach number $M_d = 0{\cdot}1$ (see Figure 1). Solutions still exist for higher initial values of $D$, but they are not as well behaved. If $M_d$ is increased above this range, then a simultaneous increase of $D$ improves the solution while a decrease of $M_d$ worsens it. More generally, Li & Wilson (1999) find that solutions depend on a range of flow parameters which cannot be strictly constrained. However, they argue that the true solution is likely to be close to the lower limit $D = 0{\cdot}22$, being that one to yield the smoothest behaviour. Since the strength of the toroidal magnetic field $B_\Phi$ at the base of the funnel increases with $D$, and since $D \propto 1/\rho$, this term will decrease along the funnel, thus reducing the strength of the toroidal field as the matter leaves the orbital plane and starts flowing towards the stellar surface. The existence of large toroidal fields at the

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coupling region was not envisaged in early models (e.g. Ghosh & Lamb 1979a, b) in which the material in funnel flows is stress-free at the inner edge of the accretion disk. On the contrary, the large toroidal fields found by Li & Wilson (1999) and inferred by Li, Wickramasinghe & Rüdiger (1996) spin up the disk by the magnetic stress $B_\Phi B_z/4\pi$, in order to transfer the angular momentum of the accreting material back to the disk.

The most important result from the work of Li & Wilson (1999) may be that these strong toroidal fields are also responsible for magnetic accretion by causing what has been called 'magnetic levitation'. This phenomenon is due to the gradient of $B_\Phi^2/8\pi$, which exerts a significant magnetic pressure that pushes the gas in the vertical direction off the orbital plane. This initial push allows the gas to overcome the potential barrier caused by the dipolar field being 'pinched' towards the star, due to the radial balance of gravity and Lorentz forces.

## 3 Radiation Properties of Magnetically Channelled Flows

Ferrario & Wickramasinghe (1993) and Ferrario (1996) have shown that in the disked IPs, the gas in the field-channelled flow (the accretion curtains) is heated by radiation from shocks at the white dwarf surface, and produces continua and emission lines that have a significant impact on the observed properties of these systems. The study of the emission properties of magnetically channelled flows has been extended to the accretion funnels in AM Hers by Ferrario & Wehrse (1999a,b), who have treated the full 3D radiation transfer problem to establish the thermal structure of magnetically confined flows.

The 3D radiative transfer equation is given by

$$\mathbf{n}\cdot\nabla I = \kappa(S - I)\,. \qquad (2)$$

Here $\mathbf{n}$ is a unit vector in the ray direction and $S$ is the source function, which is given by

$$S = (1-\epsilon)J + \epsilon B\,, \qquad (3)$$

where $J$ is the mean intensity given by

$$J = \frac{\int_{4\pi} I(\theta,\psi)\,d\Omega}{4\pi}. \qquad (4)$$

Furthermore, $\kappa$ is the extinction coefficient, $\epsilon$ is the ratio of absorption to extinction, $\Omega$ is the solid angle and $I$ and $B$ are the radiation intensity and Planck function respectively.

Finally, the energy equation is given by

$$\kappa\epsilon(B - J) = q_{\rm mag}\,, \qquad (5)$$

where $q_{\rm mag}$ is the magnetic heating term, which depends on the strength of the toroidal field formed at the base of the accretion funnel (see Section 2). These equations are solved using the Jacobi method described in detail by Stenholm, Störzer & Wehrse (1991).

In all calculations, Ferrario & Wehrse (1999a,b) have assumed LTE level occupations, and the opacities have been computed by assuming that the accreting material has a solar abundance of elements.

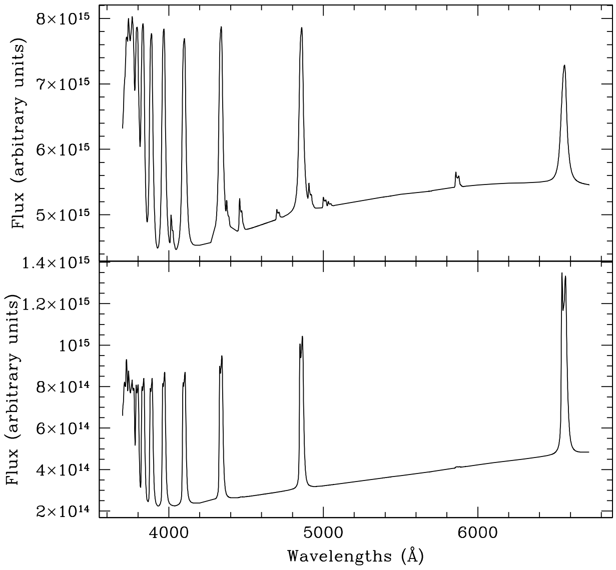


**Figure 2**—Hydrogen and helium lines: phase-averaged spectra of an accretion funnel with $\dot M = 5\times10^{16}$ g s$^{-1}$ (top) and $5\times \dot M = 10^{15}$ g s$^{-1}$ (bottom) heated by X-rays only.

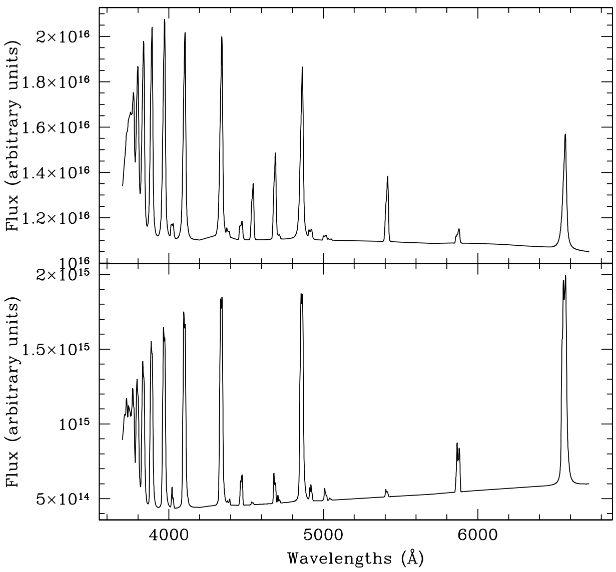


**Figure 3**—Hydrogen and helium lines: phase-averaged spectra of an accretion funnel with $\dot M = 5\times10^{16}$ g s$^{-1}$ (top) and $\dot M = 5\times10^{15}$ g s$^{-1}$ (bottom). Heating is caused by X-rays from the accretion shock and by magnetic reconnection at the base of the funnel.

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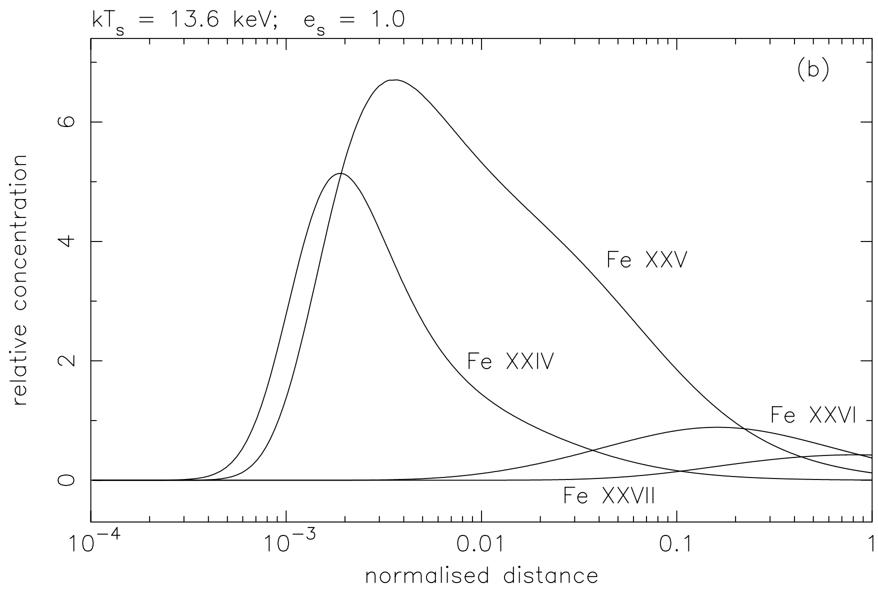


**Figure 4**—The concentration of the four highest ionisation states of Fe in the accretion shock, according to the structure model of Wu (1994). The mass of the white dwarf is 0·5 M⊙ and the ratio of cyclotron cooling to bremsstrahlung cooling at the shock is $\epsilon_s = 1$.

The solution of the above radiation transfer equation gives, self-consistently, the thermal structure of the funnel. Ferrario & Wehrse (1999a,b) show that while models that allow only for X-ray heating can explain the observed intensities of the Balmer lines, they cannot, at the same time, explain the intensities of the HeI and HeII lines in the optical spectra. These lines appear to be formed mainly in the magnetically heated transition region near the orbital plane. Ferrario & Wehrse (1999a,b) show that with the inclusion of this region, through the magnetic heating factor $q_{\rm mag}$ in equation (5), models can be constructed that are in close agreement with the optical line and continuum emission observed in AM Herculis systems; that is, they exhibit a flat or inverted Balmer decrement, HeI lines and a strong HeII $\lambda$4686 line (see Figures 2 and 3).

Ferrario & Wehrse (1999a,b) also showed that the emission line profiles can vary dramatically in velocity and shape over the orbital period of the white dwarf. They showed further that the continuum emission from the accretion funnel provides an important source of unpolarised background radiation, which reduces the degree of polarisation of the cyclotron radiation from the accretion shocks, and produces the polarisation standstills that are a well-known characteristic of these systems.

## 4 Iron Lines from AM Herculis Binaries

When high-speed matter decelerates abruptly near the surface of the accreting white dwarf, a shock is formed, heating up the matter to temperatures as high as ~10–50 keV. These temperatures are sufficient to ionise heavy elements such as Fe to various ionisation states. The shock-heated matter cools when settling onto the white dwarf surface, thus allowing atomic transitions to occur.

The accretion column therefore has a stratified structure: the flow velocity and the temperature are high in regions near the shock, and low in regions near the white dwarf surface. Because of the temperature stratification, the ionisation of elements varies along the accretion column. As a result, different lines are emitted at different heights above the white dwarf surface (Figure 4). The emitters have different velocities at different heights, and so the emission lines have energy shifts characterised by the location of the emitter.

Wu (1999) reported calculations of H- and He-like Fe lines emitted from the shock-heated region in AM Herculis-type binaries, and showed that these these lines are prominent for typical parameters found in AM Herculis systems. They can be used to diagnose the accretion flow. Their study has demonstrated that with the spectral resolution of the new generation satellites, e.g. AXAF and XMM, they will even be able to use the H- and He-like lines of Fe and other elements to map the post-shock flow velocities near the surface of the white dwarf.

## 5 Stability Properties of Two-temperature Radiative Accretion Shocks

Saxton & Wu (1999) presented calculations of the stability of the accretion shock that forms on the surface of an accreting magnetic white dwarf in AM Herculis type systems, in an attempt to explain the observed properties of the quasi-periodic oscillations sometimes seen in these systems. They showed that radiative cooling may cause thermal instability in the post-shock structure of the accretion flow settling onto a magnetic white dwarf. The

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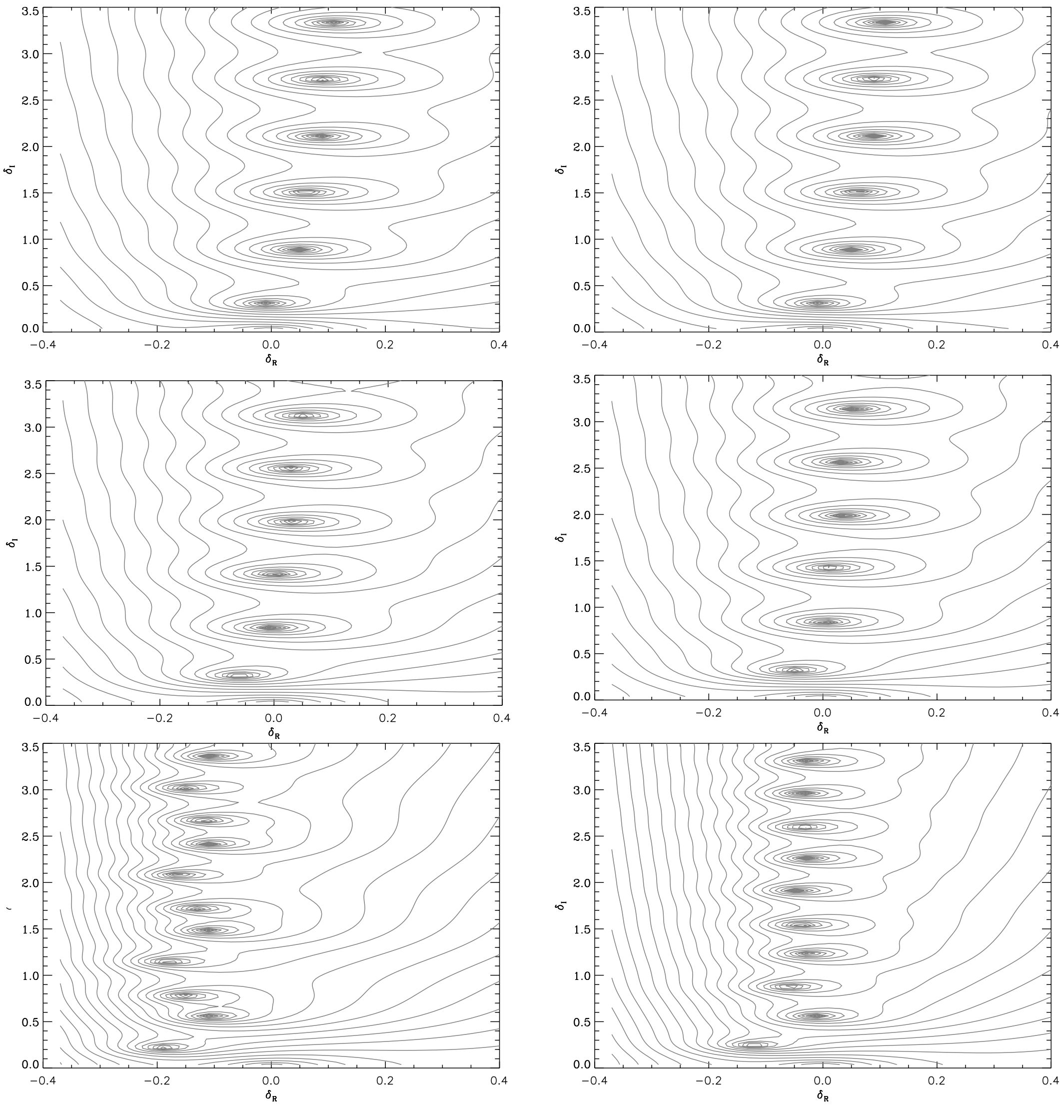


**Figure 5**—Eigenmodes of the single- and two-temperature calculations (left and right column respectively). The rows from top to bottom correspond to ratios of cyclotron cooling to bremsstrahlung cooling at the shock of $\epsilon_s = 0$, 1 and 100. For the two-temperature case we adopt as the ratio of electron to ion pressure at the shock $\sigma_s = 1$, and the parameter for the efficiency of electron–ion energy exchange is $\psi_{ei} = 1$.

stability and oscillatory properties depend on the functional forms and relative efficiencies of the cooling processes present, and also on the efficiency of energy exchange between the electrons and ions, which may in general have different temperatures. For conditions appropriate for accreting magnetic white dwarfs, we perform a linear stability analysis with unequal electron and ion temperatures and two competing cooling processes: bremsstrahlung cooling, which promotes instability, and cyclotron cooling, which tends to dampen oscillations.

As with a single-temperature flow, the mode frequencies exhibit approximately linear quantisation. The frequency spacing depends mainly on the efficiency of cyclotron cooling. The modes' stabilities are sensitively dependent on the global parameters, and consecutive modes do not necessarily have similar stabilities. Except when the electron and ion pressures are very different at the shock, increasing the cyclotron cooling efficiency increases the stability of each mode. Transverse perturbations destabilise the modes over certain wavenumber ranges, but these ranges are reduced when cyclotron cooling is important, unless the two fluid components' pressures differ greatly at the shock. Two-temperature conditions have little effect on the oscillatory properties when bremsstrahlung is the dominant cooling process, but a cyclotron-dominated shock is sensitive to the two-temperature parameters. When the electron–ion exchange is very weak, the lower boundary loses importance and the oscillatory properties are determined by the energy exchange rather than the cooling (Figure 5).

## 6 Conclusions

The papers presented on magnetic cataclysmic variables at the workshop on 'Magnetic Fields and Accretion' covered a wide range of topics

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which included: the magnetosphere accretion stream interaction and mechanisms responsible for initiating funnel flow ('the magnetic levitation model'), the thermal structure of accretion funnels, predictions of the X-ray Fe line spectra of accretion shocks, and the origin of the quasi-periodic shock oscillations. As can be judged from the summaries of the relevant papers presented in this report, this is an area of research with many unsolved problems, and one which is likley to remain active for many years to come.

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