ACCRETION DISK CORONAE

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SUMMARY. Accretion disk coronae around compact objects are the result of strong magnetic activity in the inner regions of accretion disks. Part of the accreting energy is dissipated in te corona and can be observed as hard X-ray emission with a time variability caused by the coronal structures. The interaction of disk coronae with neutron stars and black holes may cause quasiperiodic oscillations respectively flare type emission.

INTRODUCTION. Many accretion driven X-ray sources show a two component spectrum characterized by a soft X-ray component and a hard X-ray power law tail. The spectrum originates from an optically thick accretion disk radiating as a blackbody with a radial temperature distribution and a hot corona comptonizing the soft black body photons, thus forming a hard tail. Burm (1988) calculated the resulting comptonization spectrum using a Monte Carlo method applied to a disk-corona model consisting of magnetic coronal loops with a length ℓ for which a scaling law

$$T_{cor}^{5/2} = 3.6 \times 10^5 \, p_{cor} \ell \qquad (1)$$

has been derived (Burm; 1986).
It is assumed that all accreting matter is assembled in a thin disk drifting inwards with a velocity that is slow compared to the orbital velocity and where the vertical structure is determined by hydrostatic equilibrium. The structure of such a thin steady disk is described by the standard model, based on the conservation equations. The energy sink is the black body radiation of the optically thick disk and the energy source is produced by the viscous dissipation in the differentially rotating disk represented by the turbulent and magnetic stress tensor $t_{R\phi}$. The key assumption in the standard model is that the stress tensor is assumed to be proportional to the pressure ($t_{R\phi} = \alpha p$), where α is a constant independent of the radius, which can be made plausible on dimensional grounds.

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MAGNETIC ACTIVITY IN ACCRETION DISKS

A small magnetic field in an accretion disk will be amplified by the differential rotation, while turbulence creates a fluctuating component. The combination of differential rotation and helical turbulence acts as a dynamo whose efficiency is described by the ratio of growth and decay time expressed by the dynamo number N

$$N = A\Omega h^3/\beta^2, \tag{2}$$

where the net turbulent helicity $A = tv^2/3\beta$ and $\beta = v^2t$, where t is the turbulent correlation time. Following Pudritz (1981), we can estimate the dynamo number assuming $t = \Omega^{-1}$ and the turbulent correlation length $\ell = h$ (the disk thickness). Then with $v = Mv_s$, M being the turbulent Mach number, and $h/r = v_s/v_\phi$ for a thin disk it follows that $N = 0.3\ M^{-2}$. For subsonic turbulence we expect an efficient dynamo action resulting in strong and localized field fluctuations. The growth of magnetic fields is limited by magnetic buoyancy caused by the gravity acting on magnetic flux tubes. Burm (1985) estimated the Maxwell stress limited by buoyancy: $t_{R\phi} = 0.23\ M_t^3\ p_{gas}$. Consequently buoyancy puts severe limits to the field strengths in the disk causing large scale fields to emerge from the disk, thus forming magnetic layers on both sides of the disk consisting of loops and streamer type structures similar as observed in the Solar Corona.

However, small scale magnetic fields may be confined in the disk, thus forming magnetic cells. Equipartition type fields or even much stronger fields may be present on small scales, where line tying prevents them from escaping. As a first approximation the disk field may be considered to exist of turbulent magnetic cells stretched by the differential rotation until the magnetic stresses oppose the shear. Eardley and Lightman (1975) and Coroniti (1981) made such an approach, focussing on magnetic reconnection as the dominant field limiting mechanism for small scale fields in the disk. After the cell stretching is stopped by the magnetic stress the magnetic pressure gradients pinch the plasma in the center of the cell. The magnetic field lines are thus forced to reconnect, which ultimately results in the fission of the elongated flux cell into two smaller cells. This fission process occurs on an typical reconnection timescale. Hence the distortion stores shear motion into magnetic energy which is released by the reconnection process primarily into radial motion. The two remaining cells do not follow the Kepler rotation since they are slowed down. The two cells move apart radially in order to adjust their angular momentum.

FORMATION OF A DISK CORONA

The presence of a corona coupled to the disk exerts a torque on the disk whose effect is hidden in the parameter α describing the total stresses. Ionson and Kuperus (1985) separated the internal stresses α_i from the external stresses α_e where of course $\alpha = \alpha_i + \alpha_e$. Then the disk luminosity, which is related to the soft X-ray luminosity is $L_{disk} = 3\,\alpha_i p\, h\, \Omega / 4$, while the total luminosity is $L_{tot} = L_{disk} + L_{cor} = 3\,\alpha\, p\, h\, \Omega / 4$. Hence $\alpha = \alpha_i(1 + L_{cor}/ L_{disk})$; the external stresses are directly related to the coronal emission. Only a fraction of the accreted gravitational energy is emitted by the disk; the remainder is radiatively vented by the overlying corona. It is important to note that coronal dissipation has a stabilizing effect on the disk since it reduces the ratio of radiation pressure to gas pressure in proportion to the rate at which the disk couples non-thermal energy into the corona. Kuperus and Ionson (1985) estimated the upper limit of L_{cor} by considering a coronal magnetic loop as the load of a resonant electric circuit. If one assumes that all the energy that is delivered to the corona is used to heat the corona *which consists of loops of length $\ell = h$ filling a fraction f of the* disk a good approximation of the coronal luminosity is given by:

$$L_{cor} = 8\, f\, \frac{B_{cor}}{B_{disk}}\, (v_A^d)^2\, \alpha\, \rho\, v_s. \tag{3}$$

Using the hydrostatic equilibrium condition $h/r = v_s/v_\phi$, the ratio of coronal to disk luminosity is given by

$$\frac{L_{cor}}{L_{disk}} = 10\, f\, \left(\frac{B_{cor}}{B_{disk}} \right) \left(\frac{v_A^d}{v_s^d} \right)^2. \tag{4}$$

This expression is remarkable in the sense that it neither depends on the disk thickness nor on the parameter α. The last statement is only correct if $\alpha \ll 1$. Let us assume that the fields fan out into the corona in the same way as they do in the solar corona. Then $f = 1$ and eq. (4) shows that the emission ratio is directly proportional to the ratio of magnetic pressure and gas + radiation pressure in the disk, which may be locally much larger than one but averaged over the disk of the order of unity. It therefore seems that the observed large ratios of hard to soft X-ray emission of black hole accretion disks can be understood by the emission of magnetically structured and electrodynamically coupled disk coronae.

The observable ratio of hard to soft X-ray emission is a new way to search the internal magnetic structure of an accretion disk. Not only does it reveal the magnetic energy content but the important turbulent nature of the disk magnetic field may be studied by careful Fourier analyses of the time fluctuations on a wide variety of scales such as observed in Cygnus X-1. Note that in the Sun the ratio $L_{cor}/L_{phot} = 10^{-6}$, which is indicative for the small magnetic energy content of the solar photosphere. Actually $\langle B^2\rangle/8\pi p(\mathrm{phot}) \approx 10^{-5}$.

INTERACTION OF DISK CORONAE WITH NEUTRON STARS AND BLACK HOLES

In order to explain the spectral characteristics of quasiperiodic oscillating X-ray sources (QPO), Stollmann and Kuperus (1988) developed a model where the magnetic field of the central neutron star interacts with disk coronal loops located around the Alfvén radius. It can be shown that in this case energy is transferred from the neutron star to the disk corona. Consider a loop with an obliquely rotating neutron star magnetic field. The loop is anchored in the disk rotating

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with the Kepler velocity, while the neutron star magnetic field inside the Alfvén radius is supposed to rotate with the neutron star angular velocity Ω^*. In a coordinate system fixed to the loop, the loop experiences an oscillating stellar field with a frequency equal to the beat frequency $\Omega_B = \Omega_K - \Omega^*$. The magnetic periodicity at radius R is given by

$$B_S(R) = B_o(R) + B_1(R) \cos \Omega_B t \tag{5}$$

In order to estimate the power consumption the loop is considered as a forced oscillator with a forcing term $F = B_o B_1 \ell \cos \Omega_B t$. The maximum amplitude is reached when $\Omega = \omega_o$, the characteristic frequency of the loop. Assuming that the damping of the oscillation is due to the emission of magnetoacoustic waves generated by the oscillating surface of the filament, Stollman and Kuperus found that one loop may contribute up to a few percent of the Eddington luminosity. This shows that the rotating neutron star may be an important energy source to heat the disk corona.

The magnetic field in the accretion disk corona around a black hole becomes detached from the accreting matter once the matter approaches the horizon in the sense that closed loops will dissipate at the stretched horizon, while open field lines accumulate near the horizon (Thorne et al., 1986).

This decoupling of field and matter near the horizon has profound consequences for the activity around a black hole. The open field lines of one polarity generate a magnetic pressure that may eventually prevent further accretion and divert the matter along the field funnel, thus forming jets. However, there is no reason why only one polarity will be present. Hence the accumulation of one polarity is likely to be followed by the accumulation of the opposite polarity, thereby generating flare type disturbances. The peculiar behaviour of the accreting coronal magnetic fields around the horizon might be another source for time variability of hard X-ray emission in black hole accreting X-ray sources.

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