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2D and 3D MHD simulations of disk accretion by rotating magnetized stars: Search for variability

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Abstract

We performed 2D and full 3D magnetohydrodynamic simulations of disk accretion to a rotating star with an aligned or misaligned dipole magnetic field. We investigated the rotational equilibrium state and derived from simulations the ratio between two main frequencies: the spin frequency of the star and the orbital frequency at the inner radius of the disk. In 3D simulations we observed different features related to the non-axisymmetry of the magnetospheric flow. These features may be responsible for high-frequency quasi-periodic oscillations (QPOs). Variability at much lower frequencies may be connected with restructuring of the magnetic flux threading the inner regions of the disk. Such variability is specifically strong at the propeller stage of evolution.

Keywords: Accretion disks; Magnetized stars; Dipole field; X-ray; Variability

1. Rotational equilibrium state and two main frequencies

We first investigated slow viscous disk accretion to a rotating star with a dipole magnetic field in axisymmetric (2.5D) numerical simulations. Quiescent initial conditions were developed so that we were able to observe accretion for a long time (Romanova et al., 2002). These simulations have shown that many predictions of the theories developed in the 1970's (e.g., Pringle and Rees, 1972; Ghosh and Lamb, 1978, 1979) are correct. Namely, we observed that (1) the accreting matter is stopped by the magnetosphere at the magnetospheric radius r_m, where the ram pressure $\rho v^2 + p$ equals the magnetic pressure $B^2/8\pi$, and is then lifted up and accretes to the star through funnel flows; (2) the magnetosphere influences the structure of the disk to a distance $r_\Psi \approx (2\text{–}4)r_m$; (3) a star may spin-up, spin-down, or may be in the *rotational equilibrium state* depending on the ratio between magnetospheric radius r_m and corotation radius $r_{co} = (GM/\Omega_*^2)^{1/3}$, as predicted by Ghosh and Lamb (1978, 1979). We searched for the rotational equilibrium state and investigated this state in detail (Long et al., 2005). Namely, we fixed the parameters of the disk and magnetic moment of the star, and changed the angular velocity of the star, Ω_*. We found the angular velocity Ω_{eq} at which the angular momentum flux to the star is zero on an average. Fig. 1 shows the variation of fluxes at the surface of the star for the run with $r_{co} = 5$: the matter flux $\dot{M}$ and the angular momentum fluxes $\dot{L}_m$ and $\dot{L}_f$ associated with the matter and the magnetic field, respectively. The flux $\dot{L}_f$ (which always dominates over $\dot{L}_m$) varies but is approximately zero on an average. We found that in the rotational equilibrium state $r_{co}/r_m \approx 1.4\text{–}1.7$. Fig. 2 shows an example of matter flow in the rotational equilibrium state. We see that matter accretes to the star through a funnel flow, and that some field lines are closed and others "balloon out" or are radially stretched by the accreting matter. Part of the magnetosphere, however, is always closed or only partially open,

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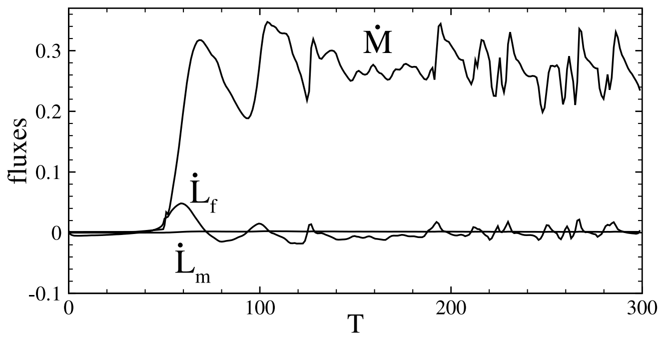

Fig. 1. Fluxes in the rotational equilibrium state. $\dot{M}$ is the matter flux, $\dot{L}_f$ is the angular momentum flux associated with the field (it varies in time but is zero on an average), and $\dot{L}_m$ is an angular momentum flux associated with matter (it is about 100 times smaller than $\dot{L}_f$).

and this interaction region is important for the spin-up/spin-down of the star. The fluxes in Fig. 1 vary with time because of the above ''ballooning out'' of the magnetic filed and reconnection events in the magnetosphere. We observed that, in the rotational equilibrium state, the rotation of the star is locked at some value $\Omega_{eq} \approx k\Omega_m$, where $k \approx (1.4–1.6)$ and Ω_m is angular velocity of the disk at the magnetospheric radius. The number k is smaller (larger) at smaller (larger) magnetic moments of the star μ. These two frequencies, $\nu_* = (2\pi)^{-1}\Omega_*$ and $\nu_m = (2\pi)^{-1}\ \Omega_m$ may represent two fundamental frequencies in each binary system in the equilibrium state. Fig. 3 (left panel) shows that for our typical case, as shown in Fig. 2, this ratio $\nu_m:\nu_* \approx 3:2$ (see Fig. 3, left panel). This ratio is reminiscent of the typical ratio between the frequencies of the kHz QPOs observed from many LMXBs (van der Klis, 2000; Wijnands et al., 2003). The surface of the star may be ''marked'' by hot spots associated with accretion or thermonuclear burning at the surface of the star, while the inner disk radius, which is approximately equal to magnetospheric radius r_m, may be marked by enhanced density in the disk or with enhanced reconnection at the boundary between magnetosphere and the disk. Matter often accumulates and forms a larger density peak, or ring, at the radius $r_{ring} \approx r_m$, thus giving a ''mark'' to this region. However, in some cases, the density peak is located at larger distances, as is shown in Fig. 3 (right panel). The position of this peak varies with the accretion rate. It is closer to r_m during periods of enhanced accretion. In case of accretion to a misaligned dipole, the ring typically breaks into two spiral arms (see next section) which rotate with the frequency of the inner regions of the disk.

2. 3D Simulations and high-frequency QPOs

We performed full three-dimensional simulations of the disk-magnetosphere interaction for aligned angular momenta of the star and the disk, and for different mis-

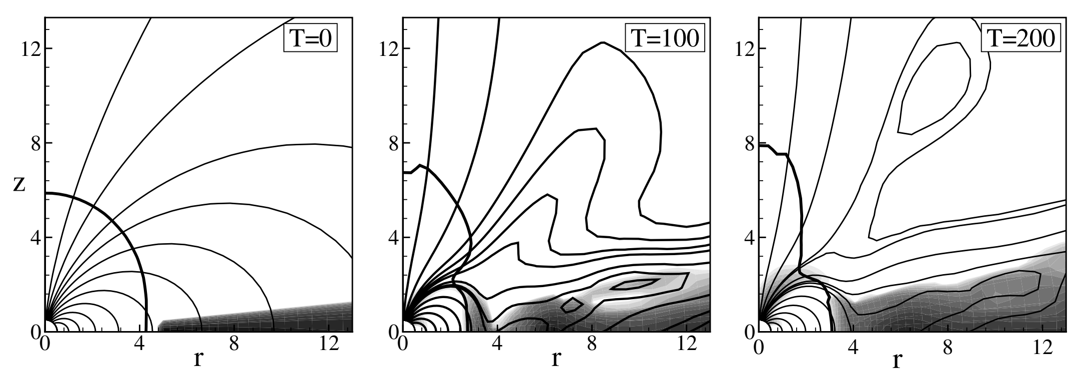

Fig. 2. Density distribution (background), magnetic field lines (thin lines) and the $\beta = 1$ line (thick line) where the matter ram pressure equals the magnetic pressure.

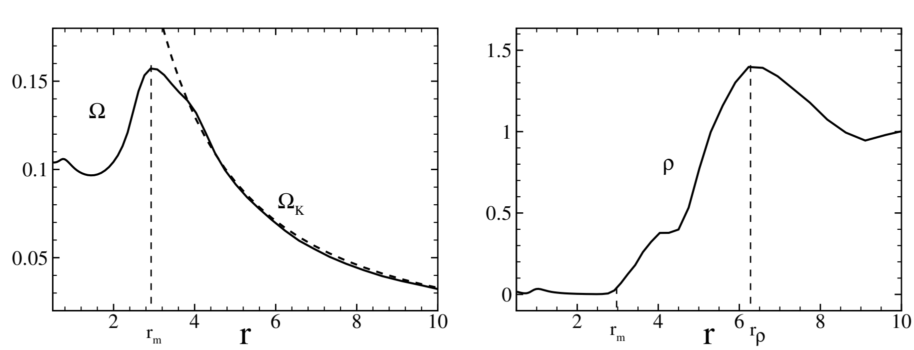

Fig. 3. (Left panel) Radial distribution of the angular velocity in the equatorial plane. The dashed line shows the Keplerian velocity. (Right panel) Density distribution.