PROPELLER-DRIVEN OUTFLOWS AND DISK OSCILLATIONS

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ABSTRACT

We report the discovery of propeller-driven outflows in axisymmetric magnetohydrodynamic simulations of disk accretion to rapidly rotating magnetized stars. Matter outflows in a wide cone and is centrifugally ejected from the inner regions of the disk. Closer to the axis there is a strong, collimated, magnetically dominated outflow of energy and angular momentum carried by the open magnetic field lines from the star. The "efficiency" of the propeller may be very high in the respect that most of the incoming disk matter is expelled from the system in winds. The star spins-down rapidly due to the magnetic interaction with the disk through closed field lines and with corona through open field lines. Diffusive and viscous interaction between magnetosphere and the disk are important: no outflows were observed for very small values of the diffusivity and viscosity. These simulation results are applicable to the early stages of evolution of classical T Tauri stars and to different stages of evolution of cataclysmic variables and neutron stars in binary systems. As an example, we have shown that young rapidly rotating magnetized CTTSs spin-down to their present slow rotation in less than 10^6 years.

1. INTRODUCTION

Different accreting magnetized stars are expected to be in the propeller regime during their evolution. Examples include accretion to fast rotating neutron stars (e.g., Davidson & Ostriker 1973; Illarionov & Sunyaev 1975; Stella, White, & Rosner 1986; Lipunov 1992; Treves, Colpi & Lipunov 1993; Cui 1997; Alpar 2001; Mori & Ruderman 2003), white dwarfs in cataclysmic variables, and classical T Tauri stars (CTTSs) at the early stages of their evolution. The propeller regime is characterized by the fact that the azimuthal velocity of the star's outer magnetosphere is larger than the Keplerian velocity of the disk at that distance.

Different aspects of the propeller regime were investigated analytically (Davies, Fabian & Pringle 1979; Lovelace, Romanova & Bisnovatyi-Kogan 1999; Ikhsanov 2002; Rappaport, Fregeau, & Spruit 2004; Eksi, Hernquist, & Narayan 2005) and studied with computer simulations (Wang & Robertson 1985; Romanova et al. 2003; Romanova et al. 2004 -hereafter RUKL04).

However, only relatively "weak" propellers were investigated earlier (RUKL04), in which a star spins-down, but no significant outflows were observed. In this paper we report on axisymmetric (2.5D) simulations of "strong" propellers, where significant part of the disk matter is redirected to the propeller-driven outflows. We observed that the disk oscillates between "high" and "low" states and expels matter to conical outflows quasi-periodically. The quasi-periodic outbursts associated with the disk-magnetosphere interaction were predicted earlier by Aly & Kuijpers (1990) and observed in simulations by Goodson et al. (1997, 1999), Matt et al. (2002), Romanova et al. (2002 - hereafter - RUKL02), Kato et al. (2004), von Rekowski & Brandenburg (2004), RUKL04, Yelenina & Ustyugova (2005). However, none of the earlier simulations concentrated on the propeller stage, and only few oscillation periods were obtained in earlier simulations. We report on modeling of propeller stage, where numerous oscillations were observed.

2. MODELING OF THE PROPELLER-DRIVEN OUTFLOWS

We have done axisymmetric MHD simulations of the interaction of an accretion disk with magnetosphere of a rapidly rotating star. What is meant by rapid rotation is that the corotation radius of the star $r_{cr} = (GM_*/\Omega_*^2)^{1/3}$ is smaller than the magnetospheric radius r_m which is determined by the balance between the pressure of the star's magnetic field and the ram pressure of the disk matter.

The numerical model we use is similar to that of RUKL02 and RUKL04. Specifically, (1) a spherical coordinate system (r,θ,ϕ) is used to give high resolution near the dipole; (2) the complete set of MHD equations is solved to find the eight variables $(\rho, v_r, v_\theta, v_\phi, B_r, B_\theta, B_\phi, \varepsilon)$ (with ε the specific internal energy); (3) a Godunov-type numerical method is used; (4) special "quiescent" initial conditions were used so that we were able to observe slow viscous accretion from beginning of simulations (see details in RUKL02). Compared to RUKL02, we now include the magnetic diffusivity. The viscosity and diffu-

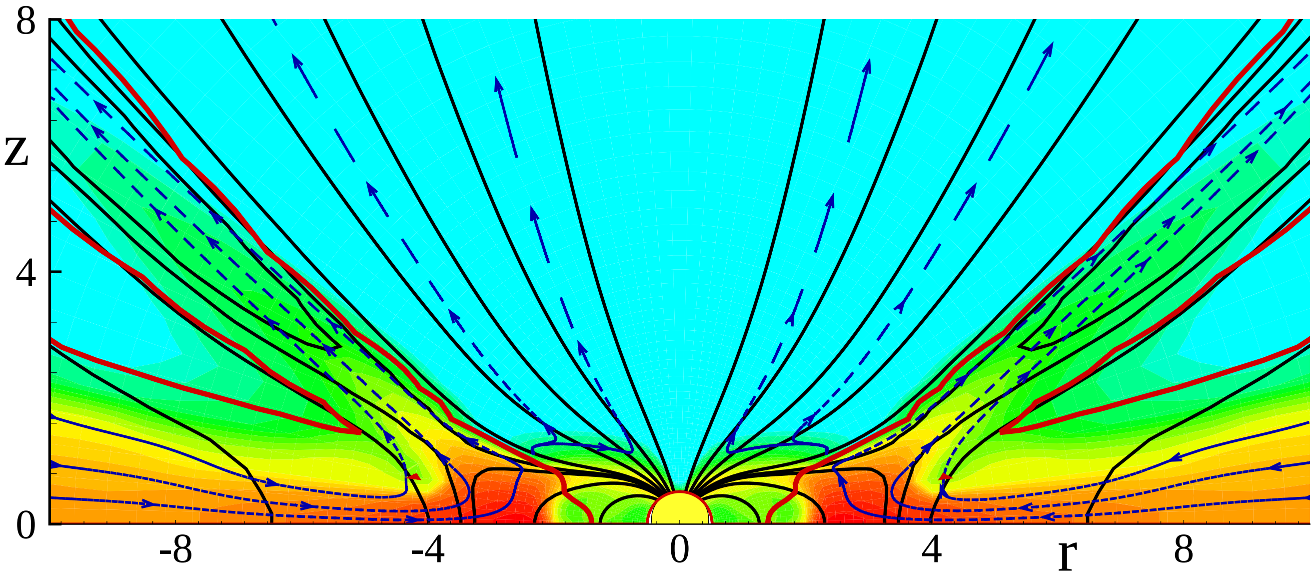

FIG. 1.— Example of matter flow in the "high" state (at $t/P_0 = 924$). The color background shows the density distribution which changes from red ($\rho = 1.5$) to blue ($\rho = 0.0005$). The solid black lines are magnetic field lines. The dark-blue lines/arrows are streamlines of the matter flow with the length of arrows proportional to velocity. The bold red line shows the surface where the matter pressure equals to magnetic pressure.

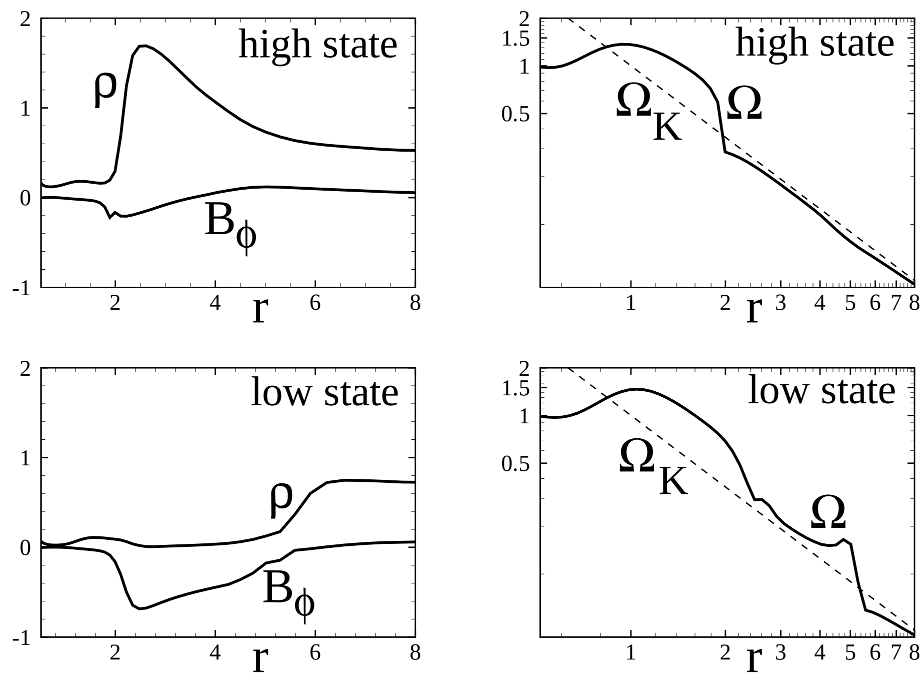

FIG. 2.— The left-hand panels show the radial variation of the density ρ and azimuthal magnetic field B_ϕ above the equatorial plane. The right-hand panels show the angular velocity Ω and the Keplerian angular velocity Ω_K for comparison.

sivity are determined by turbulent fluctuations of the velocity and magnetic field (e.g., Bisnovatyi-Kogan & Ruzmaikin 1976) with both the kinematic viscosity $\nu_{\rm t}$ and the magnetic diffusivity $\eta_{\rm t}$ of the disk plasma described by $\alpha-$coefficients as in the Shakura and Sunyaev model. That is, $\nu_{\rm t} = \alpha_{\rm v} c_s^2/\Omega_K$ and $\eta_{\rm t} = \alpha_{\rm d} c_s^2/\Omega_K$, where Ω_K is the Keplerian angular velocity in the disk, c_s is the isothermal sound speed, and $\alpha_{\rm v}$ and $\alpha_{\rm d}$ are dimensionless coefficients $\lesssim 1$. In RUKL04 we investigated a range of small viscosities and diffusivities, $\alpha_{\rm v}$, $\alpha_{\rm d} \sim 0.01-0.02$ and found no significant matter outflows. This paper investigates a wider range of $\alpha-$ parameters and finds substantial outflows for $\alpha_{\rm v} \gtrsim 0.1$ and $\alpha_{\rm d} \gtrsim 0.1$ in the propeller regime. Enhanced turbulence near the disk/magnetosphere boundary may arise because the radial gradient of the specific angular momentum is negative resulting in instability (Ustyugova et al. 2005). To model the diffusivity terms in the MHD equations, we used an implicit numerical scheme and the ICCG-method of solution of linear equations.

2.1. Reference Units. The MHD equations were solved in dimensionless form so that the results can be applied to different systems. We take the reference mass $M_0 = M_*$, a scale $R_0 = 2R_*$, and a matter flux $\dot{M}_0$ which is close to the average matter flux through the disk. Then we derive a reference density $\rho_0 = \dot{M}_0/v_0 R_0^2$, a velocity $v_0 = (GM_0/R_0)^{1/2}$, a time-scale $t_0 = R_0/v_0$, and an angular velocity $\Omega_0 = 1/t_0$. The reference magnetic field is $B_0^2 = \rho_0 v_0^2$. Thus $B_0 = \sqrt{\rho_0} v_0$. A reference magnetic moment is $\mu_0 = B_0 R_0^3 = \sqrt{\dot{M}_0 v_0} R_0^2$. The value of the magnetic moment used in our simulations μ_* is typically 10 times larger than μ_0 so that we introduce new reference variable $\mu_{00} = 10\mu_0$. The magnetic field at the surface of the star is $B_* = \mu_{00}/R_*^3$. The reference angular momentum flux is $N_0 = \dot{M}_0 v_0 R_0$. We measure time in units of the rotational period of a Keplerian disk at R_0, $P_0 = 2\pi t_0$. We solve the MHD equations for the normalized variables, $\tilde{\rho} = \rho/\rho_0$, $\tilde{v} = v/v_0$, $\tilde{B} = B/B_0$, etc. and below show plots for normalized variables (with tilda's dropped). In paragraph 2.5 we show an example for CTTSs and millisecond pulsars in real units.

2.2. Disk Oscillations and Outflows. Here, we discuss results for a representative simulation run where outflows occurred. The parameters are $\mu_* = \mu_{00}$, $\Omega_* = \Omega_0$ (co-rotation radius $r_{cr} = R_0$), $\alpha_{\rm v} = 0.3$, and $\alpha_{\rm d} = 0.2$. The disk-magnetosphere interaction was found to be quasi-periodic. The system oscillates between a "high" state, where the inner radius of the disk is closest to the star, and a "low" state where the disk is at the largest distance from the star. Figure 1 shows an example of matter flow in the "high" state. The outflow is launched into a conical shell of half-angle $\theta \sim 45° - 60°$. Many field lines are opened, and a major part of the matter flow to the wind is along the neutral line of the magnetic field. Analysis of the forces shows that the dominant force "pushing" matter to the wind is the centrifugal force (Blandford & Payne 1982). At smaller θ there is a magnetically dominated outflow of the much lower-density matter, which propagates with high-velocity along the open field lines of the star (see, e.g., Lovelace et al. 2002; Ustyugova et al. 2005).

Our simulations show that: (1) matter accumulates in the disk and moves inward; (2) it comes close to the star and penetrates diffusively into the closed magnetosphere; (3) the disk matter acquires angular momentum from the rapidly rotating magnetosphere and is expelled as outflows; (4) a small amount of matter accretes to the star through a funnel flow; (4) the disk is pushed outward by the rapidly rotating magnetosphere and the cycle repeats. Many field lines inflate and open during outflow stage (see also Fendt & Elstner 2000) and some magnetic flux annihilates and may be a source of X-ray flares which are often observed in young stars (Feigelson & Montmerle 1999).

Figure 2 shows the radial distribution of density ρ, angular velocity Ω, and azimuthal magnetic field B_ϕ in the "high" state (top panels) and "low" state (bottom panels). In the "high" state, the disk has a closest approach to the star of $r_d \approx 2.5$, and the density in the inner disk is large. The magnetosphere rotates with super-Keplerian velocity. Azimuthal component of the field is small. In the "low" state, the disk is pushed outward, the density is lower, and the magnetic field lines are twisted up, forming modified expanded magnetosphere similar to the case of "weak" propellers (RUKL04). We conclude that no outflows were observed in weak propellers (RUKL04), because the diffusivity and specific matter flux were too low.

2.3. Efficiency of Propeller and Variability. We performed simulations for a range of stellar magnetic moments μ_*, angular velocities Ω_*, and viscosity and diffusivity coefficients, $\alpha_{\rm v}$ and $\alpha_{\rm d}$, and calculated the time-averaged matter fluxes to the star $\langle \dot{M}_s \rangle$ and to the wind, $\langle \dot{M}_w \rangle$, and the efficiency of the propeller,

$$\mathcal{R} \equiv \frac{\langle \dot{M}_w \rangle}{\langle \dot{M}_s \rangle} \approx 13.0 \left(\frac{\mu_*}{\mu_{00}}\right)^2 \left(\frac{\Omega_*}{\Omega_0}\right)^{10.5} \left(\frac{\alpha_{\rm d}}{0.2}\right)^{2.1} \left(\frac{\alpha_{\rm v}}{0.2}\right)^{2.5} .$$

The ratio $\mathcal{R}$ may be very large, $\mathcal{R} \gtrsim 50 - 100$; that is, almost all of the matter coming inward in the disk may be ejected by the rapidly rotating magnetosphere. The dependence of $\mathcal{R}$ on μ_*, Ω_*, and $\alpha_{\rm v}$ is such that stronger ejection is observed in cases of stronger field, faster rotation and larger viscosity. However, the dependence on $\alpha_{\rm d}$ has a turnover point at approximately 0.2. For $\alpha_{\rm d} \lesssim 0.2$,

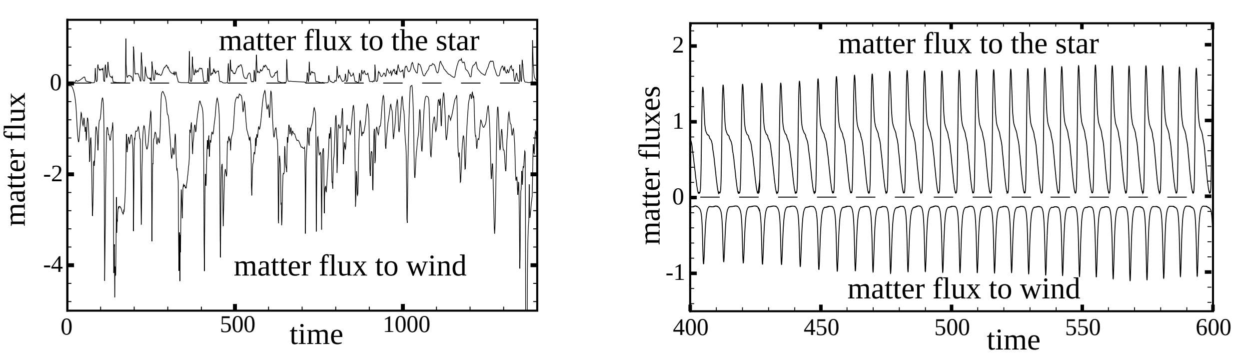

Fig. 3.— The left-hand panel shows the matter fluxes to the wind and to the star for our reference case. The right-hand panel shows the quasi-periodic variations of the mass fluxes which we find for larger viscosity, in this case, $\alpha_{\rm v} = 0.6$.

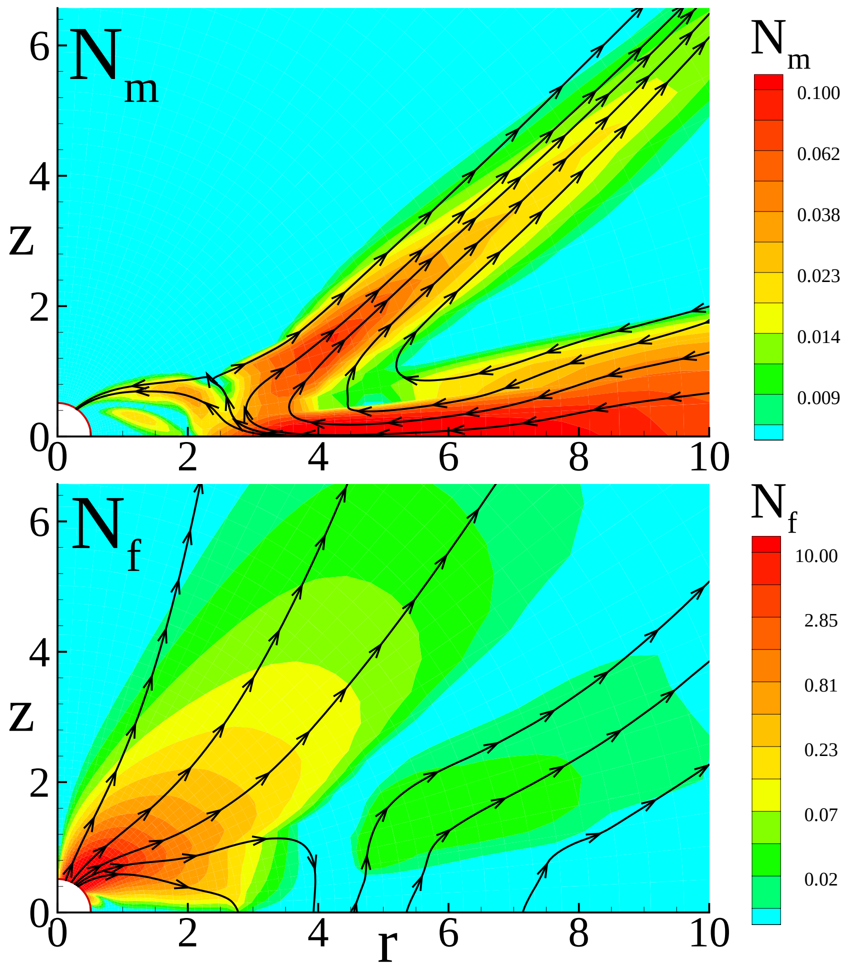

FIG. 4.— Color background and streamlines show fluxes of angular momentum carried by the matter (top panel) and by the field (bottom panel) in the "high" state ($t/P_0 = 924$). Note that the scales are different, because N_f is very large near the surface of the star. However, the total integrated fluxes N_m and N_f have comparable values.

$\mathcal{R}$ increases with $\alpha_{\rm d}$, while for larger values it decreases (Ustyugova et al. 2005). This paper shows the dependencies only for $\alpha_{\rm d} \lesssim 0.2$.

It is important to note that no significant outflows were observed when the diffusivity was relatively low, $\alpha_{\rm d} \lesssim 0.1$. This is because at low $\alpha_{\rm d}$ the penetration of the disk matter into the magnetosphere is not significant. Further, no outflows were observed at low viscosity. Analysis of the stresses show that the viscous stress is largest at the disk-magnetosphere boundary, and thus it adds to the "friction" and angular momentum transport from magnetosphere to the disk. From other side, the matter flux in the disk is proportional to the $\alpha_{\rm v}$ and at larger $\alpha_{\rm v}$, disk penetrates to deeper, faster rotating layers of magnetosphere. Both factors are important in generation of outflows, which appear at $\alpha_{\rm v} \gtrsim 0.1$. Outflows were observed at a wide range of the magnetic Prandtl numbers, $P_m = \nu_{\rm t}/\eta_{\rm t} = \alpha_{\rm v}/\alpha_{\rm m} \approx 0.2-6$ and thus do not require the dominance of viscosity or diffusivity. Instead, both α parameters should be larger than 0.1. Note, that the observed oscillations are completely determined by the processes at the disk-magnetosphere boundary. They are different from the viscous instability oscillations of the disk (Kato 1978) which can not be investigated by our numerical model.

The amplitude of the fluxes changes rapidly (see Figure 3). There is a typical time-scale of variations $\tau_{\rm qpo}$ in each case which depends on main parameters μ_*, Ω_*, $\alpha_{\rm d}$, and $\alpha_{\rm v}$. For given $\alpha_{\rm d}$ and $\alpha_{\rm v}$, the "quasi-period" increases with μ_* and Ω_*. It varies in the range $\tau_{\rm qpo} = (5-100)P_0$. We observed that for values of the diffusivity $\alpha_{\rm d} = 0.2$, but relatively high viscosities $\alpha_{\rm v}$ ranging from 0.6 to 1, the oscillations become highly periodic. In one of of sample runs a quasi-period changes from $\tau_{qpo} = 10P_0$ to $6.5P_0$ (see Figure 3, right panel). Period changes due to the fact that the inner disk radius moved closer to the star.

2.4. Angular Momentum Transport and Spinning-down. The angular momentum flux carried by the disk matter is re-directed by the rapidly rotating magnetosphere to the outflows (top panel of Figure 4). Furthermore, there is a strong outflow of angular momentum (and energy) carried by the twisted open magnetic field lines from the star $\langle N_f \rangle$, the Poynting flux, and the closed field lines connecting the star and disk (bottom panel of Figure 4; see also Lovelace et al. 2002). The time averaged total angular momentum flux from the star is $\langle N_s \rangle \approx -3.1(\mu_*/\mu_{00})^{1.1}(\Omega_*/\Omega_0)^{2.0}(\alpha_{\rm d}/0.2)^{0.46}(\alpha_{\rm v}/0.2)^{0.1}$. For our typical parameters the spin-down associated with open and closed field lines are comparable. However, at larger Ω_* and/or μ_*, the outflow along the open field lines dominates (see related cases in Lovelace et al. 1995; Matt & Pudritz 2004), while at lower Ω_* or μ_*, the situation reverses and a larger flux is associated with the closed field lines (like in Ghosh & Lamb 1979; RUKL02).

The spin-down time-scale follows from equating the torque $\langle N_s \rangle N_0$ to $I_* d\Omega_*/dt$, where $I_* \approx 10^{45}\mathrm{gcm}^2$ is the moment of inertia of the star. For the period of the star $P_* = 2\pi/\Omega_*$, we obtain: $P_*(t) = P_*(0)(1 + t/t_{\rm sd})$, where the spin-down time is

$$t_{\rm sd} \approx 0.036 \left(\frac{M_*}{\dot{M}_0}\right) \left(\frac{\mu_{00}}{\mu_*}\right)^{1.1} \left(\frac{0.2}{\alpha_{\rm d}}\right)^{0.46} \left(\frac{0.2}{\alpha_{\rm v}}\right)^{0.1}.$$

2.5. Young CTTSs and Millisecond Pulsars. Our results can be directly applied to stars with relatively small magnetospheres, $r_m \lesssim (3-10)R_*$, for example, to CTTSs or to accreting millisecond pulsars. Thus, for a CTTS with a mass $M_* = 0.8 M_\odot$, radius $R_* = 2R_\odot$, an accretion rate $\dot{M}_0 \approx 5 \times 10^{-8}$ $M_\odot$/yr, and other typical parameters $\alpha_{\rm d} = 0.2$, $\alpha_{\rm v} = 0.2$, and $\mu_* = \mu_{00}$, we obtain $t_{\rm sd} \approx 5.8 \times 10^5$ yr. We also derive dimensional values: $\mu_* \approx 6.2 \times 10^{36}$ Gcm^3, $B_* \approx 2.2 \times 10^3$ G and $P_* \approx 1$ day. Thus, if young CTTSs have strong magnetic field, then they spin-down rapidly to their presently observed slow rotation rate.

Accreting millisecond pulsars have a different history of evolution: they spin-up from slow to fast rotation. However, they may have episodes in the propeller regime. For a neutron star with mass $M_* = 1.4 M_\odot$ and similar accretion rate $\dot{M}_0 \approx 5 \times 10^{-8}$ $M_\odot$/yr, we find $t_{sd} \approx 10^6$ yr. Taking $R_* = 10^6$ cm and $\mu_* = \mu_{00}$, we find $\mu_* \approx 7.0 \times 10^{27}$ Gcm^3, $B_* \approx 7 \times 10^9$ G, $P_* \approx 1.3$ ms. In this case t_{sd} represents the time-scale of spin change for rapidly rotating millisecond pulsars.

3. CONCLUSIONS

In the propeller regime of disk accretion to a rapidly rotating star, we find from axisymmetric MHD simulations that the disk oscillates strongly and gives quasi-periodic outflows of matter to wide-angle ($\chi \approx 45° - 60°$) conical winds. At the same time there is strong field-dominated (or Poynting) outflow of energy, angular momentum and matter along the open field lines extending from the poles of the star. Matter outflows with high velocities and is magnetically driven. The outflows occur for conditions where the magnetic diffusivity and viscosity are significant, $\alpha_{\rm v,d} \gtrsim 0.1$. For smaller values of the diffusivity, the disk oscillates but no outflows are observed (RUKL04). The observed oscillations and outbursts are a robust result, based on a numerous simulations at different parameters with more than a 100 oscillation periods observed in many runs. The period of oscillations varies in different runs in the range $\tau_{\rm qpo} \sim (5-100)P_*$. It increases with μ_* and Ω_*. We observed that the oscillations for relatively large $\alpha_{\rm v}$ become highly periodic with definite quasi-periods. More detailed analysis of these features will be reported later. A star spins-down rapidly due to both the disk-magnetosphere interaction and the angular momentum outflow along the open field lines. The results are applicable to young CTTSs, neutron stars, and cataclysmic variables.

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