PROPELLER-DRIVEN OUTFLOWS AND DISK OSCILLATIONS

M. M. Romanova,¹ G. V. Ustyugova,² A. V. Koldoba,³ and R. V. E. Lovelace⁴

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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 the corona through open field lines. Diffusive and viscous interaction between the 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 (CTTSs) and to different stages of evolution of cataclysmic variables and neutron stars in binary systems. As an example, we show that young rapidly rotating magnetized CTTSs spin down to their present slow rotation in less than 10⁶ yr.

Subject headings: accretion, accretion disks — magnetic fields — stars: magnetic fields — X-rays: stars

1. INTRODUCTION

Different types of 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 et al. 1986; Lipunov 1992; Treves et al. 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 have been investigated analytically (Davies et al. 1979; Li & Wickramasinghe 1997; Lovelace et al. 1999; Ikhsanov 2002; Rappaport et al. 2004; Ekşi et al. 2005) and studied with computer simulations (Wang & Robertson 1985; Romanova et al. 2003, 2004, hereafter RUKL04).

However, previous studies (RUKL04) investigated only relatively “weak” propellers, in which a star spins down, but no significant outflows were observed. In this paper we report on axisymmetric (2.5-dimensional) simulations of “strong” propellers, where a 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 discussed by Aly & Kuiper (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) and RUKL04. However, none of the earlier simulations concentrated on the propeller stage, and only a few oscillation periods were obtained in earlier simulations. We report on a modeling of the 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 the magnetosphere of a rapidly rotating star. Here rapid rotation means that the corotation radius of the star, $r_c = (GM/\Omega^2)^{1/3}$ 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 $(r, \theta, \phi)$ is used to give high resolution near the dipole; (2) the complete set of MHD equations is solved to find the eight variables $\rho, v_r, v_\theta, v_\phi, B_r, B_\theta, B_\phi, e$, where $e$ is the specific internal energy; (3) a Godunov-type numerical method is used; (4) special “quiescent” initial conditions are used so that we are able to observe slow viscous accretion from the beginning of the simulations (see details in RUKL02). Compared to RUKL02, we now include magnetic diffusivity in the code. We suggest that both viscosity and diffusivity are determined by turbulent fluctuations of the velocity and magnetic field (e.g., Bisnovatyi-Kogan & Ruzmaikin 1976), where both the kinematic viscosity $\nu$ and the magnetic diffusivity $\eta$ of the disk plasma are described by $\alpha$-coefficients, as in the Shakura & Sunyaev model. That is, we take $\nu = \alpha_c c/\Omega_k$ and $\eta = \alpha_d c/\Omega_k$, where $\Omega_k$ is the Keplerian angular velocity in the disk, $c$ is the isothermal sound speed, and $\alpha_c$ and $\alpha_d$ are dimensionless coefficients $\leq 1$. In RUKL04 we investigated a range of small viscosities and diffusivities, $\alpha_c, \alpha_d \sim 0.01–0.02$, and found no significant matter outflows. This paper investigates a wider range of $\alpha$-parameters and finds substantial outflows for $\alpha_c \geq 0.1$ and $\alpha_d \geq 0.1$ 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. 2006). To model the diffusivity terms in the MHD equations, we used an implicit numerical scheme and the ICCG method for solving linear equations.

¹ Department of Astronomy, Cornell University, Ithaca, NY 14853-6801; romanova@astro.cornell.edu.
² Keldysh Institute of Applied Mathematics, Russian Academy of Sciences, Moscow, Russia; ustyug@ssp.Keldysh.ru.
³ Institute of Mathematical Modeling, Russian Academy of Sciences, Moscow, Russia; koldoba@ssp.Keldysh.ru.
⁴ Departments of Astronomy, and Applied and Engineering Physics, Cornell University, Ithaca, NY 14853-6801; RVL1@cornell.edu.
The MHD equations were solved in dimensionless form so that the results can be applied to different systems. We take the reference mass $M_0 = M_\star$, a scale $R_0 = 2R_\star$, and a matter flux $M_0$ that is close to the average matter flux through the disk. We then derive a reference density $\rho_0 = M_0/(v_o R_0^2)$, a velocity $v_o = (GM_0/R_0)^{1/2}$, a timescale $t_o = R_0/v_o$, and an angular velocity $\Omega_o = 1/t_o$. The reference magnetic field is $B_0 = \rho_0^{1/2}v_o$, and so $B_0 = \rho_0^{1/2}v_o$. A reference magnetic moment is $\mu_0 = B_0R_0^3 = (M_0v_o)^{1/2}R_0^3$. The value of the magnetic moment used in our simulations, $\mu_\star$, is typically 10 times larger than $\mu_0$, so we introduce a new reference variable $\mu_\star/\mu_0 = 10\mu_0$. The magnetic field at the surface of the star is $B_\star = \mu_\star/\mu_0R_\star$. The reference angular momentum flux is $N_0 = M_\star v_\star R_\star$. We measure time in units of the rotational period of a Keplerian disk at $R_\star$, $P_\star = 2\pi v_\star$. We solve the MHD equations for the normalized variables, $\bar{\rho} = \rho/\rho_0$, $\bar{v} = v/v_o$, $\bar{B} = B/B_0$, etc., and below show plots for normalized variables (with tildes dropped). In § 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 in which outflows occurred. The parameters are $\mu_\star = \mu_\star/\mu_0 = \Omega_\star = \Omega_0$ (corotation radius $r_\star = R_\star$), $\alpha_\star = 0.3$, and $\alpha_v = 0.2$. 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 $\chi \sim 45^\circ$ to $60^\circ$. 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 shows that the dominant force “pushing” matter to the wind is centrifugal force (Blandford & Payne 1982). At smaller $\theta$ there is a magnetically dominated outflow of the much lower density matter (e.g., Lovelace et al. 2002, Ustyugova et al. 2006).

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 onto the star through a funnel flow; and (5) the disk is pushed outward by the rapidly rotating magnetosphere, and the cycle repeats. Many field lines inflate and open during the 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 $\rho$, angular velocity $\Omega$, and azimuthal magnetic field $B_\phi$ in the high (top panels) and low states (bottom panels). In the high state, the disk has a closest approach to the star of $r_g \approx 2.5$, and the density in the inner disk is large. The magnetosphere rotates with super-Keplerian velocity. The 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 a modified expanded magnetosphere similar to the case of

![Flow Diagram](image-url)
“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 $\mu_s$, angular velocities $\Omega_s$, and viscosity and diffusivity coefficients, $\alpha_s$ and $\alpha_m$, and calculated the time-averaged matter fluxes to the star ($M^*_s$) and to the wind, ($M^*_w$), and the efficiency of the propeller,

$$ R \equiv \frac{\langle M^*_w \rangle}{\langle M^*_s \rangle} \approx 13.0 \left( \frac{\mu_s}{\mu_{50}} \right)^2 \left( \frac{\Omega_s}{\Omega_{50}} \right)^{10.5} \left( \alpha_m \right)^{2.1} \left( \alpha_s \right)^{2.5}. $$

The ratio $R$ may be very large, $R \gtrsim 50$–100; that is, almost all of the matter coming into the disk may be ejected by the rapidly rotating magnetosphere. The dependence of $R$ on $\mu_s$, $\Omega_s$, and $\alpha_s$ is such that stronger ejection is observed in cases of stronger field, faster rotation, and larger viscosity. However, the dependence on $\alpha_m$ has a turnover point at approximately 0.2. For $\alpha_s \lesssim 0.2$, $R$ increases with $\alpha_m$, while for larger values it decreases (Ustyugova et al. 2006). This paper shows the dependencies only for $\alpha_s \lesssim 0.2$.

It is important to note that no significant outflows were observed when the diffusivity was relatively low, $\alpha_s \lesssim 0.1$. This is because at low $\alpha_s$ the penetration of the disk matter into the magnetosphere is not significant. Furthermore, no outflows were observed at low viscosity. Analysis of the stresses shows 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 disk. On the other hand, the matter flux in the disk is proportional to the $\alpha_s$, and at larger $\alpha_s$ the disk penetrates to deeper, faster rotating layers of magnetosphere. Both factors are important in the generation of outflows, which appear at $\alpha_s \gtrsim 0.1$. Outflows were observed at a wide range of the magnetic Prandtl numbers, $Pr_m = \nu/\eta = \alpha_s/\alpha_m \approx 0.2$–6, and thus do not require the dominance of viscosity or diffusivity. Instead, both $\alpha$-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 cannot be investigated by our numerical model.

The amplitude of the fluxes changes rapidly (see Fig. 3). There is a typical timescale of variations $\tau_{\text{qpo}}$ in each case, which depends on the main parameters $\mu_s$, $\Omega_s$, $\alpha_m$, and $\alpha_s$. For given $\alpha_s$ and $\alpha_m$, the quasi-period increases with $\mu_s$ and $\Omega_s$, and varies in the range $\tau_{\text{qpo}} = (5$–100)$P_s$. We observed that for values of the diffusivity $\alpha_m = 0.2$, but relatively high viscosities $\alpha_s$ ranging from 0.6 to 1, the oscillations become highly periodic. In one of the sample runs the quasi-period changes from $\tau_{\text{qpo}} = 10P_s$ to 6.5$P_s$ (see Fig. 3, right panel). Period varied because 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 redirected by the rapidly rotating magnetosphere to the outflows (top panel of Fig. 4). Furthermore, there is a strong outflow of angular momentum carried by the twisted open magnetic field lines from the star ($N_i$), the Poynting flux, and the closed field lines connecting the star and the disk (bottom panel of Fig. 4; see also Lovelace et al. 2002). The time-averaged total angular momentum flux from the star is

$$ \langle N_i \rangle \approx -3.1 \left( \frac{\mu_s}{\mu_{50}} \right)^{1.1} \left( \frac{\Omega_s}{\Omega_{50}} \right)^{2.0} \left( \alpha_m \right)^{0.46} \left( \alpha_s \right)^{0.1}. $$

![Fig. 3.—Left panel shows matter fluxes to wind and to star for reference case. The right panel shows the quasi-periodic variations of the mass fluxes that we find for larger viscosity, in this case, $\alpha_s = 0.6$.](image1)

![Fig. 4.—Color background and streamlines show fluxes of angular momentum carried by matter (top panel) and by field (bottom panel) in high state ($eP_s = 924$). Note that the scales are different, because $N_i$ is very large near the surface of the star. However, the total integrated fluxes $N_m$ and $N_f$ have comparable values.](image2)
For our typical parameters the spin-down associated with open and closed field lines are comparable. However, at larger $\Omega_\star$ and/or $\mu_\star$, the outflow along the open field lines dominates (see related cases in Lovelace et al. 1995; Matt & Pudritz 2004), while at lower $\Omega_\star$ or $\mu_\star$, the situation reverses and a larger flux is associated with the closed field lines (as in Ghosh & Lamb 1979; RUKL02).

The spin-down timescale follows from equating the torque $\langle N_e \rangle R_{\star}$ to $I_d d\Omega/dt$, where $I_d \approx 10^{44}$ g cm$^2$ is the moment of inertia of the star. For the period of the star $P_\star = 2\pi/\Omega_\star$, we obtain $P(t) = P(0)(1 + \alpha_\star t)$, where the spin-down time is

$$t_{sd} \approx 0.036 \left( \frac{M_\star}{M_\odot} \right) \left( \frac{\mu_\odot}{\mu_\star} \right)^{-1/11} \left( \frac{0.2}{\alpha_d} \right)^{0.46} \left( \frac{0.2}{\alpha_c} \right)^{0.11}.$$  

2.5. Young CTTSs and Millisecond Pulsars

Our results can be directly applied to stars with relatively small magnetospheres, $r_m \approx (3-10) R_\star$, for example, to CTTSs or to accreting millisecond pulsars. Thus, for a CTTS with a mass $M_\star = 0.8 M_\odot$, radius $R_\star = 2 R_\odot$, accretion rate $\dot{M}_\star \approx 5 \times 10^{-8} M_\odot$ yr$^{-1}$ and other typical parameters $\alpha_d = 0.2$, $\alpha_c = 0.2$, and $\mu_\star = \mu_\odot$, we obtain $t_{sd} \approx 5.8 \times 10^3$ yr. We also derive dimensional values $\mu_\star \approx 6.2 \times 10^{16}$ G cm$^3$, $B_\star \approx 2.2 \times 10^3$ G, and $P_\star \approx 1$ day. Thus, if young CTTSs have a strong magnetic field, they spin down rapidly to their currently 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 $M_\star = 1.4 M_\odot$ and similar accretion rate $\dot{M}_\star \approx 5 \times 10^{-8} M_\odot$ yr$^{-1}$, we find $t_{sd} \approx 10^4$ yr. Taking $R_\star = 10^6$ cm and $\mu_\star = \mu_\odot$, we find $\mu_\star \approx 7.0 \times 10^{27}$ G cm$^3$, $B_\star \approx 7 \times 10^{9}$ G, and $P_\star \approx 1.3$ ms. In this case $t_{sd}$ represents the timescale 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 produces quasi-periodic outflows of matter to wide-angle ($\chi \approx 45^\circ$–$60^\circ$) conical winds. At the same time there is a strong field-dominated (or Poynting) outflow of energy and angular momentum along the open field lines extending from the poles of the star. The outflows occur for conditions in which the magnetic diffusivity and viscosity are significant, ($\alpha_d$, $\alpha_c$) $\approx 0.1$. 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 $\tau_{osc} \sim (5-100) P_\star$, increasing with $\mu_\star$ and $\Omega_\star$. We observed that the oscillations for relatively large $\alpha_c$ become highly periodic, with definite quasi-periods. A 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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