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Properties of strong and weak propellers from MHD simulations

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ABSTRACT

The propeller regime has been studied using axisymmetric numerical simulations, where matter accretes from a thin turbulent disk and interacts with a rotating magnetized star. A wide range of propeller strengths has been studied, from very strong (where the magnetosphere rotates much more rapidly than the inner disk) to very weak (where the magnetosphere rotates only slightly faster than the inner disk). We observed, that in all propellers, the disk-magnetosphere interaction is a strongly non-stationary process. However, the time-averaged characteristics of propeller outflows depend almost entirely on the fastness parameter, ω_s, which is the ratio of the stellar angular velocity to the inner disk's Keplerian velocity. The relative amount of matter ejected into the wind (the efficiency of the propeller) and its velocity, energy and angular momentum increase with ω_s. In addition, qualitative differences were observed between the strong and weak propellers: in the strong propellers, matter is accelerated above the escape velocity, forming large-scale outflows that consist of conically-shaped winds and a magnetic (Poynting flux) jet. In the weak propellers, matter flows into a widely-opened, conically-shaped wind with sub- or super-escape velocities that may partly fall back to the disk at some distance from the star. Stars spin down and a star-disk systems lose energy and angular momentum, which flow into winds and jets. Simulations were performed in dimensionless form for stars with magnetospheres of $5-7$ stellar radii. Results of the simulations can be applied to different types of magnetized stars, including Classical T Tauri stars (CTTSs), cataclysmic variables (CVs), and accreting millisecond pulsars (MSPs).

1. Introduction

Magnetized stars are expected to be in the propeller regime if the magnetosphere rotates more rapidly than the inner disk (e.g., Illarionov and Sunyaev 1975; Lovelace et al., 1999). Signs of the propeller regime have been observed in Classical T Tauri stars (CTTSs) (e.g., Bouvier et al. 2007; Donati et al., 2010; Grinin et al., 2015; Cody et al., 2016), cataclysmic variable AE Aqr (e.g., Mauche 2006; Wynn et al., 1997), and a few accreting millisecond pulsars (MSPs) at the ends of their outbursts, when the accretion rate decreased and the disk moved away from the star (e.g., van der Klis et al., 2000; van der Klis 2006; Patruno et al., 2009; Patruno and D'Angelo 2013; Bult and van der Klis 2014). Recently, transitional millisecond pulsars were discovered, where a millisecond pulsar transits between the state of an accreting MSP, and that of a radiopulsar (e.g., Papitto et al., 2013; Ferrigno 2014; Linares 2014; Patruno et al., 2014).[1] In these types of stars, the propeller regime is expected in the transition between these two states. In fact, different observational properties of transitional MSPs may be connected with the propeller state, such as the highly variable X-ray radiation (e.g., Ferrigno 2014; Patruno et al., 2014; Archibald 2015), γ−ray flares (e.g., De Martino et al. 2010) and radiation in the radio band with a flat spectrum, which indicates the presence of outflows or jets (e.g., Bogdanov 2015; Deller et al., 2015). Another interesting observational feature is the presence of accretion-induced pulsations, observed at very low accretion rates in some transitional MSPs and the CV AE Aqr. According to theoretical estimates, at low accretion rates, the inner disk should be far away from the star and accretion should be blocked by the centrifugal barrier of the propelling star (e.g., Archibald 2015; Papitto and Torres 2015; Papitto et al., 2015). However, observations show, that a small amount of matter accretes onto the star in spite of the centrifugal barrier. These observational properties of propeller candidate stars have not been well-understood.

The propeller regime has been studied in a number of theoretical works and numerical simulations. Illarionov and Sunyaev (1975) and Lovelace et al. (1999) investigated the strong propeller regime analytically. They suggested that the propelling star ejects all of the accreting

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[1] Transitional MSPs were predicted long ago (e.g., Bisnovatyi-Kogan and Komberg 1974; Alpar et al., 1982), but were not discovered until recently.

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matter into the wind, and *no matter accretes onto the star*.

In other analytical works and 1D numerical simulations it was suggested that the magnetosphere rotates only slightly faster than the inner disk, that is, the propeller is relatively weak, and *there are no outflows* (e.g., Sunyaev and Shakura 1977; Spruit and Taam 1993; D'Angelo and Spruit 2010,2012). In their models, the excess angular momentum is transferred back to the disk, forming a "dead" disk, and matter of the inner disk accretes onto the star quasi-periodically due to the cyclic process of matter accumulation and accretion.

The propeller regime has also been studied in a number of axisymmetric (2.5D) simulations (e.g., Romanova et al., 2005,2009; Ustyugova et al., 2006; Lii et al., 2014), which have shown that: **(a)** Both accretion and outflows are present; **(b)** The process of disk-magnetosphere interaction is strongly non-stationary, where the inner disk oscillates and matter accretes onto a star and is ejected into the winds in brief episodes; **(c)** Most of the matter flows into conically-shaped winds. In addition, a small amount of matter may flow into a magnetic (Poynting flux) jet; **(d)** A star spins down due to outflow of angular momentum along the open and closed field lines.

In these earlier studies, only stars with relatively small magnetospheres were modelled ($r_m \lesssim 3R_\star$, where $R_\star$ is the stellar radius). However, most of the propeller candidate stars have larger magnetospheres, which is why we adjusted the model in such ways as to allow us to model the stars with larger magnetospheres, $r_m \approx (5-7)R_\star$.

In addition, the earlier numerical simulations were mainly focused on very strong propellers, where the magnetosphere rotates much more rapidly than the inner disk (e.g., Romanova et al. 2009). However, propellers of lower strengths have not been systematically studied.

Some of the major questions are: (1) What are the properties of accretion and outflows in propellers of different strengths? In particular, (2) Which parts of the inner disk matter flow into the wind? (3) What is the velocity of matter in the wind? (4) What is the opening angle of the wind? (5) What is the rate of stellar spin-down? (6) How much energy flows into the outflows? (7) How do these properties depend on the strength of the propeller?

To answer these questions, we performed a number of axisymmetric simulations of propellers of different strengths and studied the properties of matter, energy and angular momentum flow in these propellers.

The plan of the paper is the following. In Section 2 we discuss the fastness parameter. We describe our numerical model in Section 3, and show the main results of our simulations and analysis in Sections 4 and 5. In Section 6 we derive the conditions for inflation and find the intervals of time between the inflation events. We conclude in Section 7. Appendix A provides the details of the numerical model. Appendix B shows different methods for deriving the magnetospheric radius and discusses the possible origins of scatter. Appendix C shows variation of different values in representative models. Appendix D provides examples of applications to different types of stars.

2. Fastness parameter ω_s

To characterize the strength of propellers, we will use the fastness parameter, which is defined as (e.g., Ghosh 2007)[2]:

$$\omega_s = \frac{\Omega_\star}{\Omega_K(r_m)} , \qquad (1)$$

where $\Omega_\star$ is the angular velocity of the star and $\Omega_K(r_m)$ is the Keplerian angular velocity of the inner disk at the magnetospheric radius, r_m, where the magnetic stress in the magnetosphere is equal to the matter stress in the disk:

$$\frac{B_p^2 + B_\phi^2}{8\pi} = \rho(v_p^2 + v_\phi^2) + p . \qquad (2)$$

Here, ρ is density, p is thermal pressure, v_p, v_ϕ and B_p, B_ϕ are the poloidal and azimuthal components of velocity and the magnetic field, respectively.[3]

In the case of a Keplerian disk, $\Omega_K(r_m) = (GM_\star/r_m^3)^{1/2}$, the fastness parameter can be presented in the form of:

$$\omega_s = \left(\frac{r_m}{r_{\rm cor}}\right)^{\frac{3}{2}} , \qquad (3)$$

where $r_{\rm cor}$ is the corotation radius, at which the angular velocity of the star matches the Keplerian angular velocity of the inner disk, $\Omega_\star = \Omega_K$:

$$r_{\rm cor} = \left(\frac{GM_\star}{\Omega_\star^2}\right)^{1/3} . \qquad (4)$$

The importance of the fastness parameter for the analysis of the propeller regime can be shown through a simplified analysis of the forces. In the case of a thin, cold accretion disk, the matter pressure is small, and the main forces acting on the matter of the inner disk are the gravitational, centrifugal and magnetic forces. In the strong propellers ($\omega_s > > 1$), the centrifugal force is expected to be the main force driving matter into the outflows (e.g., Romanova et al., 2009; Lii et al., 2014), so that the total force acting on a unit mass of the disk is dominated by effective gravity:

$$g_{\rm eff} = g + g_c ,$$

where $g = -GM_\star/r^2$ and $g_c = \Omega_\star{}^2 r$ are the gravitational and centrifugal acceleration, respectively. Taking into account the fact that at the inner disk $g(r_m) = -GM_\star/r_m^2 = -\Omega_K(r_m)^2 r_m$, we obtain:

$$g_{\rm eff} = -\Omega_K^2(r_m) r_m + \Omega_\star{}^2 r_m = \Omega_K^2(r_m) r_m(\omega_s^2 - 1) . \qquad (5)$$

One can see that $g_{\rm eff} \sim (\omega_s^2 - 1)$. In the cases of relatively strong propellers, $\omega_s > > 1$, the power-law dependence $g_{\rm eff} \sim \omega_s^2$ is expected. In reality, the magnetic force also contributes to acceleration and collimation of matter in the wind, and therefore the dependencies may be more complex. Nevertheless, we suggest that the fastness parameter may be an important parameter in determining the properties of the propeller regime.

3. The numerical model

We performed axisymmetric simulations of disk accretion onto a rotating magnetized star in the propeller regime. The model is similar to that used in the simulations of Lii et al. (2014), but with a few differences. Below, we briefly discuss the main features of the numerical model. More technical details of the model are described in Appendix A.

We consider accretion onto a magnetized star from an accretion disk, that is cold and dense, while the corona above and below the disk is hot and rarefied. The disk is geometrically thin, with an aspect ratio of $h/r \approx 0.15$, where h is the semi-thickness of the disk. The disk is about 2.7 times thinner than that used in Lii et al. (2014).

A star with an aligned dipole magnetic field is placed at the center of the coordinate system. Initially, the star rotates slowly, with a Keplerian angular velocity corresponding to a corotation radius of $r_{\rm cor} = 10R_\star$. We

[2] In our earlier studies of accretion onto slowly-rotating (non-propelling) stars, the fastness parameter determined different properties of the magnetospheric accretion (Blinova et al., 2016).

[3] In the cases of *slowly-rotating* stars (non-propellers), the magnetospheric radius has been derived theoretically from the balance of the largest components of the stresses: $B_p^2/8\pi = \rho v_\phi^2$, where B_p is the magnetic field of a star that is suggested to have a dipole field, and v_ϕ is the Keplerian angular velocity of the inner disk: $r_m = k[\mu_\star^4/(\dot{M}^2 GM_\star)]^{1/7}$, where $\mu_\star = B_\star R_\star^3$ is the magnetic moment of a star with a surface field of $B_\star$, $\dot{M}$ is the accretion rate in the disk, and $M_\star$ and $R_\star$ are the mass and radius of the star, respectively (e.g., Lamb et al. 1973). The dimensionless parameter $k \approx 0.5-0.6$ (e.g., Long et al., 2005; Zanni and Ferreira 2013). However, in the propeller regime, the magnetosphere departs from the dipole shape and the poloidal velocity v_p may become comparable to or larger than the azimuthal velocity v_ϕ. For this reason, we use Eq. (2) for finding r_m.