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LAUNCHING OF JETS BY PROPELLER MECHANISM

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RESUMEN

Hemos llevado a cabo una serie de simulaciones de acreción de disco sobre una estrella de neutrones magnetizada en rotación en el regimen de "hélice". Estas muestran que las hélices pueden ser débiles (sin flujos hacia el exterior) o fuertes (con flujos hacia el exterior). Los flujos dirigidos aparecen solamente cuando la "fricción" entre el disco y la magnetósfera es suficientemente grande, y cuando el flujo de materia en acreción no es muy pequeño. El gas fluye en un cono y es eyectado en forma centrífuga de las regiones internas del disco. Más cerca del eje, hay un flujo de energía y momento angular dominado por efectos magnéticos. La eficiencia de la hélice puede ser muy alta en el sentido de que la mayoría del gas que atraviesa el disco es eyectado en forma de vientos. El ritmo de rotación de la estrella disminuye rapidamente por la interacción con las líneas de campo cerradas en el disco y abiertas en la corona. Este mecanismo puede operar en una variedad de condiciones cuando la estrella magnetizada rota con velocidad super-Kepleriana en la frontera con la magnetósfera. Creemos que en general cualquier objeto con rotación super-Kepleriana puede producir flujos a partir de un disco, si la fricción entre ellos es lo suficientemente grande.

ABSTRACT

We carried out axisymmetric simulations of disk accretion to a rapidly rotating magnetized star in the "propeller" regime. Simulations show that propellers may be "weak" (with no outflows), and "strong" (with outflows). Investigation of the difference between these two regimes have shown that outflows appear only in the case where the "friction" between the disk and magnetosphere is sufficiently large, and when accreting matter flux is not very small. 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. This mechanism may act in a variety of situations where magnetized star rotates with super-Keplerian velocity at the magnetospheric boundary. We speculate that in general any object rotating with super-Keplerian velocity may drive outflows from accreting disk, if the friction between them is sufficiently large.

Key Words: **ISM: JETS AND OUTFLOWS — STARS: MAGNETIC FIELDS**

1. INTRODUCTION

Fast rotating accreting magnetized neutron stars or white dwarfs are expected to be in the propeller regime during their evolution (Davidson & Ostriker 1973; Illarionov & Sunyaev 1975; Stella, White, & Rosner 1986; Lipunov 1992; Treves, Colpi, & Lipunov 1993; Cui 1997; Alpar 2001; Mori & Ruderman 2003). 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; Li & Wickramasinghe 1997; Lovelace, Romanova, & Bisnovatyi-Kogan 1999; Ikhsanov 2002; Rappaport, Fregeau, & Spruit 2004; Eksi, Hernquist, & Narayan 2005) and studied with computer simulations. However only the case of quasi-spherical accretion was investigated in the axisymmetric simulations (Romanova et al. 2003) and the instabilities in the equatorial plane were investigated in case of disk accretion in 2D simulations (Wang & Robertson 1985).

We performed axisymmetric (2D) simulations of disk accretion to a fast rotating star in the propeller regime. Simulations have shown that in some cases a star spins-down but no outflow form (Romanova et al. 2004, hereafter RUKL04). In other cases strong outflows form (Romanova et al. 2005, here-

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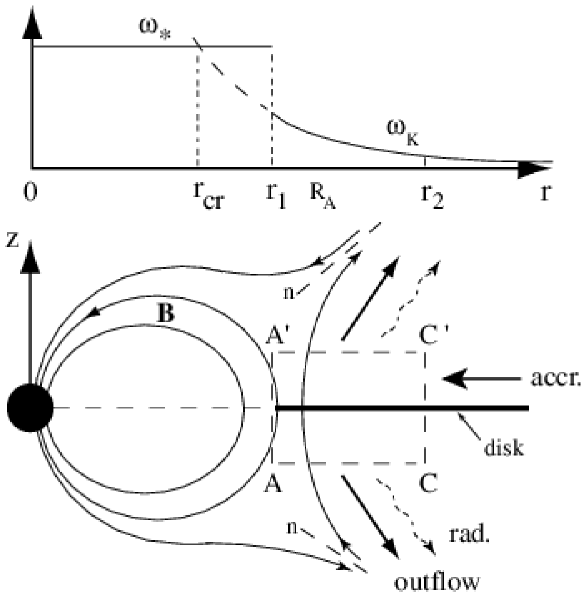

Fig. 1. The sketch demonstrates the basic principles of the propeller stage (from Lovelace et al. 1999)

after RUKL05); Ustyugova et al. 2005). In these Proceedings we discuss launching of jets and winds by propeller mechanism

2. A MODEL

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, that is where modified plasma parameter $\beta = (p+\rho\mathbf{v}^2)/(\mathbf{B}^2/8\pi) = 1$. Here $\mathbf{B}$ is the surface magnetic field of the star, Ω_* is angular velocity of the star.

The numerical model we use is similar to that of Romanova et al. (2002, hereafter RUKL02; 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).

We suggest that both viscosity and diffusivity 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 $\eta_{\rm t}$ described by $\alpha-$coefficients as in the Shakura and Sunyaev model. That is, we take $\nu_{\rm t} = \alpha_{\rm v} c_s^2/\Omega_K$ 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.

3. "WEAK" AND "STRONG" PROPELLERS

Simulations have shown that there are two types of propellers: "weak" propellers, at which a star strongly spins-down, but no significant outflows were observed (RUKL04), and "strong" propellers, at which a robust outflows of matter and magnetic energy are launched from the magnetosphere of the propelling star (RUKL05, Ustyugova et al. 2005). There are two conditions which are necessary to launch the outflows:

- Relatively high "friction" between magnetosphere and the disk, which we determined by viscosity and diffusivity;
- Relatively high specific matter flux (flux per unit area) in the disk, which is regulated by a number of parameters, including viscosity.

Figure 2 demonstrates the difference between weak and strong propellers. Top panel shows weak propeller, where matter flux is not strong enough to penetrate inward and also the "friction" between magnetosphere and the disk is not sufficient to launch outflows, and the bottom panel shows the case when outflows are successfully launched.

In case of"weak" propellers (RUKL04), a star strongly spins-down, but no significant outflows were observed. In case of "strong" propellers significant part of the disk matter is re-directed to the propeller-driven outflows (RUKL05; Ustyugova et al. 2005).

We observed that the disk oscillates between "high" and "low" states and expels matter to conical outflows quasi-periodically. In the high state matter comes closer to the disk and outflows are stronger. In the low state matter is pushed back by expanding magnetosphere and outflows are weaker. Figure 3 shows matter flow in the high (top panel) and low (bottom panel) states. Angular momentum of

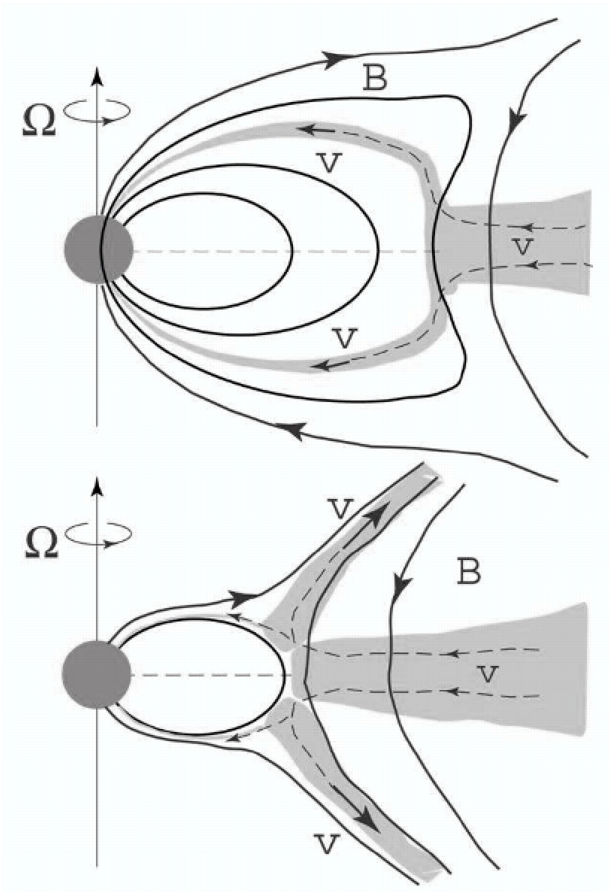

Fig. 2. The sketch demonstrates the difference between the weak (top panel) and strong (bottom panel) propellers.

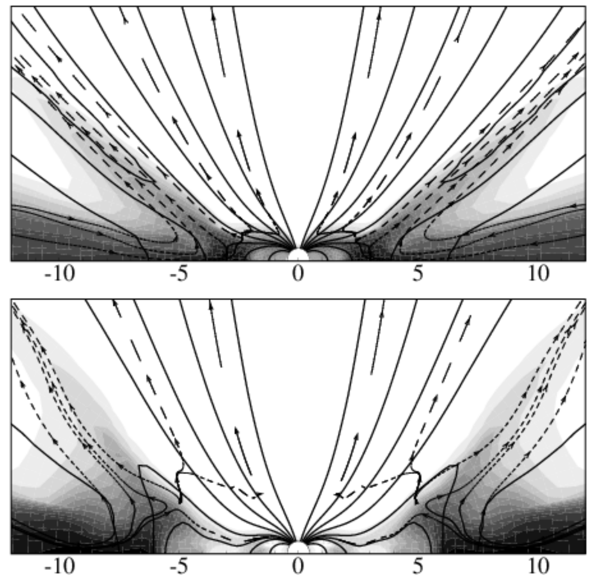

Fig. 3. Top panel shows example of matter flow in the "high" (top panel) and "low" (bottom panel) states. The background shows the density distribution, solid lines are magnetic field lines, vectors are velocity vectors. The top panel shows results of simulations after $T = 924$ Keplerian periods of rotation P_0 at $r = 1$. The bottom panel shows the flow 10 periods later.

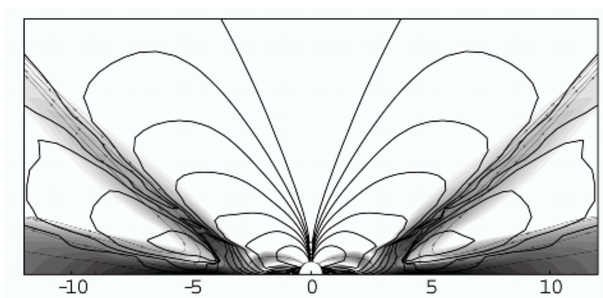

Fig. 4. The background and streamlines with arrows show the distribution of angular momentum carried by matter. Solid lines show distribution of angular momentum carried by the field.

the disk is re-directed by the fast rotating magnetosphere and flows to the conical wind (see Figure 4). A star loses its angular momentum through magnetic stresses. Part of this angular momentum is associated with the closed field lines connecting a star with the inner regions of the disk. Other part flows away along the open field lines connecting a star with corona. Fast rotation of the star at the propeller regime leads to enhanced opening of the magnetic field lines, specifically those located in the axial region. Field lines inflate and open forming the magnetic "tower" (see Figure 5). Most of the region is magnetically-dominated excluding the disk and conical wind where matter dominates. Figure 6 shows distribution of β. Most of matter flows to this conical outflow, which we call the "wind". From other side, some matter flows to the axial region located above the conical winds. We call this part of outflow "the jet". Jet typically has lower density but much higher velocity. This is also the region where significant energy flows due to the twisted magnetic field lines (Poynting flux).

4. QUASI-PERIODIC OSCILLATIONS

Simulations have shown that the system oscillates between the high and low states. The quasi-periodic outbursts associated with the disk-magnetosphere interaction were discussed earlier by Aly & Kuijpers (1990) and observed in simulations by Goodson et al. (1997, 1999), Matt et al. (2002),

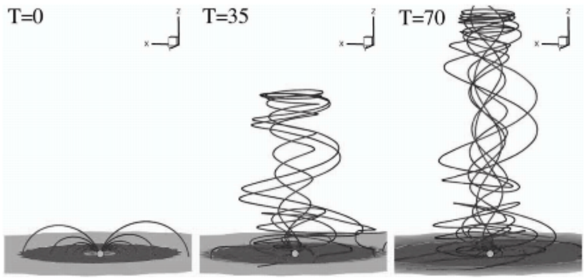

Fig. 5. Magnetic field of the dipole strongly inflates as a result of the fast rotation of the star forming the magnetic "tower" from RUKL04).

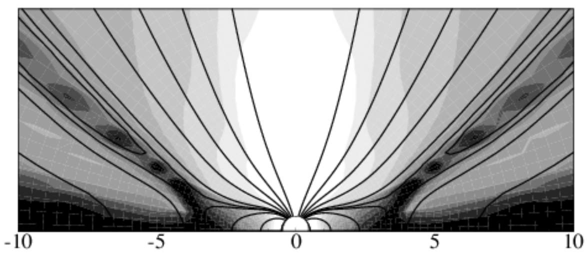

Fig. 6. The background shows distribution of the modified plasma parameter $\beta = (p + \rho v^2)/(B^2/8\pi)$.

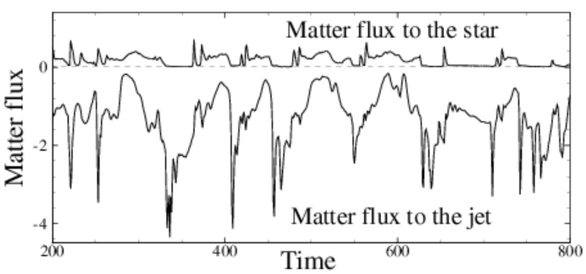

Fig. 7. Variation of matter fluxes to the star and to the jet for the case $\alpha_{\rm v} = 0.3$ and $\alpha_{\rm d} = 0.2$.

RUKL02, Kato et al. (2004), von Rekowski & Brandenburg (2004) and RUKL04. However, none of the earlier simulations concentrated on the propeller stage, and only few oscillation periods were obtained in earlier simulations. In recent simulations of strong propellers numerous oscillations were observed (RUKL05).

In many cases the quasi-periodic oscillations are not very well tuned (see Figure 7), and the time-scale of oscillations depends on parameters. At larger magnetic moments μ and Ω_*, time-scale is longer. We also observed that at larger values of viscosity oscillations become very well tuned (see Figure 8).

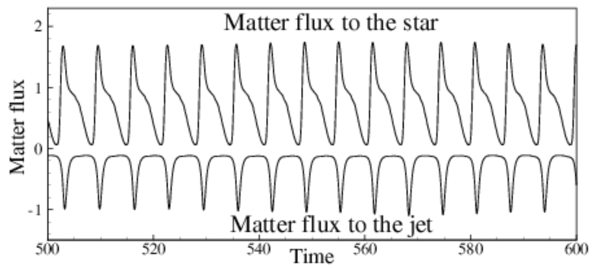

Fig. 8. Variation of matter fluxes to the star and to the jet for the case $\alpha_{\rm v} = 0.6$ and $\alpha_{\rm d} = 0.2$ (from RUKL05).

5. 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 (Figure 4). Furthermore, there is a strong outflow of angular momentum carried by the twisted open magnetic field lines from the star $\langle N_f \rangle$, the Poynting flux and closed field lines connecting a star and the disk. The time averaged total angular momentum flux from the star is $\langle N_s \rangle / N_0 \approx -3.1(\mu_*/\mu_{00})^{1.1}(\Omega_*/\Omega_0)^{2.0}(\alpha_{\rm d}/0.2)^{0.46}(\alpha_{\rm v}/0.2)^{0.1}$. 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 derived value $\langle N_s \rangle / N_0$ and the relation $N_* = I_* d\Omega_*/dt$, where $I_* \approx 0.4 M_* R_*^2$ is 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

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

Our simulations may be directly applied only to stars with relatively small magnetospheres, $r_m \sim 3-10R_*$, this is why we show below an example for millisecond pulsars. For a neutron star with mass $M_* = 1.4 M_\odot$ and accretion rate $\dot{M}_0 \approx 5 \times 10^{-8}$ $M_\odot$/yr, we find the spin-down time $t_{sd} \approx 10^6$ 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.

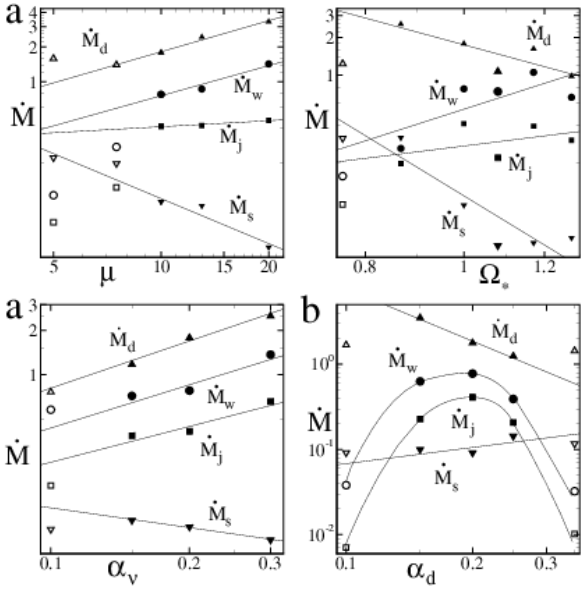

Fig. 9. Dependence of matter fluxes on the main parameters of simulatons for reference run. $\dot{M}_d$ - matter flux through the disk, $\dot{M}_w$ - to the wind, $\dot{M}_j$ - to the jet, $\dot{M}_s$ - to the star (from Ustyugova et al. 2005).

One can see that for larger magnetospheres, the spin-down will be faster.

6. EFFICIENCY OF PROPELLER

We changed the main parameters of the model: magnetic moment of the star μ, angular velocity of the star Ω_*, viscosity $\alpha_{\rm v}$ and diffusivity $\alpha_{\rm d}$ coefficients and calculated matter fluxes to the wind $\dot{M}_w$, to the jet $\dot{M}_j$, to the star $\dot{M}_s$ and total matter flux through the disk $\dot{M}_d$. Figure 9 shows dependencies of these fluxes on the main parameters. One can see that at larger magnetic moment and angular velocity of the star, more matter flows to the winds/jets and less matter accretes to the star. The efficiency of propeller may be very high, so that most of disk matter may be re-directed to the jet and wind. Matter fluxes to the wind and jet also increase with increase of viscosity. Dependence on diffusivity, however, has a maximum near $\alpha_{\rm d} \approx 0.2$. At smaller values, the diffusivity helps to increase the "friction" between magnetosphere and the disk, because the disk matter penetrates through the field lines of magnetosphere and thus magnetosphere transports its angular momentum. However at larger values of $\alpha_{\rm d}$ the slippage of field lines through the disk matter become significant and the coupling between the disk matter and magnetosphere decreases. It is clear that in case of "weak" propellers the coupling between magnetosphere and the disk was not strong enough to transport the angular momentum from the star to the disk, and no outflows were observed.

7. POSSIBLE APPLICATION TO BLACK-HOLE SYSTEMS

It is interesting to note that disk oscillations and quasi-periodic outbursts were observed in microquasars (see, e.g., this volume), which have a black hole in the center. The nature of these oscillations is not known and the similarity between our simulations and observations of microquasars may be accidental. However, the question is discussed in the literature, that in case of the black hole systems, the magnetic flux may accumulate in the inner regions of the disk, and then reconnect, and this may lead to quasi-periodic oscillations and outbursts to jets (e.g., Mayer, this volume). However, it is still not clear (1) how magnetized matter of the inner regions of the disk interact with the black hole, or (2) can rapidly rotating black hole influence to the rotation of the inner regions of the disk through magnetic field lines? If Kerr black hole transports its angular momentum to the inner regions of the disk, then these regions of the disk will rotate with super-Keplerian velocity and may act as propeller. In fact, a star with the dipole magnetic field, or, a black hole may be compared to the rotating super-Keplerian ball which transports part of its angular momentum to the surrounding matter which may flow to the jets during periods of enhanced accretion. Note, that in microquasars periods of outflow are associated with enhanced accretion rates (e.g., Novak, this volume). Interesting to note, that in full GR simulations of the disk accretion to a black hole, it was observed that the black hole does transport angular momentum to the disk (Hawley & Krolik, this volume). Future simulations are needed with the larger magnetic field in the disk to understand the interaction of the rapidly rotating black hole with the disk.

8. 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 and angular momentum along the open field lines extending from the poles of the star. 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.

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REFERENCES

Alpar, M. A. 2001, ApJ, 554, 1245
Aly, J. J., & Kuijpers, J. 1990, A&A, 227, 473 73
Bisnovatyi-Kogan, G. S., & Ruzmaikin, A. A. 1976, Ap&SS, 42, 401
Cui, W. 1997, ApJ, 482, L163
Davidson, K., & Ostriker, J. P. 1973, ApJ, 179, 585
Davies, R. E., Fabian, A. C., & Pringle, J. E. 1979, MNRAS, 186, 779
Eksi, K. Y., & Alpar, M. A. 2003, ApJ, 599, 450
Eksi, K. Y., Hernquist, L., & Narayan, R. 2005, ApJ, 623, L41
Feigelson, E. D., & Montmerle, T. 2005, ARA&A, 37, 363
Ghosh, P., & Lamb, F. K. 1979, ApJ, 234, 296
Goodson, A. P., Böhm, K.-H., Winglee, R. M. 1999, ApJ, 524, 142
Goodson, A. P., Winglee, R. M., & Böhm, K.-H., 1997, ApJ, 489, 199
Illarionov, A. F., & Sunyaev, R. A. 1975, A&A, 39, 185
Ikhsanov, N. R. 2002, A&A, 381, L61
Kato, S. 1978, MNRAS, 185, 629
Kato, Y., Hayashi, M. R., & Matsumoto, R. 2004, ApJ, 600, 338
Li, J., & Wickramasinghe, D. T. 1997, in ASP Conf. Ser. 121, Accretion Phenomena and Related Outflows, ed. D. T. Wickramasinghe, G. V. Bicknell, & L. Ferrario (San Francisco: ASP), 241
Lipunov, V. M. 1992, Astrophysics of Neutron Stars, (Berlin: Springer-Verlag)
Lovelace, R. V. E., Romanova, M. M., & Bisnovatyi-Kogan, G. S. 1995, MNRAS, 275, 244
_________. 1999, ApJ, 514, 368
Matt, S., Goodson, A. P., Winglee, R. M., & Böhm, K.-H. 2002, ApJ, 574, 232
Matt, S., & Pudritz, R. E. 2004, ApJ, 607, L43
Mori, K., & Ruderman, M. A. 2003, ApJ 592, L75
Rappaport, S. A., Fregeau, J. M., & Spruit, H. 2004, ApJ, 606, 436
Romanova, M. M., Toropina, O. D., Toropin, Yu. M., & Lovelace, R. V. E. 2003, ApJ, 588, 400
Romanova, M. M., Ustyugova, G. V., Koldoba, A. V., & Lovelace, R. V. E. 2002, ApJ, 578, 420 (RUKL02)
_________. 2004, ApJ, 616, L151 (RUKL04)
_________. 2005, ApJ, 635, L165 (RUKL05)
Stella, L., White, N. E., & Rosner, R. 1986, ApJ, 308, 669
Treves, A., Colpi, M., & Lipunov, V. M. 1993, A&A, 269, 319
von Rekowski, B., & Brandenburg, A. 2004, A&A, 420, 17
Ustyugova, G. V., Koldoba, A. V., Romanova, M. M., & Lovelace, R. V. E. 2006, ApJ, 646, 304
Wang, Y.-M., & Robertson, J. A. 1985, A&A 151, 361

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