Populations of High Energy Sources in Galaxies
Proceedings IAU Symposium No. 230, 2005
E. J. A. Meurs & G. Fabbiano, eds.

doi:10.1017/S1743921306007769

Spin changes in X-ray pulsars

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Abstract. The conventional picture of disk accretion onto magnetized neutron stars has been challenged by the spin changes observed in a few X-ray pulsars, and by theoretical results from numerical simulations of disk-magnetized star interactions. Here we present a model for the torque exerted by accretion disks on magnetized neutron stars, assuming accretion continues even for fast rotators.

Keywords. accretion disk, pulsars, magnetic field.

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1. Introduction

Magnetic fields play an important role in transferring angular momentum between neutron stars and accretion disks. In the model developed by Ghosh & Lamb (1979) the stellar magnetic field lines are assumed to penetrate the accretion disk, and become twisted because of the differential rotation between the star and the disk. The resulting torque can spin up or down the central star, depending on the star's rotation, magnetic field strength, and mass accretion rate. However, this standard model has been challenged by recent observational and theoretical investigations on accreting X-ray pulsars (Bildsten *et al.* 1997; Galloway *et al.* 2002; Romanova *et al.* 2003, 2004). The puzzling issues include (1) abrupt spin reversals in X-ray pulsars, (2) spin-down in millisecond X-ray pulsars throughout the outburst, (3) spin-down rates increasing with accretion rate, and (4) accretion in the "propeller" regime.

2. The torque

We adopt the following assumptions during both accretion and propeller phases.

(1) The azimuthal component B_ϕ of the field on the surface of the disk is generated by rotation shear (Wang 1995)

$$\frac{B_\phi}{B_z} = \begin{cases} \gamma(\Omega_* - \Omega_{\rm K})/\Omega_{\rm K}, & \Omega_* \leqslant \Omega_{\rm K} \\ \gamma(\Omega_* - \Omega_{\rm K})/\Omega_*, & \Omega_* > \Omega_{\rm K}, \end{cases} \tag{2.1}$$

where B_z is the vertical component of the field, the parameter γ is of order unity, Ω_* and $\Omega_{\rm K}$ are the stellar spin rate and the Keplerian angular velocity in the disk.

(2) The inner radius R_0 of the disk is at the magnetospheric radius $R_{\rm m}$ (Davidson & Ostriker 1973),

$$R_0 \simeq R_{\rm m} = \left(\frac{\mu^4}{2GM\dot{M}^2}\right)^{1/7}, \tag{2.2}$$

where $\mu = B_* R_*^3$ is the magnetic moment of the neutron star.

(3) In the magnetosphere the angular momentum transfer rate is given by,

$$N_0 = \xi \dot{M} (GMR_0)^{1/2} (1 - \omega), \tag{2.3}$$

where $\omega = \Omega_*/\Omega_{\rm K}(R_0)$ and $0 < \xi < 1$.

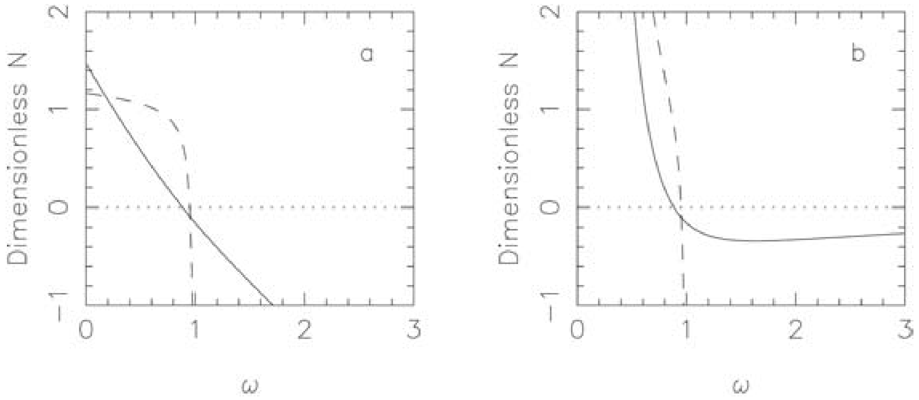

Figure 1. The solid lines show the dimensionless torque (a) $N/\dot{M}(GMR_0)^{1/2}$ and (b) $N/(\mu^2/3R_c^3)$ as a function of the fastness parameter ω. The dashed lines represent the standard model.

The total torque exerted on the star by the disk is then

$$N = \begin{cases} \dot{M}(GMR_0)^{1/2}[\xi(1-\omega) + \frac{\sqrt{2}\gamma}{3}(1 - 2\omega + \frac{2\omega^2}{3})], & \omega \leqslant 1 \\ \dot{M}(GMR_0)^{1/2}[\xi(1-\omega) + \frac{\sqrt{2}\gamma}{3}(\frac{2}{3\omega} - 1)], & \omega > 1. \end{cases} \tag{2.4}$$

Figures 1a and 1b show the dependence of the dimensionless torque $N/\dot{M}(GMR_0)^{1/2}$ and $N/(\mu^2/\sqrt{2}R_c^3)$ on ω in solid curves with $\xi = \gamma = 1$, respectively. The dashed curves in the figures represent the results in the disk model of Wang (1995) for comparison. In Fig. 1a there is no singularity problem in this work when $\omega \to 1$, the parameter space range for ω for spin-down with accretion is also much wider. The critical fastness parameter ω_c, at which $N = 0$, is $\omega_c \simeq 0.884$. Furthermore, it indicates that, for constant $\dot{M}$, the spin-down torque increases with Ω_* ($\propto \omega$), in line with the numerical simulation results by Romanova *et al.* (2004). Figure 1b shows how the torque varies with $\omega \propto \dot{M}^{-3/7}$ when μ and Ω_* are invariant. One can see that the spin-down torque is not a monotonous function of ω (or $\dot{M}$) when $\omega > \omega_c$. The spin-down torque takes the maximum value when $\omega \simeq 1.634$. Thus a given spin-down torque can correspond to two values of ω. *When* $\omega > 1.634$, *the spin-down torque increases with* $\dot{M}$, which is opposite to the dependence in the standard model, but consistent both with the observational fact in the X-ray pulsar GX 1+4 that the X-ray flux appears to be increasing with the spin-down torque (Chakrabarty 1995), and with the numerical simulation results by Romanova *et al.* (2004).

Acknowledgements

This work was supported by NSFC under grant number 10025314 and MSTC under grant number NKBRSF G19990754.

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