On the Magnetic Field of the Ultraluminous X-Ray Pulsar M82 X-2

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Abstract

The discovery of the ultraluminous X-ray pulsar M82 X-2 has stimulated lively discussion on the nature of the accreting neutron star. In most of the previous studies the magnetic field of the neutron star, ranging from $\lesssim 10^9$ G to $> 10^{14}$ G based on the standard thin, magnetized accretion disk model. However, under super-Eddington accretion the inner part of the accretion disk becomes geometrically thick. In this work we consider both radiation feedback from the neutron star and the sub-Keplerian rotation in a thick disk. We find the dipole magnetic field is likely $\lesssim 10^{13}$ G. The predicted accretion rate change can be used to test the proposed models by comparison with observations.

1 Disk Models

1.1 Thin-disk model

Our thin disk model is based on the original work of Ghosh & Lamb (1979) and modified by Wang (1987, 1995).

In this model the NS magnetic field lines are assumed to thread the accretion disk due to various instabilities and freeze with the disk plasma, so they become twisted and exert a torque on the NS due to differential rotation between the NS and the disk.

The total torque on the NS can be written as

$$N = N_0 + N_+ + N_- = N_0 f(\omega_s).$$

where $f(\omega_s) = 1 - \frac{\omega_s}{\omega_c}$ is a function of the "fastness parameter" $\omega_s \equiv \Omega_s/\Omega_K(r_0)$.

So we can get

$$-\frac{a\dot{P}_{-10}}{\mu_{30}^{2/7}P^2\dot{m}^{6/7}} = 1 - \frac{b\mu_{30}^{6/7}}{P\dot{m}^{3/7}},$$

where $\dot{m} = \dot{M}/\dot{M}_{cr}$ is the accretion rate, with $\dot{M}_{cr}$ being the maximum accretion rate for a NS, a and b is the parameters of some constants.

1.2 Thick-disk model

For a rapidly accreting NS,

- radiation inside the disk and from the NS becomes important in determining the dynamics and structure of the inner disk region.
- the rotation of the disk matter becomes sub-Keplerian, that is

$$\Omega(r) = A\Omega_K(r),$$

where $A = \sqrt{1 - \frac{L_{co}}{L_{cr}}} = \sqrt{1-\dot{m}}$. Taking into account possible beamed emission, we can write a more general form as $A = \sqrt{1-\beta\dot{m}}$

The equation for the spin evolution becomes

$$-\frac{a\dot{P}_{-10}}{A^{6/7}\mu_{30}^{2/7}P^2\dot{m}^{6/7}} = 1 - \frac{b\mu_{30}^{6/7}}{A^{10/7}P\dot{m}^{3/7}}.$$

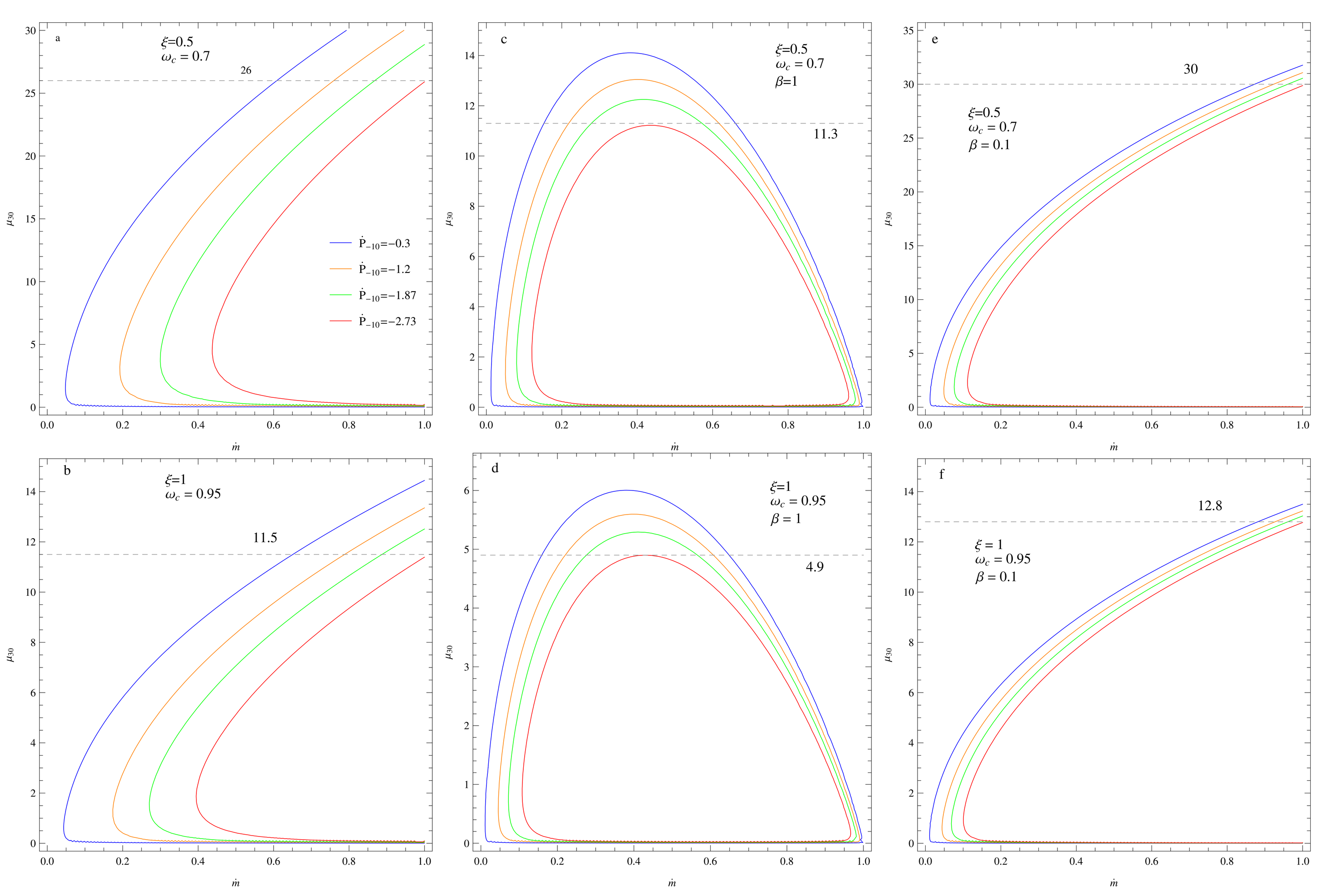

Figure 1: The $\mu_{30} - \dot{m}$ relations for M82 X-2 in thin and thick disk models considering all four measured values of the period derivative,

Table: Results of figure 1

panel	a	b	c	d	e	f
disk model	thin disk model		thick disk model			
ξ	0.5	1	0.5	1	0.5	1
ω_c	0.7	0.95	0.7	0.95	0.7	0.95
β	–		1		0.1	
μ_{30}	<26	<11.5	<11.3	<4.9	<30	<12.8

2 Results

- Taking $\dot{M}_{cr} = 10^{20}$ gs^{-1}, the calculated $\mu_{30} - \dot{m}$ relations are shown in Figure 1 (Only the common values of the μ_{30} for the four curves give a self-consistent estimate of μ_{30}.) and the results was listed in Table.
- Figure 2 shows the predicted mass accretion rates based on the results in Figure 1 with $\mu_{30} = 10$.

  The size relation of $\dot{m}$ between the first three points and the last one can be used to test which model can better reproduce the observed ones. These can be compared with the light curve (Fig. 1 in Bachetti et al., 2014) . *If the variation in the X-ray flux was mainly contributed by X-2*, the thick disk model is consistent with observations while the thin disk model is disfavored.

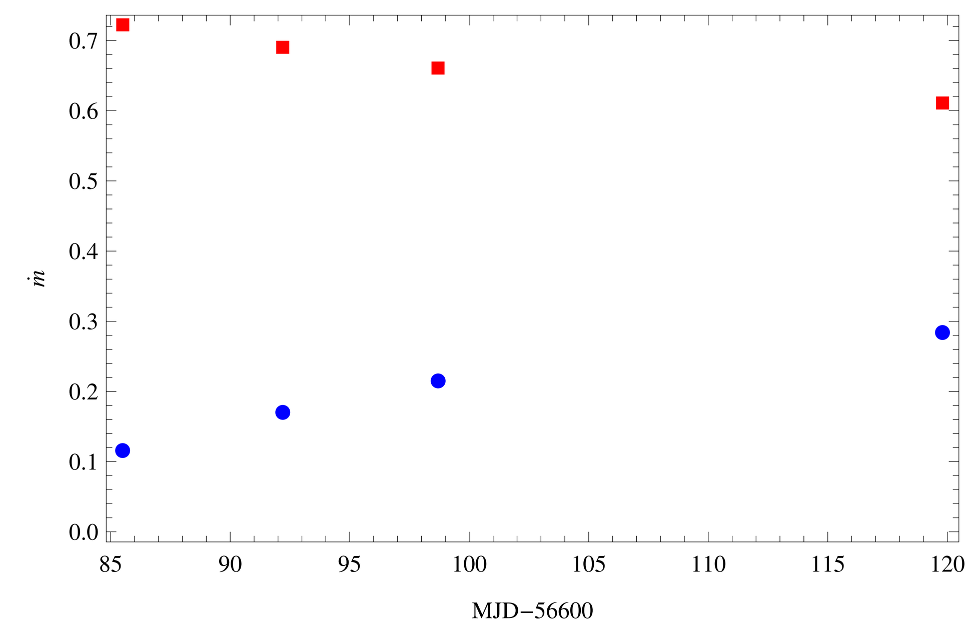

Figure 2: The blue dots represent the solutions of the thin disk model and the left branch solutions of the thick disk model with $\beta = 1$ while the red squares represent the right branch solutions in the thick disk model.

3 Discussion

- We demonstrate that the observed spin variations in M82 X-2 and the other NS ULXs require super-Eddington accretion, where the thin disk models are not self-consistent.
- We develop a thick disk model showing that the magnetic field of M82 X-2 is $\lesssim$ a few 10^{13} G, depending on the maximum accretion rate $\dot{M}_{cr}$, suggesting that M82 X-2 is a NS with a traditional dipole field The predicted flux change in this case also seems to be in agreement of observations.

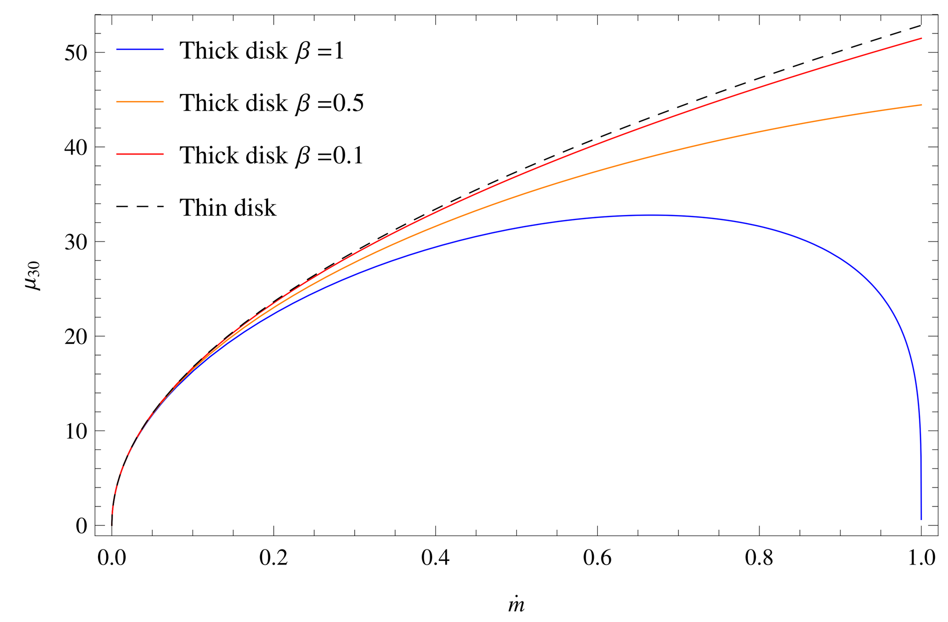

Figure 3: The $\mu_{30} - \dot{m}$ relations of the thin and thick disk models with $\xi = 0.5$ when the inner disk radius equals the corotation radius.

- Assuming that the propeller effect occurs at luminosity of $\sim 10^{40}$ ergs^{-1} in M82 X-2, a comparison of the $\mu - \dot{m}$ relation is shown in Figure 3, showing that in the thin disk model μ always increases with $\dot{m}$ under the condition of $r_0 = r_c$, while in the thick disk case, μ becomes smaller and decreases with $\dot{m}$ when $\dot{m} > 0.4\dot{m}_{cr}$, This is consistent with the current view that magnetars are very young NSs (with ages less than a few 10^4 yr), since a magnetar's field decays by Ohm diffusion and Hall drift on a timescale $< 10^{5-6}$ yr.
- A caveat in our work is that we assume that radiation from the NS is nearly isotropic. It has been suggested that X-ray radiation from the three NS ULXs is highly isotropic because of super-Eddington accretion. However, a very narrow pulse profile would be expected in the context of highly beamed radiation, which is in sharp contrast with the sinusoidal pulse profiles observed in both M82 X-2 and XMMU J235751.1−323725 in NGC7793 P13. These features imply nearly isotropic radiation and its physical origin needs further exploration.

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References

[1] Andersson, N., Glampedakis, K., Haskell, B., & Watts, A. L. 2005, MNRAS, 361, 1153

[2] Bachetti, M., Harrison, F. A., Walton, D. J., et al. 2014, Nature, 514, 202

[3] Ghosh, P., & Lamb, F. K., 1979, ApJ, 234, 296

[4] Wang, Y.-M. 1987, A&A, 183, 257; 1995, ApJL, 449, L153