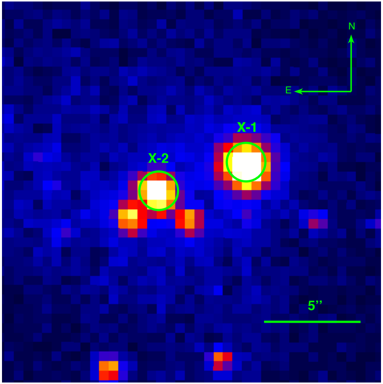
Super-Eddington accretion onto a magnetized neutron star

Anna Chashkina, Pavel Abolmasov and Juri Poutanen

University of Turku, Nordita and SAI MSU

April 18, 2017

Motivation. Ultraluminous X-ray pulsars

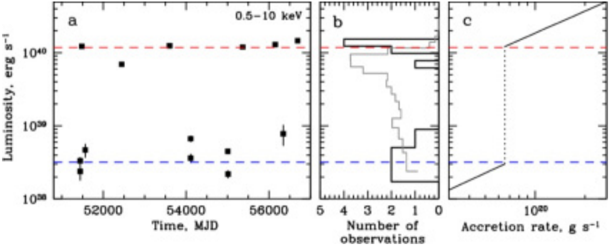


(Tsygankov et al., 2015)

- M82 X2 (Bachetti et al., 2014). $L_x \sim 10^{40}$erg s^{-1}. Spin period $p_s = 1.37$s, $\dot{p} \sim 10^{-10}$s s^{-1}
- NGC 7793 P13 (Israel et al., 2017). $L_x = 5 \times 10^{39}$erg s^{-1}. Spin period $p_s = 0.42$s
- NGC 5907 (Israel et al., 2016). $L_x \sim 10^{41}$erg s^{-1}. Spin period $p_s = 1.13$s, $\dot{p} \sim 5 \times 10^{-9}$s s^{-1}

M82 X2: Magnetic field

- Standard magnetic field B $\sim 10^{12}$G:
  - Bachetti et al., 2014
  - Lyutikov, 2014
- Low magnetic field B $\sim 10^{9}$G:
  - Kluzniak and Lasota, 2015
- High magnetic field B $\gtrsim 10^{14}$G:
  - Tsygankov et al., 2015



Irradiation from the column. Possible effects

- Pressure gradient is important

$$v_r \frac{\partial v_r}{\partial R} - \frac{v_\phi^2}{R} = -\frac{1}{\rho}\frac{\partial P}{\partial R} - \frac{GM}{R^2}$$

- Magnetospheric radius increases

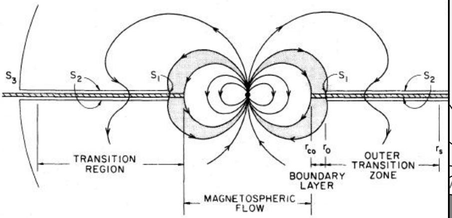
$$R_{in} = \xi \left(\frac{\mu^2}{2\dot{M}\sqrt{2GM_{ns}}} \right)^{2/7}$$

$\mu = BR_{ns}^3/2$ - dipolar magnetic moment, if B is polar magnetic field at the NS surface (and no higher multipoles present)

- Non-local Eddington limit when $P_{rad} = P_{mag}$.

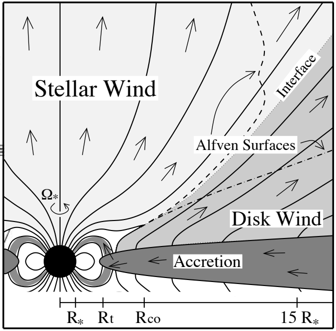
Magnetospheric accretion: Theory

Magnetically-threaded disk:



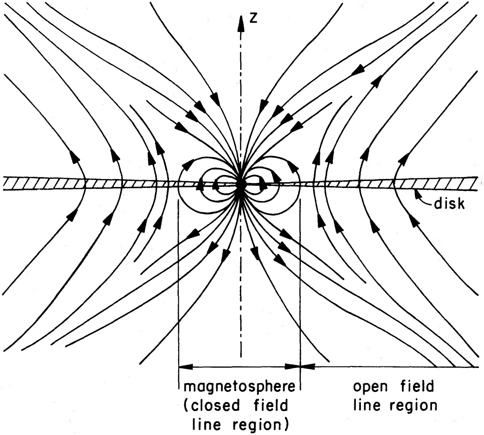
Ghosh and Lamb 1979, Wang 1987, Kluzniak and Rappaport 2007

Narrow boundary layer



Matt and Pudritz 2005, Scharlemann 1978, Anzer and Boerner 1980

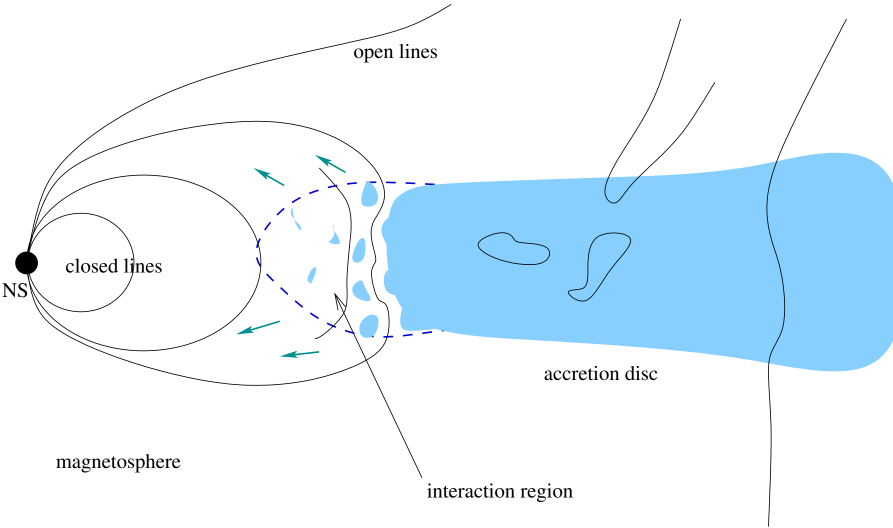
Magnetospheric accretion: Simulations



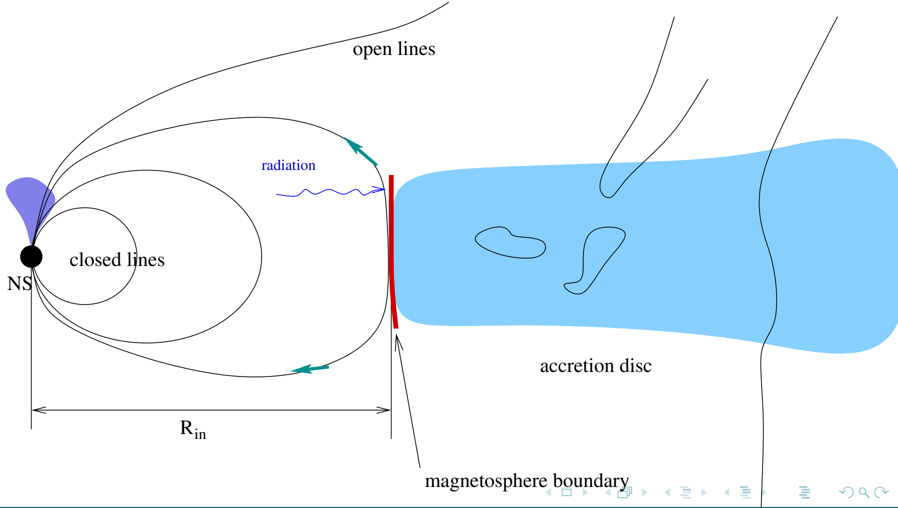
Open field lines

Lovelace et al. 1995, Parfrey et al. 2016

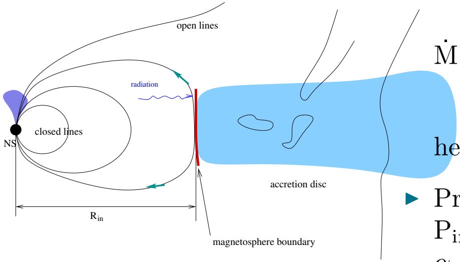
Our approach (general picture)



Our approach (neglecting radial extention of the transition layer)



Boundary conditions



- Excess angular momentum is removed by magnetic and radiation stresses

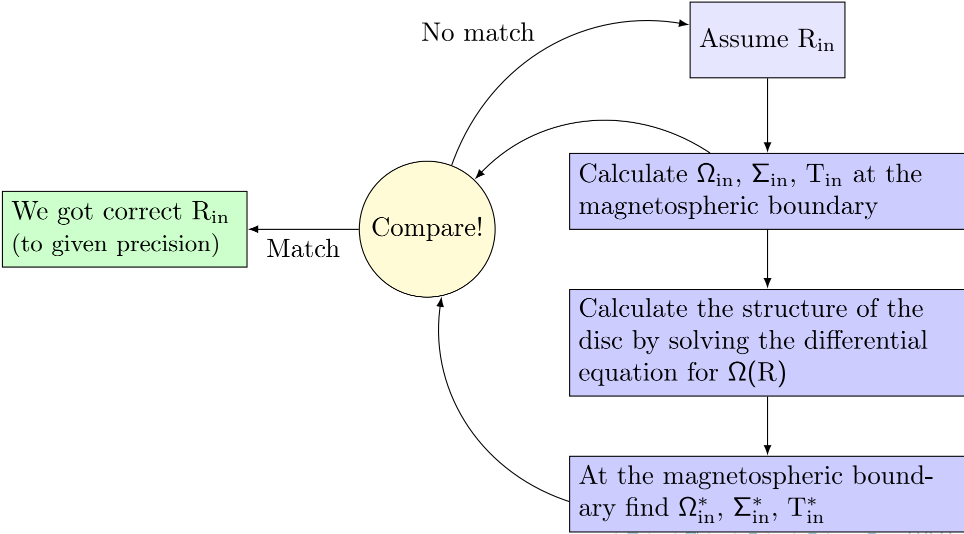
$$\dot{M}(\Omega_{in} - \Omega_{ns})R_{in}^2 = k_t \frac{\mu^2 H_{in}}{R_{in}^4} + L \frac{\Omega_{in}}{c^2} H_{in} R_{in}$$

here $k_t = \dfrac{B_\phi}{B_z}$

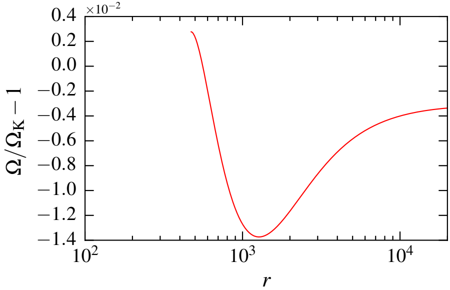
- Pressure balance at the boundary $P_{in} = P_{mag} + P_{rad}$ and α-prescription:

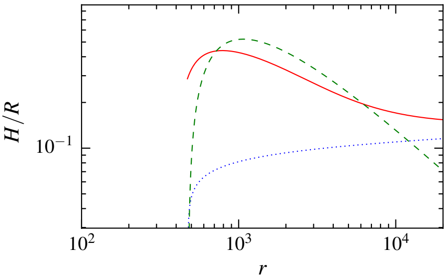
$$W_{r\phi}^{in} = 2\alpha \left(\frac{\mu^2 H_{in}}{8\pi R_{in}^6} + \frac{L H_{in}}{4\pi R_{in}^2 c} \right)$$

Scheme of solution



Disc structure

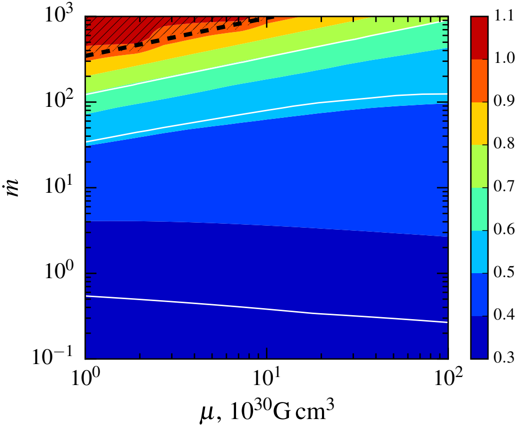




$\mu = 10^{31}\mathrm{G\ cm^3}$, $\dot{\mathrm{m}} = 500\,\dot{\mathrm{M}}_{\mathrm{Edd}}$, $\xi = 0.78$

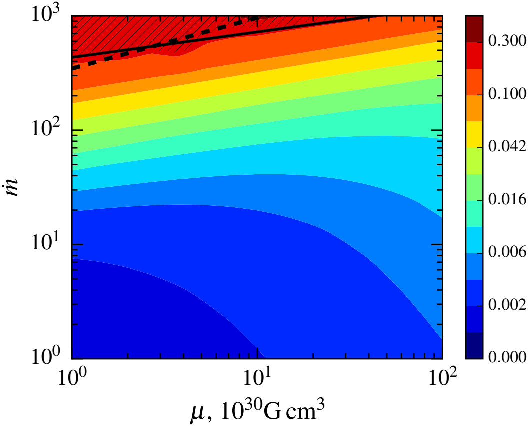
Our model, standard Shakura-Sunyaev's radiation pressure dominated and gas pressure dominated discs are shown.

Results. Magnetosheric radius ξ



White lines correspond to $(H/R)_{max} = 0.03$, 0.1 and 0.3.

Results. The influence of radiation. $\xi(\eta = 0.1) - \xi(\eta = 0)$



η is accretion efficiency

Results. ULXs

M82 X2

Without irradiation $\xi \simeq 0.7$ and $B \simeq 10^{14}$G. With irradiation $\xi \simeq 0.8$ and $B \simeq 7.4 \times 10^{13}$G

η \ α	0.01	0.05	0.1	0.5	1
0	161	72	51	22	16
0.1	157	62	36	–	–
0.2	153	52	10	–	–

Table: Magnetic moments μ in units 10^{30}G cm^3 for different values of η and α. All the calculations were made for $\dot{m} = 500$ ($L = 10^{40}$ erg s^{-1}) and $p_s = 1.37$ s, aimed to reproduce the properties of ULX-pulsar M82 X-2.

NGC 7793 P13

Without irradiation $\xi \simeq 0.7$ and $B \simeq 1.4 \times 10^{13}$G. With irradiation $\xi \simeq 0.7$ and $B \simeq 1.7 \times 10^{13}$G

Conclusions

- $\xi = \dfrac{R_{in}}{R_A}$ is not constant. It depends on magnetic field and accretion rate
- ξ is tightly related to inner disc thickness H_{in}/R_{in} and reaches about 1 when $H_{in}/R_{in} \to 1$
- It is important to take into account irradiation by the column when the inner disc becomes thick
- irradiation can strongly alter the flows in the magnetosphere
- In radiation-pressure-dominated disc $R_{in} \propto \alpha^{2/9}\mu_{30}^{4/9}$ is independent of $\dot{M}$

Approximations of ξ

Boundary condition:

$$\dot{M}(\Omega_{in} - \Omega_{ns})R_{in}^2 = k_t \frac{\mu^2 H_m^2}{R_{in}^4} + L \frac{\Omega_{in}}{c^2} H_{in} R_{in}$$

In dimensionless form:

$$\omega_{in} = \frac{r_{in}^{3/2}}{1 - \eta h_{in}/r_{in}} \left(2\lambda \frac{k_t \mu_{30}^2 h_{in}}{\dot{m} r_{in}^6} + \frac{p_*}{p_s} \right)$$

Assume $\omega_{in} = 1$ and large p_s. We have:

$$\xi_\infty = 2^{1/7} (2k_t)^{2/9} \left(\frac{\lambda \mu_{30}^2}{\dot{m}} \right)^{-4/63} h_{in}^{2/9}$$

Gas pressure dominated disc:

$$\xi_{\infty,B} \sim (\mu_{30}^2)^{2/483} \dot{m}^{26/483} \alpha^{-2/69}$$

Radiation pressure dominated disc:

$$\xi_{\infty,A} = 2^{1/7} \left(\frac{73\alpha}{24} \right)^{2/9} \frac{\dot{m}^{2/7}}{(\lambda \mu_{30}^2)^{4/63}}$$

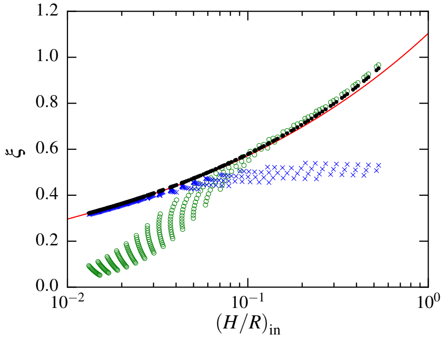
Approximasions of ξ

Gas pressure dominated disc:

$$\xi_{\infty,\mathrm{B}} \sim (\mu_{30}^2)^{2/483}\dot{\mathrm{m}}^{26/483}\alpha^{-2/69}$$

Radiation pressure dominated disc:

$$\xi_{\infty,\mathrm{A}} = 2^{1/7}\left(\frac{73\alpha}{24}\right)^{2/9}\frac{\dot{\mathrm{m}}^{2/7}}{(\lambda\mu_{30}^2)^{4/63}}$$



It is interesting that for radiation dominated disc

$$\mathrm{r}_{\mathrm{in}} = \xi_{\infty,\mathrm{A}}\mathrm{r}_{\mathrm{A}} = \left(\frac{73\alpha}{24}\right)^{2/9}(\lambda\mu_{30}^2)^{2/9} \text{ is independent of } \dot{\mathrm{m}}$$

Eddington limits

Non-local Eddington limit:

$$\frac{\mathrm{P_r}}{\mathrm{P_{mag}}} = \frac{\mathrm{L}}{4\pi \mathrm{R_{in}^2 c}} \Big/ \frac{\mu^2}{8\pi \mathrm{R_{in}^6}} = 2^{-4/7}\eta \left(\frac{\lambda\mu_{30}^2}{\dot{\mathrm{m}}}\right)^{1/7} \xi^4$$

$$\frac{\mathrm{P_r}}{\mathrm{P_{mag}}} = \left(\frac{73\alpha}{24}\right)^{8/9} \eta\dot{\mathrm{m}} \left(\lambda\mu_{30}^2\right)^{-1/9} \simeq 0.5\frac{\eta}{0.1}\left(\frac{\alpha}{0.1}\right)^{8/9} \mu_{30}^{-2/9}\dot{\mathrm{m}}$$

$$\dot{\mathrm{m}}_1 = \frac{1}{\eta}\left(\frac{24}{73\alpha}\right)^{8/9} (\lambda\mu_{30}^2)^{1/9} \simeq 430\frac{0.1}{\eta}\left(\frac{0.1}{\alpha}\right)^{8/9} \mu_{30}^{2/9}$$

Local Eddington limit:

$$\dot{\mathrm{m}}_2 \simeq \frac{4}{3\sqrt{5}}\left(1 - \frac{1}{\sqrt{2}}\right)^{-1} (\lambda\mu_{30}^2)^{2/9} \left(\frac{73\alpha}{24}\right)^{2/9} \simeq 350\left(\frac{\alpha}{0.1}\right)^{2/9} \mu_{30}^{4/9}$$