Super-Eddington accretion luminosity of highly magnetized neutron stars

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Breaking The Limits
Super-Eddington accretion on compact objects.
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Super-Eddington X-ray pulsars

Pulsing ULX M82 X-2
(Bachetti et al. 2014)

\[ L \approx 10^{40} \text{ erg s}^{-1}, \quad P \approx 1.37 \text{ s} \]

Other pulsing ULX! See Israel’s talk

Eddington luminosity

\[
L_{Edd} = \frac{4\pi GMc}{0.2(1 + X)} \approx 1.4 \cdot 10^{38} \frac{M}{M_\odot} \text{ erg s}^{-1}
\]

\(0.2(1+X)\approx \kappa_T\) - electron scattering opacity, \(X \approx 0.74\) – hydrogen mass fraction

Many transient X-ray pulsars have higher luminosities during giant (type II) outbursts

LMC X-4 - up to \(2 \cdot 10^{39}\) erg s\(^{-1}\) in flares (Moon et al. 2003);
SMC X-1 \(\approx 7 \cdot 10^{38}\) erg s\(^{-1}\) (Naik & Paul 2004);
A0538-66 up to \(8 \cdot 10^{38}\) erg s\(^{-1}\) (Maraschi et al. 1983);
GRO J1744-28; V0332+53 etc.

(Tsygankov et al. 2016)
Super-Eddington fluxes.

Magnetic field importance.

\[ f_{rp} = \frac{V_{ff}^2}{d} > g \quad \rightarrow \quad F > F_{Edd} \]

Kulkarni & Romanova 2013

Eddington flux from \( f_{rad} = g \)

\[ g \rightarrow F_{Edd} \approx 10^{37} \text{ erg s}^{-1} \]

Low Luminosity

ram pressure of free falling matter

radiation dominated shock

deceleration zone
Super-Eddington fluxes.

Magnetic field importance.

\[ f_L \gg g \rightarrow F \gg F_{Edd} \]

High Luminosity

\[ > 10^{38} \text{ erg s}^{-1} \]

Kulkarni & Romanova 2013

Eddington flux from

\[ f_{rad} = g \]

H

NS

d

free falling matter

deceleration surface

Lorentz force

slowly settling matter or "accretion column"

gravity

radiation pressure
Models: Some previous works

Basko & Sunyaev 1976  
Basic ideas, first numerical models

Wang & Frank 1981  
First 2D simulations

Lyubarskij & Sunyaev 1988  
Physics of accretion column structure

Becker & Wolff 2007 +  
Spectra

Postnov et al. 2015  
2D models, diffusion approximation for radiation transfer

Kawashima et al. 2016  
2D radiation-hydrodynamic simulations
Radiation supported accretion column

Main assumptions

on the base of Lubarsky & Sunyaev 1988 and Basko & Sunyaev 1976

Vertical direction

Hydrostatic equilibrium

\[ F_{II}(h) = F_{Edd}(h), \quad P_{tot} \approx P_{rad} \approx \frac{\varepsilon_{rad}}{3} = \frac{aT^4}{3} \]

\[ \frac{dP_{rad}(h)}{dh} = -\rho \frac{\kappa_{II} F_{Edd}(h)}{c} \]

Horizontal direction

Radiation transfer

\[ \frac{d\varepsilon_{rad}(x,h)}{dx} = -3\rho \frac{\kappa_{\perp} F(h)}{c} \frac{2x}{d} \]
Radiation supported accretion column

Toy model: Constant density.

**Vertical direction**

Hydrostatic equilibrium

$$\varepsilon_{rad}(0,h) \approx \frac{3 \tau_{II}}{c} F_{Edd}(h)$$

**Horizontal direction**

Radiation transfer

$$F_{\perp}(h) \approx \frac{2c \varepsilon_{rad}(0,h)}{3 \tau_{\perp}} \approx 2 \frac{\tau_{II}}{\tau_{\perp}} F_{Edd}(h)$$
Radiation supported accretion column

Toy model: Constant density.

\[
F_{\perp}(h) \approx 2 \frac{\tau_{\perp}}{\tau_{\parallel}} F_{Edd}(h)
\]

Integration over the surface

\[
L \approx 40 \left( \frac{l/d}{50} \right) \left( \frac{\kappa_T}{\kappa_\perp} \right) f(H/R) \, L_{Edd}
\]

\[
L^{**}(H = R) \approx 2 \times 10^{39} \left( \frac{l/d}{50} \right) \left( \frac{\kappa_T}{\kappa_\perp} \right) \text{erg s}^{-1}
\]

\[
H(x) \approx H \left( 1 - 4 \frac{x^2}{d^2} \right) \text{ approximate parabolic shape}
\]
Magnetic opacities

Cyclotron energy

\[ E_C = 11.5 \left( \frac{B}{10^{12} \text{ G}} \right) \text{ keV} \]

Averaging over thermal spectrum is important

\[ kT \ll E_C \Rightarrow \kappa_\perp \ll \kappa_T \]

Photon energy

\[ E = h\nu \]

\[ \kappa_X \propto \kappa_T \frac{E^2}{\left( E - E_C \right)^2} \]

\[ \kappa_O \propto \kappa_T \]

\[ B = 4.4 \times 10^{12} \text{ G}, \quad \theta = 90^\circ \]

Mushtukov et al. 2016

X-mode

O-mode

\[ \frac{E}{m_e c^2} \]
Magnetic opacities

Averaging over thermal spectrum is important

\[ kT \geq E_C \quad \rightarrow \quad \kappa_\perp \approx \kappa_T \]

\[ B = 4.4 \times 10^{12} \, G, \quad \theta = 90^\circ \]

Mushtukov et al. 2016
Accretion geometry importance

Low luminosity. Gas pressure dominated disc.

Assumption: accretion curtain thickness equals accretion disc thickness

\[ H_D \propto L^{3/20} \implies \frac{l}{d} \propto L^{-4/35} \]

Toy model dependence is almost unchanged

\[ L \approx 40 \left( \frac{l/d}{50} \right) \left( \frac{\kappa_T}{\kappa} \right) f \left( \frac{H}{R} \right) L_{Edd}^{1.1} \]
Accretion geometry importance

High luminosity. Radiation pressure dominated disc.

Assumption: the same $Z_C = H_D$. BUT $H_D \approx R_m$ ?

$H_D \propto L \rightarrow l/d \propto L^{-9/7}$

$L \approx 40 \left( \frac{l/d}{50} \right) \left( \frac{\kappa_T}{\kappa_\perp} \right) f(H/R) L_{Edd}$

Toy model dependence is changed significantly
Numerical (pseudo) one-dimensional model. Final assumptions.

Aim is to find the column height $H$ which corresponds to given $L$

Quasi-dipole geometry

$$B(h) = B \left( \frac{R + h}{R} \right)^{-3}$$

Mass conservation law

$$\frac{\dot{M}}{2S_{D}} = \rho V$$

Velocity profile (by hand, weak point)

$$V \propto h^{\xi}, \quad V(H) = \frac{V_{ff}(H)}{7}$$

$$\xi = [1 \div 5] \quad \text{Wang & Frank 1981} \quad \xi = 5 \quad \text{Basko & Sunyaev 1976}$$

results coincides inside factor of two

Iteration scheme, because $\kappa_{\perp}$ depends on temperature $T$
Numerical (pseudo) one-dimensional model.
Some results.

Higher NS magnetic field strength $B \rightarrow$ less opacity $\kappa_\perp$ and optical thickness $\tau_\perp \rightarrow$ higher effective temperature $T_{\text{eff}}$ less column height at the same luminosity or higher luminosity at the same column height.
Maximum possible luminosities vs. $B$

Toy model

$l/d = 50$

$\kappa_\perp = \kappa_T$
Application to M 82 X-2

Our theoretical curve for maximum luminosity (apparent can be much larger due to beaming)

Propeller effect

Supercritical accretion disc

Column

Hot spot

$L \, [\text{erg} \, s^{-1}]$

$B \, [\text{G}]$

$10^{12}$ $10^{13}$ $10^{14}$ $10^{15}$

$10^{36}$ $10^{37}$ $10^{38}$ $10^{39}$ $10^{40}$ $10^{41}$
Possible propeller effect in M 82 X-2
Tsygankov et al. 2016

Two preferable states (?)

Transitions due to propeller effect at $R_m = R_{CO}$ ?
Possible propeller effect in M 82 X-2

\[ R_m = R_{CO} \rightarrow B \propto L_{tr} P_{sp}^{7/3} \]
Conclusions

Our simplified model can qualitatively explain high luminous X-ray pulsars existence with luminosities up to $10^{40}$ erg s$^{-1}$ typical for M82 X-2 assuming high magnetic field strength ($10^{14} - 10^{15}$ G).

Possible luminosity transitions in M82 X-2 due to propeller effect confirm $B \sim 10^{14}$ G (Tsygankov et al. 2016).

Accretion geometry is very important and cannot be correctly included at the moment. There is potential possibility for maximum luminosities increasing due to geometry effects.
Outlook

Introduction.
   Super-Eddington X-ray pulsars.
Magnetic field importance.
   Super-Eddington fluxes.
Accretion columns. Basic ideas.
Maximum possible luminosities.
Conclusions.
Magnetic opacities

Description of the radiation transfer using two normal modes

\[ E = h \nu \]

\[ E_C = 11.5 \left( \frac{B}{10^{12} \text{ G}} \right) \text{ keV} \]

Photon energy

Cyclotron energy