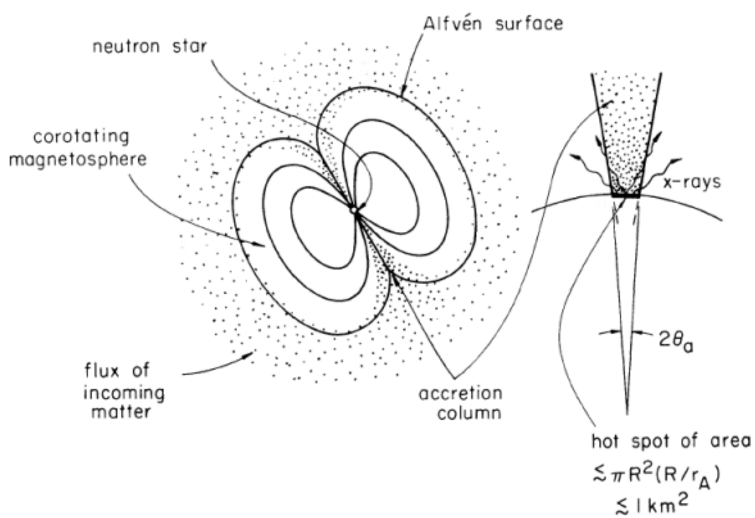
X-ray Emissions from Magnetic Polar Regions of Neutron Stars

Hajime Inoue
Meisei University

Since discoveries of Her X-1 (Giacconi et al. 1971) and Cen X-3 (Tananbaum et al. 1972) with Uhuru, more than 100 X-ray pulsars have been found.

General consensus on situations of X-ray pulsars

- a close binary of a strongly magnetized neutron star + a normal star
- an accretion flow from the normal star to the neutron star
- a magneto-boundary surface at ~ 10^8 cm where the magnetic pressure of the NS once stops the flow
- two channeled flows along magnetic funnels to the magnetic poles at the NS surface
- X-ray emissions from the polar regions at the NS surface
- an oblique rotation of the magnetic axis, causing X-ray pulsation



schematic diagrams by Lamb, Pethick & Pines (1973)

Studies on structures of the polar X-ray emitting regions

Davidson (1973)

A simple treatment

kinetic energy ⇨ radiation energy

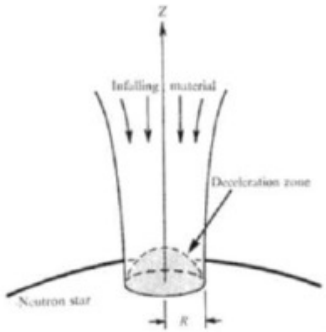


Fig. 1 Base of an accretion funnel. The z axis extends upward from a magnetic pole of the neutron star.

low accretion rate case ⇨ generalization to higher accretion rate

more detailed study to reproduce X-ray spectra

Becker & Wolff (2007)

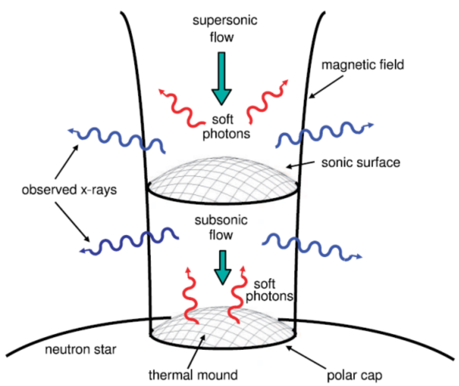


Fig. 1.—Schematic depiction of gas accreting onto the magnetic polar cap of a neutron star. Seed photons are created throughout the column via bremsstrahlung and cyclotron emission, and additional blackbody seed photons are emitted from the surface of the thermal mound near the base of the column.

Inoue (1975)

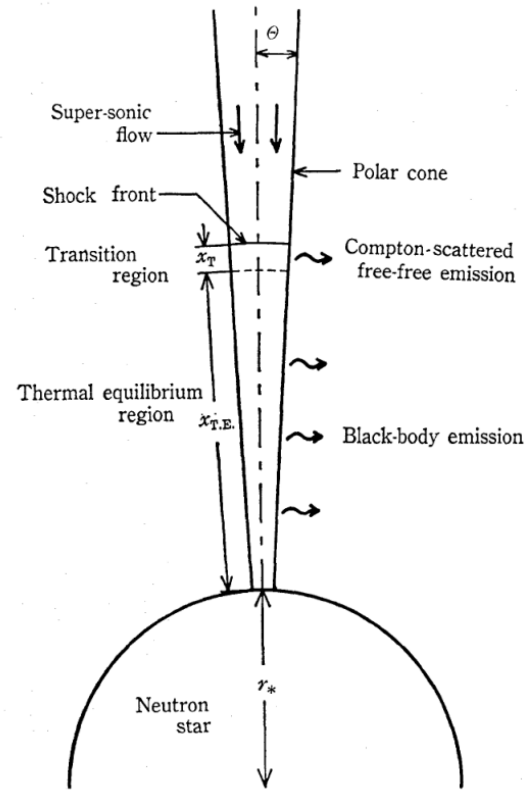
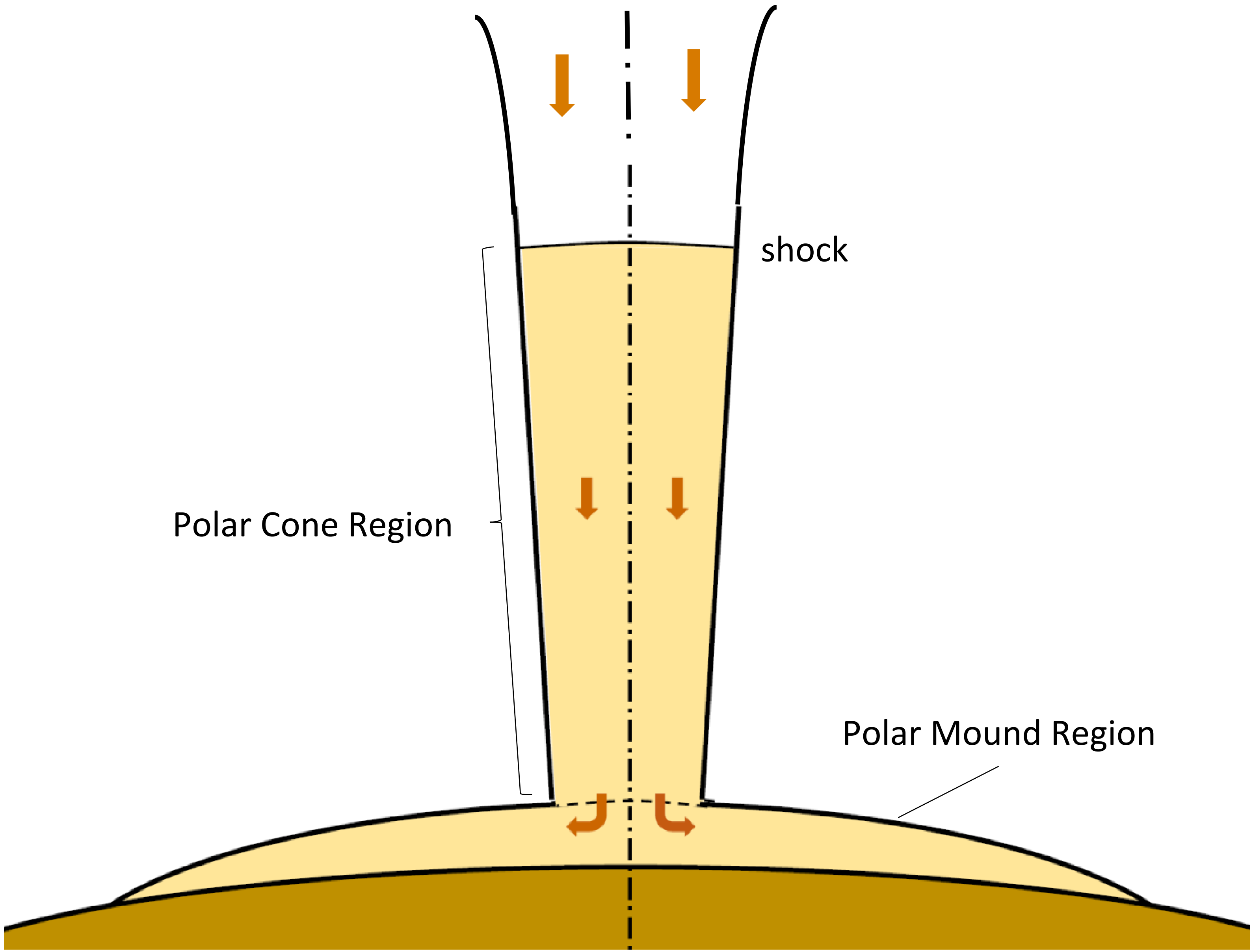


Fig. 1. Schematic diagram of the polar cone near the stellar surface.

more detailed study

This talk : Inoue (2019, in preparation)

Model-configurations of an X-ray emitting polar region of a neutron star



Model for accretion flow in the Polar Cone Region on a neutron star

Assumptions

- quasi-radial, steady flow in a polar cone
- narrow cone $\Theta << 1$

  averaged over a cross section of the cone
- radiation energy dominant

  $P = U/3 = \boxed{?}\boxed{?}/3$
- sufficiently subsonic

  kinetic energy << thermal energy
- energy loss : side-way diffusion of photons

  energy loss rate per volume : q

  $q = U/t\mathrm{D} = \rho\varepsilon\, 4c/3\boxed{?}\mathrm{T}\boxed{?}(r\boxed{?})2$

Parameters

$M/2$	accretion rate through the cone
M	mass of the neutron star
r	radial distance
Θ	opening angle of the cone
v	inflow velocity
ρ	matter density
P	radiation pressure
U	radiation energy density
ε	specific radiation energy density
t_D	effective side-way diffusion time

$\varepsilon = U/\boxed{?}$

$t_D = 4c/3\boxed{?}$

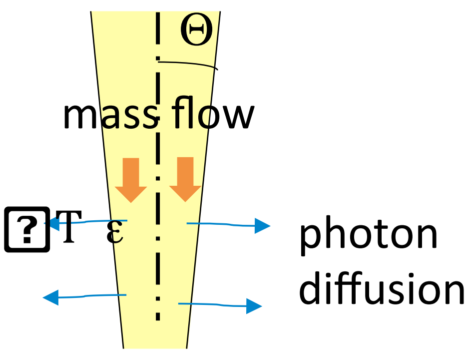
$\tau = \kappa_T\rho(r\Theta)$: optical depth

κ_T : Thomson scattering opacity

c : light velocity

Equations

- mass flow continuity $M/2 = \pi(r\Theta)^2 \rho v$
- pressure balance $dP/dr = -\rho\, \mathrm{GM}/r2$
- energy Eq. $M/2 \; d/dr\, (4/3\; \varepsilon - GM/r) = \pi(r\Theta)^2 q = 4\boxed{?}c/3\boxed{?}\mathrm{T}\;\varepsilon$



Two differential equations on ε and ρ

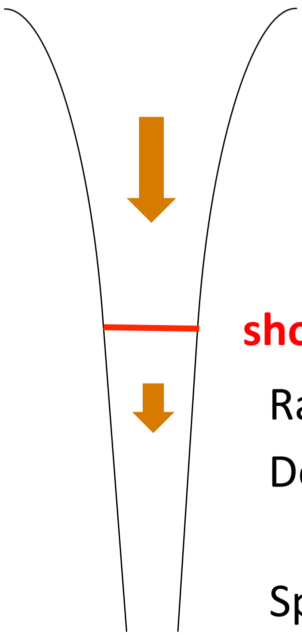
- pressure balance $\quad dP/dr = -\rho\, GM/r2 = U/3 = \boxed{?}\boxed{?}/3 \quad d\boxed{?}/dr = -\boxed{?}/\boxed{?}\ (\boxed{?}/r\mathrm{D} + 3GM/$
- energy Eq. $\quad M/2\ \ d/dr\ (4/3\ \ \varepsilon - GM/r) = \pi(r\Theta)^2 q = 4/3\boxed{?}d\boxed{?}/dr\ \ \mathrm{T}\ \varepsilon\ \boxed{?}/r\mathrm{D}\ - GM/r2$

$r_D = 3\boxed{?}\mathrm{T}/8\boxed{?}c\,M = 1.6 \times 10^5\ (M$

Boundary conditions at the top of the Polar Cone

upper-stream side of the shock

free-fall approximation



$v1 = (2GM/r)^{1/2}$

$\rho_1 = M/2\boxed{?}(r\boxed{?})2v1 = M/2\boxed{?}\boxed{?}2(GM)1/2\ \ r^{-3/2}$

$\varepsilon_1 = v12/2 = GM/r$ (specific matter energy)

shock front (top side boundary)

Radial distance of the top boundary: r_S

Density at r_S: ρ_S

$\rho_S = 4\,\rho_1(r_S)$

Specific radiation energy density at r_S: ε_S

$4/3\ \ \varepsilon_S = \varepsilon_1(r_S) = GM/rS$

Opening angle of the polar cone at r_S : Θ_S

(1) ram-pressure of the free-fall matter

$\rho_1 v_1^2 = M/2\ (2GM)1/2/\boxed{?}\boxed{?}2\ \ r^{-5}$

(2) magnetic pressure in the r- direction

$(B2/8\boxed{?})_\perp \approx Br2/8\boxed{?} \quad B\boxed{?}/Br =$

dipole approximation

$B_r = B_{r,0}\,(r/R)^{-3}$

$B_\theta = Br/2\ \ \Theta \qquad \Theta \ll 1$

(1) = (2)

$\Theta_S = (8(2GM)1/2/(Br.0R3)2)1/3\ r^{7/6}$

$= 2.4 \times 10^{-3}\ (M/1017)^{1/3}\ (M/M\mathrm{sun})^{1/6}\ (Br,$

(cgs unit)

Boundary conditions at the bottom of the Polar Cone

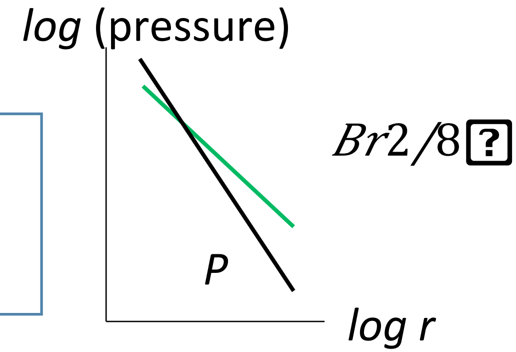
As shown next,

$P << Br2/8?$

on the top-side

$|\log P|/\log r \quad >> \quad \log(8?/Br2)/\log r$

➡ *P* should exceed $Br2/8?$, somewhere.



Boundary at the bottom of the Polar Cone

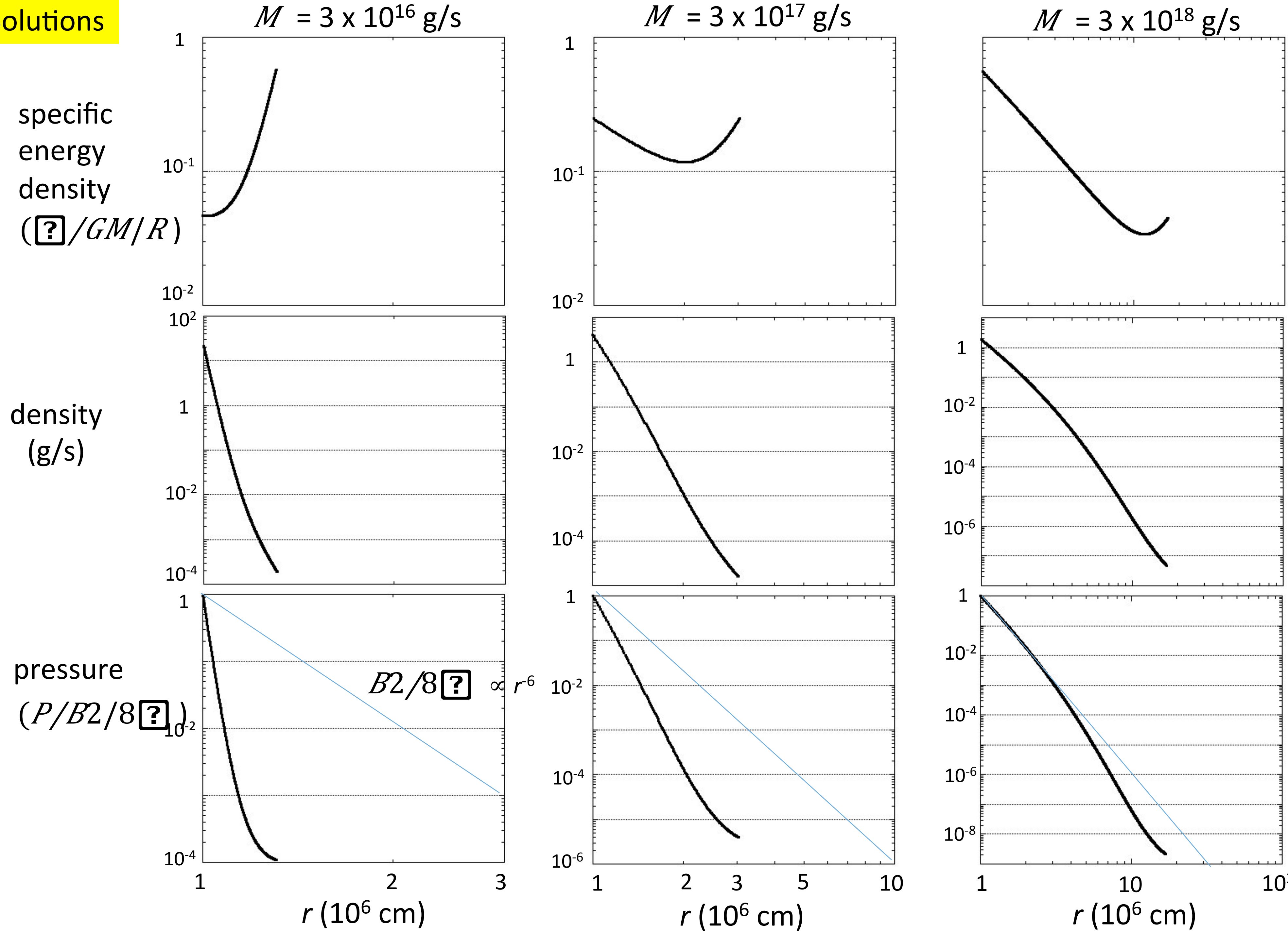
$r_B = R$: the surface of the neutron star

$P_B = ?B?B/3 = Br,02/8?$

The conical configuration should end at the place where $P_B = Br,02/8?$.
If P_B exceeds the magnetic pressure, the matter should push out the magnetic funnel.

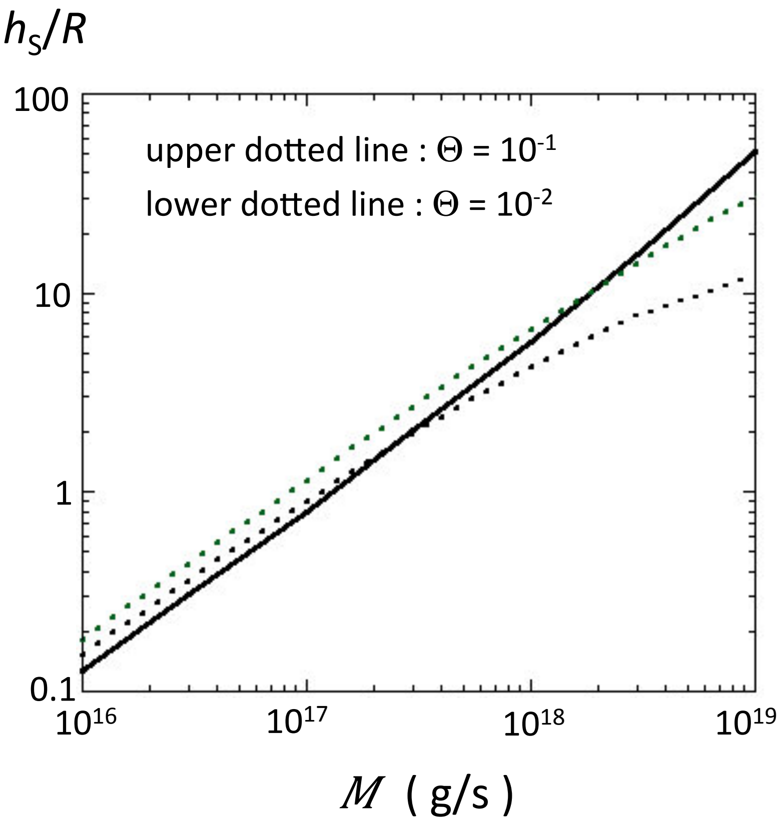
We have searched a solution which satisfies the boundary condition, $P_B = Br,02/8?$, at $r=R$, by changing the start position, r_S, in the numerical calculations.

Solutions



M = 3 x 10^16 g/s
M = 3 x 10^17 g/s
M = 3 x 10^18 g/s
specific
energy
density
(?/GM/R)
density
(g/s)
pressure
(P/B2/8?)
B2/8? ∝ r^-6
r (10^6 cm)
r (10^6 cm)
r (10^6 cm)

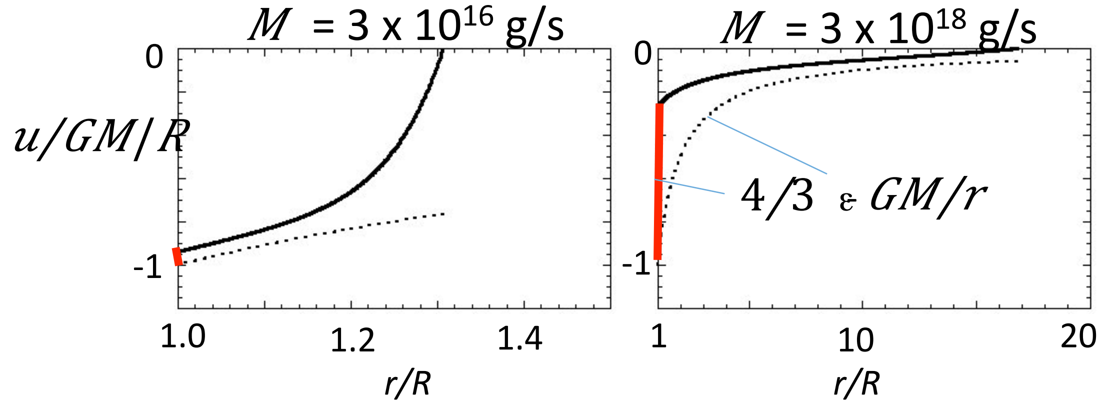
Height : $h_S = r_S - R$
Opening angle : Θ_S
of the Polar Cone

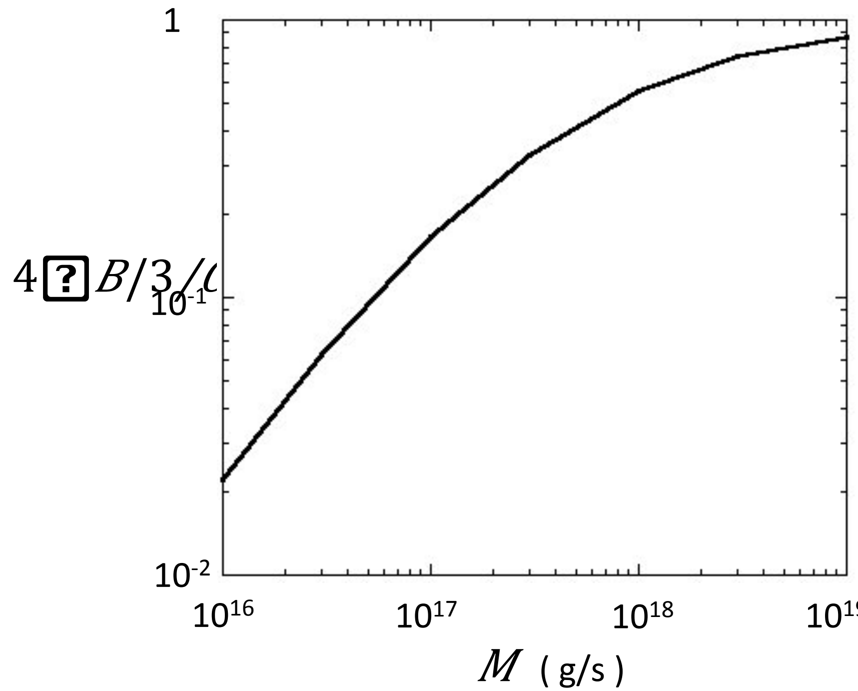


Two thin ($\Theta \approx 0.1$) columns about 10 times as high as the neutron star radius stand when $M \geq 10^{18}$ g/s.

Remaining thermal energy at the bottom of the PC

total specific energy : $u = 4/3\ \varepsilon - GM/r$



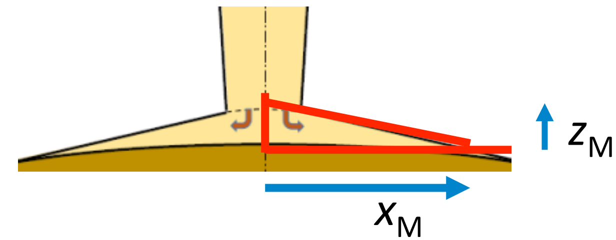


Significant amount of thermal energy still remains at the bottom of the Polar Cone when $M \approx 10^{18}$ g/s or more.

Polar Mound region

The accreted matter still tends to go down with having significant amount of thermal energy at the bottom of the Polar Cone but its thermal pressure gets stronger than the magnetic pressure of the surrounding magnetic funnel below the bottom boundary.

Thus, the matter should start expanding radially along the surface of the neutron star with dragging the magnetic lines of force. We call this region as the Polar Mound region.



Approximation : a cone with a radius, x_M and a height, z_M

Simple considerations on the structure of the Polar Mound

・The matter should radiate away the remaining thermal energy in this region to settle on the surface of the neutron star.

$M/2 = MPM/tD$

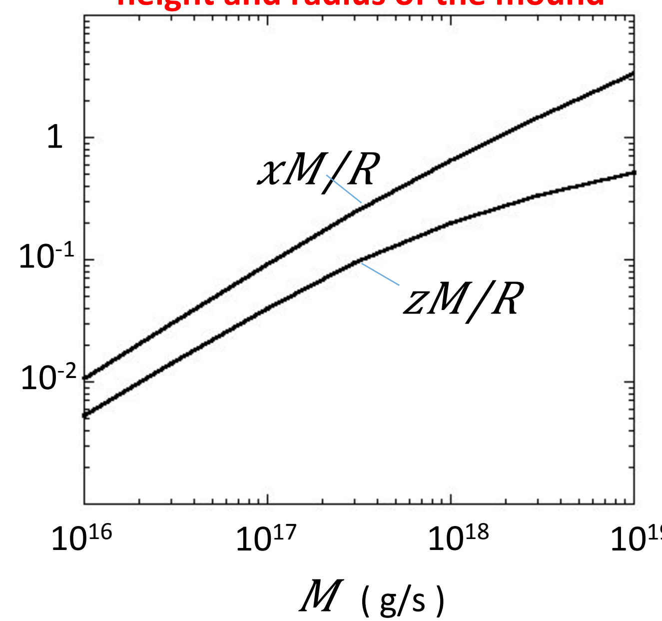
$M_{PM} = 1/3\ \pi x_M^2 z_M\ \rho$ mass within the mound

$t_D = \boxed{?}\,T\,\boxed{?}\,zM2/3c$ photon diffusion time

・The excess matter pressure should balance with the magnetic pressure strengthened by dragging.

$P = P_0\ (R - zM/R)^{-\xi}$ $B2/8\boxed{?} = P_0\ (xM2+zM2)1/2/zM$

height and radius of the mound



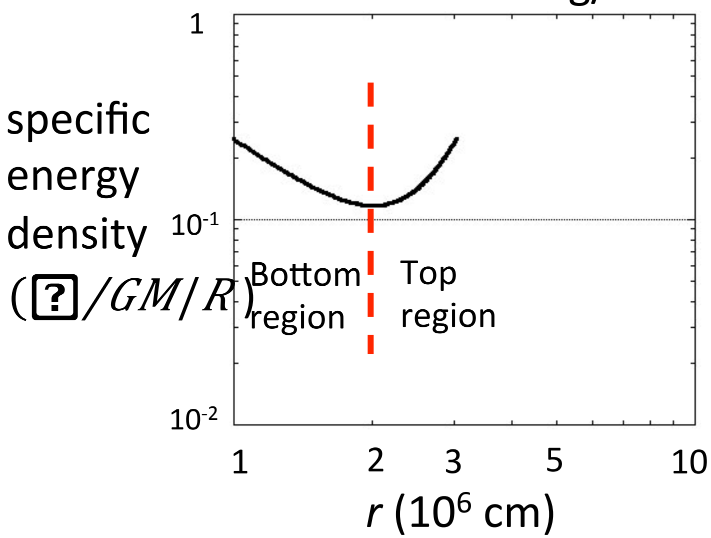
Expected X-ray emission

3 components

I) 2 components from the Polar Cone

$$dL/dr = 4 ? c/3 ? T \ \varepsilon$$

M = 3 x 10^{17} g/s

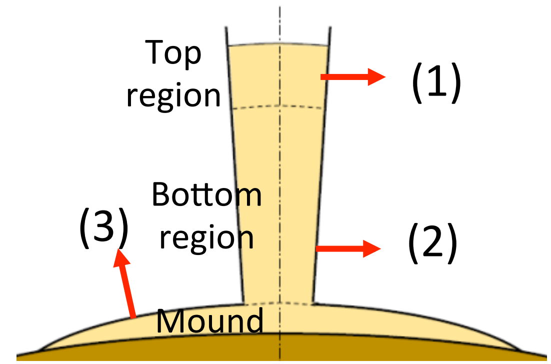


(1) X-rays from a region near the top boundary
(behind the shock)

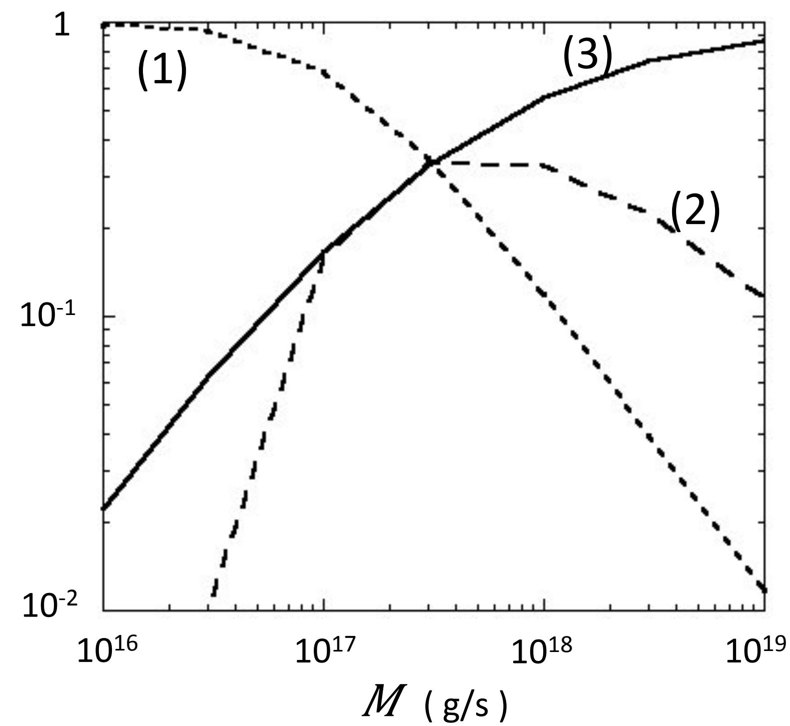
(2) X-rays from a region near the bottom boundary

II) 1 component from the Polar Mound

(3) X-rays from the Polar Mound

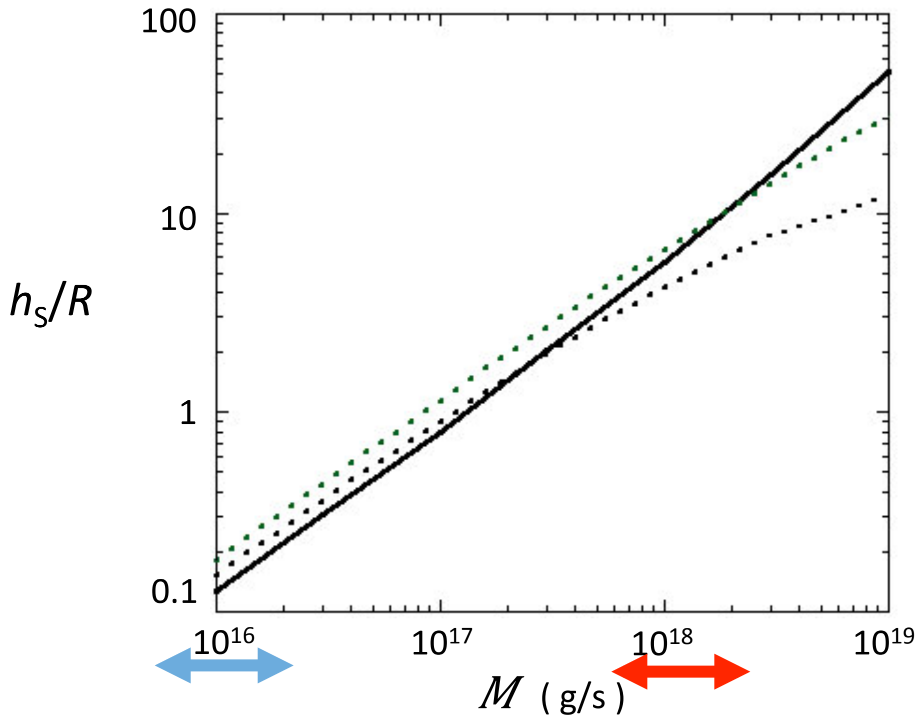


Proportions of the radiated energy of the 3 components

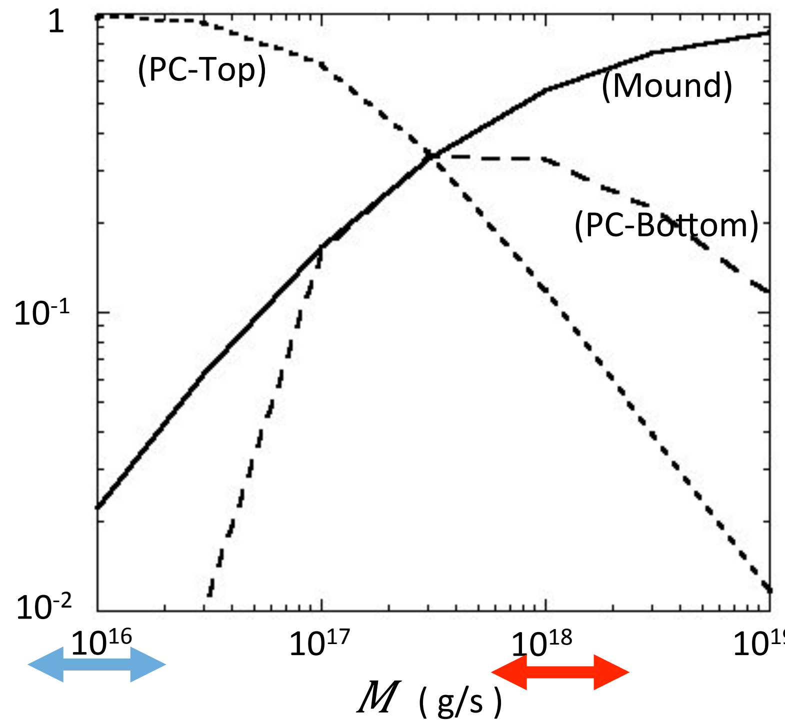


Two typical cases of accretion rate

Height of the Polar Cone



Proportions of 3 emission components



Case of low accretion rate : $\dot{M} \approx 10^{16}$ g/s

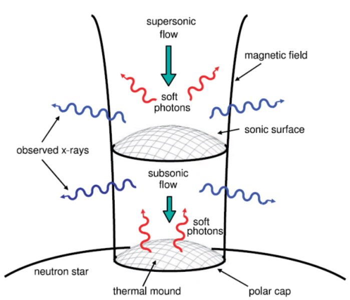
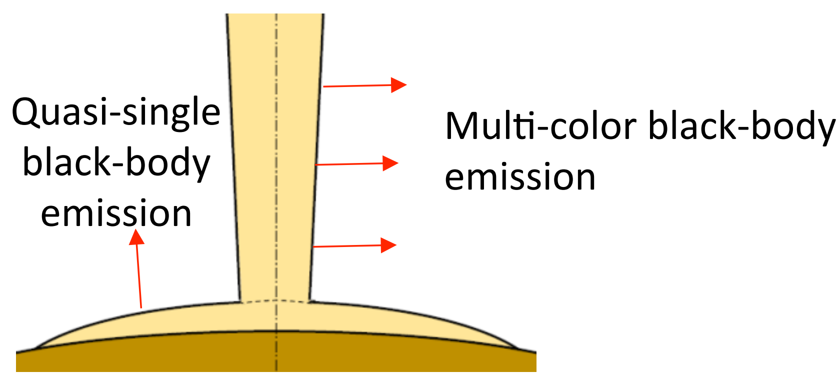


Fig. 1.—Schematic depiction of gas accreting onto the magnetic polar cap of a neutron star. Seed photons are created throughout the column via bremsstrahlung and cyclotron emission, and additional blackbody seed photons are emitted from the surface of the thermal mound near the base of the column.

Emission from a region behind the shock

Becker & Wolff (2007)

Case of high accretion rate : $\dot{M} \approx 10^{18}$ g/s



Expected X-ray spectrum

Bright X-ray pulsars

$L \approx 10^{37} \sim 10^{38}$ erg/s

$\dot{M} \approx 10^{17} \sim 10^{18}$ g/s

⇨ 2 component spectrum

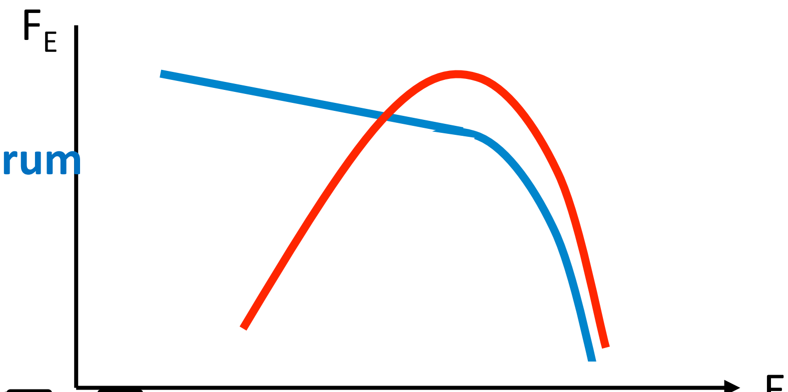
a multi-color blackbody + a blackbody

"NPEX" model well reproduces observed spectra of several X-ray pulsars. (Makishima et al. 1999)

NPEX model

$(A_n E^{-\alpha} + A_p E^2) \exp(- E/kT)$

$E^{-\alpha} \exp(- E/kT)$ ~ **multi-color blackbody spectrum**



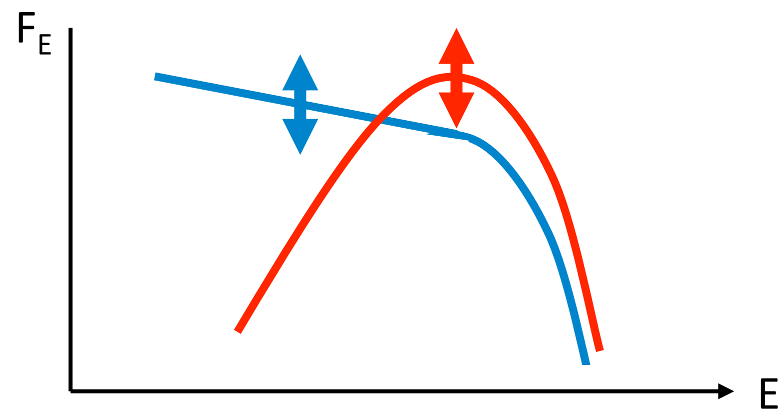
$dL_{PC}/dr = 4?c/3?T \quad \varepsilon_\varepsilon = \propto 2\pi r \Theta \; \sigma T_\propto^4 \; r^\mu$

⇩

$T_e \propto r^{(\nu+\mu+1)/4}$ ⇨ $\alpha = 6 - 2(?+?)/?+?+1$

$E^2 \exp(- E/kT)$ ~ **single blackbody spectrum**

The 2-component spectrum of a multicolor blackbody + a blackbody well reproduces Her X-1 spectra in every pulse phases by changing only normalization factors.



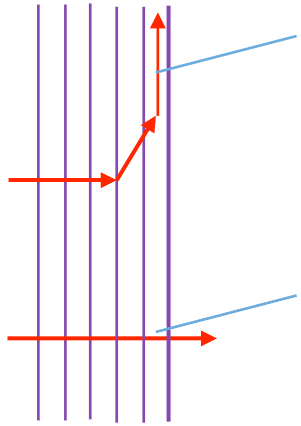
(Kondo, Dotani & Inoue 2019, in preparation)

Beam patterns of X-ray emissions

X-ray beaming in the direction of the magnetic lines of force (Basko & Sunyaev 1975)

X-rays polarized along the lines of force

X-rays polarized perpendicular to the lines of force



free from electron scattering

X-rays originally polarized along the field lines tends to be beamed in the direction of the lines of force.

free from electron scattering

X-rays originally polarized perpendicular to the lines of force should be emitted without beaming.

central side of the Polar Cone

magnetic lines of force in the surface layer of the Polar Cone

3 components in the beam pattern

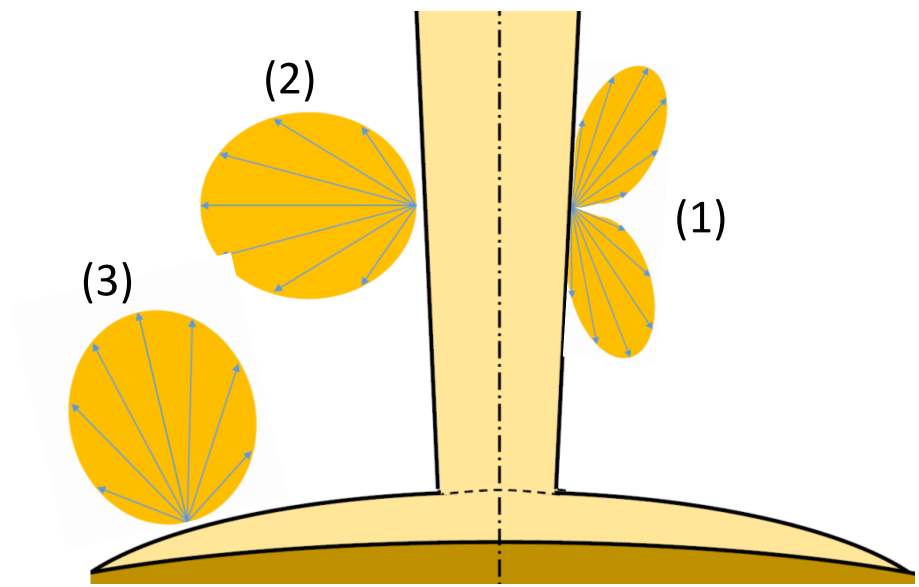
I) 2 components from the Polar Cone region

1) a narrow pencil beam

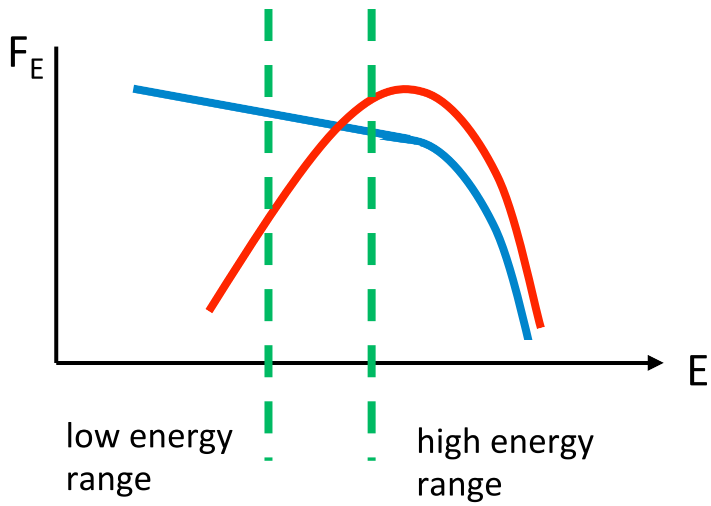
2) a broad fan beam

II) 1 component from the Polar Mound region

3) a broad pencil beam



Expected pulse profiles



low energy range

Main: the narrow pencil beam from the Polar Cone

possible to reproduce multiple peaks

high energy range

Main : the broad pencil beam from the Polar Mound

Sub: the narrow pencil beam from the Polar Cone

Observations

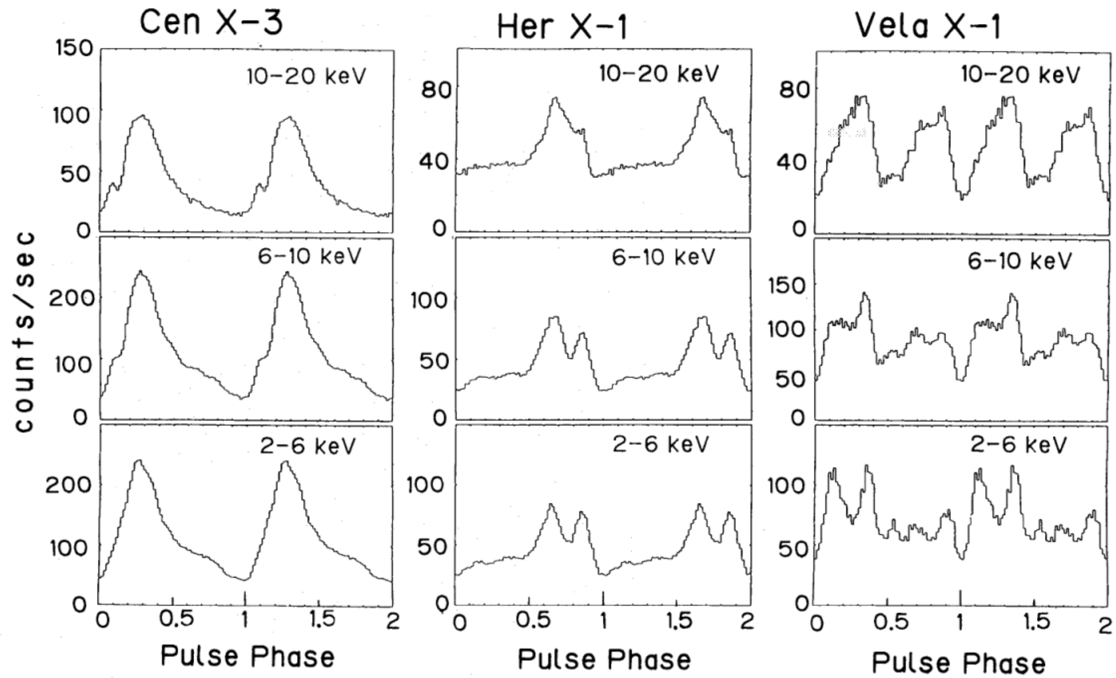


Fig. 3. Average pulse profiles observed by Tenma in three different energy bands for three typical X-ray pulsars, Cen X-3, Her X-1, and Vela X-1.

(a) single sinusoidal-like shapes with little dependence on energy (X Per, GX 304 − 1 etc.),

(b) sinusoidal-like double peaks with little energy dependence (GX 301 − 2, 4U 1538 − 52, SMC X-1 etc., the amplitudes of the two peaks are usually different),

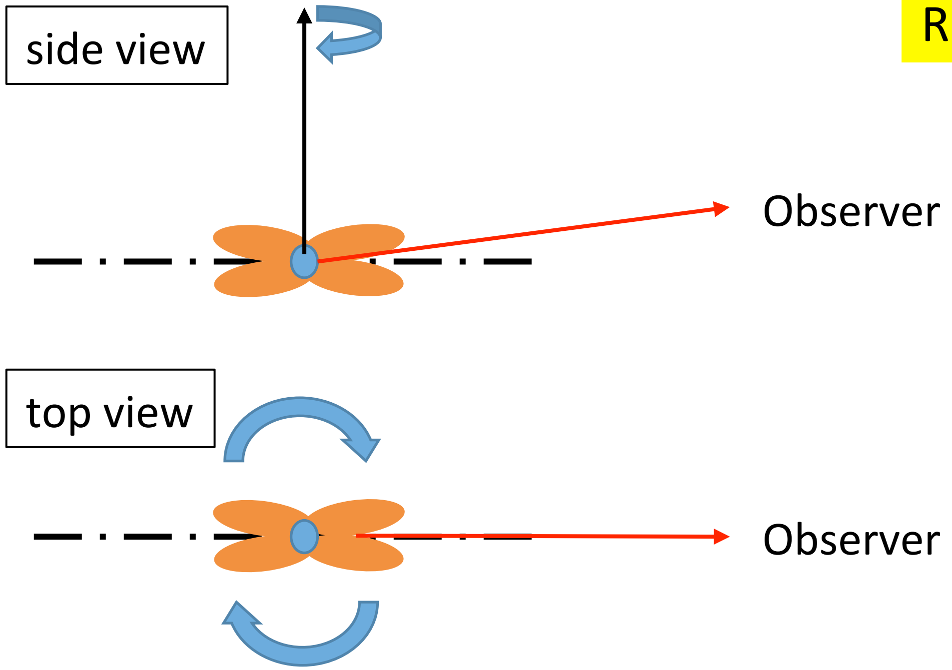
(c) an asymmetric single peak with some features (Cen X-3, GX 1 + 4 etc.),

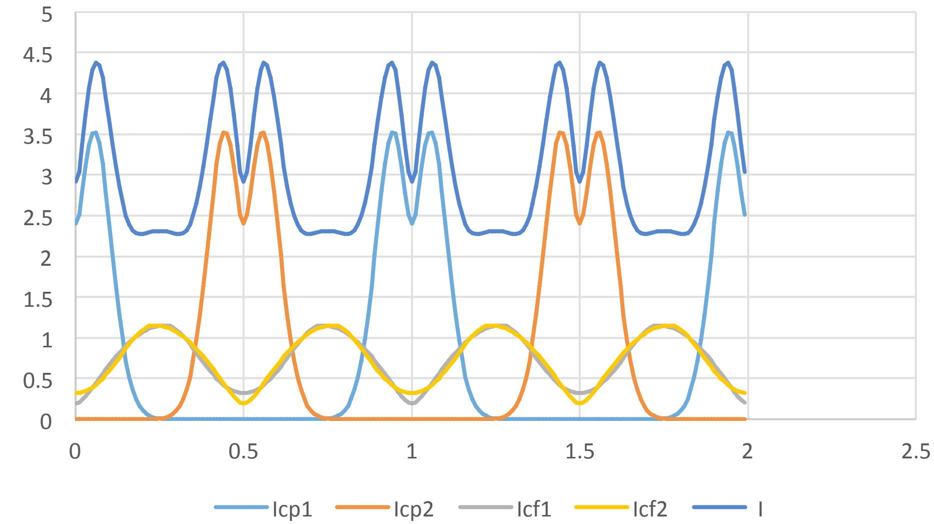
(d) a single sinusoidal-like peak at high and low energies and close adjacent double peaks in the intermediate energy range (Her X-1, 4U 1626 − 67 etc., the phase of maximum amplitude at low energies reverses by 180° with respect to that at higher energies for some sources), and

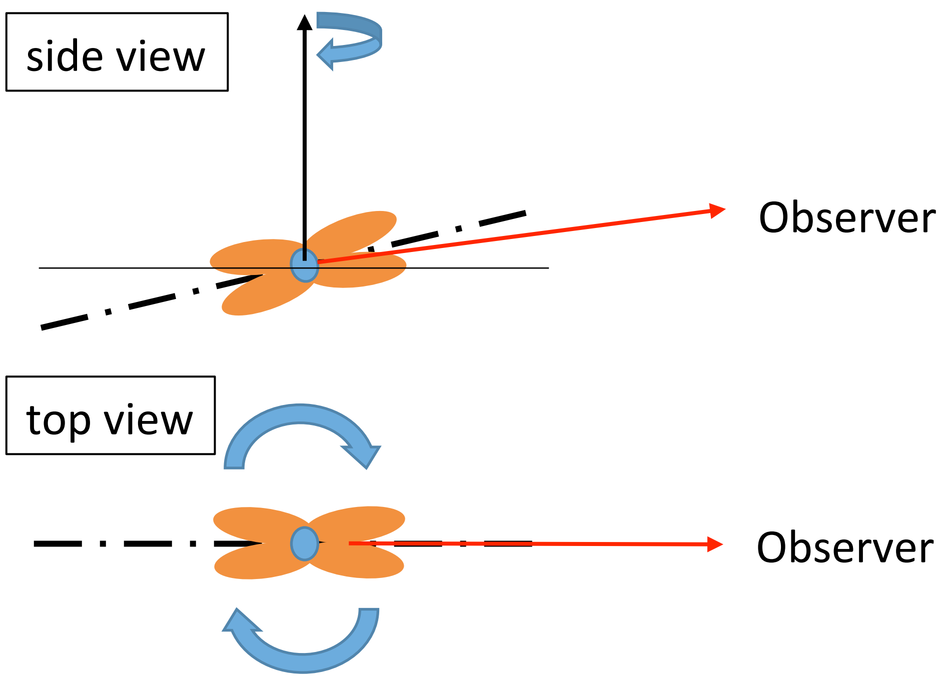
(e) double sinusoidal-like peaks at high energies and complex five peaks at low energies (Vela X-1, A 0535 + 26 etc.).

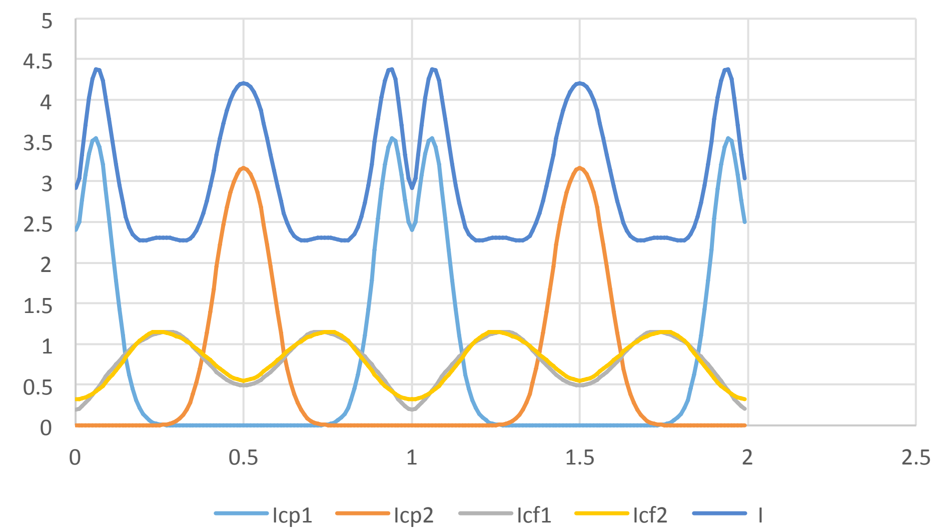
Nagase (1989)

Results of a simple pulse profile calculation



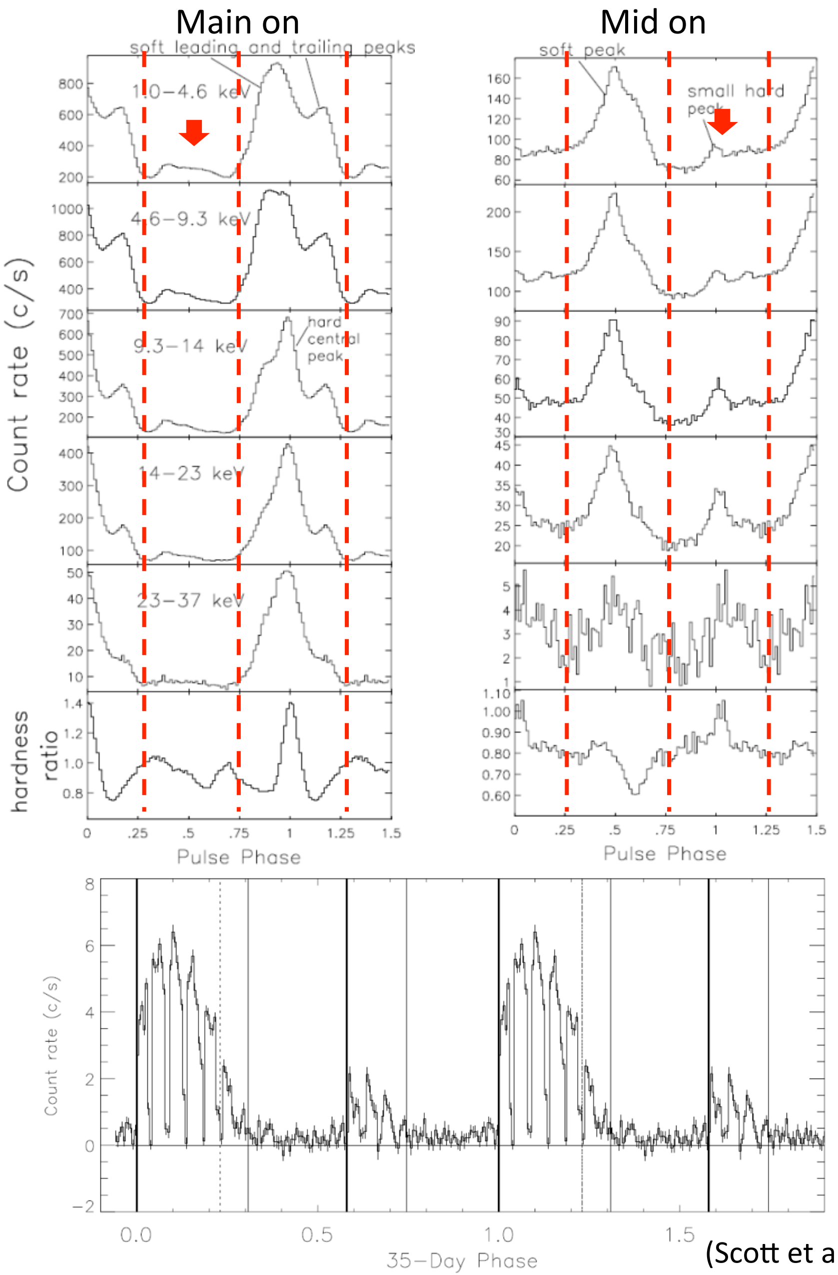






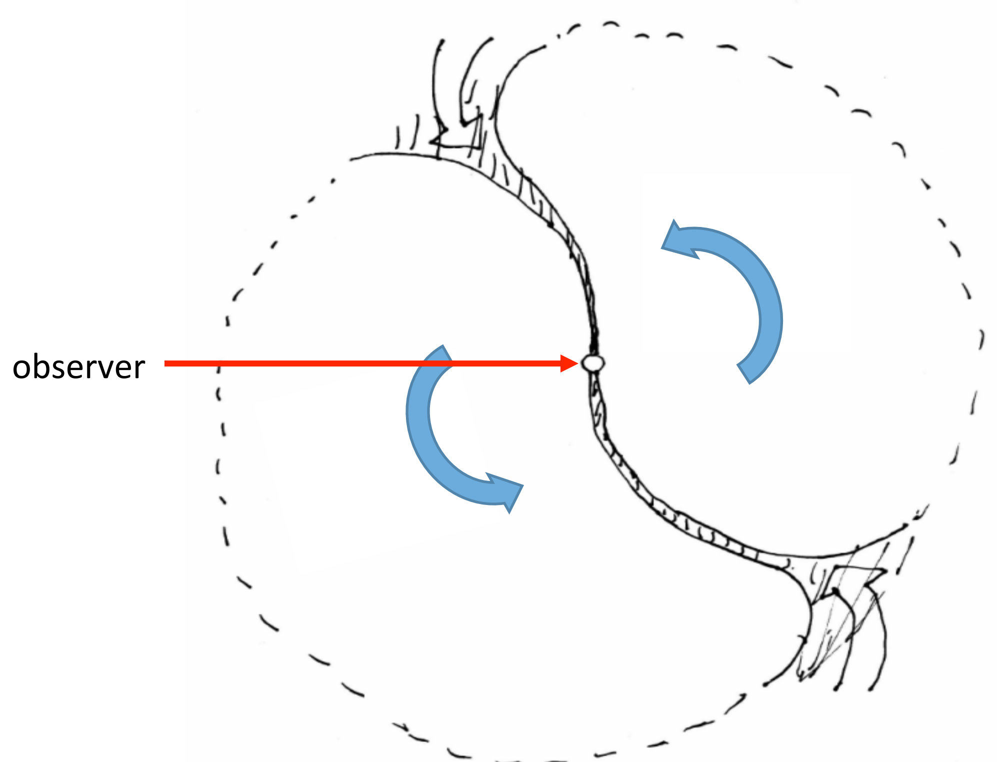
Presence of phase-dependent obscuration → complications in reproduction of the pulse profiles

Pulse profile variation of Her X-1 associated with the 35-day cycle



(Scott et al. 2000)

Accretion flow along the magnetic funnels could be optically thick and possible to periodically obscure the central X-ray source.



Summary

I have studied structures and properties of an X-ray emitting magnetic polar region on a neutron star composing of a polar cone region and a polar mound region

This model can qualitatively explain basic characteristics of observed X-ray spectra and pulse profiles of bright X-ray pulsars.