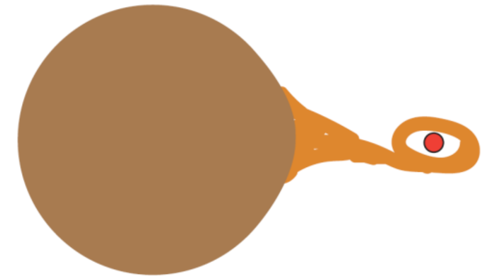
Important roles of accretion rings in X-ray binaries

Hajime Inoue

ISAS/JAXA (Professor emeritus)

“Accretion ring”

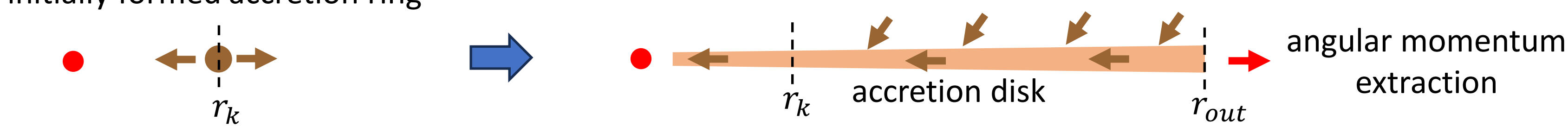


Mass-inflow from a companion star to a compact object in a close binary

The inflowing matter tends to form **a rotating ring along a Keplerian circular orbit (radius r_k) determined by a specific angular momentum given by the Coriolis force in the rotating binary system**.

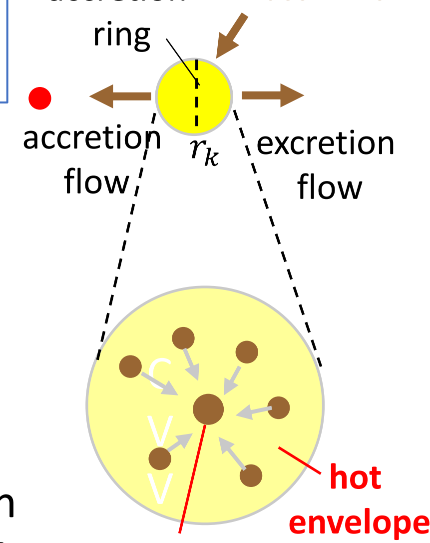
Current scenario : The accretion ring soon evolves to an accretion disk extending to $r_{out} > r_k$.

(Pringle 1981)



However, **a more reasonable solution for a steady accretion disk associated with a steady extraction of the angular momentum through the outer boundary** can be realized **for $r_{out} = r_k$** . (Inoue 2021)

The present scenario : The accretion ring is the place where an inward accretion flow starts and the angular momentum is extracted by an outward excretion flow.



Internal structure of the accretion ring

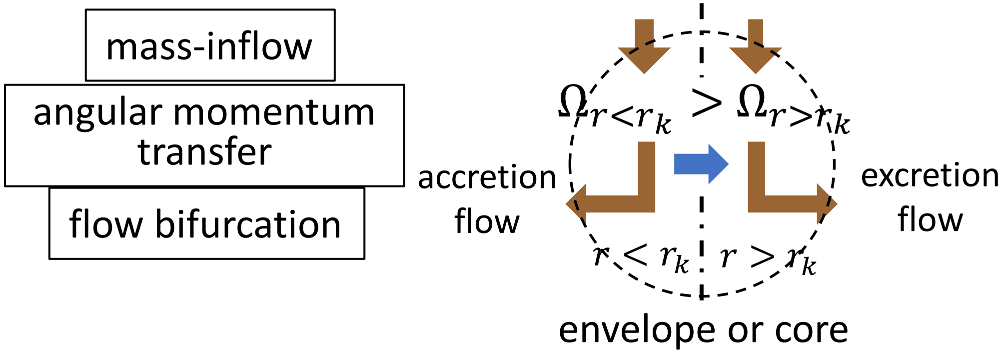
A geometrically thick ring with the virial temperature is initially be formed.

Unless the mass inflow rate is very low, time scale of the radiative cooling is shorter than that of the angular momentum transfer in the thick envelope and thus the thick ring tends to shrink to a thin ring.

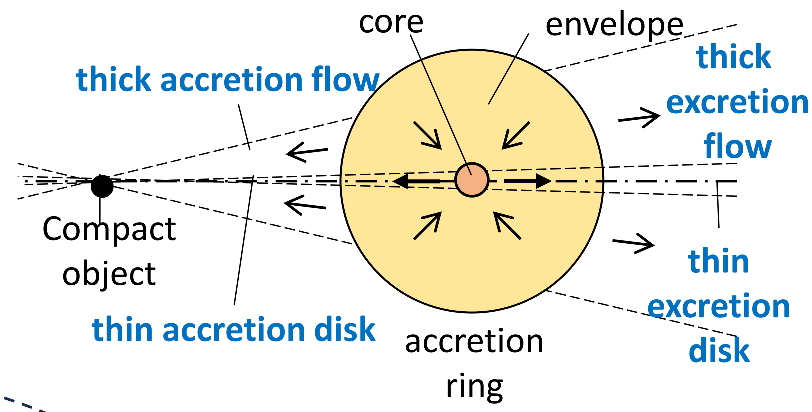
However, **under presence of X-ray heating, thermal instability** could be induced in the thick ring, which **could separate the matter into a hot & diffuse envelope and cool & dense clouds**. **The clouds could sink into** the ring-tube center, forming **a core**.

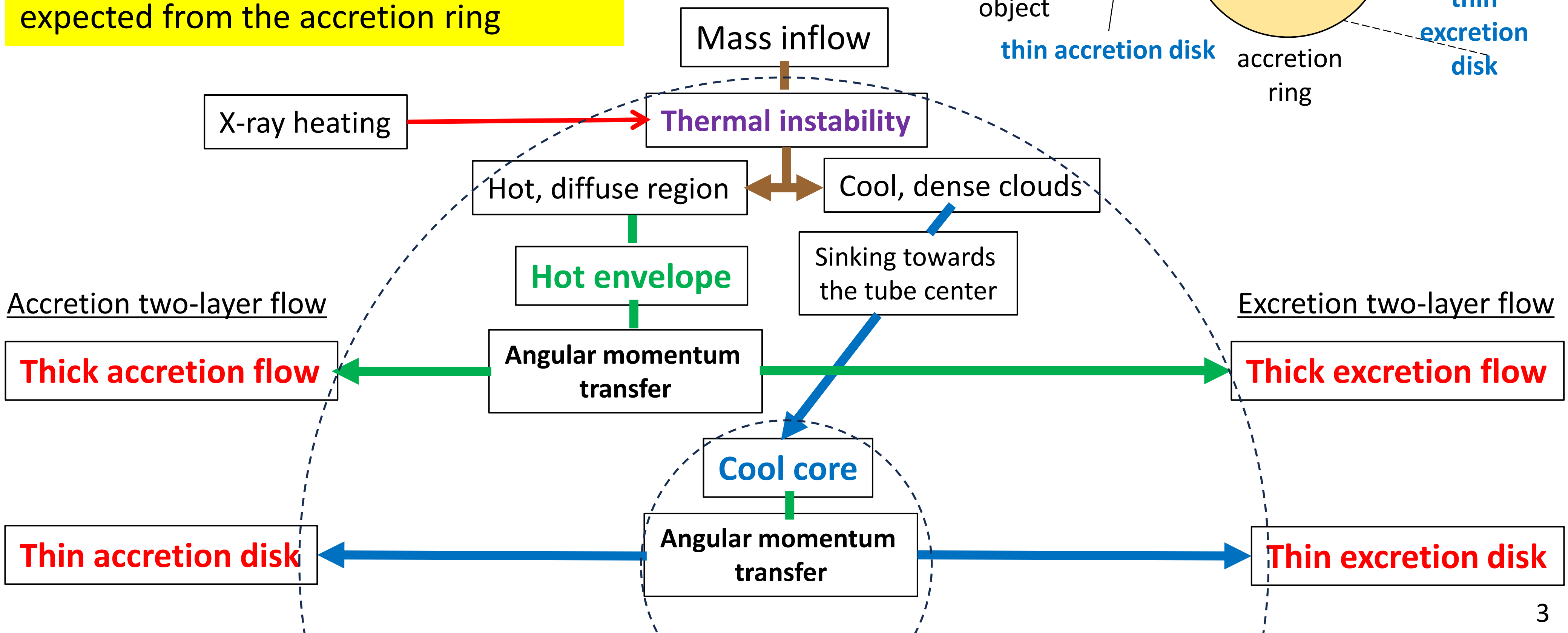
Mass-flow bifurcation in each of the hot envelope and the cool core

Initial specific angular momentum in the ring, $\ell_0 = \sqrt{r_k GM}$, and then $\Omega = \ell_0 / r^2$.



Accretion and excretion two-layer flows expected from the accretion ring



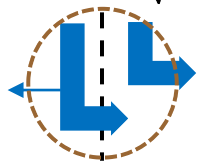


Angular momentum transfer in each of the hot envelope and the cool core

Transferred specific angular momentum

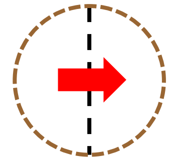
$$\ell_0 = \sqrt{r_k GM}$$

$\ell_{in} = \sqrt{r_{in}GM} \sim 0$



ℓ_0, ℓ_0 } $\ell_{out} \simeq 2\ell_0$

Specific energy transferred by the viscous torque



$$\Delta\varepsilon \simeq \ell_0 \Omega_k = \frac{GM}{r_k}$$

Final appearances of the excretion flows

Thick excretion flow

→ Radiatively inefficient outflow driven by the centrifugal force

Carrying specific angular momentum

$$\ell_{out} \simeq 2\ell_0$$

Specific total energy

$$\varepsilon_{out} \simeq \varepsilon_0 + \Delta\varepsilon \simeq \Delta\varepsilon \simeq \frac{GM}{r_k} > 0$$

$\varepsilon_0 \simeq 0$: specific total energy of the inflowing matter from the companion star

→ **Super-sonic flow** on the far outside

$$v_\infty \simeq \sqrt{\frac{2GM}{r_k}} \simeq 10^8 \text{ cm/s} \quad \text{for } r_k \simeq 10^5\, r_s$$

A likely origin of **the disk winds** often observed from X-ray binaries

(Ueda+ 1998; Kotani+ 2000; Ponti+ 2012)

Thin excretion disk

Carrying specific angular momentum $\ell_{out} \simeq 2\ell_0$

Specific total energy

$$\varepsilon_{out} \simeq \frac{GM}{2r} - \frac{GM}{r} + \left(2\sqrt{\frac{r_k}{r}} - 1\right)\frac{GM}{r}$$

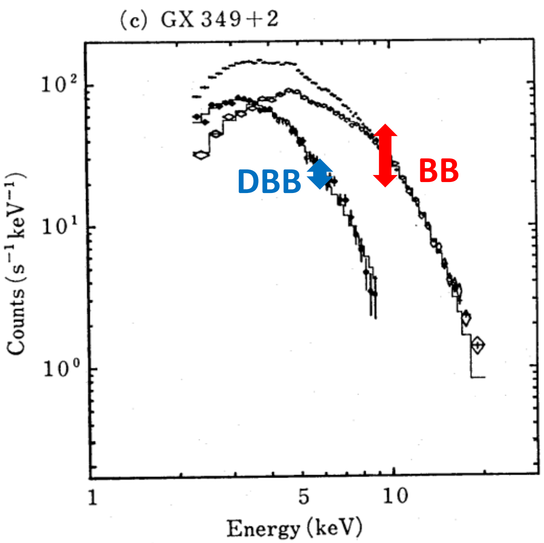
→ **In a simple case**, the matter gradually goes outward from r_k and stops at $r = 4r_k$, forming another ring (**Excretion ring**) there.

In a practical binary system, the disk flow could **turn to a flow around the Roche lobe** and return to the companion star.

Observational supports for the "accretion ring" I

Variable hard components in X-ray binaries ⇒ **"Two-layer accretion flow"**

Tenma observations of bright **weakly-magnetized neutron star binaries** (Mitsuda+ 1984)

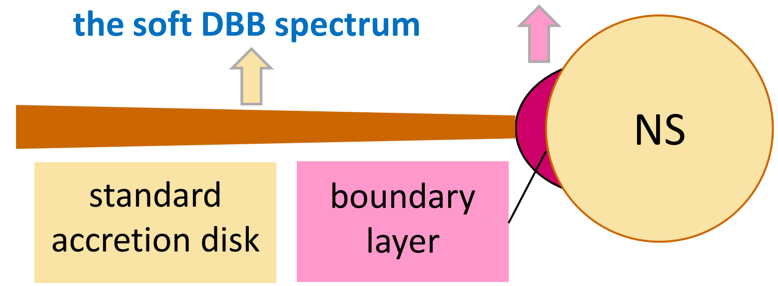


variable hard blackbody component

\+

almost constant disk blackbody component

A simple picture



If $\Omega_{NS} \ll \Omega_{in}$, the innermost rotational energy of the disk should be released in the boundary layer.

A serious problem on this picture.

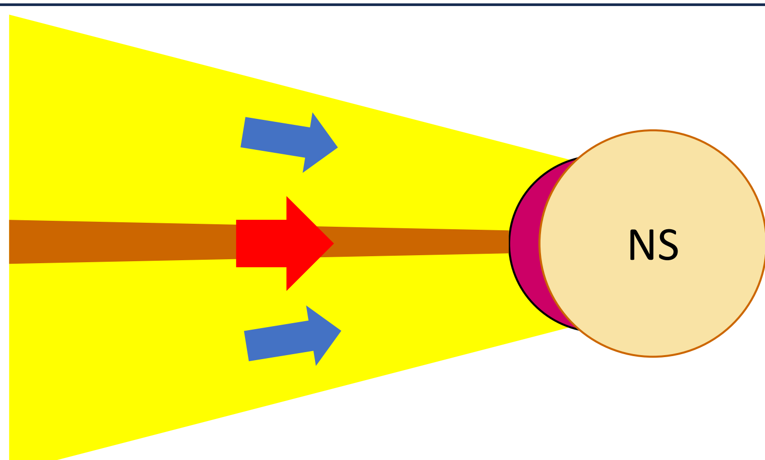
The time variations are seen on the time scale of several 10 min, which is much longer than the dynamical time scale of the boundary layer.

However, **the mass flow through the accretion disk on the up-stream side of the boundary layer has no large time-variability**.

A reasonable answer : **"Two-layer accretion flow"**

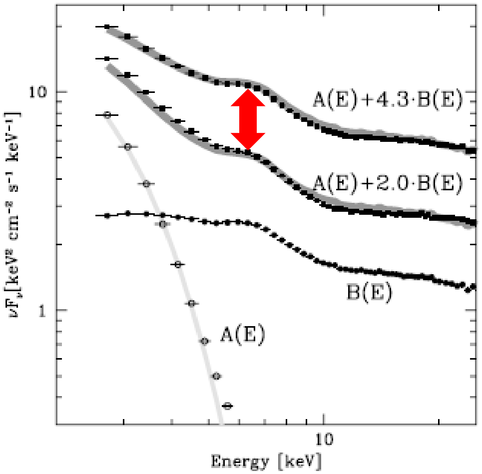
Highly variable thick flow

Almost stable thin disk



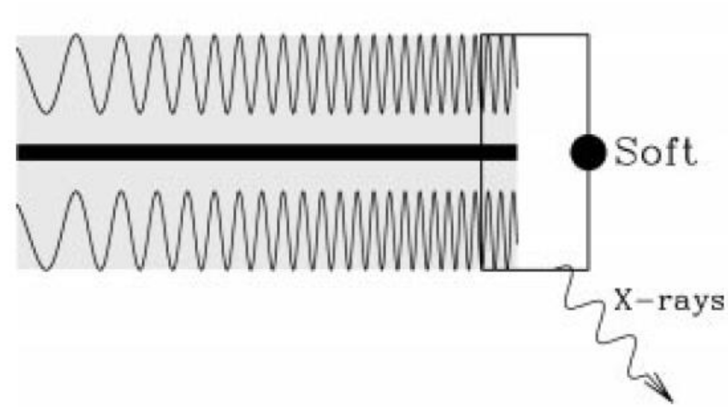
The same discussion for the black hole binary in the high/soft state

The spectral variation on the time scale of 16 s
of **Cyg x-1 in the high/soft state** (Churazov+ 2001)

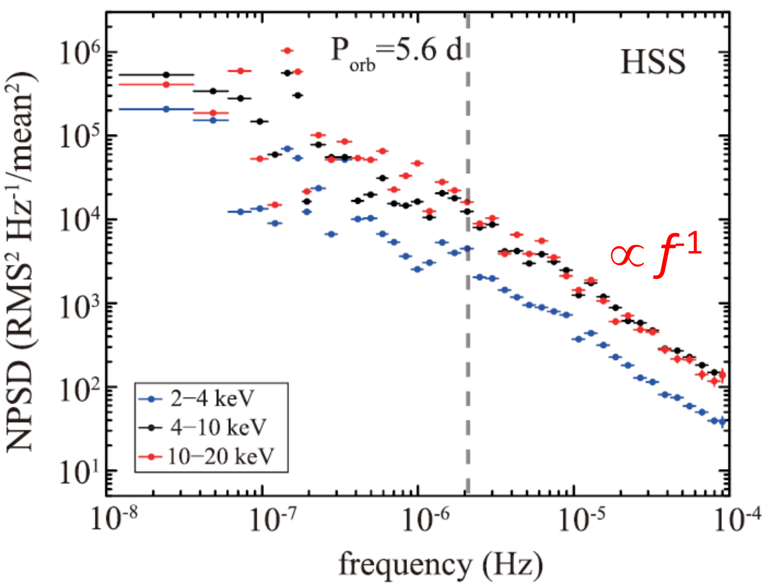


A(E): **stable disk-blackbody component**
+
B(E): **variable power-law component**

A two-layer flow is proposed.



The **power spectral density** from the **MAXI** data
of **Cyg X-1 in the high/soft state** (Sugimoto et al. 2016)



The coexistence in the spectral time variation **of the highly variable hard** power law **component and the less variable soft** disk blackbody **component** is kept **even on a time scale of 10 days**.

Consistent with
the two-layer flow from the accretion ring

Observational supports for the "accretion ring" II

Super-orbital periods in X-ray binaries ➡ **Precession of thick accretion ring**

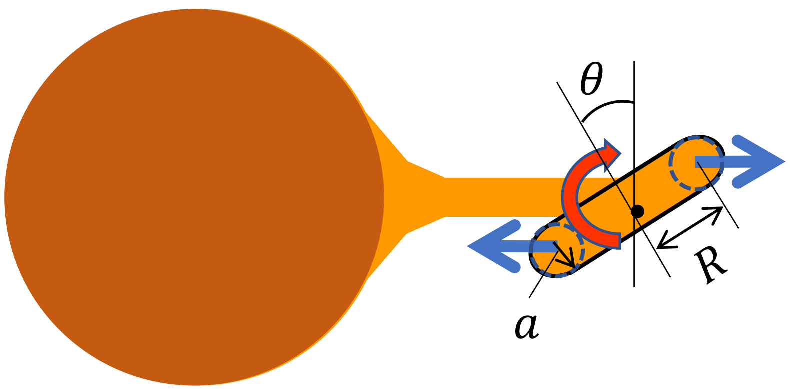
Several X-ray binaries sometimes exhibit periodic variations of X-ray fluxes with periods 10 ~ 100 times longer than the orbital periods.

Typical examples

	binary period	super-orbital period	object character
Her X-1	1.7 d	35 d	X-ray pulsar
SMC X-1	3.9 d	55 d	X-ray pulsar
LMC X-4	1.4 d	30 d	X-ray pulsar
SS433	13.1 d	162.5 d	jet object
Cyg X-1	5.6 d	294 d	black hole binary

Inoue (2012) :

When the accretion ring tilts, **the tidal force from the companion star** induces a torque on it, which **causes a precession of the ring**.



The precessing period in this case roughly agrees to the super-orbital periods as observed.

Considering a hydrostatic balance on an isothermal approximation in the ring-tube, if we tilt the rotational axis of the ring, both the ring radius (R) and the ring-tube radius (a) increases and thus the thermal energy decreases due to the adiabatic cooling.

When the ring tube is sufficiently thick, the energy-minimum exists at a certain non-zero tilt angle θ.

⬇

The precession of the accretion ring can be excited.

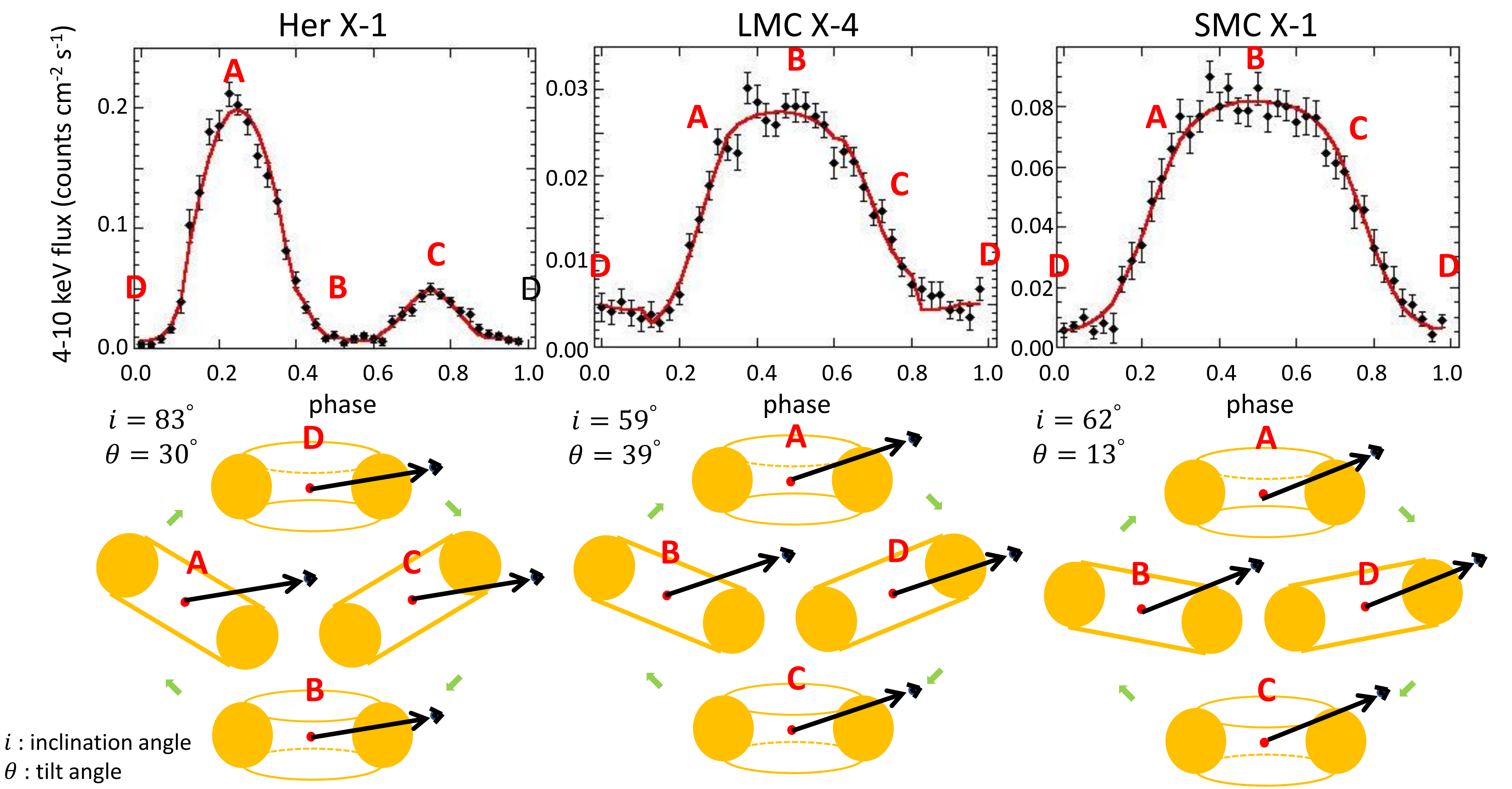
Reproduction of X-ray light curves of three X-ray pulsars, folded with the respective super-orbital periods, by a precessing ring model

Inoue (2019)

The precessing ring model

X-ray flux modulation is due to **periodic variation of optical depth** for the electron scattering **through the precessing accretion ring on the line of sight**

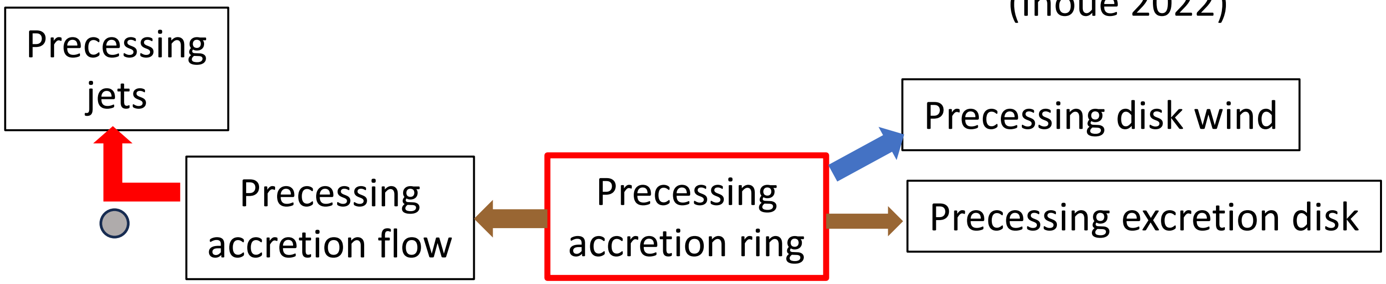
Folded light curves (2 cycles) of the sources observed with MAXI and the best fit model curves

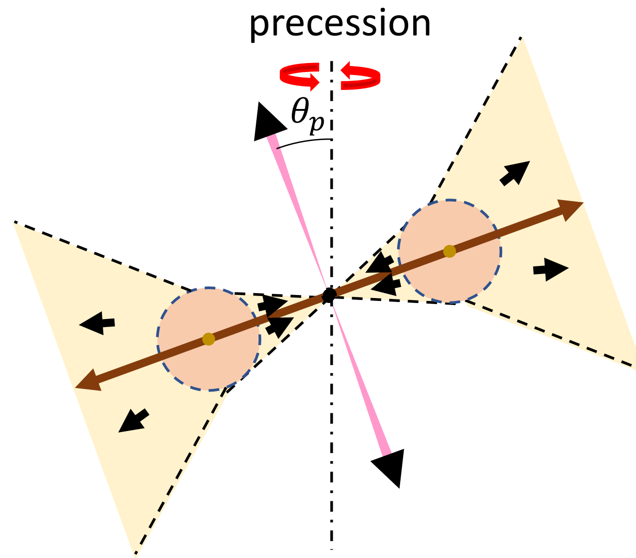


Observational supports for the "accretion ring" III

Multiple flows and their behaviors in the SS433 - W50 system

(Inoue 2022)





<u>Precessing relativistic jets</u>

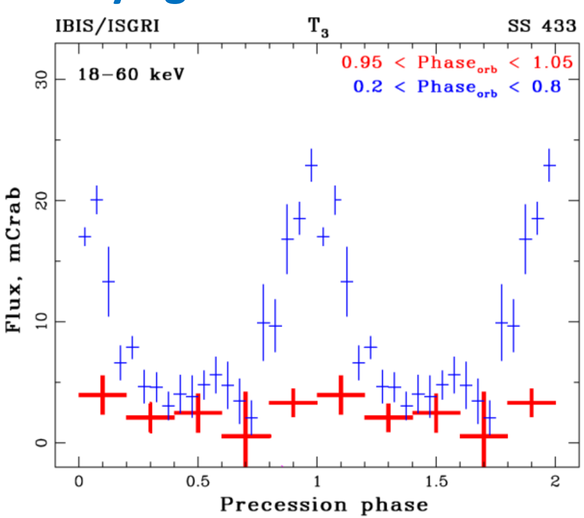
Doppler shift observations of optical lines (Margon 1984)

precession period	162.5 d
precession tilt angle	$\theta_p \simeq 20^\circ$
inclination angle	$i \simeq 79^\circ$

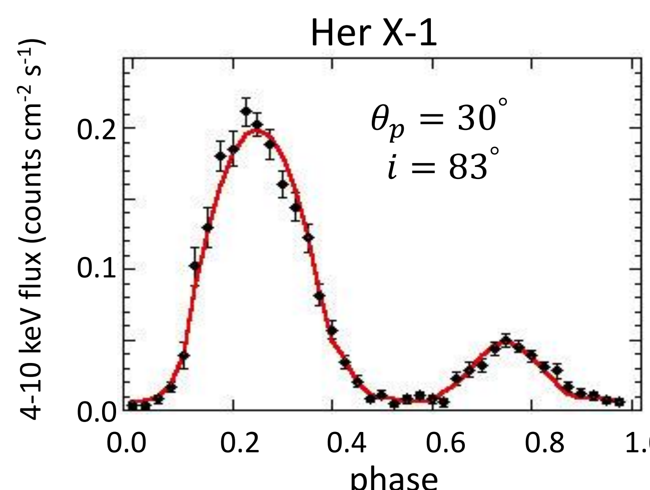
<u>Precessing accretion ring</u>

Hard X-ray light curve folded with the precession period

(Charepashchuk+ 2013)



This **looks consistent with a light curve predicted with the precessing ring model.**



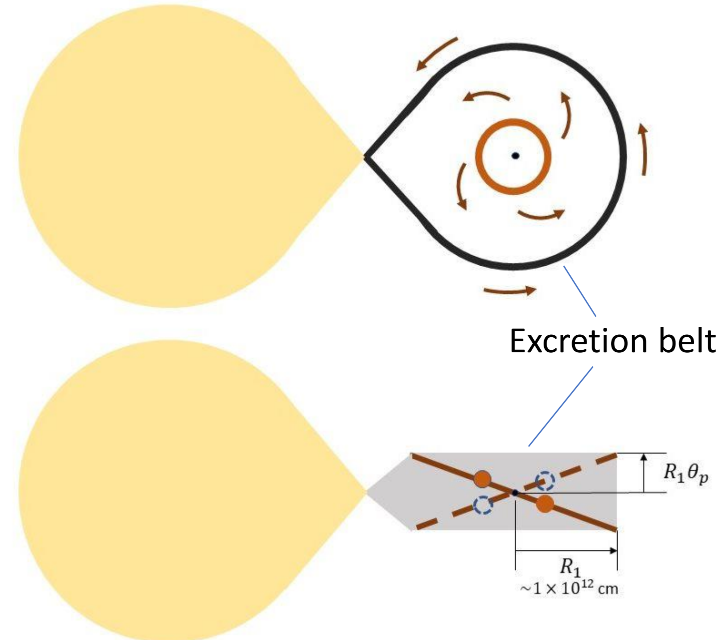
Precessing thin excretion disk in SS433

It tends to form an excretion ring at 4 r_k.

Since the Roche lobe radius $\lesssim 4r_k$, it could come to **turn around the Roche lobe** and return to the companion star.

➡ **Excretion belt** **significant contribution to the obscuration of the central engine**

A simple calculation shows that the excretion belt could have an optical thickness for the electron scattering $\tau > 1$ and significantly obscure emissions from the central engine.

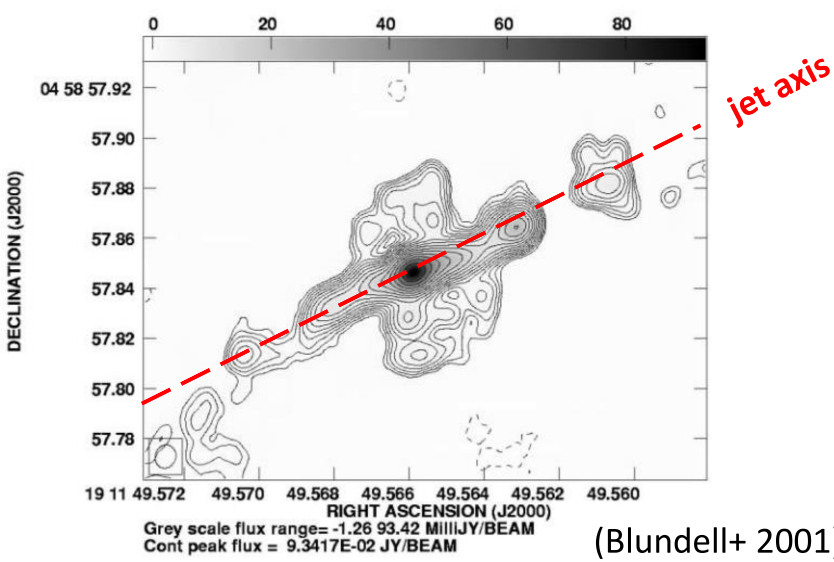


Precessing disk wind in SS433

optical line profiles

P-Cyg profiles $v_w \sim 10^8$ cm s-1

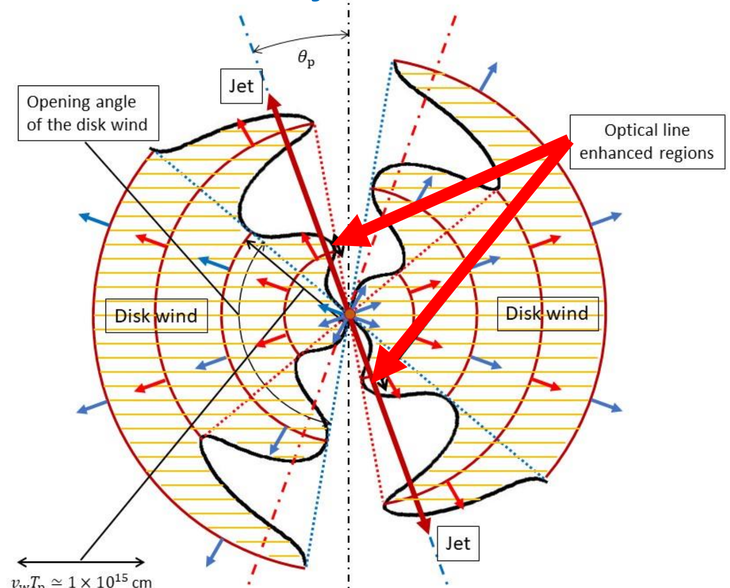
radio images



(Blundell+ 2001)

Optical line enhancement at a distance $\sim v_w T_p/2$

Interaction of the jet with the disk wind



Snap shot of a meridian cross section of the disk wind and the jet

Observational supports for the "accretion ring" IV

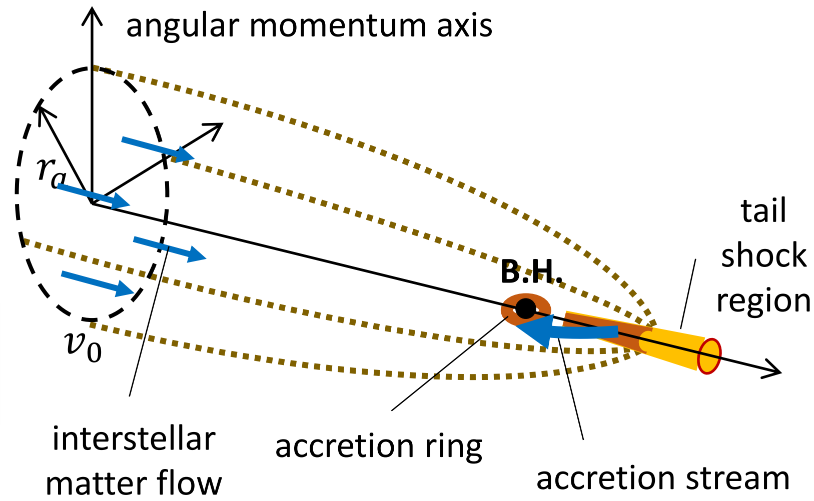
Accretion environments of AGNs (Inoue 2021b)

A supermassive black hole (BH) wanders in a region with several 10 pc extent around a galactic center (Inoue 2021a; 2024).

BH passes through inter-stellar medium in a circum-nuclear region and gets **the Bondi-Hoyle-Littleton (BHL) accretion.**

The interstellar matter trapped by the BH potential in the tail shock region inflows towards the BH as **an accretion stream**.

The inflowing matter forms **an accretion ring** at a Keplerian circular orbit determined by the specific angular momentum.



Observational elements in AGNs supporting the presence of accretion ring

Broad line region (BLR) ⇨ **Accretion ring**

The thick envelope of the accretion ring could suffer X-ray heating and have a thermally unstable situation to make the matter distribute separately in a hot gas region and cold dense clouds. This suggests that **the accretion ring could correspond to the broad line region.**

Warm absorbers $v{\sim}10^8$ cm s^{-1}

⇨ **Disk winds from accretion rings**

Two kinds of X-ray winds in Seyfert galaxies

Ultra-fast outflows (UFOs)	$v{\sim}0.1\,c$
Warm absorbers	$v{\sim}10^8$ cm s^{-1}

(Tombesi+ 2013)

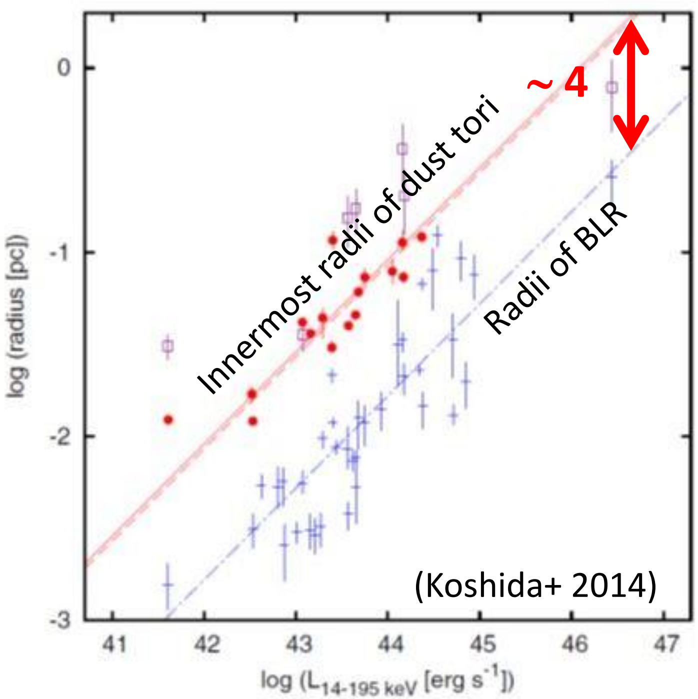
Dust torus / Water maser disk ➡ Excretion ring

An excretion disk is expected to out-flow from the accretion ring with radius, R_{ac}, and to terminate at a position of 4 R_{ac}, **forming** another ring (**excretion ring**) with radius, $\boldsymbol{R_{ex} = 4R_{ac}}$, there.

Matter out-flowing through excretion disk from the accretion ring accumulates in the excretion ring. The position of the excretion ring is considered to change in time, depending on the amplitude and direction of the specific angular momentum of the accreted matter which could be determined by the occasional accretion environment.

The position-movement of the excretion ring could make an extended structure as **a relic of the AGN activities**, which could be origins of **the dust tori or the water maser disks**.

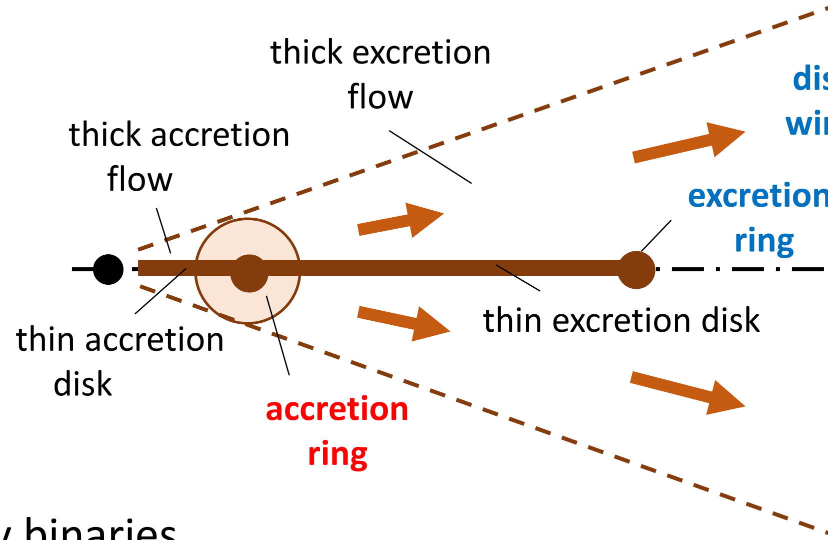
Observed relation between the BLR radius and the innermost radius of the dust torus



The ratio ~4 of the innermost radius of the dust-torus to the BLR radius can be explained, if we consider that **the innermost part of the dust torus corresponds to the excretion ring** which is now being formed.

Summary

- "Accretion ring"
  Inoue (2021, PASJ, 73, 795)
- Final appearances of the excretion flows
  Thick excretion flow ➡ Disk wind
  Thin excretion disk
  ➡ Excretion ring in AGNs
  Flow turning around the Roche lobe in X-ray binaries



- Two-layer accretion flow
  Thin accretion disk ➡ Relatively stable soft component
  Thick accretion flow ➡ Relatively variable hard component
  see **Inoue (2022, PASJ, 74, R1)** for the review on X-ray observations of accretion disks
- Precession of the accretion ring
  Basic considerations **Inoue (2012, PASJ, 64, 40)**
  Reproduction of super-orbital X-ray light curves with the precessing ring model
  Inoue (2019, PASJ, 71, 36)
- Properties derived from the precessing accretion ring in SS433
  Inoue (2022, PASJ, 74, 991)
- Accretion ring and associated outflows in AGN
  Inoue (2021, PASJ, 73, 1429)

see also **Inoue (2024, ApJ, 967:3)** for relativistic jets from slim disks