Eclipsing Light Curve for Accretion Flow around Rotating Black Hole

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Takahashi & Watarai (2006) submitted

Abstract

"The analysis of the eclipsing light curves can be a new method to determine the spin of the stellar-mass black hole if the central region of the accretion disk is occulted by the companion star."

Recently, the observational light curves for the eclipsing black-hole binary M33 X-7 was obtained by Chandra (Pietsch et al. 2006). Since the central region of the accretion disk near the event horizon is eclipsed, the physical information of the strong gravity region, e.g. black hole spin, is possibly contained in the observational data. Here, we calculate the eclipsing light curves of the black hole binaries for rotating black holes by taking into account the atmospheric smearing effects by the companion star such as photoionization by HI and HeI. We found that for the observed photon energies larger than 1 keV the atmospheric effects can not completely smeared out the information of the black hole spin. Then, the eclipsing light curves observed at higher photon energy in X-ray, i.e. >1 keV, contain the information of the black hole spin.

Motivation

Strong Gravity Region around Black Hole

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Methods for probing strong-field of gravity are so extremely limited.

1. **Direct Imaging :** **VSOP-2 (ISAS: radio)**

   MAXIM (NASA: X-ray)

2. **Spectrum:** **Suzaku & NeXT (ISAS)**

   Con-X (NASA) & Xeus (ESA)

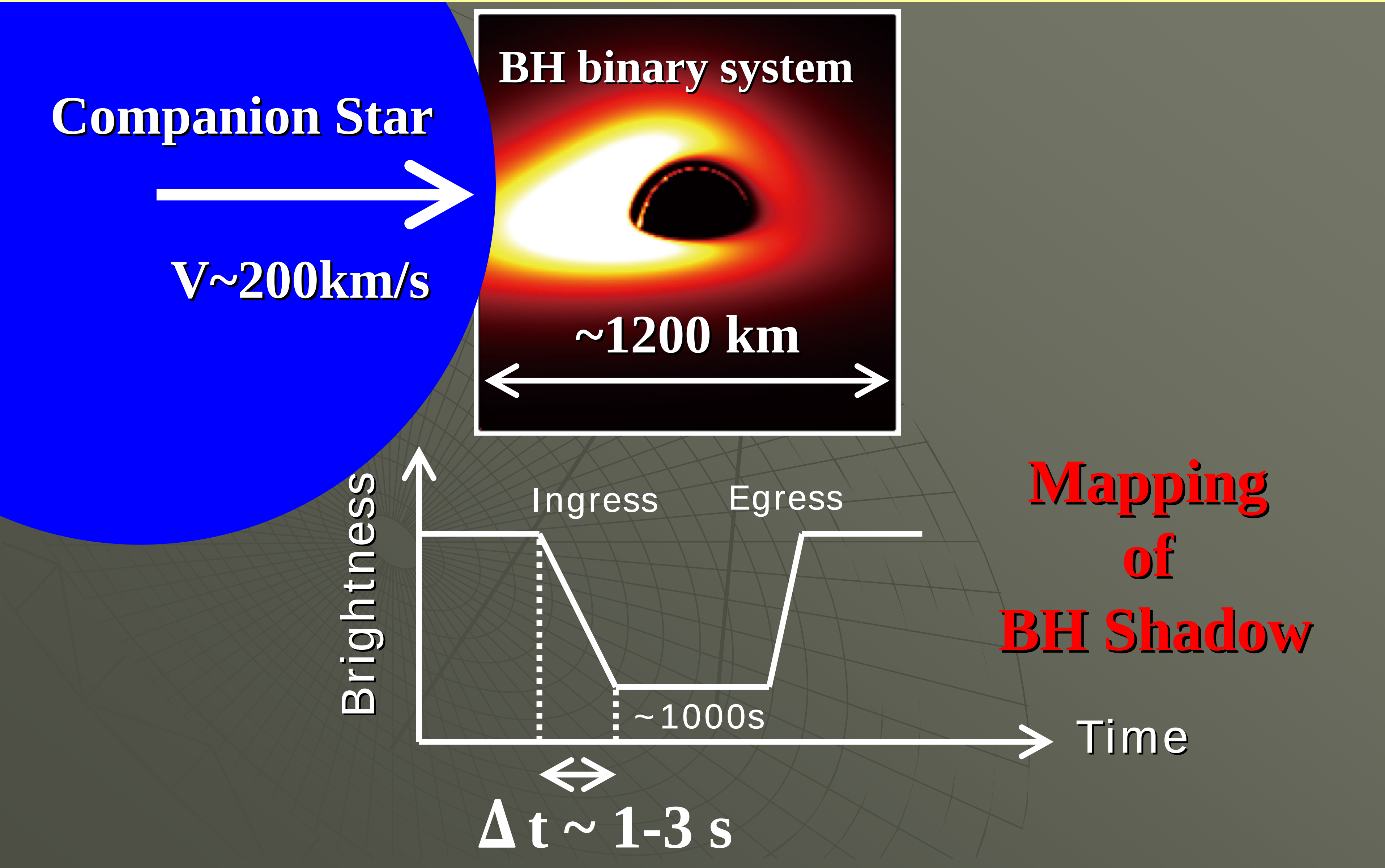
3. **Time Variavility:** **High time resolution is required.**

   Eclipsing Light Curve → Mapping of BH

Key Question 1:

Do eclipsing LCs contain the information of BH spin?

Eclipsing Light Curves



Eclipsing Light Curves & Related Sciences

Asymmetric Brightness Distribution of Accretion Disk

(Fukue 1987, Nature)

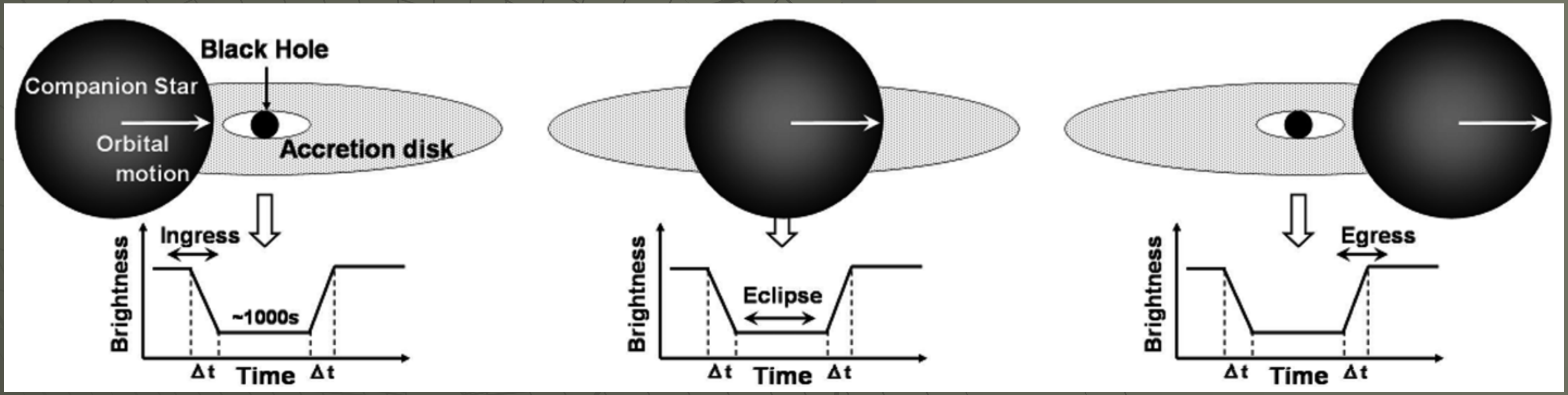
similar to Doppler mapping,
or Eclipse mapping technique

Eclipsing light curves give constraints on :

- **Brightness Profile of Disks** (Fukue 1987)
- **Mass Accretion Rate** (Watarai, Takahashi & Fukue 2005)
- **Black Hole Spin** (Takahashi & Watarai 2006 submitted)
- **Atmosphere of Companion Star** (Takahashi & Watarai 2006)

Eclipsing Light Curves : 3 Phases

(i) Ingress Phase (ii) Eclipse Phase (iii) Egress Phase



Light curves when ingress and egress is important !

→Containing physical information of BH & disk.

Watarai et al. 2005

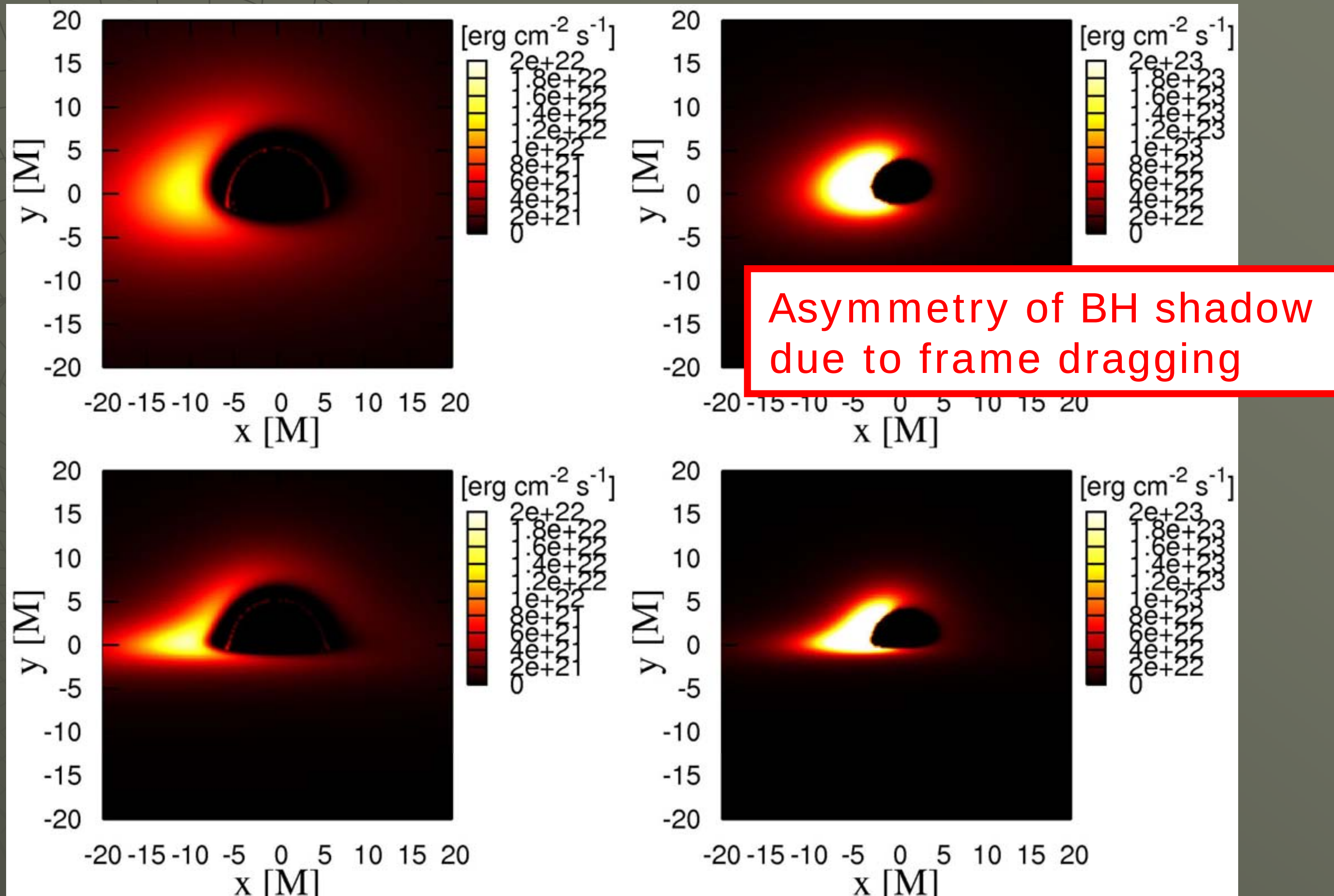
BH Shadows & BH Spin

a/M=0 : Schwarzschild BH **a/M=1 : max. Kerr BH**

Observed Inclination Angle

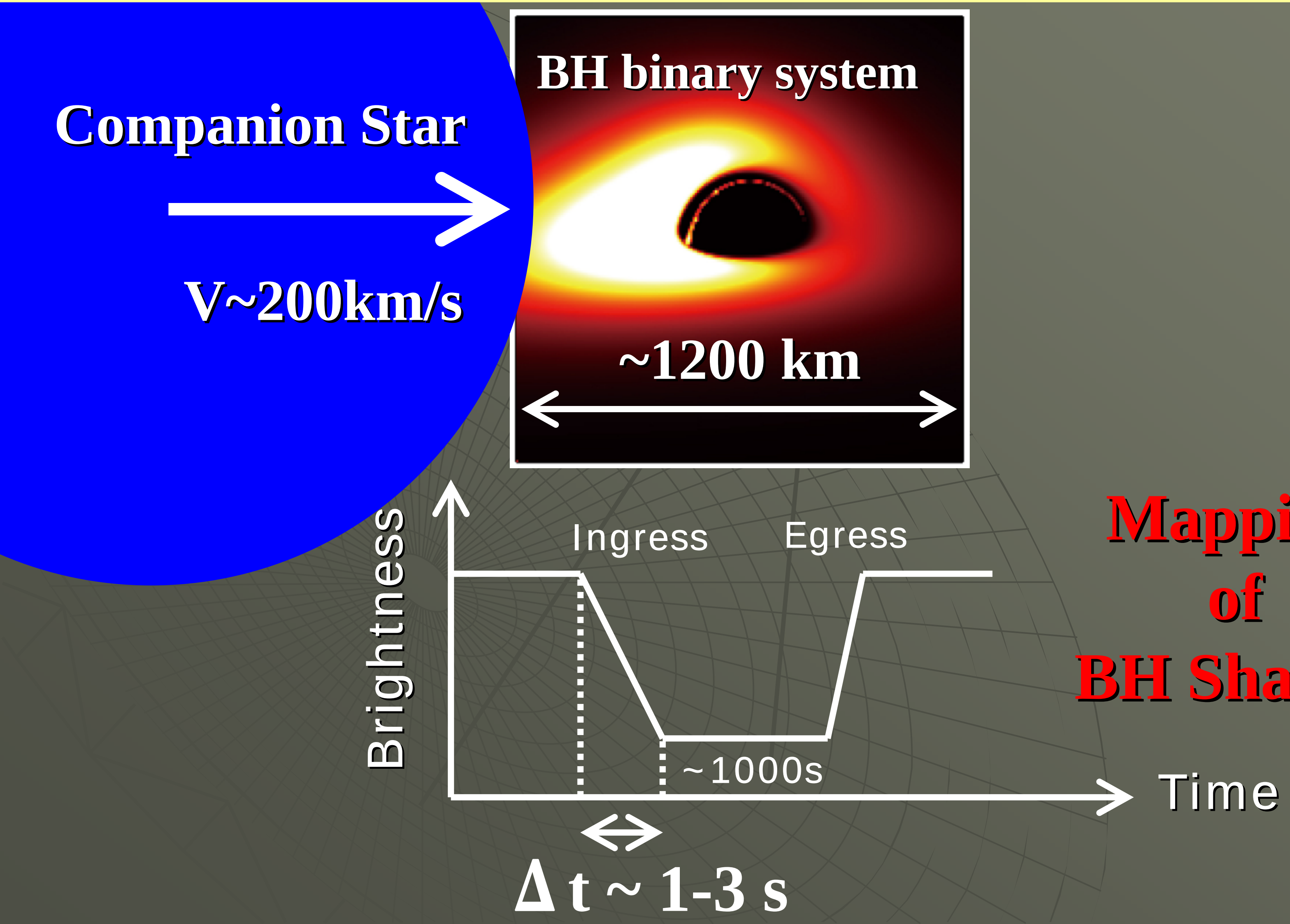
i=60°

i=80°



Relativistic Standard Accretion Disk is assumed. (Page&Thorne 1974)

Eclipsing Light Curves

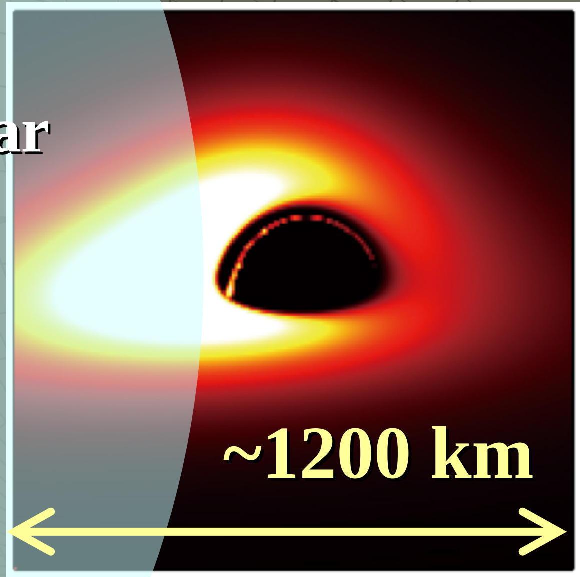


Mapping of BH Shadow

Atmosphere of Companion Star

Atmosphere of Companion Star
(Cromosphere ~ Corona)

Photosphere
of
Companion Star



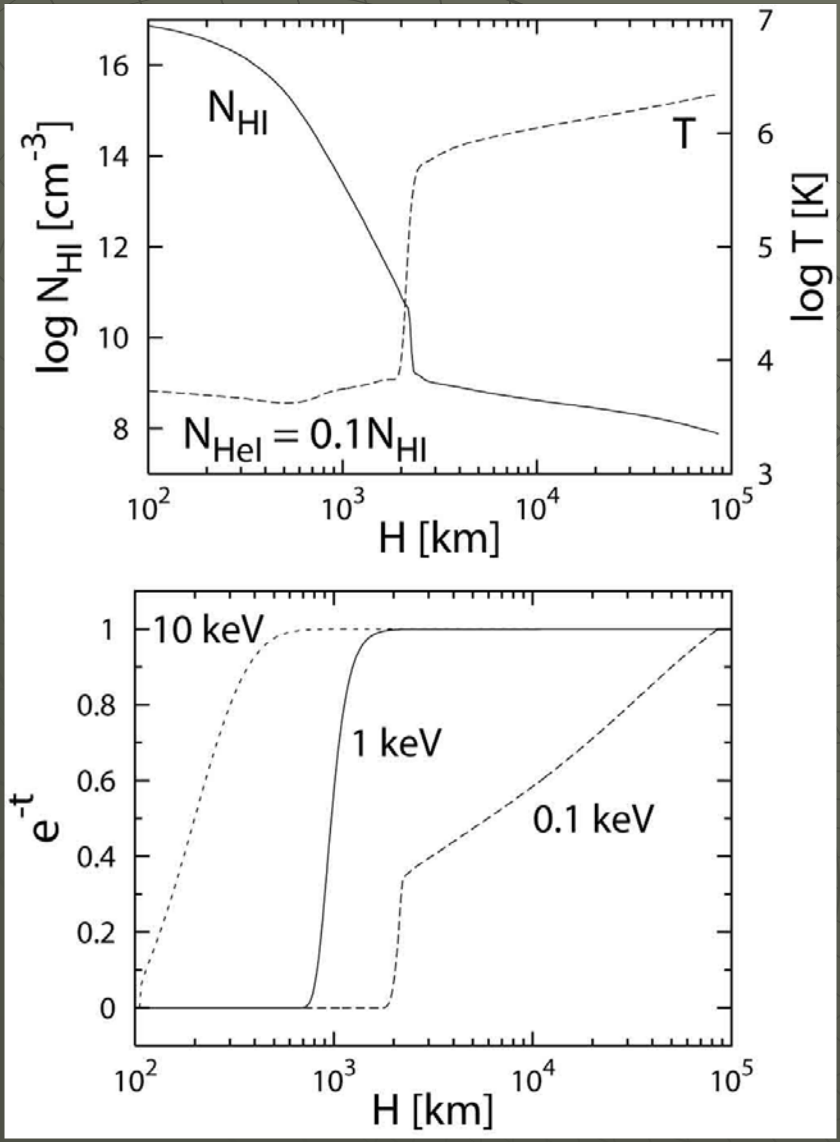
Height of Atmospphere
~ Size of the Central
Region of Disk

Δ L

Δ L ~ 2000 km

Key Question 2:
Do stellar atmosphere smear out effects of BH spin?

Atmospheric Smearing Effects



H: height from photosphere

Solar atmospheric structure is assumed. (Daw et al. 1995)

1. Chromosphere (~2000km)

→ **Photoionazation absorption by HI & HeI (for 0.1-10 keV)**
Compton scattering (for 10 keV)

2. Transition Zone

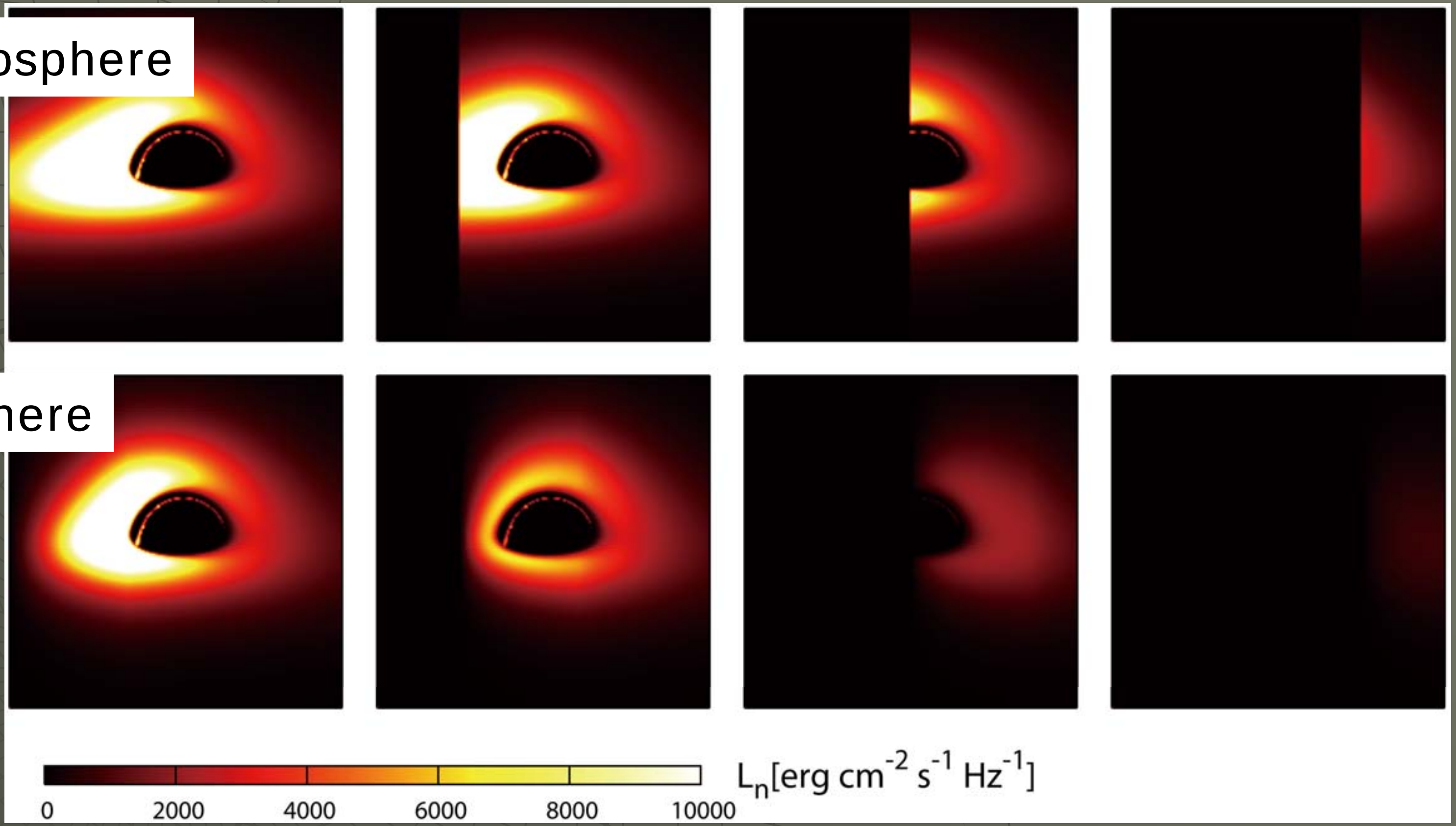
3. Corona (2000km~)

→ **Optically thin (for 1-10 keV)**
Photoionazation by HI (for 0.1keV)

BH Shadows smeared by Atmosphere

With No Atmosphere

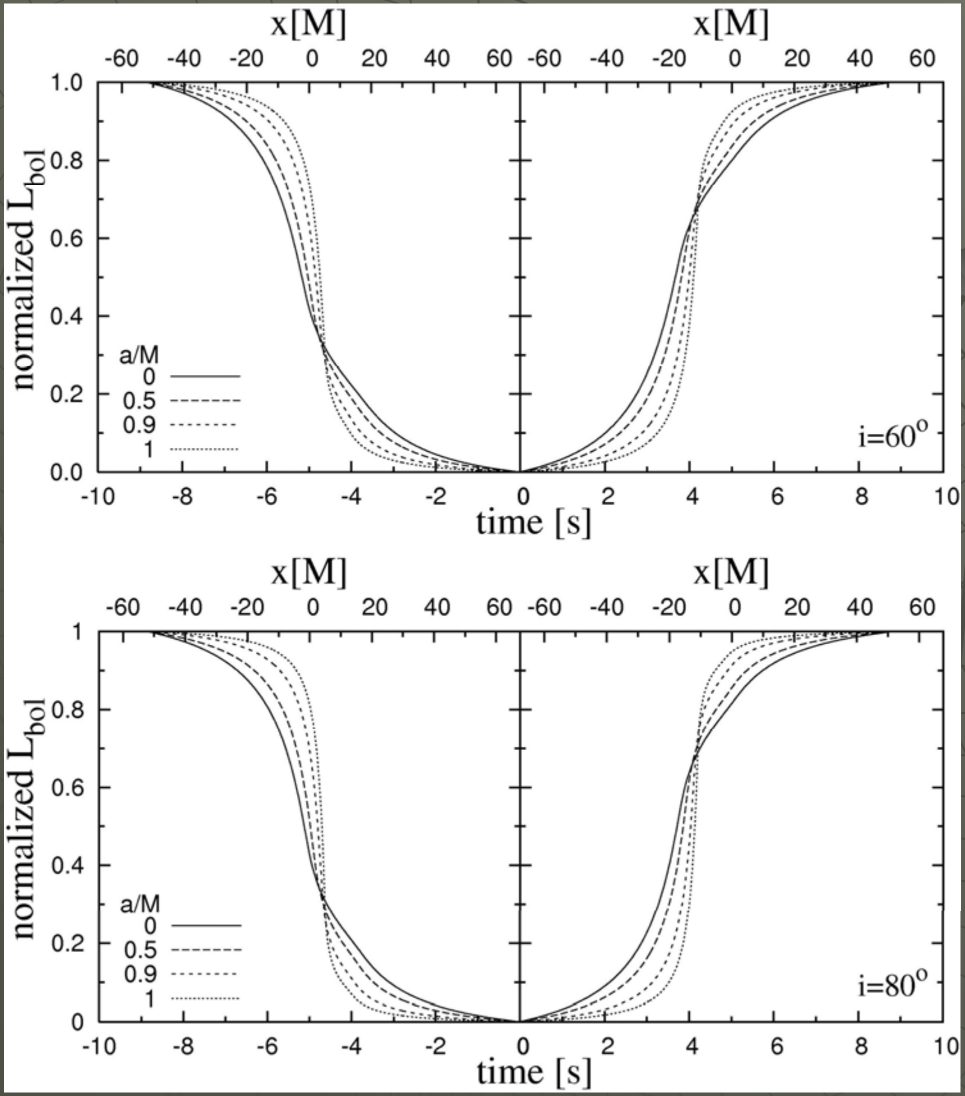
With Atmosphere



Eobs=1keV
a/M=0.5
i=80 deg

X-ray photons are mainly absorbed by photoionization of HI & HeI in chromosphere.

Light Curves : No Atmosphere



BH spin dependence is clear !

1. **Variation timescale**

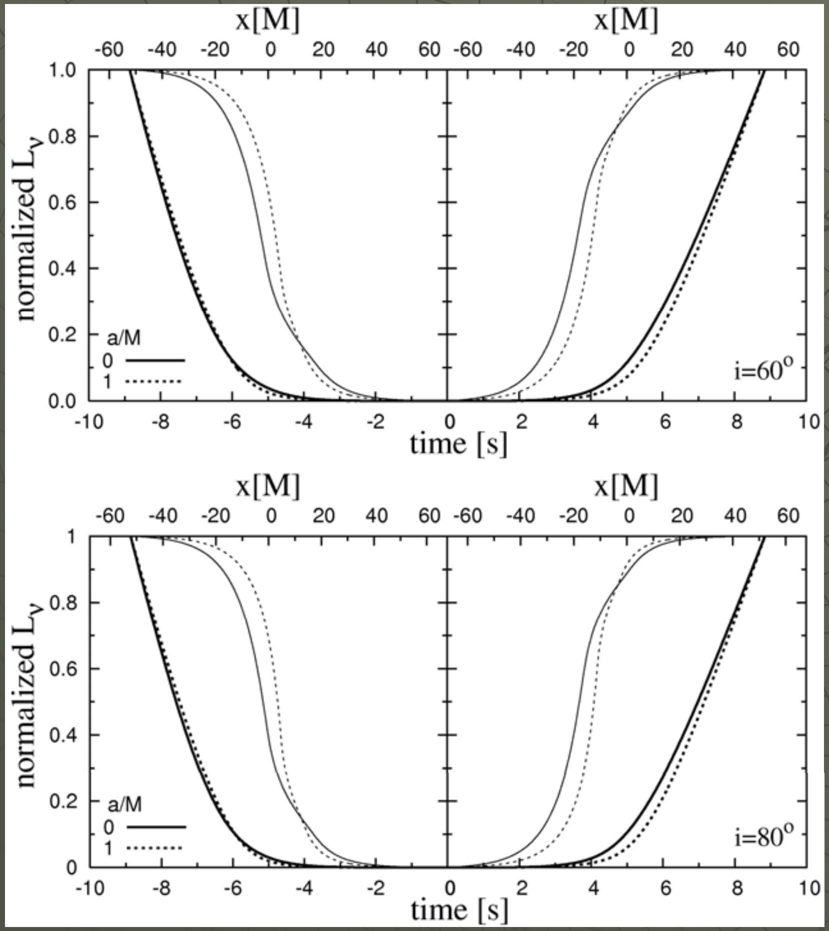
$$\sim \frac{\text{Size of Emission Region}}{\text{Transverse Velocity}}$$

2. **Most of X-ray photons come from blue-shifted part of disk.**
   → **BH spin dependence**
   - A. size of emitting region
   - B. photon energy
   - C. observed image (light bending, etc …)

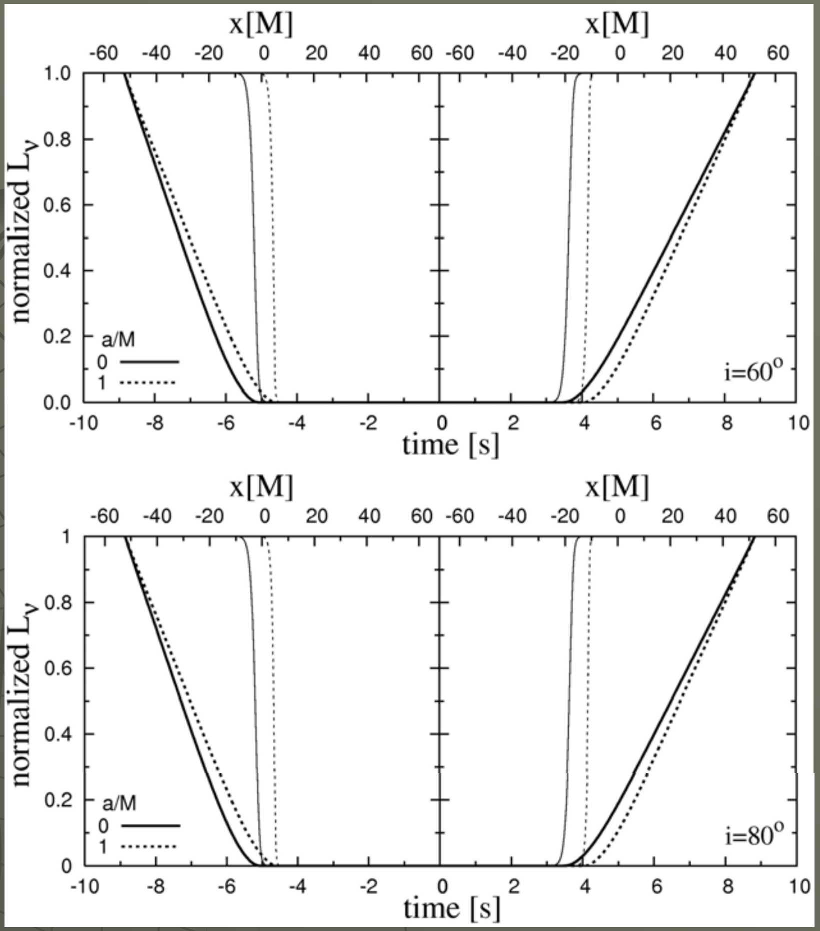
3. **Effects of inclination angle is negligible.** (LCs in upper and lower panels are nearly same.)

Light Curves : With Atmosphere

1 keV

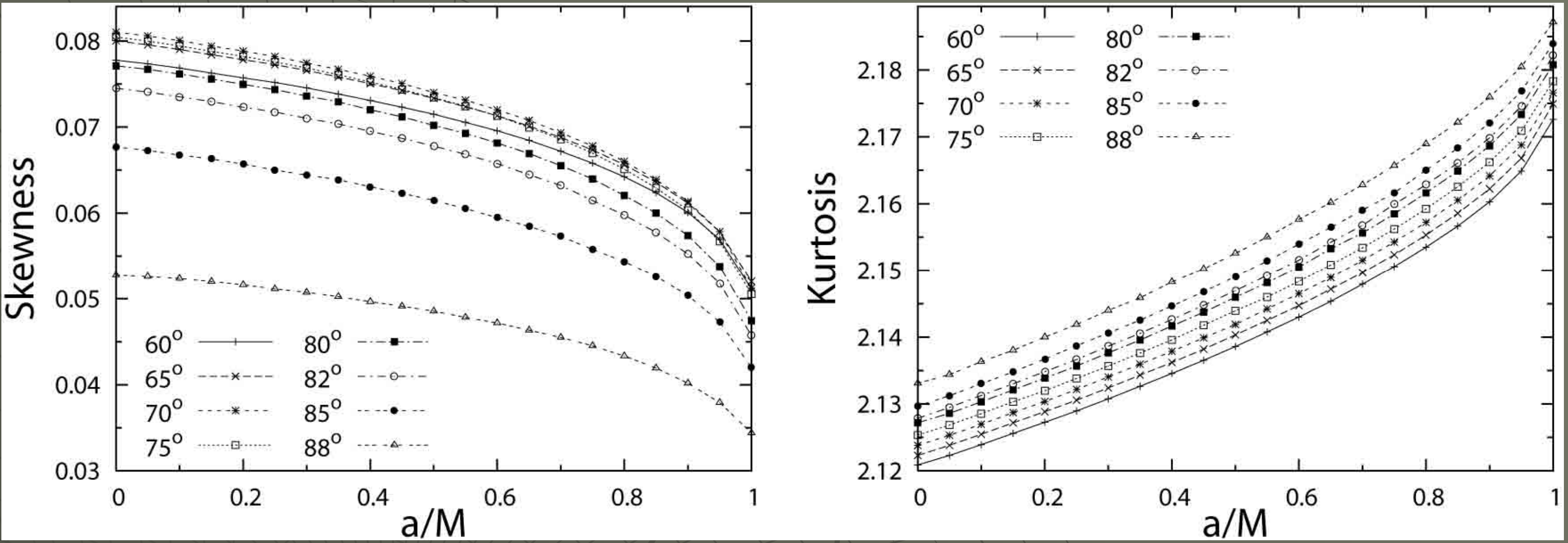


10 keV



Stellar atmosphere partly smeared out LCs, but can not completely at 1-10keV. → Signals of BH spins in LCs.

Skewness & Curtosis Analysis



$$S = \frac{1}{\sigma^3}\sum_{i=0}^{n}(t_i - \bar{t})^3 P_i,$$

$$K = \frac{1}{\sigma^4}\sum_{i=0}^{n}(t_i - \bar{t})^4 P_i,$$

Skewness → the degree of asymmetry of LCs.

Kurtosis → the degree of peakedness of LCs.

The statistical quantities of skewness and curtosis for the eclipsing light curves also shows clear dependence on BH spins.

Conclusions

Eclipsing light curves for accretion flow around rotating BHs are calculated with atmospheric effects of companion stars.

Key Question 1:
Do eclipsing LCs contain the information of BH spin?

Ans. Yes.
Variation timescale directly reflect the size of the effective emitting region determined by BH spin.

Key Question 2:
Do stellar atmosphere smear out effects of BH spin?

Ans. No. (for cases solar-type atmosphere)
LCs are partly smeared out by photoionization by HI, but not completely for 1 keV-10keV.