Partial Accretion in the Propeller Stage of Aql X-1

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Outline:

- **Introduction**
  - Low Mass X-ray Binaries
  - Accreting Millisecond X-ray Pulsars
- **Classification and Spectral Evolution of Outbursts of Aql X-1**
- **Disk Structure of LMXBs – Basic definitions**
- **Disk – Magnetosphere interaction stages;**
  - Accretion, Propeller, Radio pulsar
- **The Decay Stages of Outbursts, A new Technique**
- **Applications; Aql X-1**
- **Spectral modelling of RXTE/PCA data of Aql X-1**
- **(Very) Pre-Liminary Results from Insight-HXMT and Future Plan**
- **Summary**

Low Mass X-ray Binaries

- LMXBs are the binary systems containing a compact object (a black hole, a neutron star) and a low mass companion ($M_* < M_\odot$), also called 'donor star'.
- Accretion mechanism is Roche lobe overflow.
- Old systems. Total life time is $\approx 10^{7-9}$ yr
- Observed in the galactic disc, bulge and the globular clusters in the Milky Way
- Relatively low magnetic filed $\approx 10^{8-9}$ G.
- Recyling Scenario; LMXBs are possible incubators of millisecond pulsars. Accretion onto NS can be the reason of conversion from slow rotator NS with high magnetic field to fast spinning and low magnetic field NS.

Accreting Millisecond X-ray Pulsars

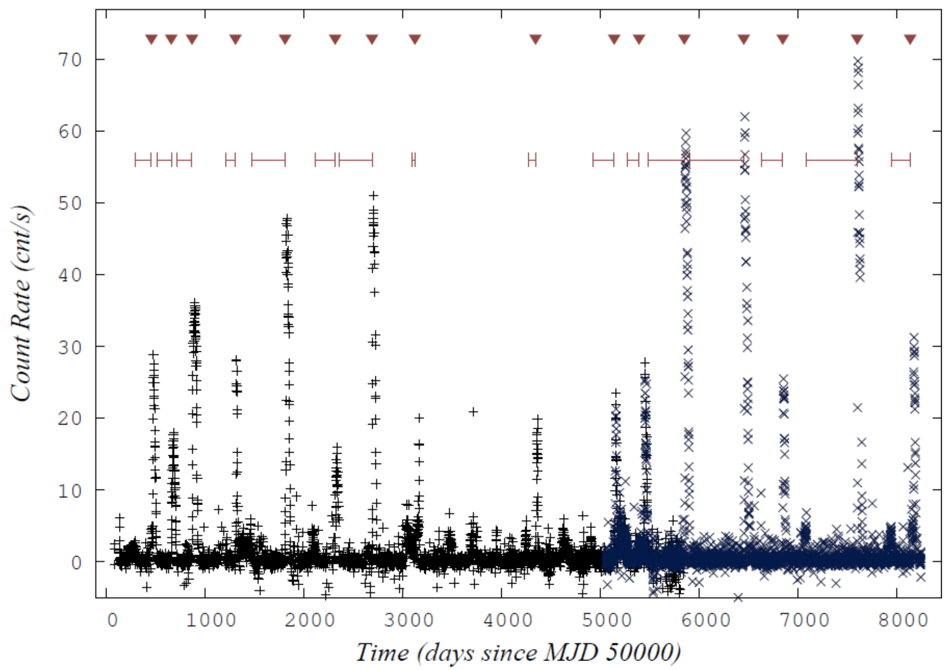
- A subset of LMXBs with 19 (?) members.
- The gas stripped from the companion is channeled out of the accretion disk onto the magnetic poles of rotating NS, giving rise to X-ray pulsations
- Show oscillations.. Differ from LMXBs...
- High spin frequency, $\nu \geq 100$Hz
- $M_{donor} \leq 1\ M_{\odot}$, B $\approx 10^{8\text{-}9}$ G

Intermittency

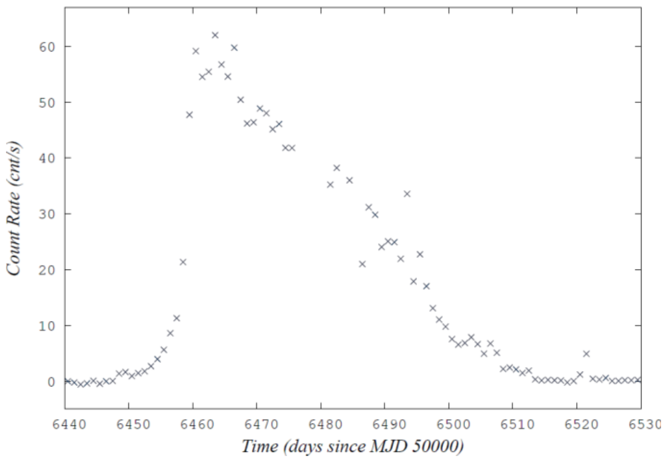
- Pulsations are not persistent.
- Only three AMXPs are detected with intermittent pulsations.
- Most interesting case is 'Aql X-1'.

Aql X-1

- V1333 Aql -- Low Mass X-ray Binary
- Quiescent $L_X \approx 10^{33}$ erg s^{-1}, Outburst $L_X \approx 10^{35}$ erg s^{-1}
- Quiescent B ≈ 17 mag, Outburst B ≈ 14 mag
- P_{orb}= 18.95 hr, Spin Frequency= 550.27 Hz
- Spectral Type of companion: K6-M0

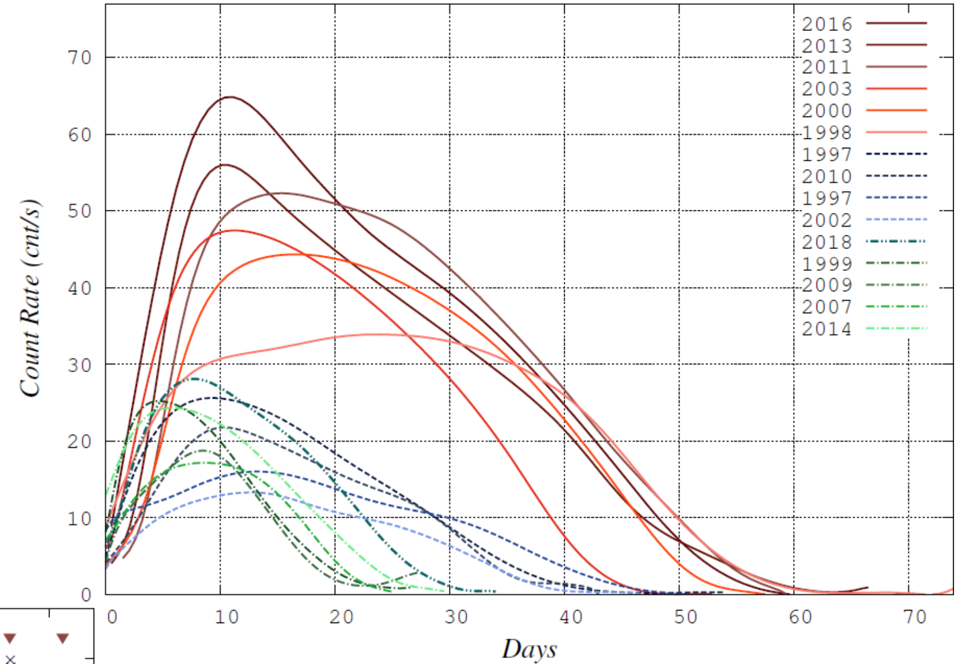


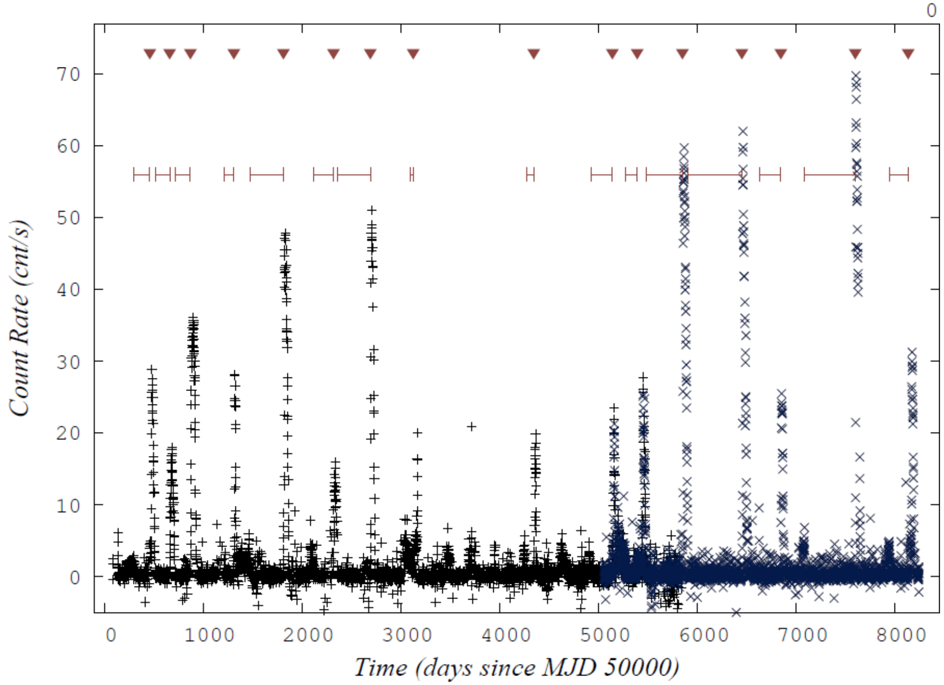
22 years light curve of Aql X-1 obtained by “Maxi” and “ASM”

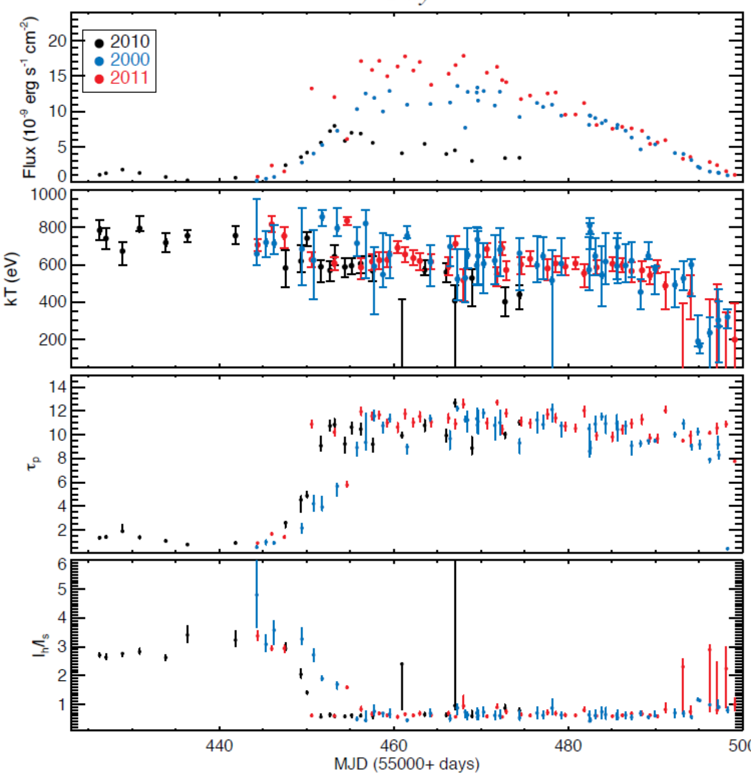


Aql X-1

- **Long – High Outbursts:**
  50-60 days, 37-61 cnt/s
- **Medium – Low Outbursts:**
  40-50 days, 13-25 cnt/s
- **Short – Low Outbursts:**
  20 days, 17-25 cnt/s







Gungor et al. 2014MNRAS.439.2717G,
Gungor et al. 2017NewA...56....1G

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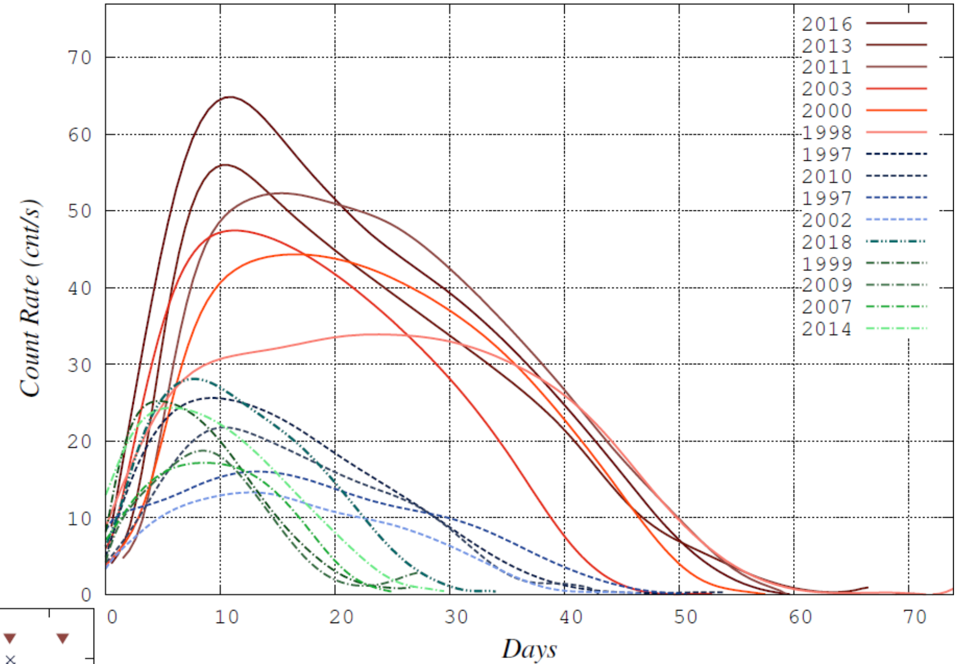

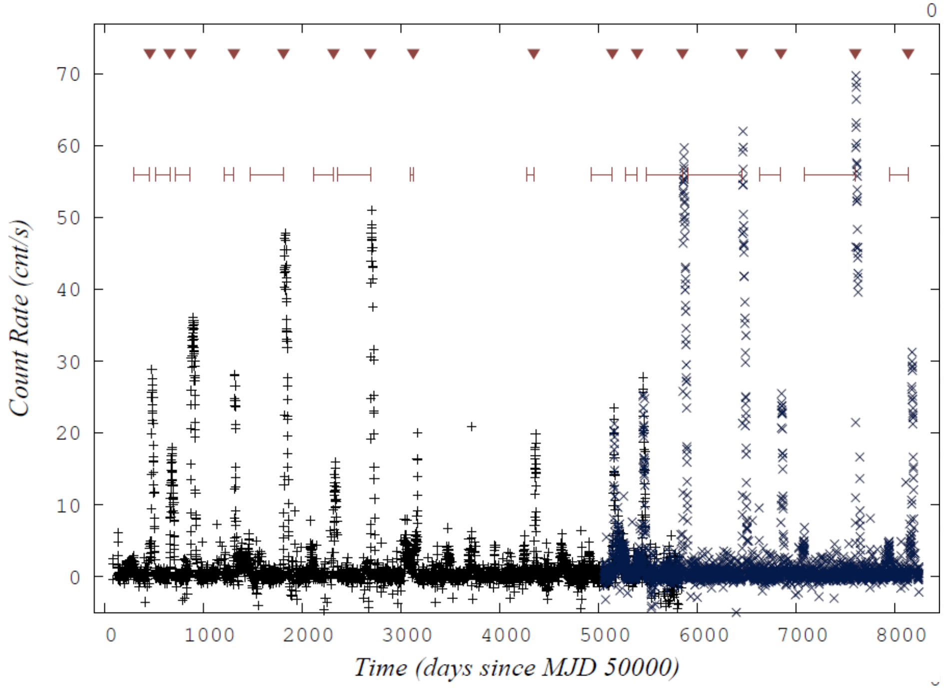

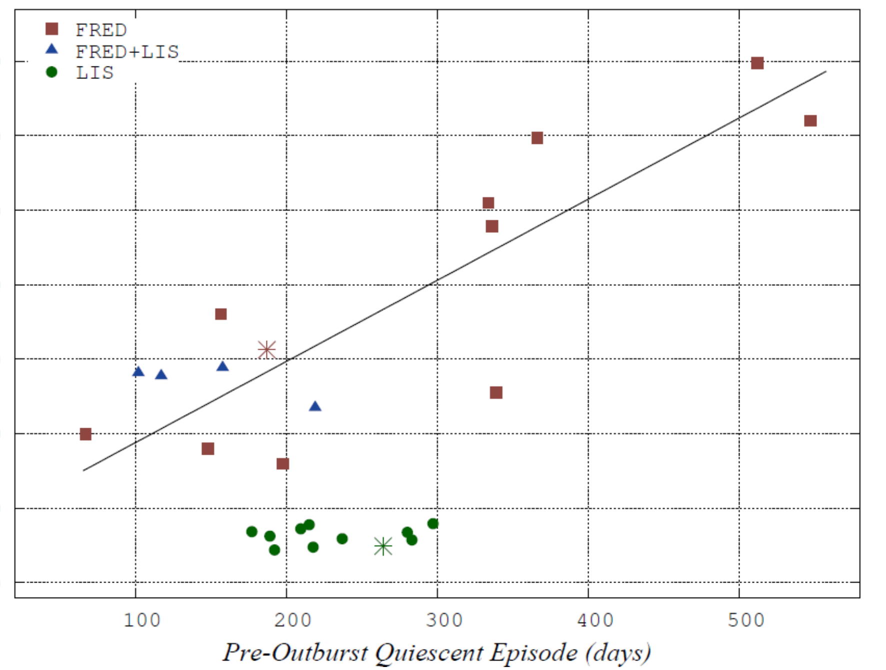

Gungor et al. 2014MNRAS.439.2717G,
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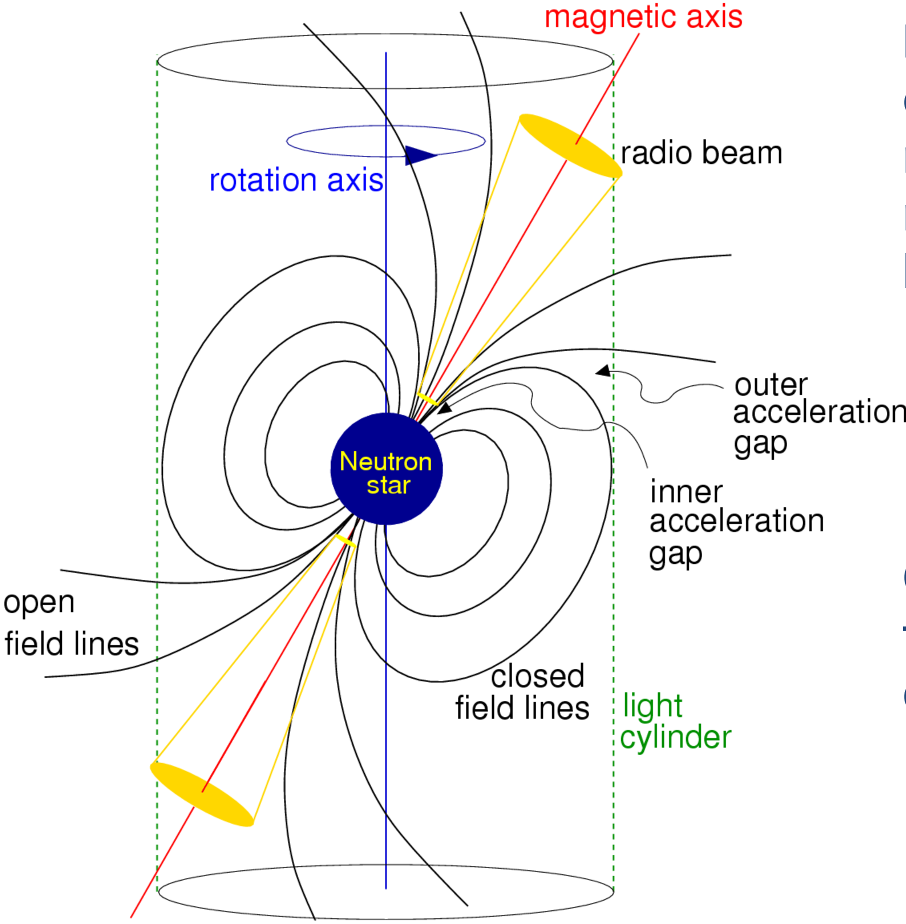
Two Critical Radii of Disk Structure



Light cylinder; The cylinder centered on the pulsar and aligned with the rotation axis at whose radius the co-rotating speed equals the speed of light

$$R_L = \frac{c}{\Omega}$$

c; *speed of light*
Ω; *angular velocity*

Corotation Radius: The radius that the angular velocity of the star is equal to Keplerian angular velocity.

$$R_{co} = \left(\frac{GM}{\Omega^2}\right)^{1/3} \qquad \Omega_K = (GM/r^3)^{1/2}$$

Basic Definitions of Disk Structure

Fastness Parameter; A ratio of the angular velocity of the star to Keplerian angular velocity at the inner disk radius.

$$\omega_* = \frac{\Omega_*}{\Omega_K(R_{in})} = \left(\frac{R_{in}}{R_{co}}\right)^{3/2}$$

Alfvén Radius; The radius where the magnetic stresses and the material stresses (ram pressure) are balanced.

$$R_A = \left(\frac{\mu^4}{2GM\dot{M}^2}\right)^{1/7} \qquad P_{mag} = \frac{B^2}{8\pi} \qquad P_{ram} = \frac{1}{2}\rho\nu^2$$

$R_{in} = \zeta\, R_A$ $\qquad$ $\zeta \cong 0.5$ **for disk accretion (Gosh & Lamb)**

Disk – Magnetosphere interaction Stages

Radio Pulsar Stage: If the inner radius of the disk is located out of the light cyclinder, the system acts as an isolated neutron star.

$$R_{in} > R_{light\ cyc}$$

- **No Accretion**
- **No Evidence of the dics existence in the X-ray light curve**

Propeller Stage: The inner radius of the disk is around the corotation radius, then not all of the material transferred from outer layers to inner layers can fall onto the pole.

$$R_{light\ cyc} > R_{in} \approx R_{co}$$

- **Partial Accretion**
- **The possible evidence is the knee between the slow decay phase to fast decay phase of an outburst.**

Disk – Magnetosphere interaction Stages

Accretion Stage: The inner radius of the disk penetrates to corotation radius. All of the material transfering inner layers falls onto the neutron star poles.

$$R_{in} < R_{co}$$

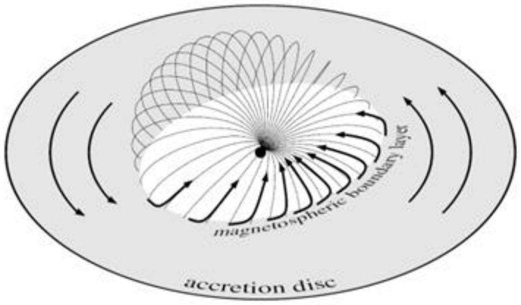
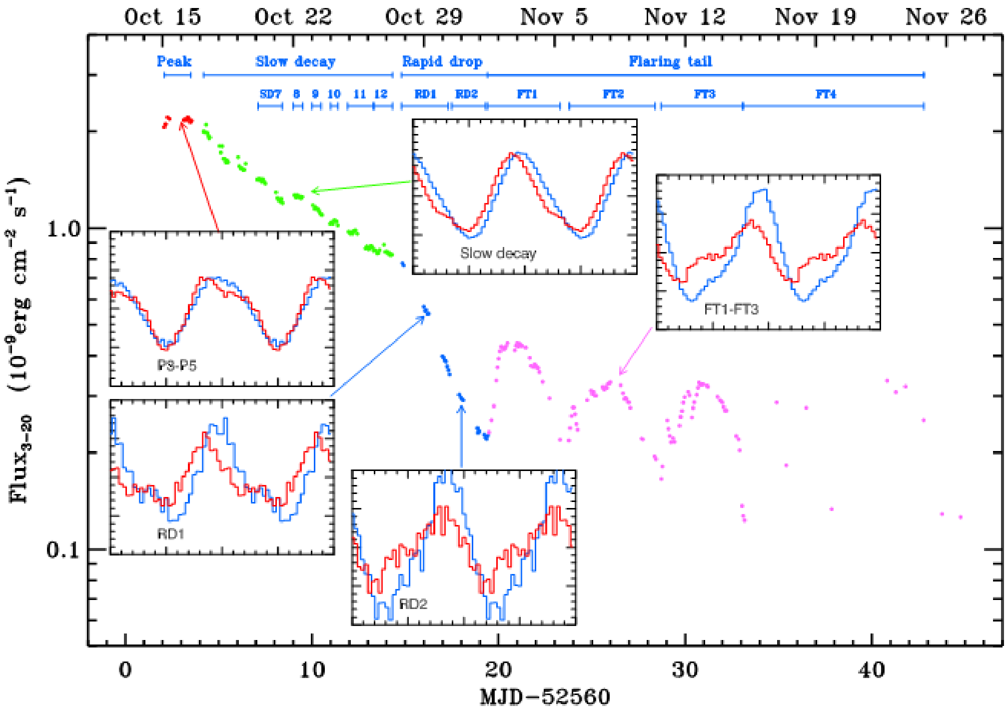


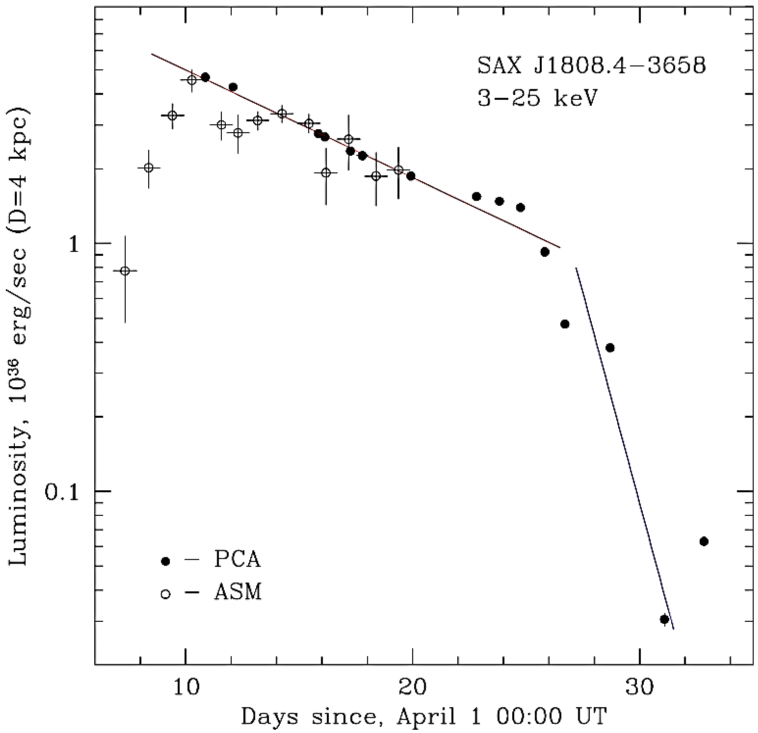
Fig. 6.3. Accretion disc around a magnetized neutron star or white dwarf. The magnetic dipole lines shown represent schematically the boundary of the magnetosphere.

Accretion Power in Astrophysics, Juhan Frank

The Decay Stages of Outbursts



2002 outburst of SAX 1808.4 – 3658, Ibragimov & Pountanen 2009



1998 outburst of SAX 1808.4 – 3658, Gifanov et al. 1998

The Decay Stages of Outbursts

- **The Slow decay phase represents the accretion stage. We fit the slow decay phase with a simple power low.**

$$L(t) = L_0\left(1+\frac{t-t_0}{\tau}\right)^{-\propto}, t_0 < t < t_{knee}, L < L_0$$

Assumption; $\dot{M}(t)$ ***follows the same trend in the propeller stage.***

- **Since** $L_X = \frac{GM\dot{M}_*}{r_*}$**, then** $f \equiv \frac{\dot{M}_*}{\dot{M}} = \frac{L_X}{L(t)} = f(t)$

The Decay Stages of Outbursts

Fastness Parameter; A ratio of the angular velocity of the star to Keplerian angular velocity at the inner disk radius.

$$\omega_* = \frac{\Omega_*}{\Omega_K(R_{in})} = \left(\frac{R_{in}}{R_{co}}\right)^{3/2} \longleftarrow \quad R_{co} = \left(\frac{GM}{{\Omega_*}^2}\right)^{1/3} \quad R_{in} = \left(\frac{GM}{\Omega_K^2(R_{in})}\right)^{1/3}$$

When $R_{in} = R_{co}$, we can define the critical mass accretion ($\dot{M}_{co}$) rate as following;

$$\dot{M}_{co} = \frac{\zeta^{7/2}\mu^2{\Omega_*}^{7/3}}{\sqrt{2}(GM)^{5/3}} \longleftarrow \quad R_A = \left(\frac{\mu^4}{2GM\dot{M}^2}\right)^{1/7} \quad R_{in} = \zeta\, R_A$$

Alfvén Radius; The radius where the magnetic stresses and the material stresses (ram pressure) are balanced.

$$P_{mag} = \frac{B^2}{8\pi} \quad P_{ram} = \frac{1}{2}\rho v^2$$

$$\omega_* = \left(\frac{\dot{M}}{\dot{M}_{co}}\right)^{-3/7} = \left(\frac{L(t)}{L_c}\right)^{-3/7} = \left(\frac{L_0\left[1+\left(\frac{t-t_0}{\tau}\right)\right]^{-\propto}}{L_c}\right)^{-3/7} = \omega_*(t)$$

The Decay Stages of Outbursts

As a result, we obtain two parameters, both depends on time

$$\omega_*(t) = \left(\frac{L_0\left(1+\frac{t-t_0}{\tau}\right)^{-\propto}}{L_c}\right)^{-3/7}$$

$$f(t) = \frac{L_X}{L_0\left(1+\frac{t-t_0}{\tau}\right)^{-\propto}}$$

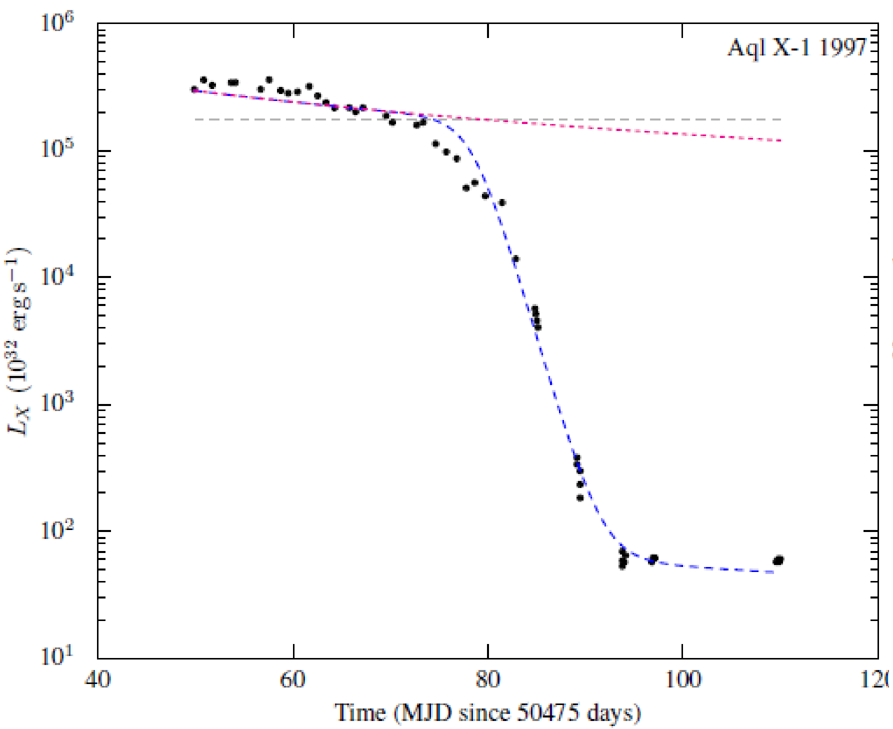
We can make a parametric plot of f vs ω_*
As expected f function shows a step function: All of the material falls onto the neutro star in accretion stage, a portion of the material falls onto the neutron star in the propeller stage and no falling material in the radio pulsar stage.

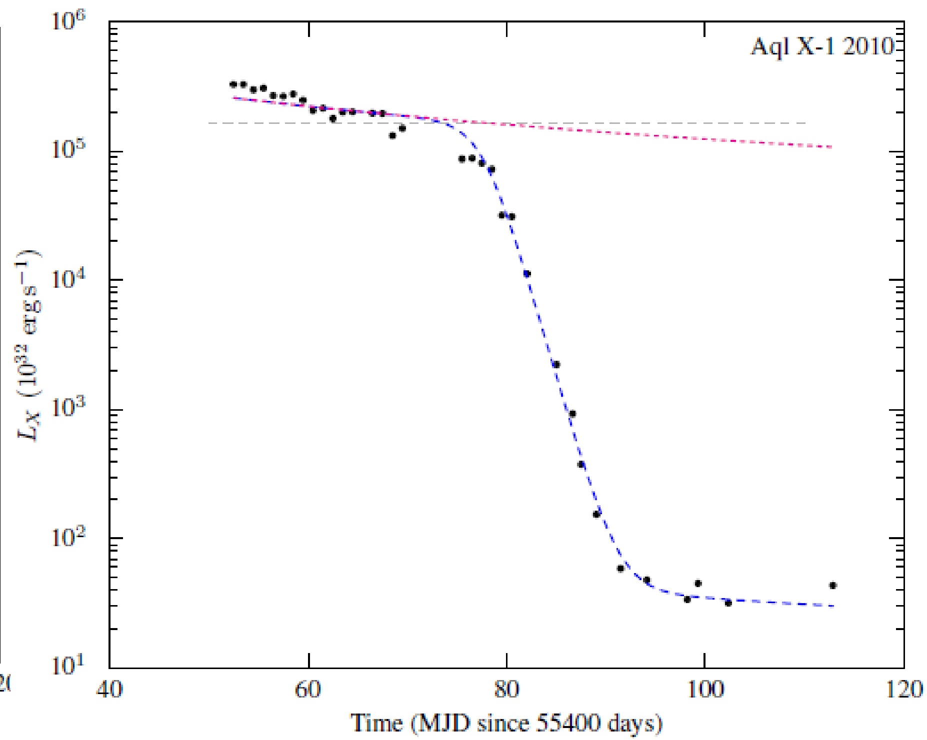
$$f(\omega) = \begin{cases} 1, & \omega < 1 \\ 0, & \omega \geq 1 \end{cases} \qquad f(\omega) = \frac{1}{2}\left[(1+f_{min}) + (1-f_{min}) \times tanh\left(\frac{\omega_c-\omega}{\delta}\right)\right]$$

A New Method to Describe Outbursts

$$f(t) = \frac{1}{2}\left[(1 + f_{min}) + (1 - f_{min}) \times tanh\left(\frac{\omega_c - \omega(t)}{\delta}\right)\right], \qquad \omega_*(t) = \left(\frac{L_0\left(1 + \frac{t - t_0}{\tau}\right)^{-\propto}}{L_c}\right)^{-3/7}$$

$$L(t) = L_0\left(1 + \frac{t - t_0}{\tau}\right)^{-\propto}, t_0 < t < t_{knee}, \qquad L_x(t) = L_0\left(1 + \frac{t - t_0}{\tau}\right)^{-\propto} \times f(t)$$





Campana, S., et al. 2014, MNRAS, 441, 1984

Observation and Data Analysis

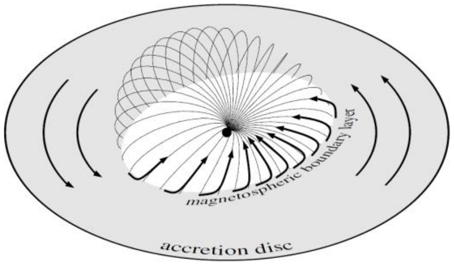
However…

The X-ray light does not only come from the pole but also few percentage of total luminosity we take, comes from the disk. To link the light curve to the propeller stage, one should first separate the light comes from the pole caused by an accretion and obtain a light curve only for magnetic pole.

- **RXTE/PCA observation of 2000 and 2011 outbursts of Aql X-1**

Model: *blackbody* + *diskblackbody* + *gauss*

- ***Blackbody* represents NS poles**
- ***Disk blackbody* represents inner disk**
- ***Gauss* represents iron line**



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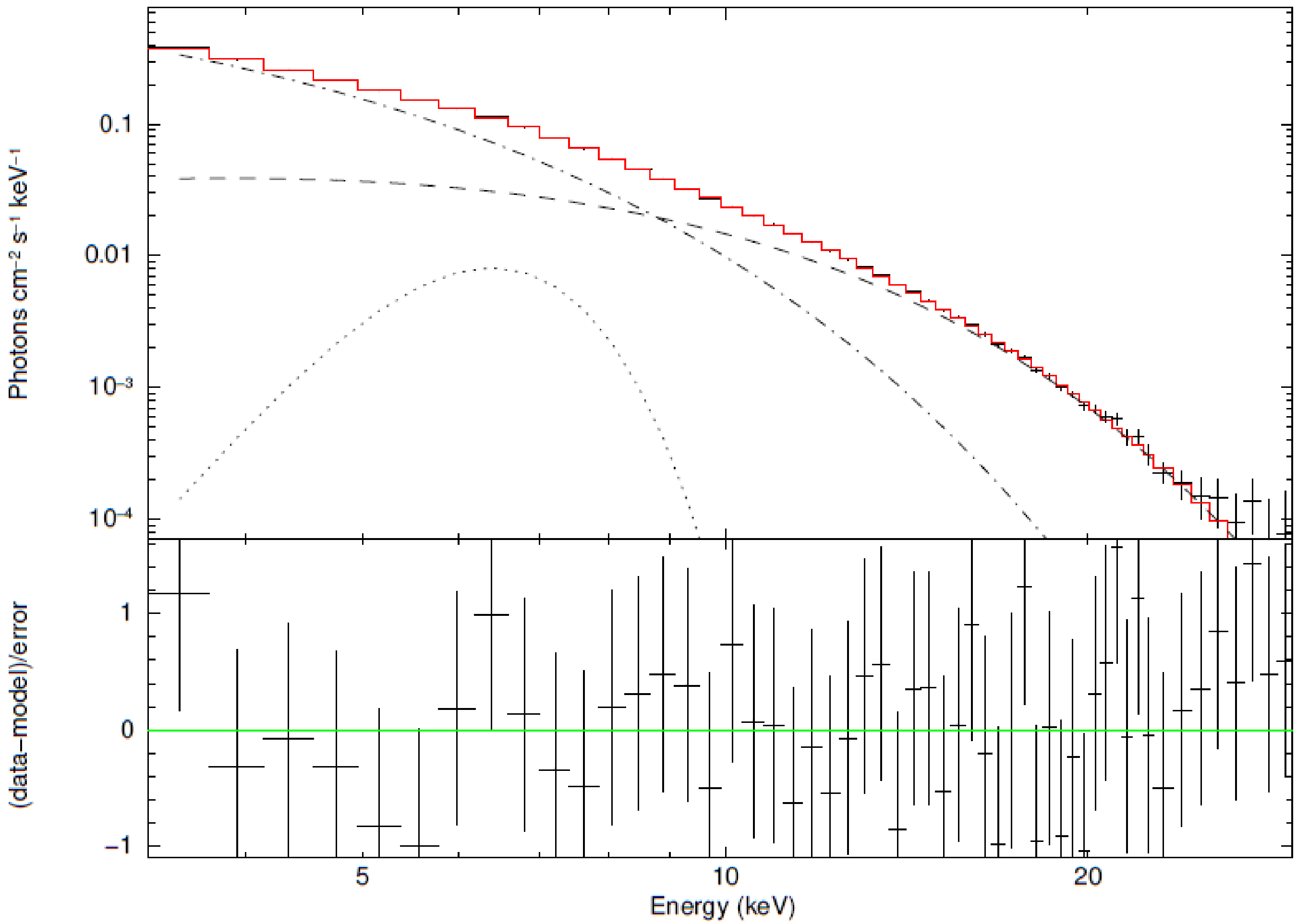
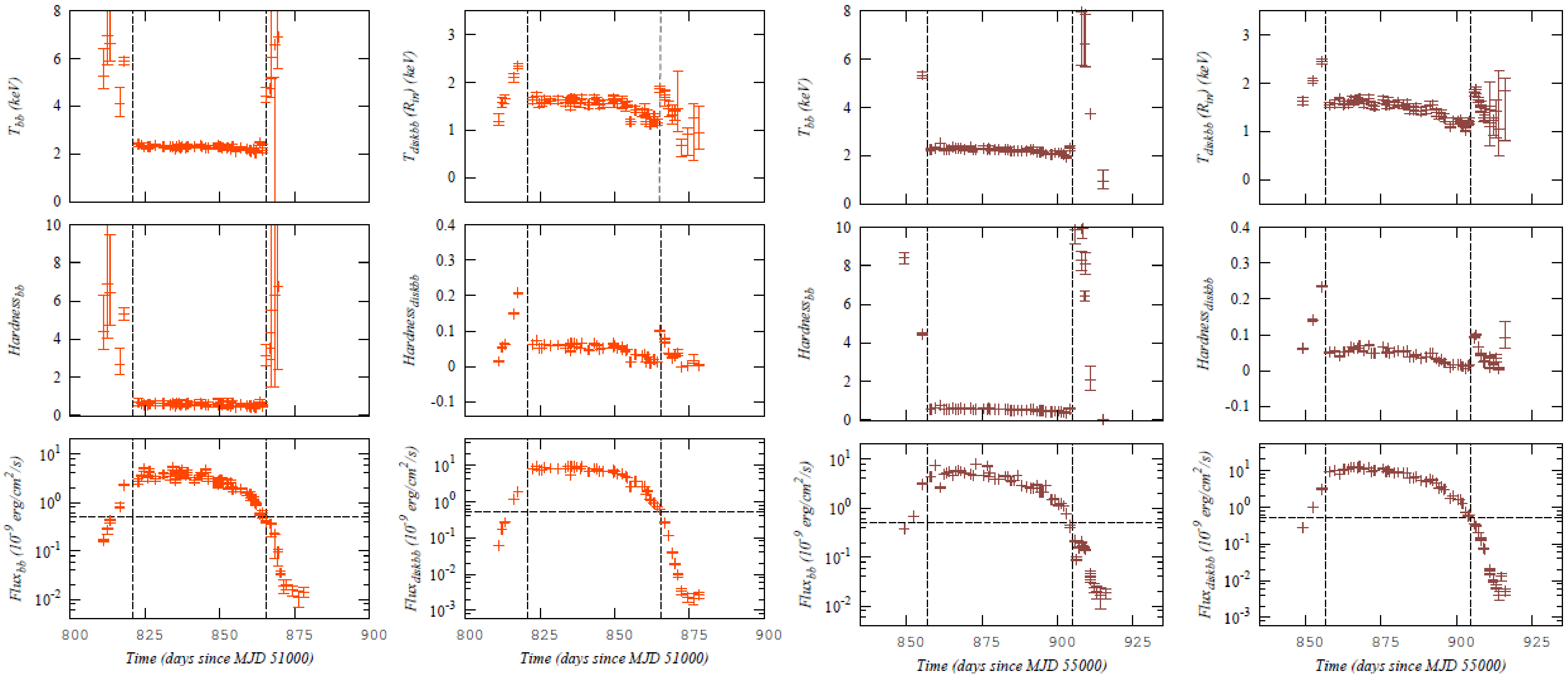
Observation and Data Analysis



An example spectrum obtained by RXTE/PCA, the model is bb+diskbb+ga

Observation and Data Analysis



Result of sprectral analyses of RXTE observation of 2000 and 2011 outbursts of Aql X-1.

The light curve for the blackbody component (bottom left), the light curve for the disk blackbody component (bottom right), the time evolution of the ratio of the flux in the range of 3-10 keV to to the flux 5-30 keV only for blackbody component (middle left), the time evolution the ratio of the flux in the range of 3-10 keV to to the flux 5-30 keV only for disk blackbody component (middle right), the time evolution of the temperature of the blackbody in keV (top left), the time evolution of the Inner disk temperature of disk blackbody component (top right).

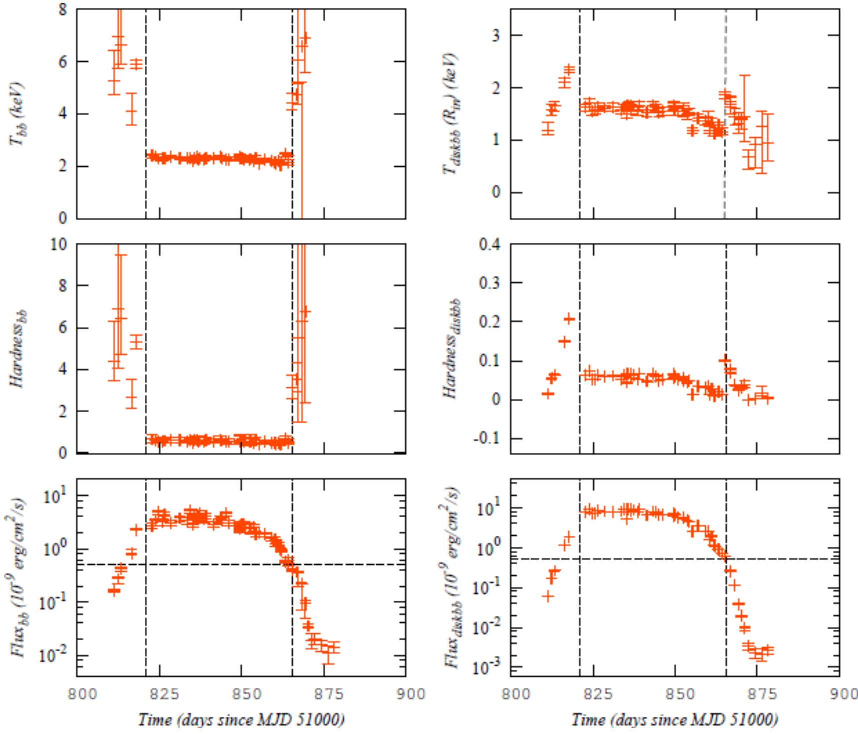
Applicatons: Aql X–1 2000 RXTE/PCA

Obs #	ObsID	MJD−51000 (days)	kT_{bbody} (keV)	kT_{diskbb} (keV)	$\chi^2/d.o.f.^a$	Hardness[b] bbody	Hardness[b] diskbb	Flux^c_{bbody}	Flux^d_{diskbb}
1	50049-01-03-00	811.28564	5.27 ± 1.12	1.19 ± 0.15	0.90	4.36 ± 1.97	1.50 ± 0.06	1.63 ± 0.08	0.60 ± 0.01
2	50049-01-03-01	812.34953	6.96 ± 1.23	1.58 ± 0.10	1.14	6.89 ± 2.81	5.45 ± 0.13	2.70 ± 0.52	1.68 ± 0.02
3	50049-01-03-02	813.27735	6.63 ± 1.40	1.64 ± 0.09	1.00	6.41 ± 1.69	6.43 ± 0.13	4.27 ± 0.49	2.63 ± 0.03
4	50049-01-04-00	816.46667	4.08 ± 0.71	2.10 ± 0.10	1.13	2.64 ± 0.92	14.93 ± 0.20	7.95 ± 1.67	11.29 ± 0.08
5	50049-01-04-01	817.79791	5.88 ± 0.16	2.35 ± 0.05	1.24	5.29 ± 0.36	20.77 ± 0.25	22.94 ± 0.40	18.80 ± 0.11
6	50049-01-04-04	822.77448	2.40 ± 0.08	1.63 ± 0.07	0.69	0.65 ± 0.19	6.23 ± 0.07	27.16 ± 4.01	77.91 ± 0.44
7	50049-01-05-00	823.76888	2.38 ± 0.07	1.71 ± 0.07	0.57	0.64 ± 0.06	7.40 ± 0.14	35.20 ± 0.20	90.30 ± 0.50
8	50049-01-05-01	824.76115	2.28 ± 0.05	1.56 ± 0.08	0.38	0.56 ± 0.11	5.15 ± 0.07	47.76 ± 4.49	72.13 ± 0.48
9	50049-01-05-02	825.75496	2.29 ± 0.08	1.57 ± 0.08	0.63	0.57 ± 0.16	5.31 ± 0.06	31.39 ± 4.32	71.95 ± 0.44
10	50049-02-01-00	826.51291	2.31 ± 0.05	1.64 ± 0.07	0.39	0.59 ± 0.12	6.31 ± 0.07	44.55 ± 4.34	86.14 ± 0.52
11	50049-02-02-00	828.53443	2.34 ± 0.05	1.61 ± 0.05	0.75	0.61 ± 0.12	5.96 ± 0.06	30.32 ± 3.03	79.80 ± 0.45
43	50049-02-15-03	861.88606	2.06 ± 0.04	1.12 ± 0.05	0.84	0.41 ± 0.04	1.05 ± 0.02	9.99 ± 0.53	11.14 ± 0.10
44	50049-02-15-04	862.09305	2.11 ± 0.05	1.13 ± 0.05	1.35	0.45 ± 0.05	1.10 ± 0.02	9.18 ± 0.57	10.45 ± 0.10
45	50049-02-15-05	863.23997	2.45 ± 0.08	1.28 ± 0.06	1.72	0.70 ± 0.09	2.13 ± 0.03	5.78 ± 0.39	9.03 ± 0.08
46	50049-02-15-06	864.20819	2.12 ± 0.11	1.16 ± 0.08	0.83	0.45 ± 0.10	1.27 ± 0.03	6.07 ± 0.67	7.24 ± 0.07
47	50049-02-15-07	864.27747	2.24 ± 0.15	1.17 ± 0.08	0.85	0.54 ± 0.14	1.31 ± 0.03	5.46 ± 0.70	7.19 ± 0.08
48	50049-03-01-00	865.27217	4.43 ± 0.34	1.86 ± 0.07	1.48	3.10 ± 0.61	10.09 ± 0.17	3.99 ± 0.17	5.83 ± 0.05
49	50049-03-02-01	866.92250	4.73 ± 0.46	1.74 ± 0.11	0.99	3.53 ± 0.63	7.87 ± 0.25	3.64 ± 0.16	2.63 ± 0.04
50	50049-03-02-00	866.97790	6.05 ± 0.89	1.67 ± 0.17	0.96	5.55 ± 4.06	6.88 ± 0.15	3.55 ± 1.55	2.45 ± 0.03
51	50049-03-03-00	868.23607	6.56 ± 1.37	1.44 ± 0.16	0.74	6.31 ± 4.82	3.75 ± 0.14	2.17 ± 1.49	1.12 ± 0.02
52	50049-03-04-00	869.47435	6.88 ± 1.28	1.32 ± 0.20	0.86	6.78 ± 4.38	2.49 ± 0.11	0.95 ± 0.47	0.38 ± 0.01

The 2000 outburst RXTE/PCA – Black body + Disk black body + Gauss

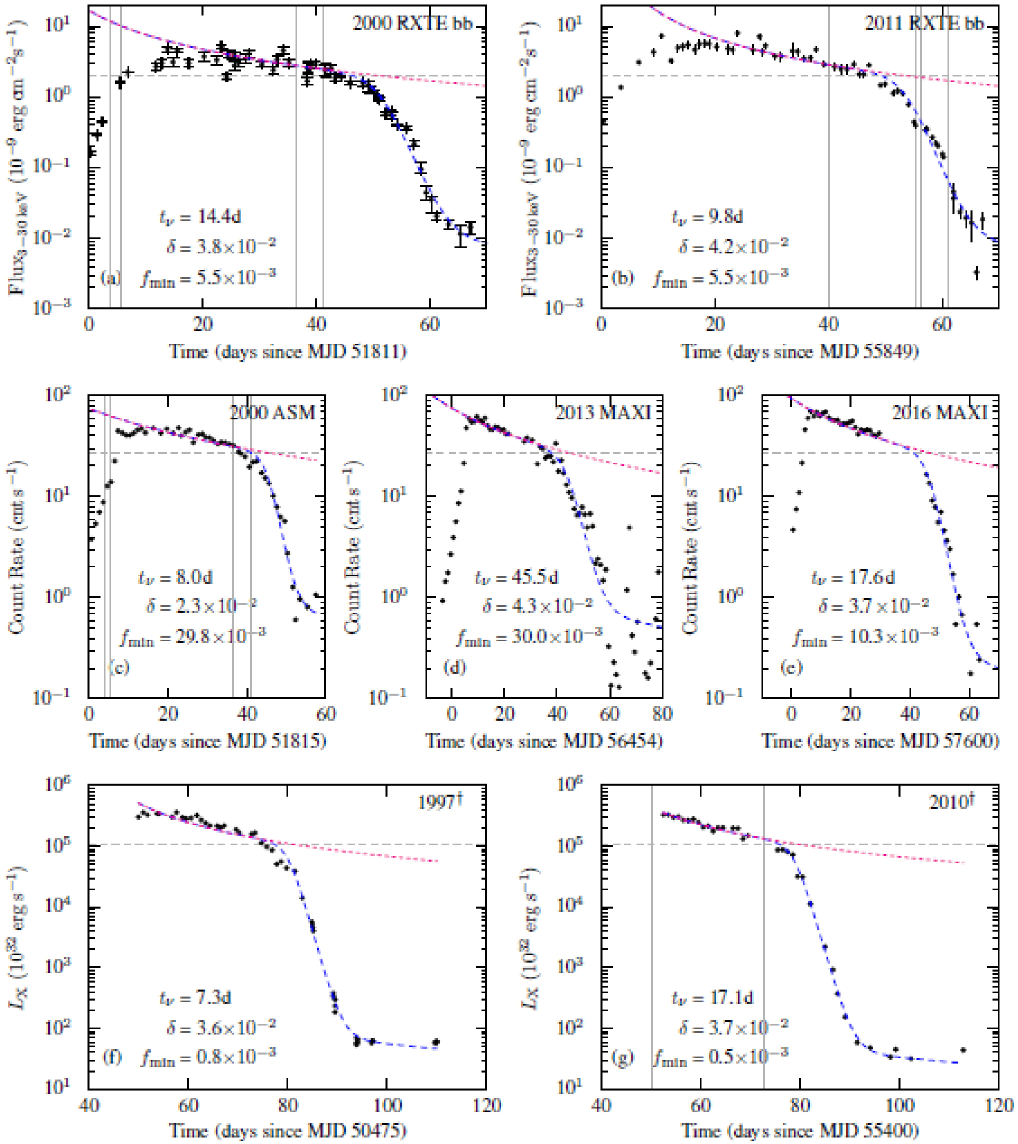
Applicatons: Aql X–1 2000 RXTE/PCA

Obs #	kT_{bbody} (keV)	τ	$\chi^2/d.o.f.^a$	Hardness[b] bbody	$Flux^c_{bbody}$
1	2.36 ± 0.30	2.72 ± 0.67	0.95	2.77 ± 0.10	1.84 ± 0.02
2	2.80 ± 0.21	2.49 ± 0.30	1.13	3.30 ± 0.09	3.37 ± 0.03
3	2.77 ± 0.21	2.76 ± 0.26	1.03	3.49 ± 0.08	5.10 ± 0.04
4	3.61 ± 0.36	2.38 ± 0.60	0.68	4.73 ± 0.07	16.74 ± 0.07
5	3.44 ± 0.70	2.44 ± 0.16	0.69	4.31 ± 0.06	24.74 ± 0.10
6	2.17 ± 0.13	0.12 ± 0.04	0.63	0.59 ± 0.01	30.91 ± 0.17
7	2.34 ± 0.05	0.01 ± 0.01	0.62	0.65 ± 0.01	34.82 ± 0.20
8	2.24 ± 0.03	0.10 ± 0.02	0.32	0.56 ± 0.01	48.09 ± 0.21
9	2.22 ± 0.05	0.01 ± 0.01	0.68	0.60 ± 0.01	30.65 ± 0.17
10	2.27 ± 0.03	0.01 ± 0.01	0.51	0.60 ± 0.01	44.13 ± 0.20
16	2.25 ± 0.03	0.13 ± 0.09	0.52	0.58 ± 0.01	40.97 ± 0.20
31	2.25 ± 0.04	0.11 ± 0.10	0.49	0.56 ± 0.01	28.96 ± 0.14
39	2.00 ± 0.03	0.06 ± 0.02	0.93	0.48 ± 0.01	16.36 ± 0.07
41	1.91 ± 0.03	0.03 ± 0.02	1.30	0.40 ± 0.01	13.82 ± 0.07
44	1.70 ± 0.06	0.45 ± 0.36	1.74	0.34 ± 0.01	12.04 ± 0.05
45	1.80 ± 0.08	0.48 ± 0.13	1.99	0.49 ± 0.01	7.85 ± 0.03
46	1.95 ± 0.04	0.01 ± 0.01	1.63	0.40 ± 0.01	6.74 ± 0.04
47	2.01 ± 0.15	0.11 ± 0.07	0.80	0.53 ± 0.01	5.65 ± 0.04
48	3.48 ± 0.45	1.63 ± 0.51	1.40	3.27 ± 0.13	4.06 ± 0.05
49	3.75 ± 0.65	2.30 ± 0.88	0.93	3.71 ± 0.19	3.71 ± 0.07
50	2.82 ± 0.40	2.83 ± 0.22	0.91	3.64 ± 0.11	4.00 ± 0.04
51	2.72 ± 0.48	2.84 ± 0.85	0.67	3.47 ± 0.15	2.49 ± 0.04
52	2.55 ± 0.56	2.98 ± 0.20	0.78	3.29 ± 0.15	1.07 ± 0.02

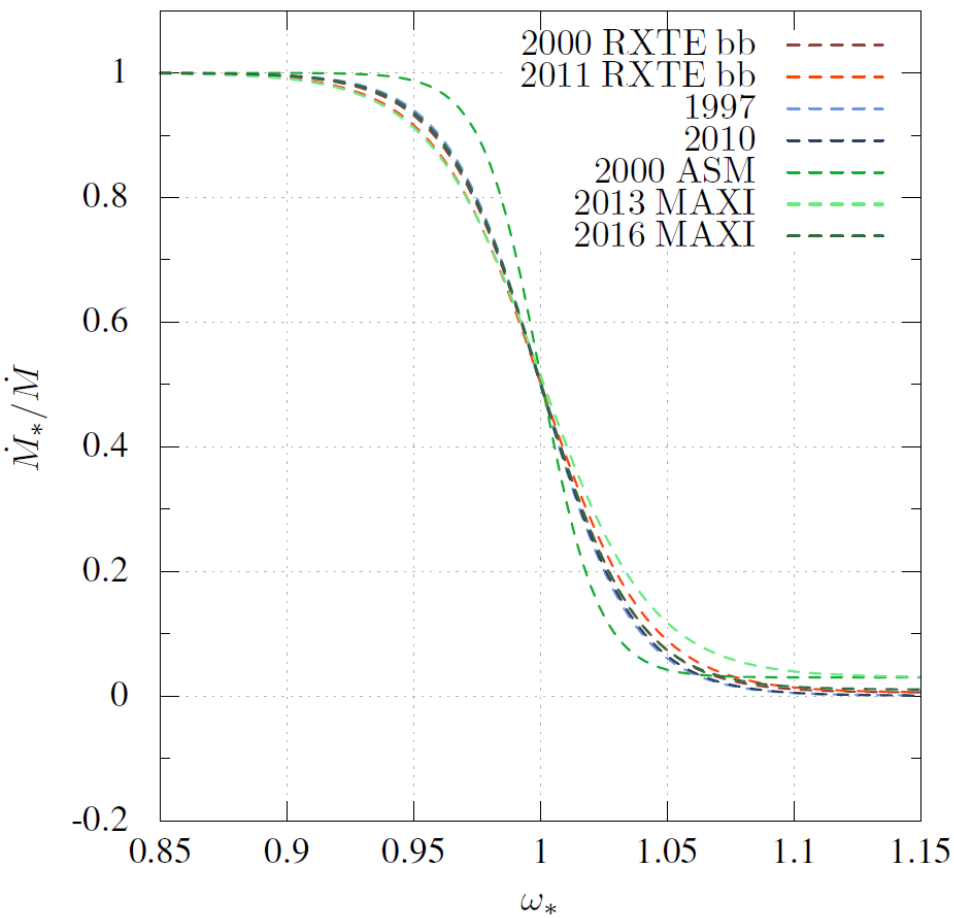


The 2000 outburst RXTE/PCA – black body + Comptonisation + disk black body + Gauss

A New Method to Describe Outbursts



Result:



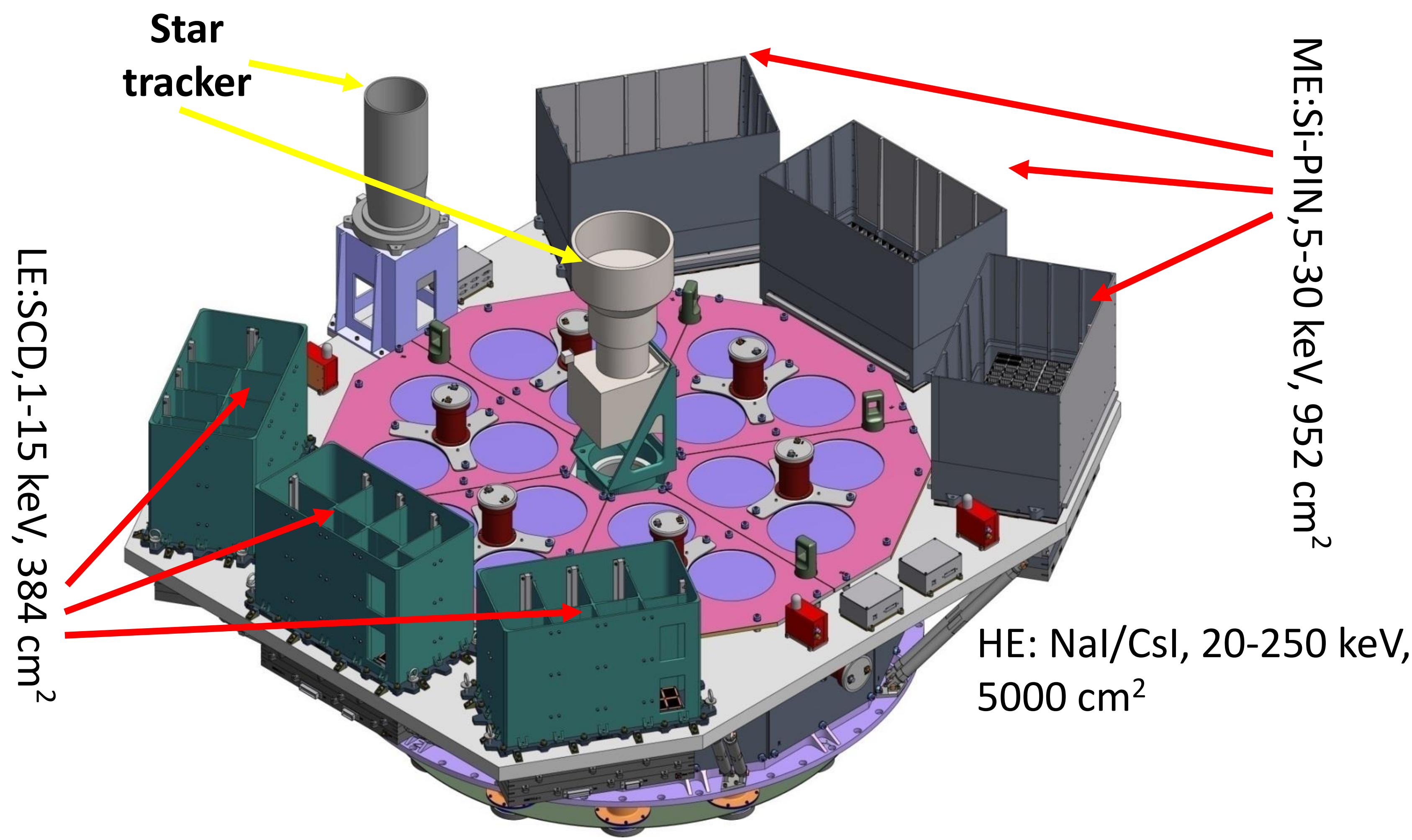
- The range $\omega_* \lesssim 0.9$ is the slow decay stage. All of the material transferred from outer disk accretes onto the NS. As $\dot{M}$ ($= \dot{M}_*$ in accretion stage) decreases in time, the luminosity declines (slow decay stage) while $R_{\rm in}$ expands back to $R_{\rm c}$.
- The range $0.9 \lesssim \omega_* \lesssim 1.1$ is the partial accretion regime. A fraction of inflowing material to the inner layers of the disk may transfer onto the NS. The rest may be thrown to outer layers of the disk or expelled from the system via jet mechanism.
- The range $\omega_* \gtrsim 1.1$ is the fully developed propeller stage and the neutron star may even act as an isolated NS (Ekşi & Alpar 2005).

$$f(\omega) = \begin{cases} 1, & \omega < 1 \\ 0, & \omega \geq 1 \end{cases}$$

$$f(\omega) = \frac{1}{2}\left[(1 + f_{min}) + (1 - f_{min}) \times tanh\left(\frac{\omega_c - \omega}{\delta}\right)\right]$$

Pre-liminary Results from Insight-HXMT

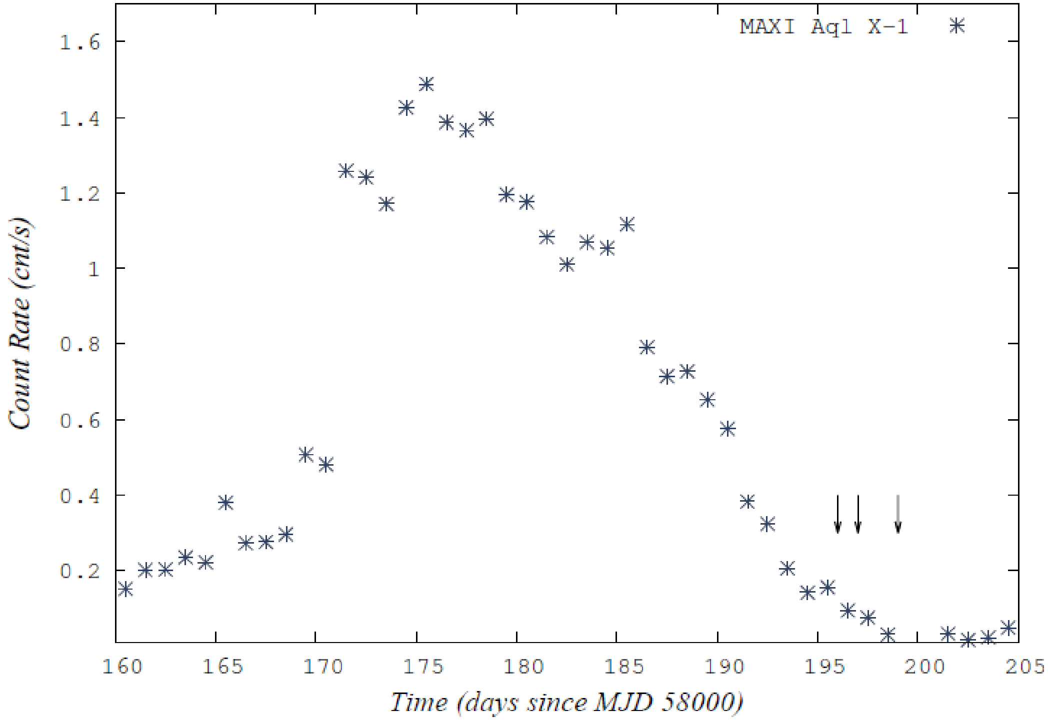
HuiYan – Hard X-ray Modulation Telescope



Pre-liminary Results from Insight-HXMT

Aql X-1 has been observed by Insight-HXMT three times just after the transition from the soft state to the hard state.

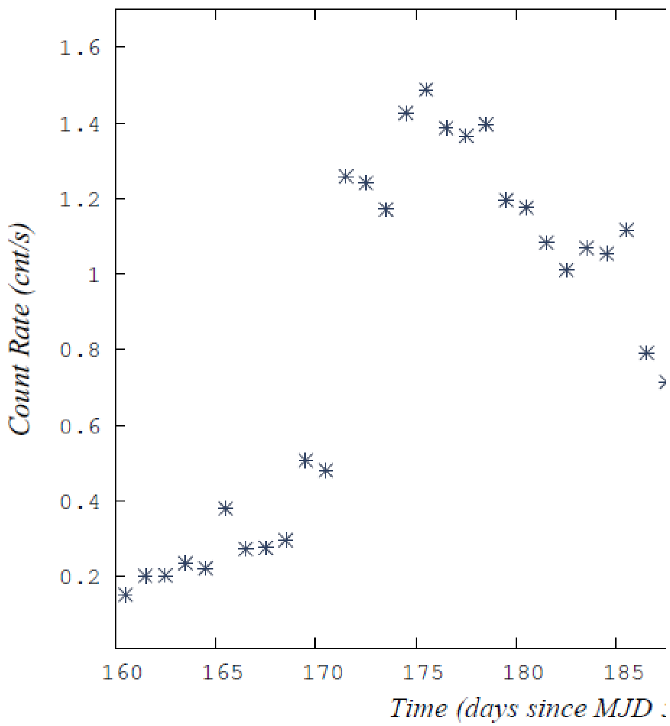
- **2018/3/19 19:09:24 O011466801001 10ks Exposure**
- **2018/3/20 19:01:00 O011466801002 10ks Exposure**
- **2018/3/22 06:00:39 O011466801003 10ks Exposure**

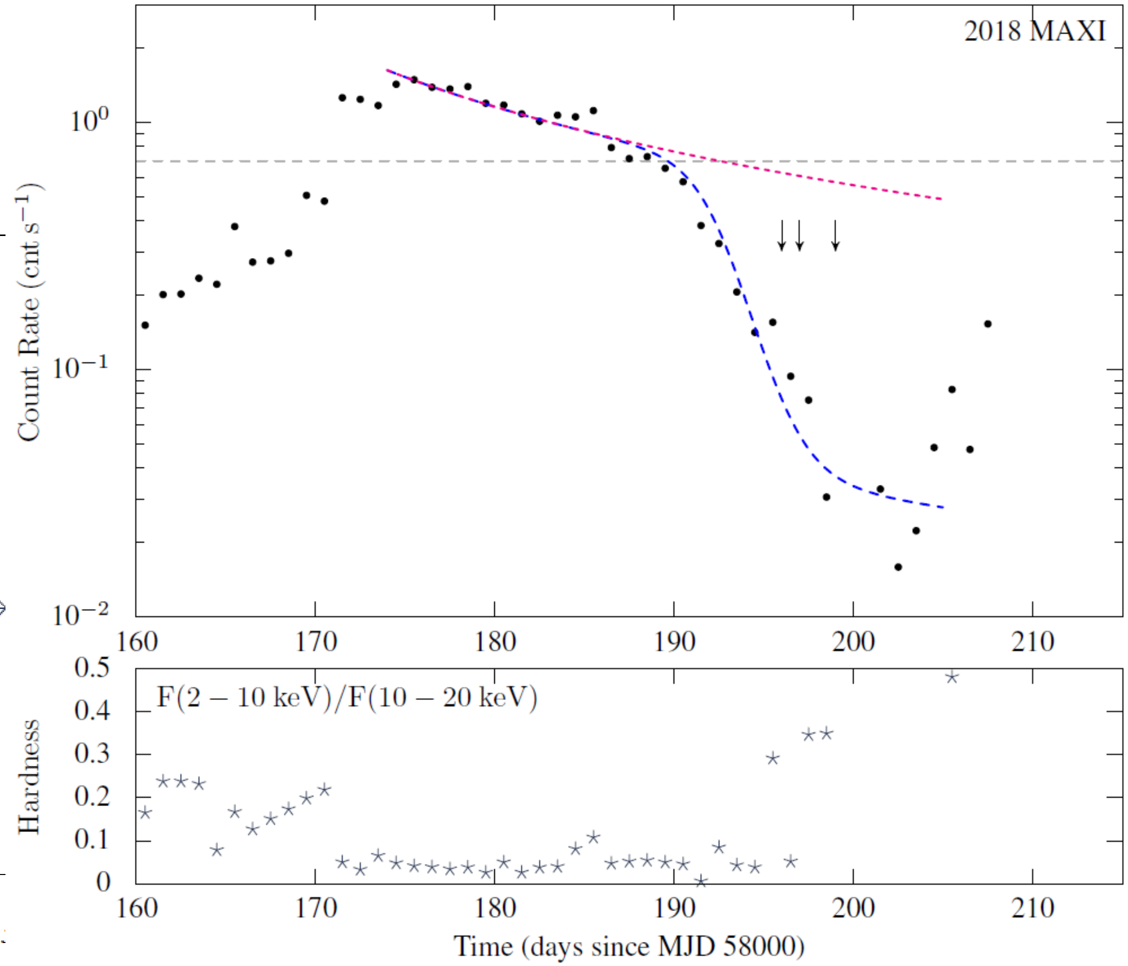


Pre-liminary Results from Insight-HXMT

Aql X-1 has been observed by Insight-HXMT three times just after the transition from the soft state to the hard state

- **2018/3/19 19:09:24**
- **2018/3/20 19:01:00**
- **2018/3/22 06:00:39**





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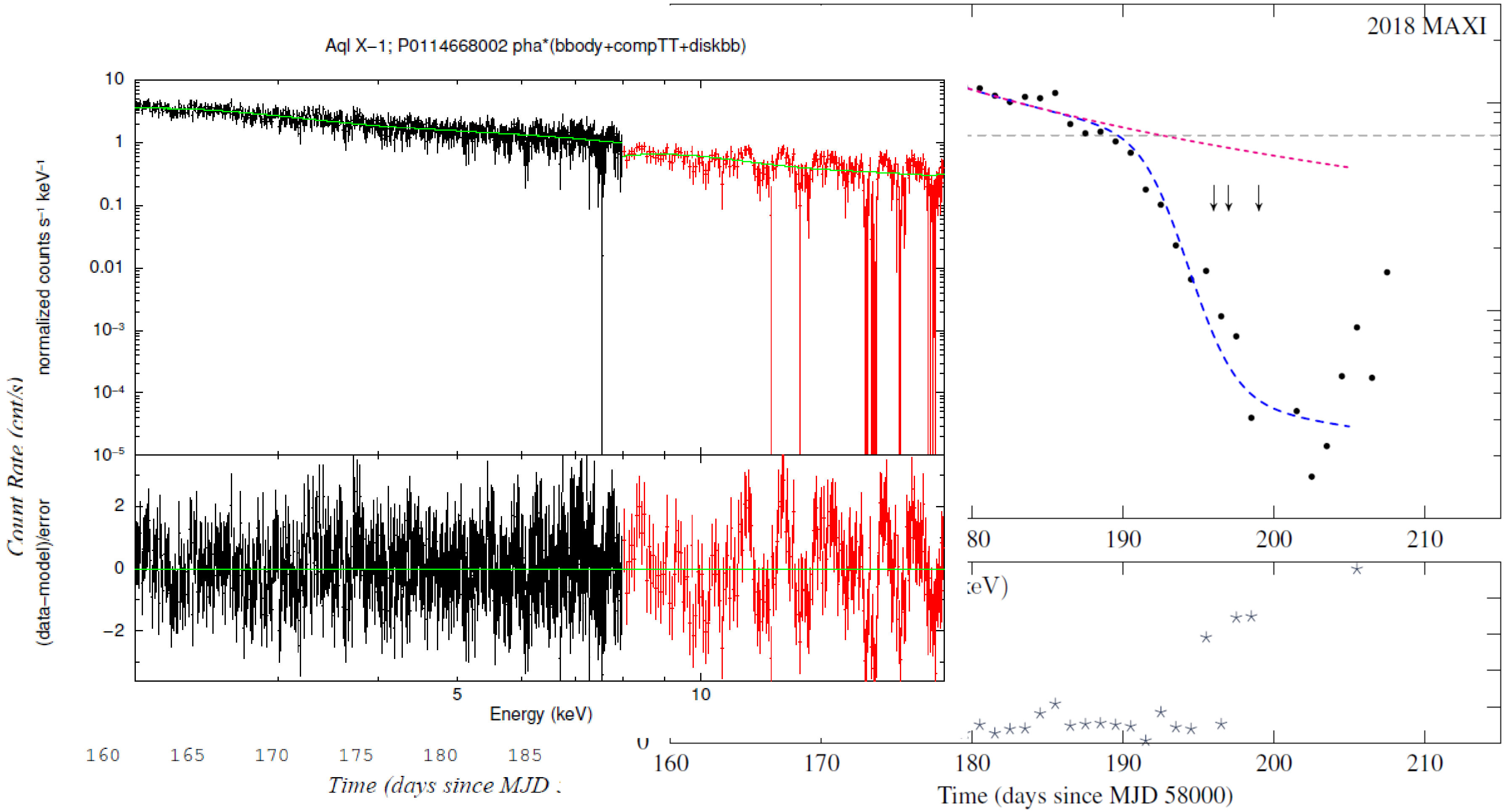

Summary and Discussion:

- We classified outbursts of Aql X-1 depending on duration and maximum flux. We analysed three outbursts of Aql X-1 observed by RXTE. We obtained evolution of physical parameters and showed that the spectral evolutions are similar in three different classes.
- We invented a method to obtain mass ratio accreting onto the NS in the propeller stage depending on fastness parameters.
- We analysed RXTE/PCA and obtained a light curve only caused by accretion!!.
- We argued possible propeller effect on the fast rising phase as well as on the exponential decay phase.
- We applied the method and showed the outbursts with different max luminosity and duration follows the similar trend in $f(\omega_*)$ evolution during outburst.

Thanks for listening

Can GÜNGÖR

Dr.

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