Super-Eddington outburst in a binary system: V4641 Sgr

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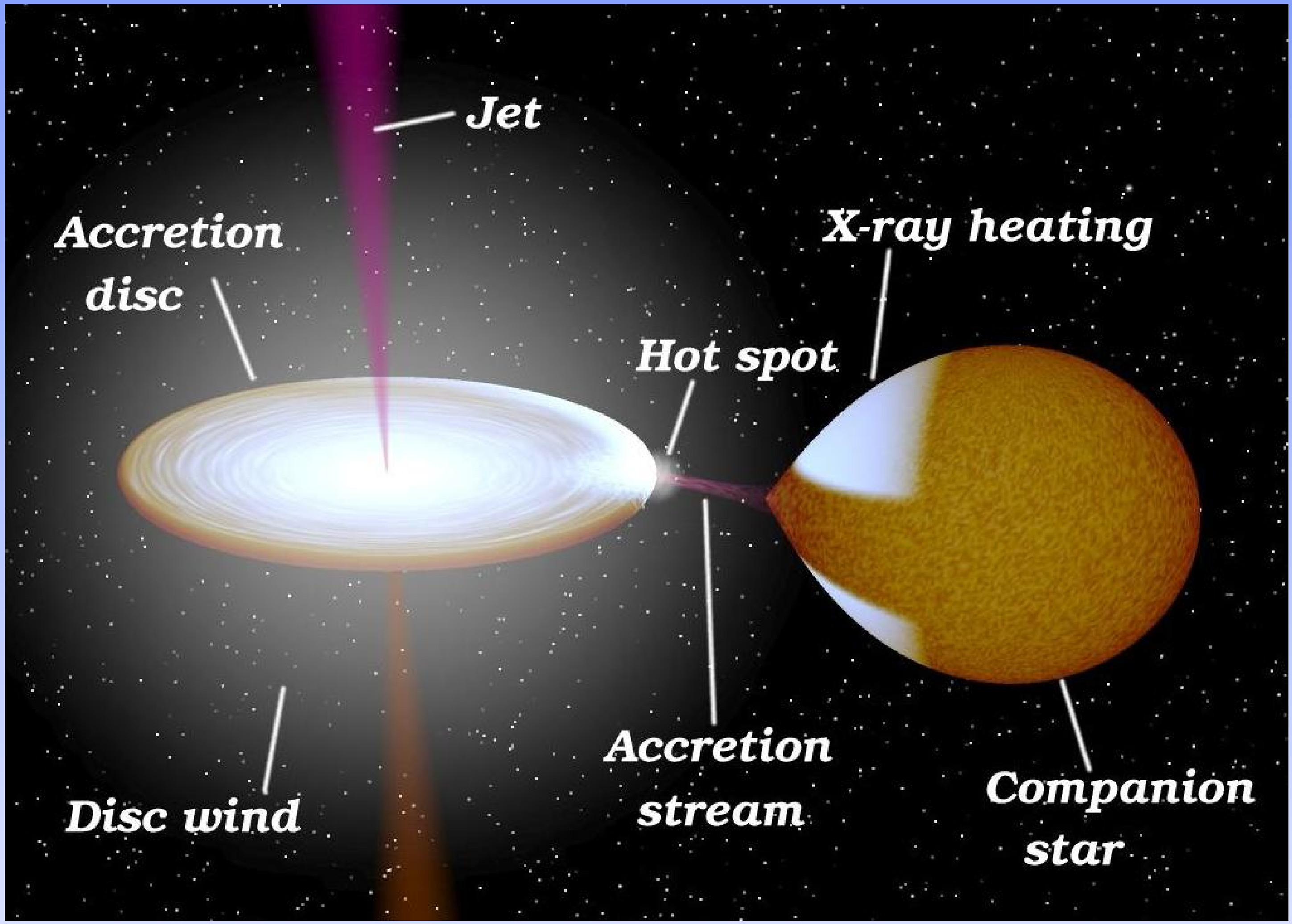

In our galaxy there exist more than 200 binaries, containing a black hole or a neutron star. More than 1/3 of them are transients

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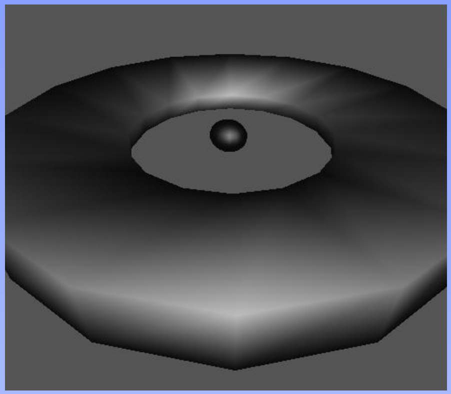
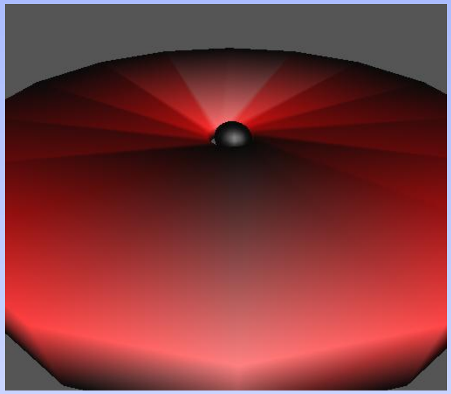
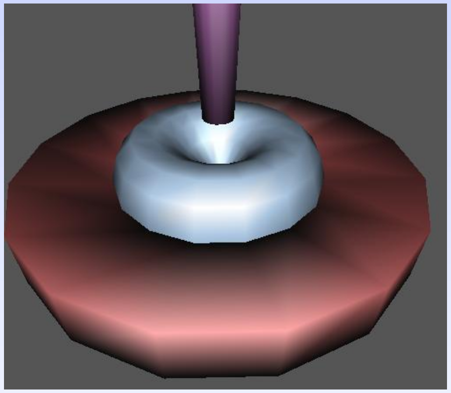


Off-state: disk is passive, no energy release. X-ray emission $L_x < 10^{33}$ erg/sec. Optical emission is dominated by the companion star

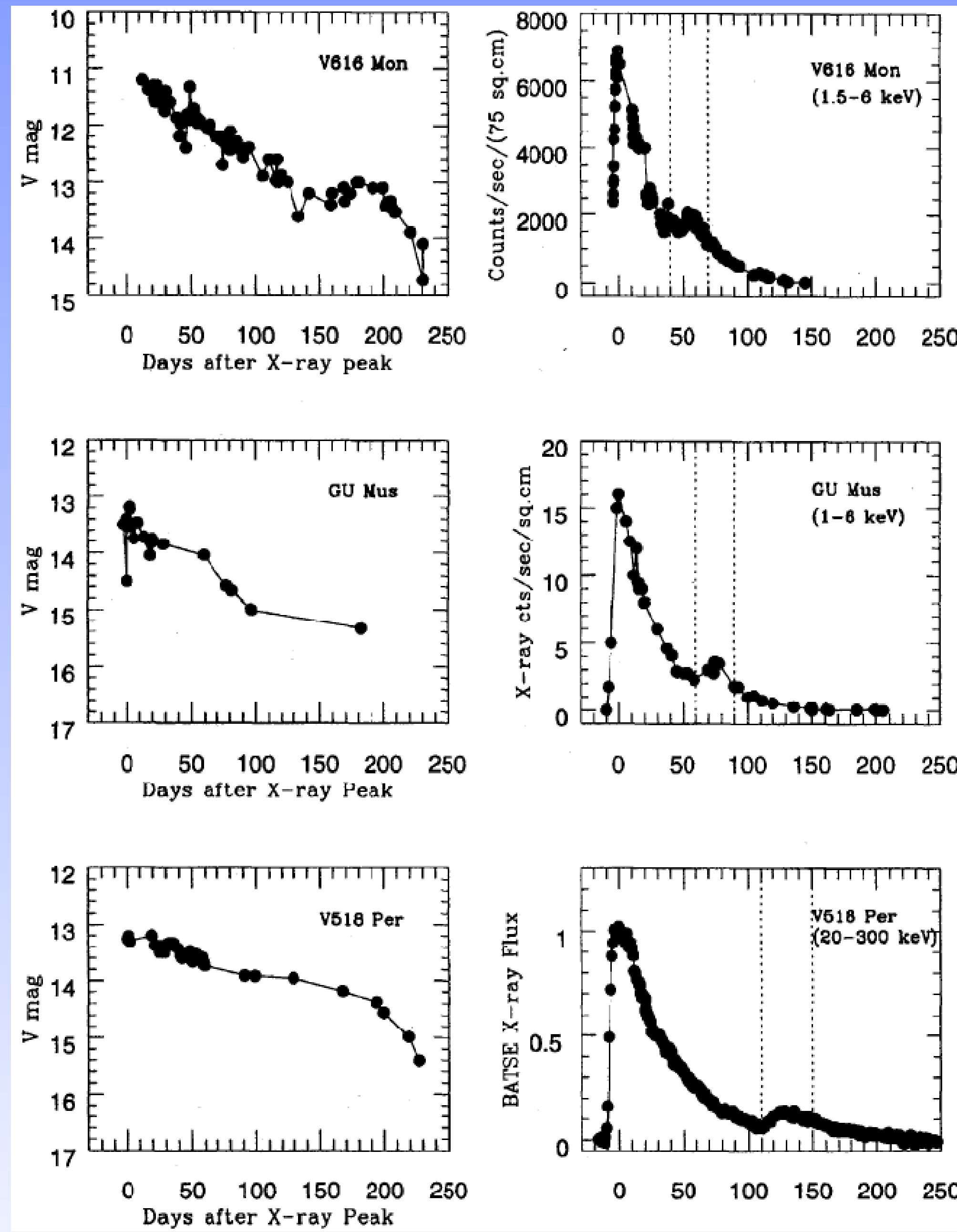


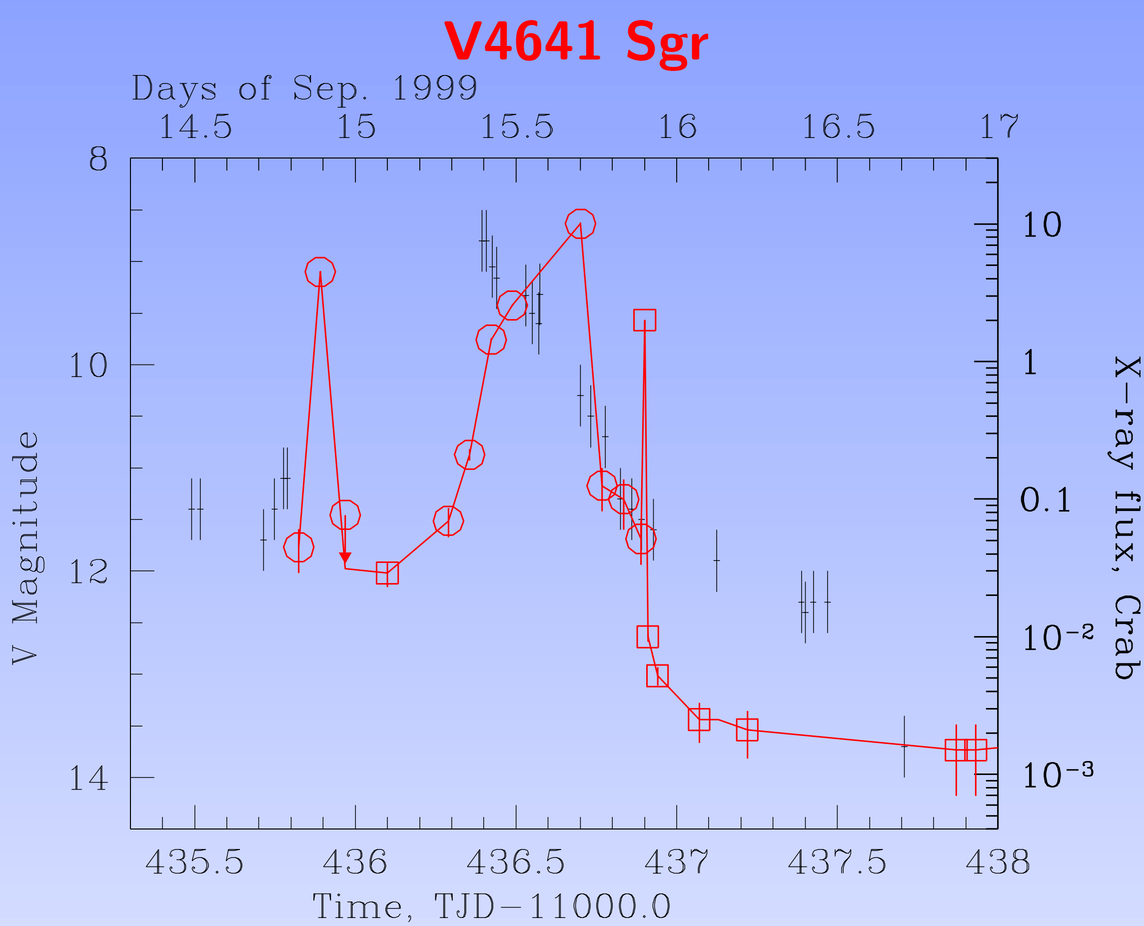
High state: disk is active, goes down to the innermost stable orbit, energy release $\sim L_{Edd} \sim 1.4 \cdot 10^{38} (M/M_{\odot})$ erg/sec. Optically thick disk strongly contributes to X-ray emission. Optical emission usually is dominated by reprocessing of X-rays

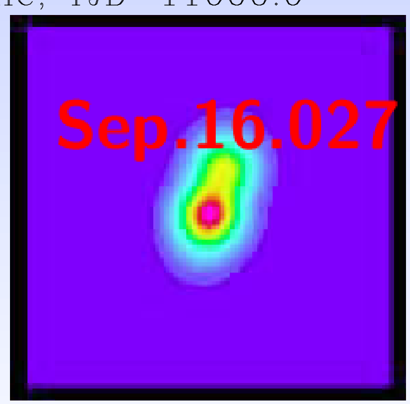


Low state: disk is active, but optically thick (geometrically thin) flow perishes at some radius, therefore its contribution to X-rays is small. Innermost region is hot and optically thin. Usually flares in radio (jet?)

Typical X-ray Novae: Nova Mon 1975, Nova Mus 1991, Nova Per 1992 ...







- **May be it is just another ordinary X-ray Nova?**

BUT!

- **All fronts (rise and decay) are *extremely* fast! In usual Novae – the rise ∼5 days, decay ∼30-50 days. Here we have ∼0.5 days in optics and ~ 0.1 days in X-rays!**

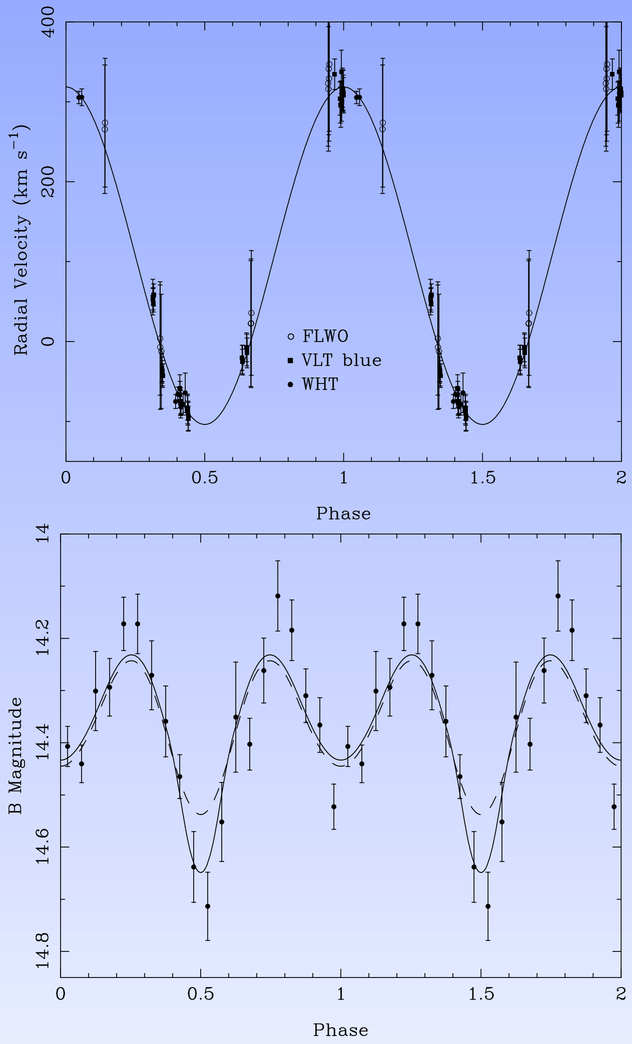
- **Extended source on a radio image immidiately after X-ray/optical outburst, microquasar?**

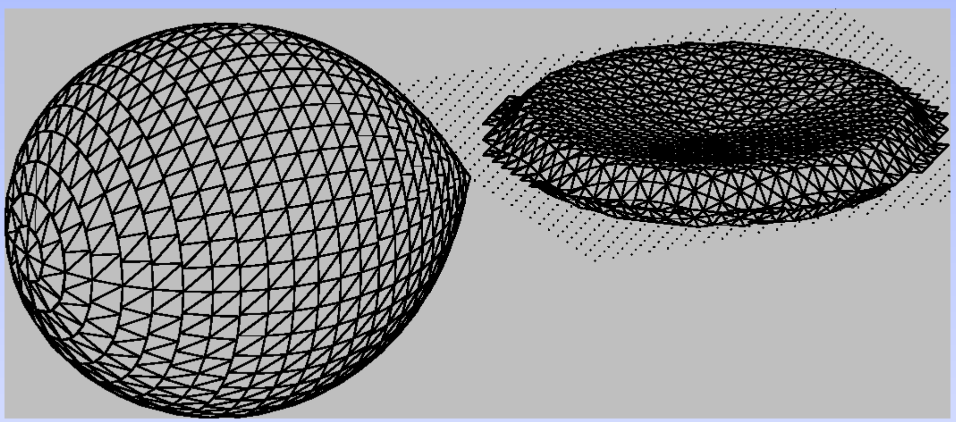
- **Not simple object! Interesting!**

Discovery of V4641 Sgr

- Originally discovered in 1978 (V.Goranskij) in optics
- First detection in X-rays - Feb.1999 by BeppoSAX and RXTE (in't Zand et al. 1999, Markwardt et al. 1999). SAX J1819.3-2525=XTE J1819-254
- Since then – relatively quiet behavior (m_v ~14 in optics, ~10-30 mCrabs in X-rays) till Sep. 1999
- In Sep. 1999 - flares in: X-rays (12 Crabs), optics (m_v ~8.5), radio (~0.5 Jy)

Optical observations and parameters of the system





Orosz et al. 2000

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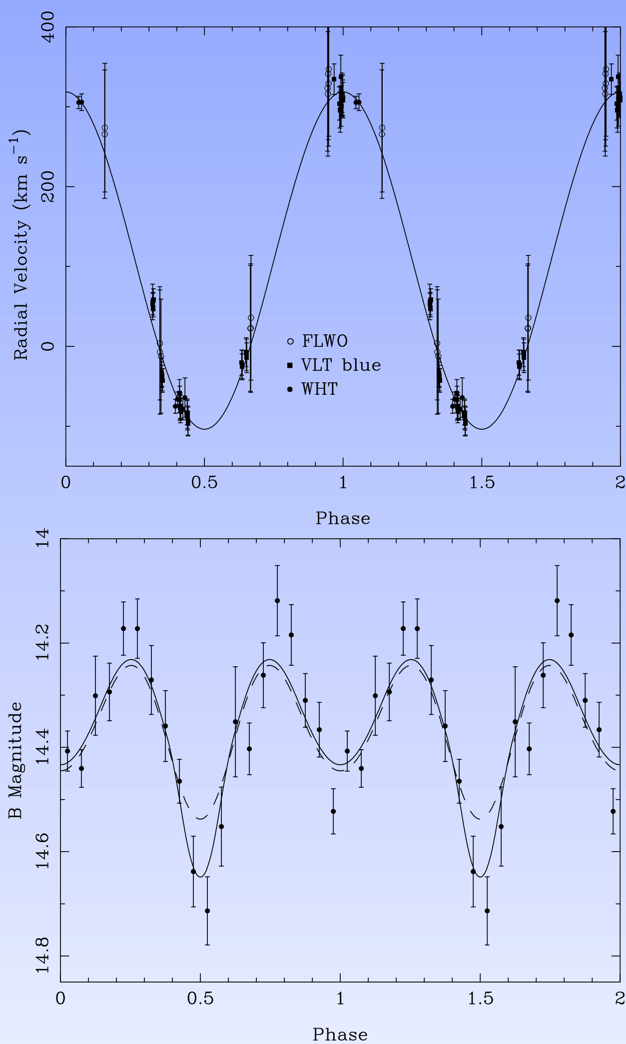
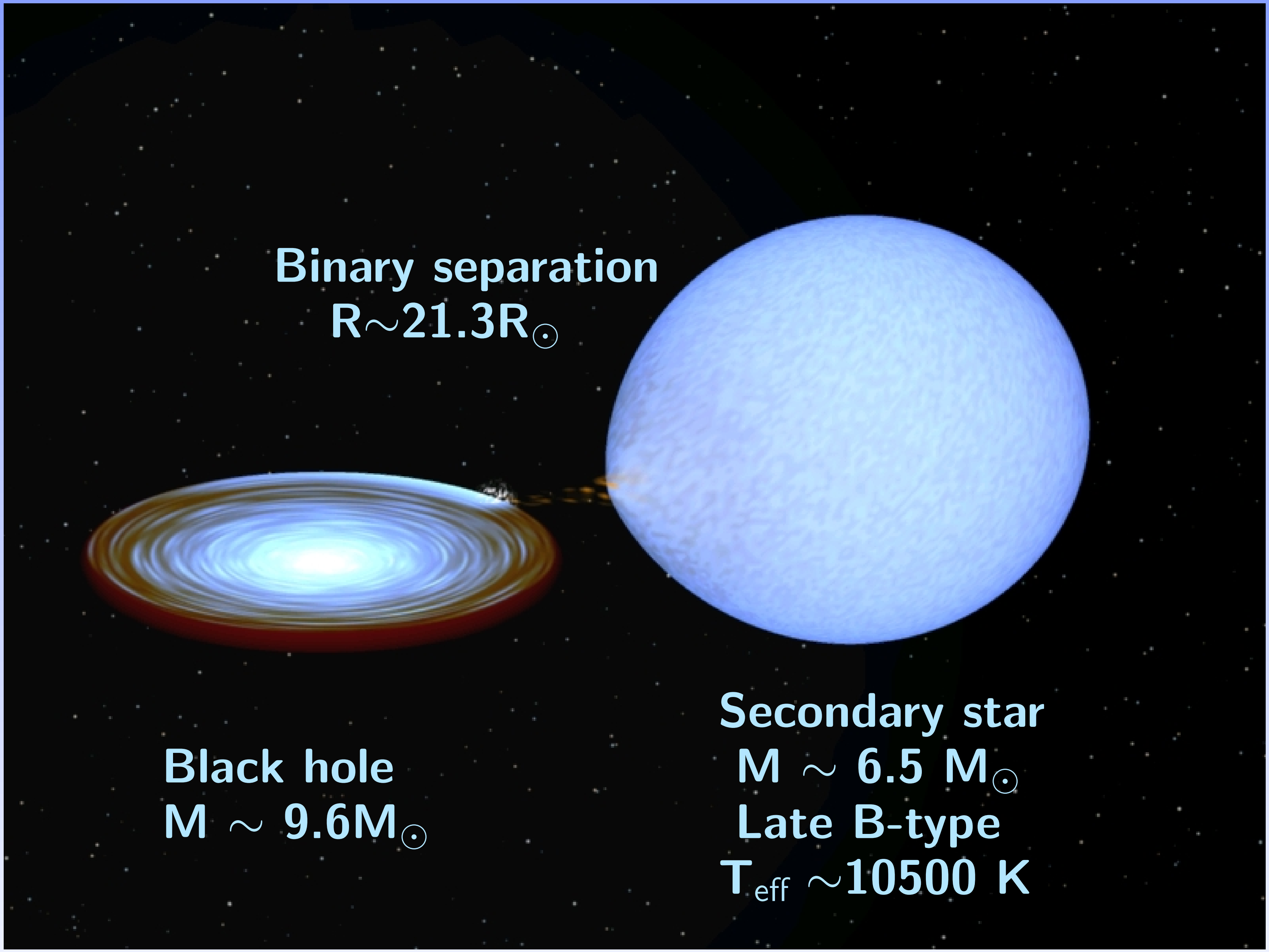


Orosz et al. 2000

Binary period	**2.8173 days**
Mass function	$\sim$ **2.74** $M_\odot$
Black hole mass	$\sim$**9.6** $M_\odot$
Secondary star mass	$\sim$**6.5** $M_\odot$
Mass ratio	$\sim$ **1.5**
Orbital separation	$\sim$ **21.3** $R_\odot$
Secondary star radius	$\sim$ **7.5** $R_\odot$
Inclination	$\sim 70^\circ$
Distance	**9.6 kpc**


Binary separation
R∼21.3R$_\odot$
Black hole
M ∼ 9.6M$_\odot$
Secondary star
M ∼ 6.5 M$_\odot$
Late B-type
T_{eff} ∼10500 K

Change of the optical brightness

$\Delta m_V \sim 5$ **during the outburst! Factor of 100 increase of the optical luminosity! What is the reason for that? Is it common/normal or outstanding?**

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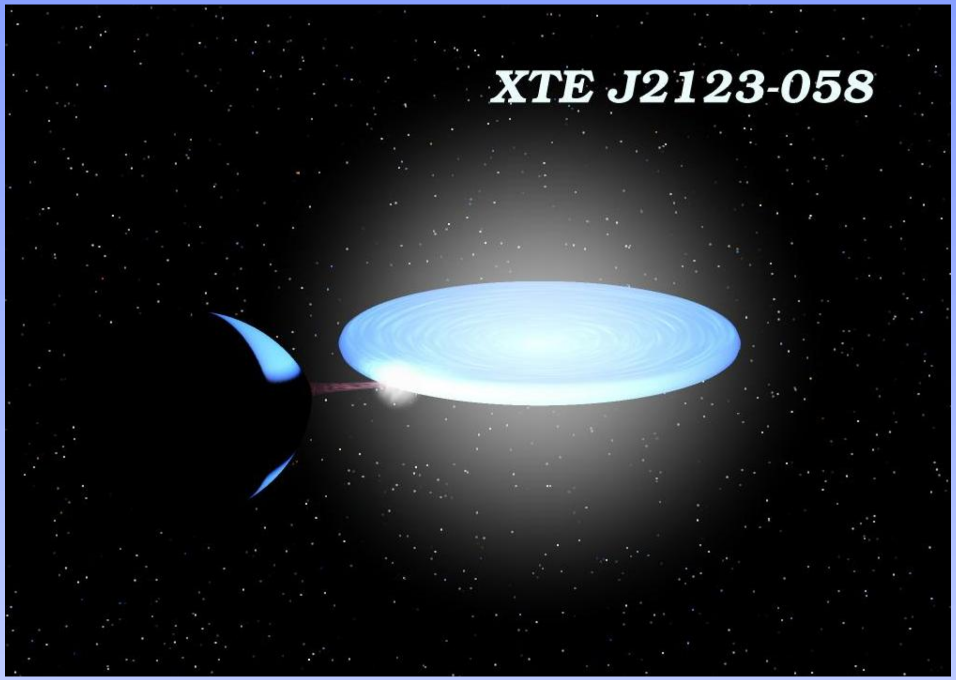
- **Usually the increase of optical brightness of X-ray Novae is caused by the contribution of the accretion disk**
- **It is common for X-ray Novae to demonstrate $\Delta m_v \sim 5$. But only if the X-ray Nova is the low mass X-ray binary ! Such huge change of the optical brightness was never observed in high mass systems**
- **What is the difference?**

Low mass X-ray binary

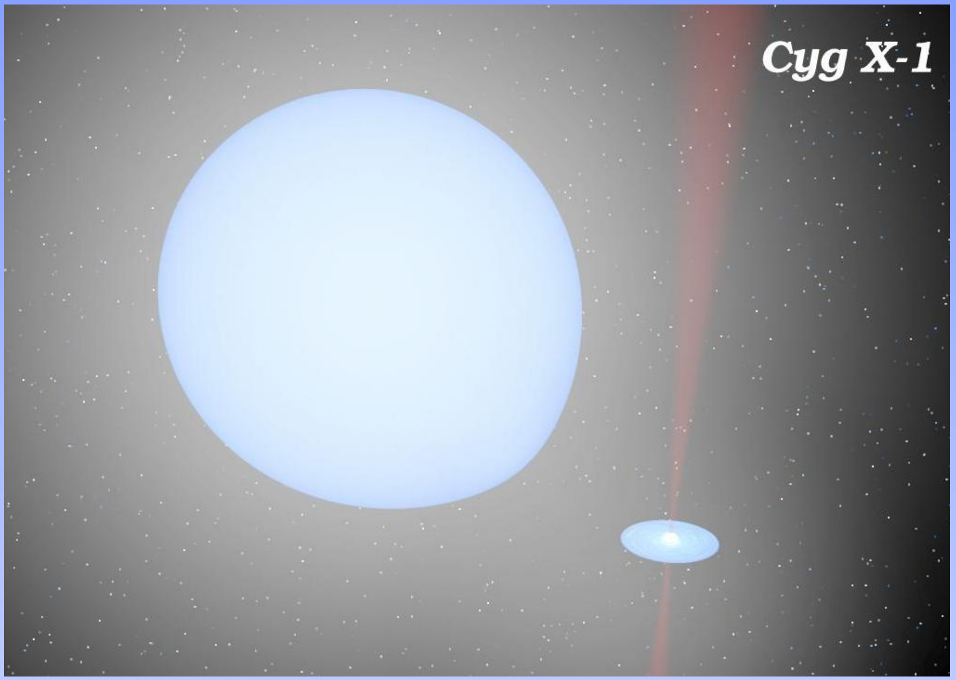
- Optical companion is small $M < M_\odot$. Ratio of the accretion disk size to the companion star size is large
- Surface temperature of the companion star $T < 5000$K. Much smaller than the surface temperature of the accretion disk "at work" (T_{disk} ~10 000–20 000K)
- Change of the optical brightness of the system during the X-ray outburst could be higher than > 100 times ($\Delta m_v > 5$)
- A0620-00, Nova Mus. 1991, Nova Per.1992 ....

High mass X-ray binary

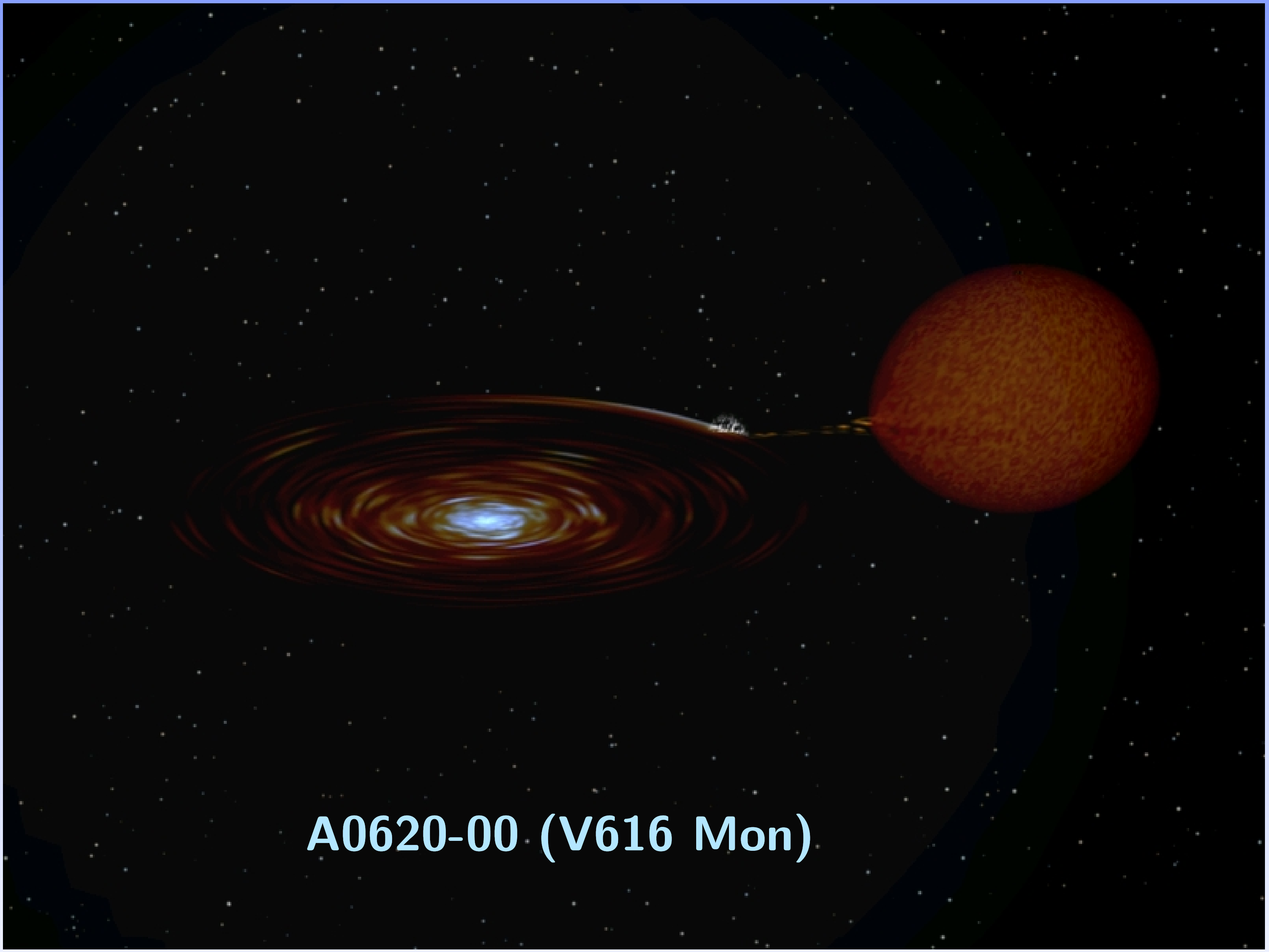
- Optical companion is large $M > 3 - 5M_\odot$. Ratio of the accretion disk size to the companion star size is not more than unity.
- Surface temperature of the companion star T ~10 000-30 000K
- Change of the optical brightness of the system during the X-ray outburst is of the order of ~2–3 (Δm_v hardly higher than 1)
- Cyg X-1, A0535+26 ...

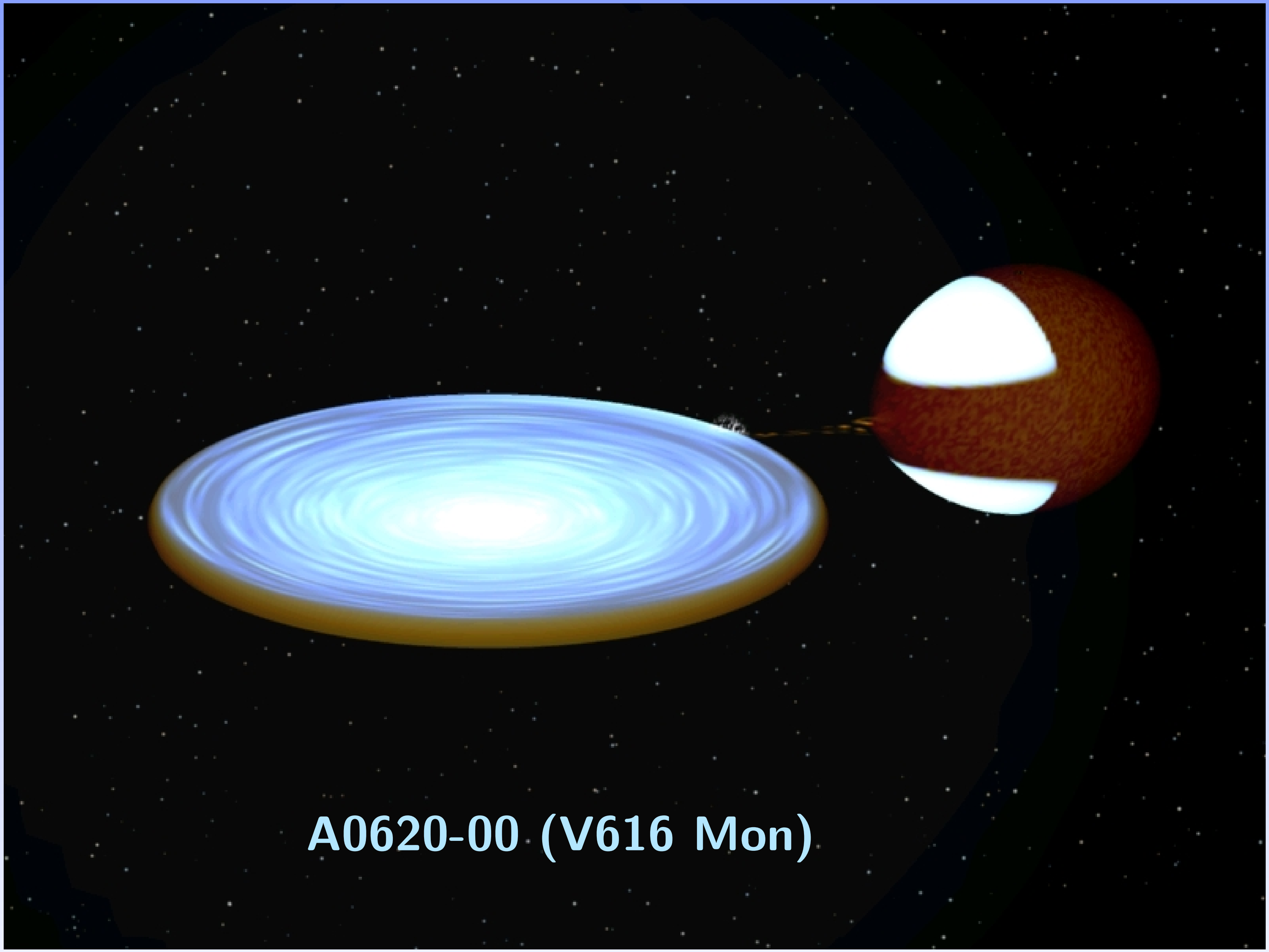


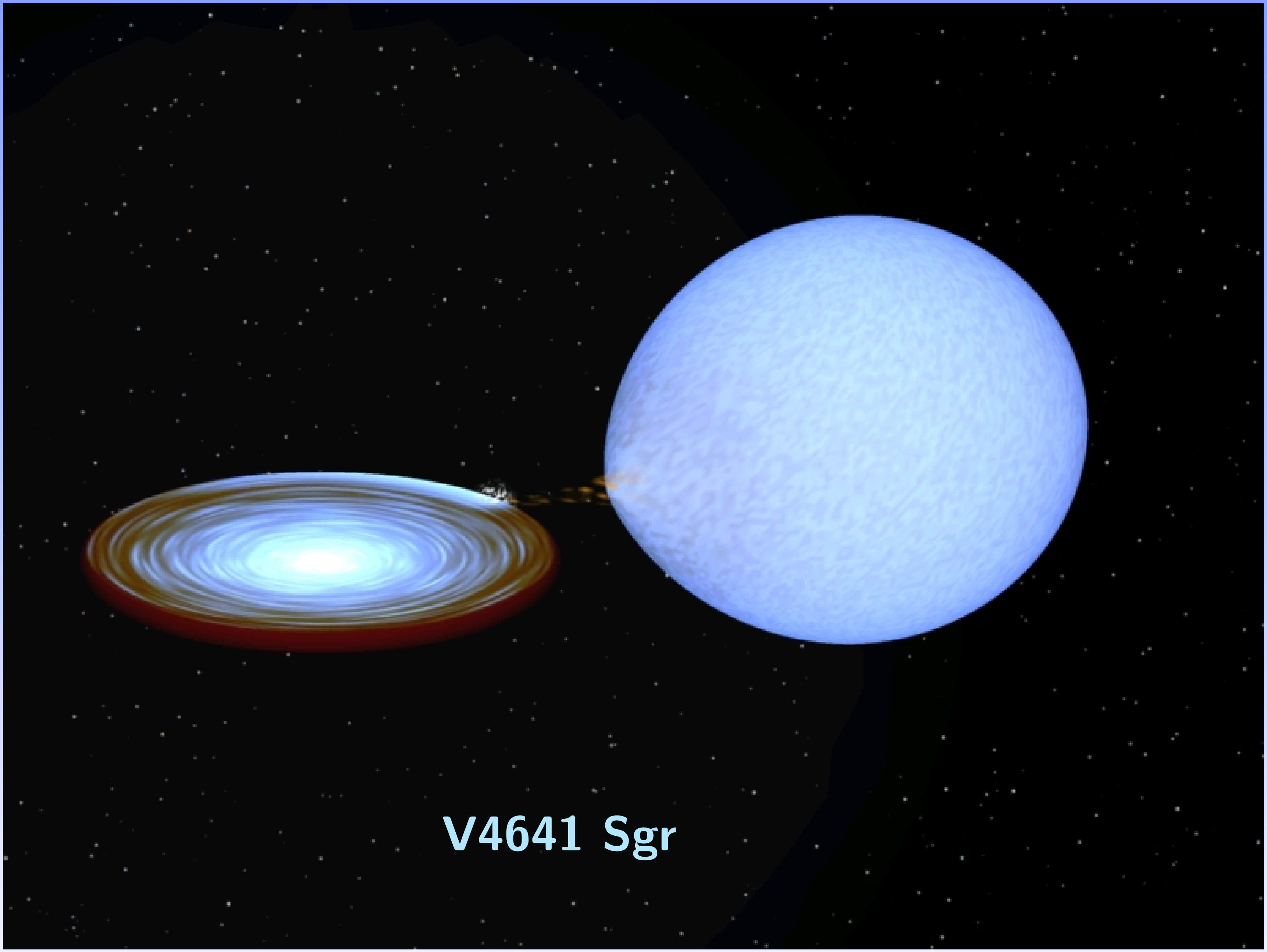
$T_{star} \sim 4500$**K**

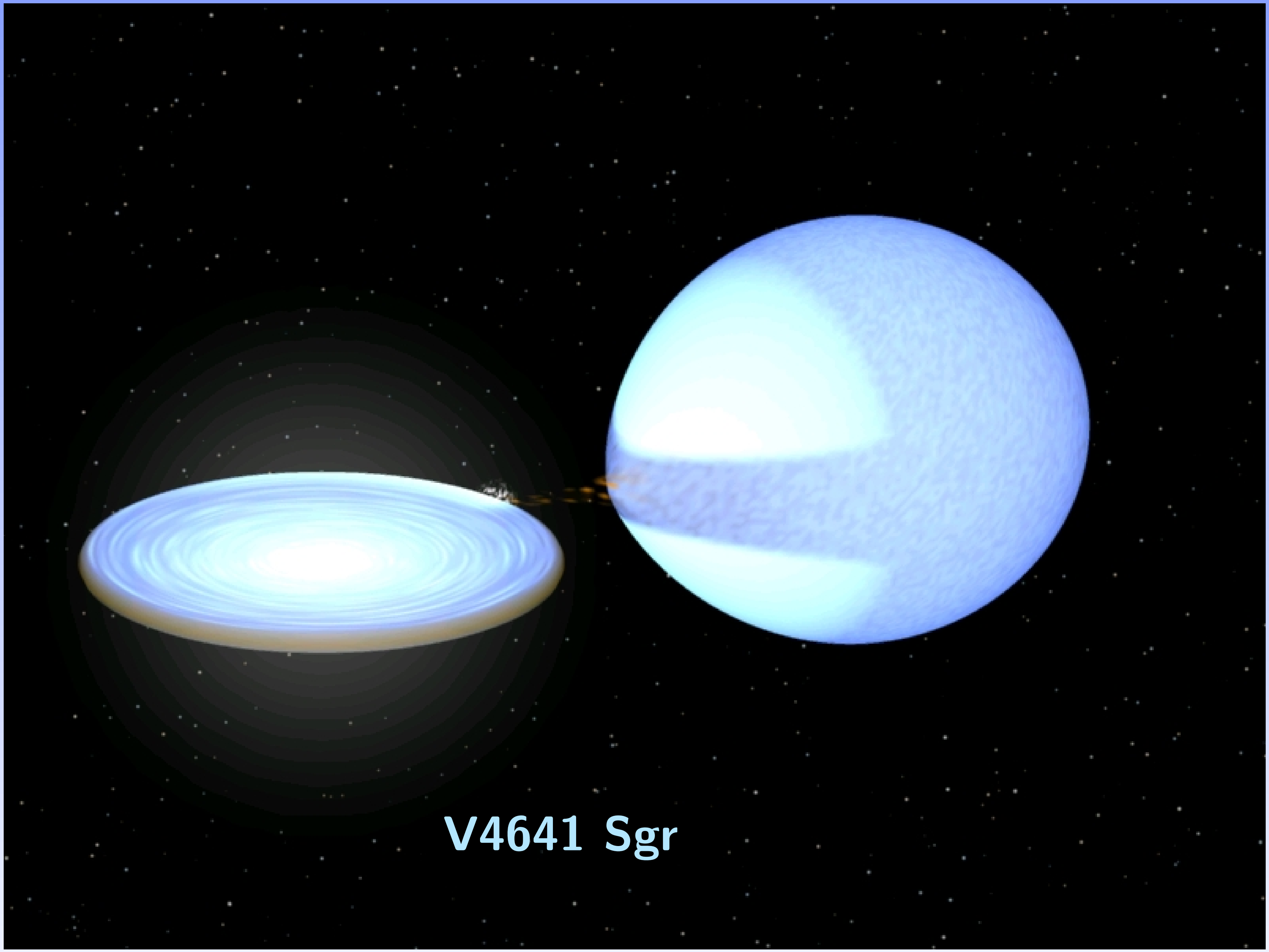


$T_{star} \sim 32000$**K**


A0620-00 (V616 Mon)

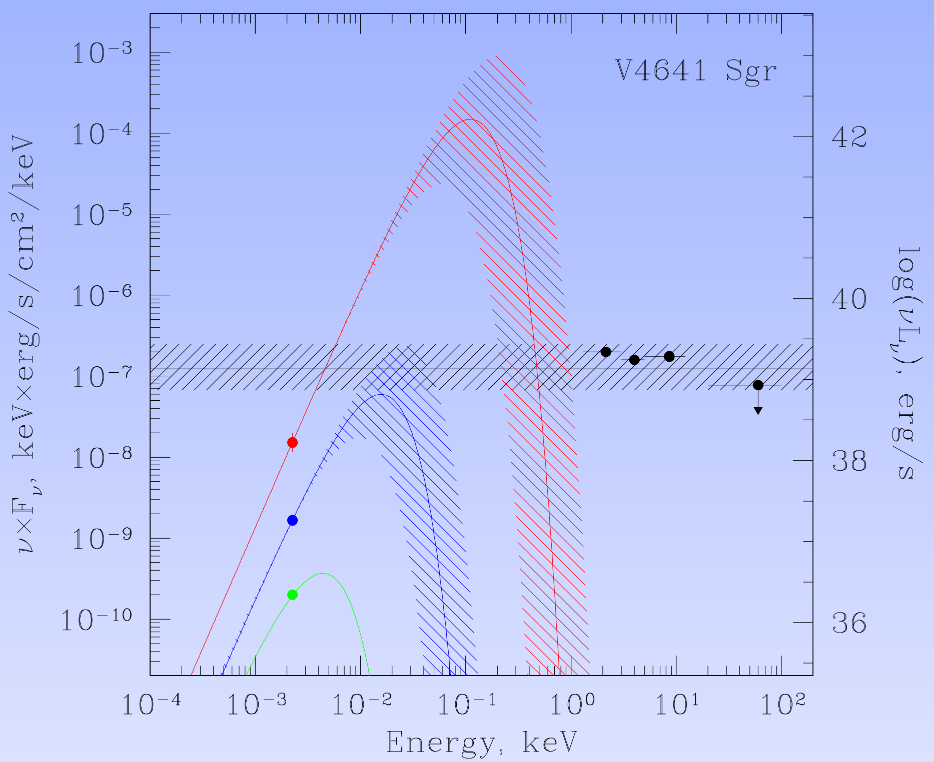

A0620-00 (V616 Mon)


V4641 Sgr


V4641 Sgr

If the emission is optically thick (black body) then:

- **Optical band lies almost at the Rayleigh-Jeans part of spectra of both AD and the star**
- **It means: $L_{opt} \propto T \propto L_{bol}^{1/4}$**
- **Increase $\sim$100 in $L_{opt} \rightarrow$ increase 10^8 in the bolometric luminosity (more accurate calculation gives "only" 10^6).**
  $L_{bol,max} \sim 10^{42}$ ergs/s!?



How to avoid 1000-Eddington luminosity?

- **All super-Eddington fluxes are assumed, not observed**
- **Observed optical, and X-ray luminosities are** ***close to the Eddington level***

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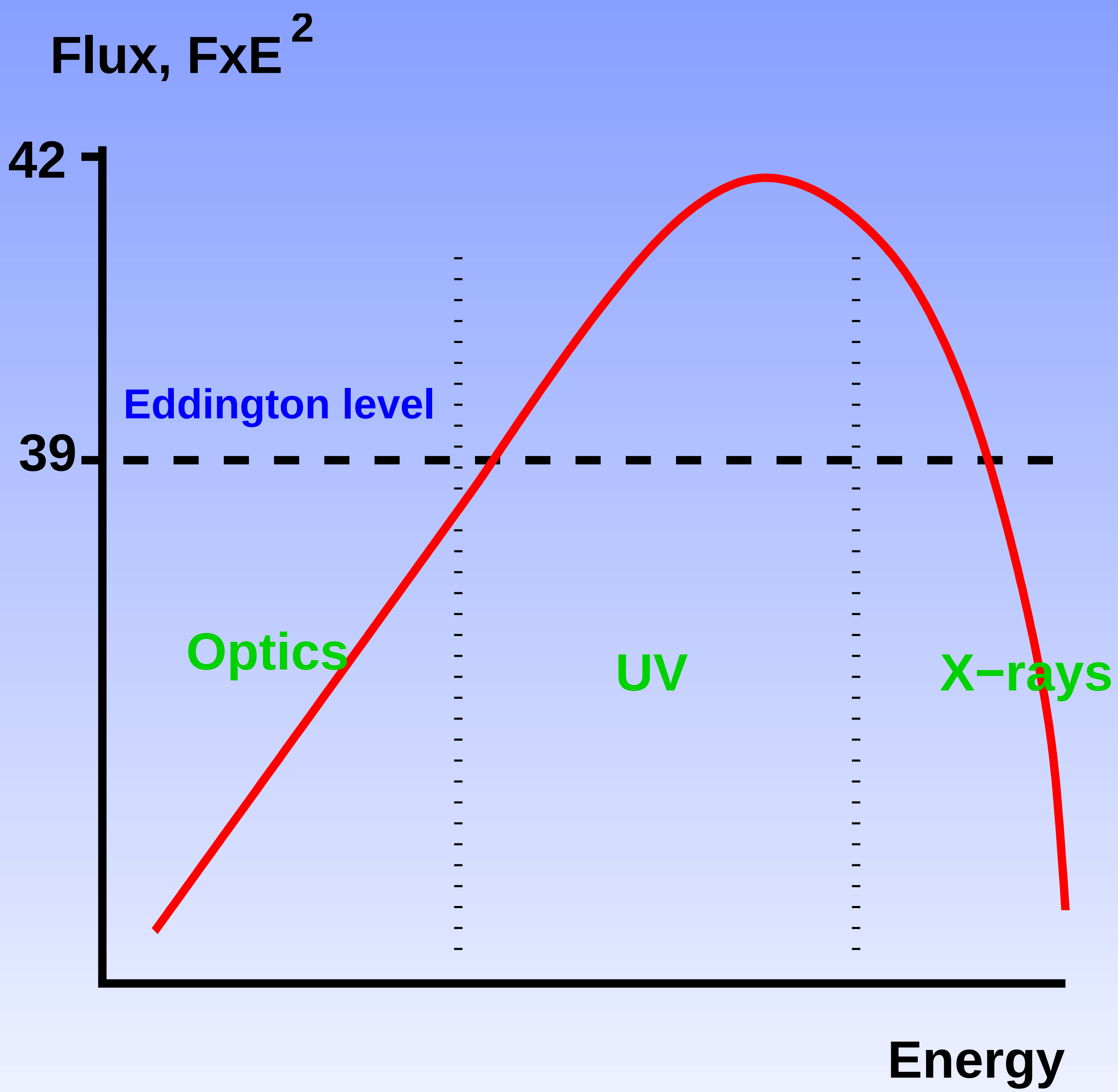
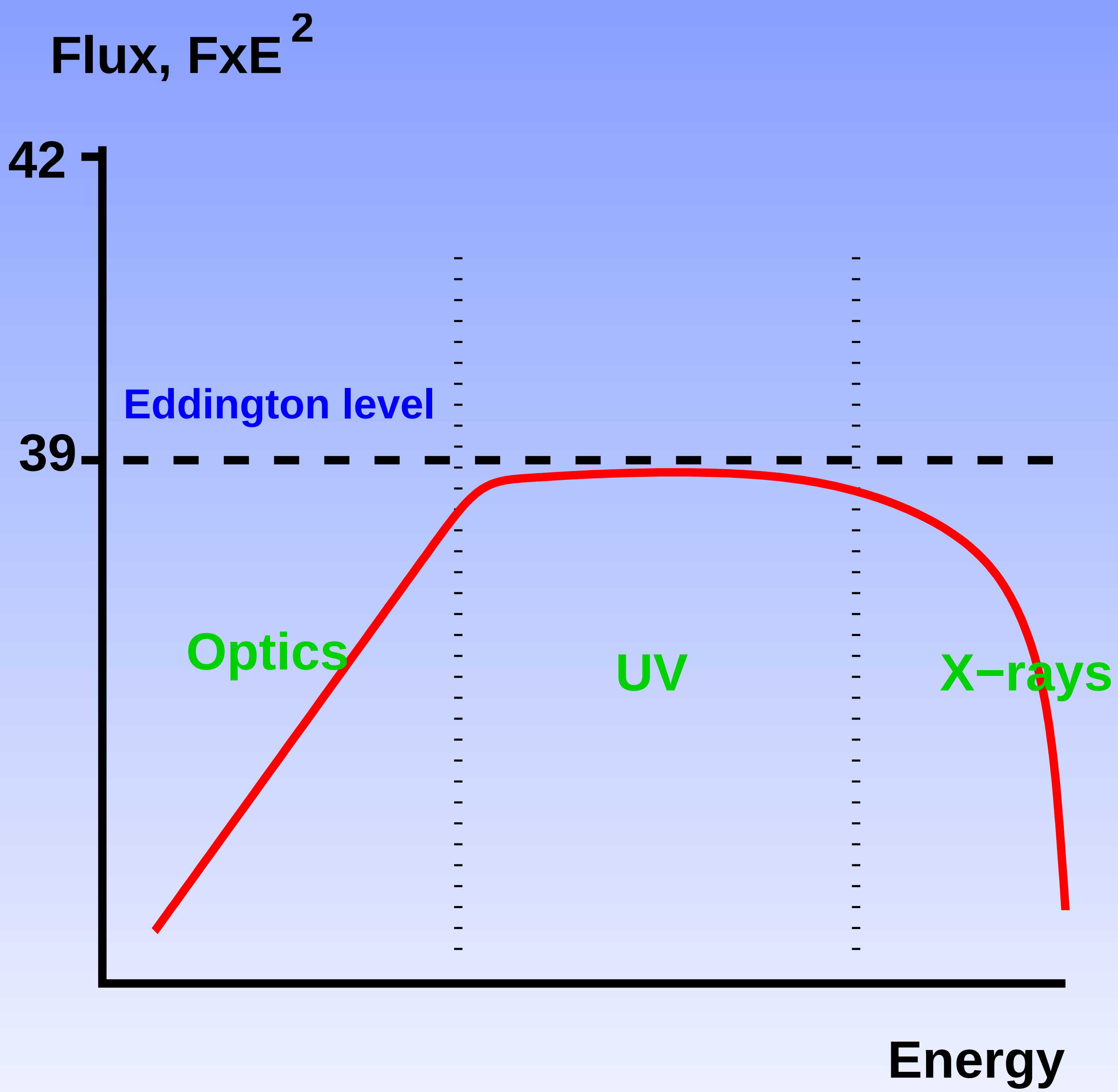
The emitting region should be rarified → envelope?

Why not? If observed luminosities are already close to Eddington, may be the radiation puffs up the envelope?



Flux, FxE 2
42
39
Eddington level
Optics
UV
X−rays
Energy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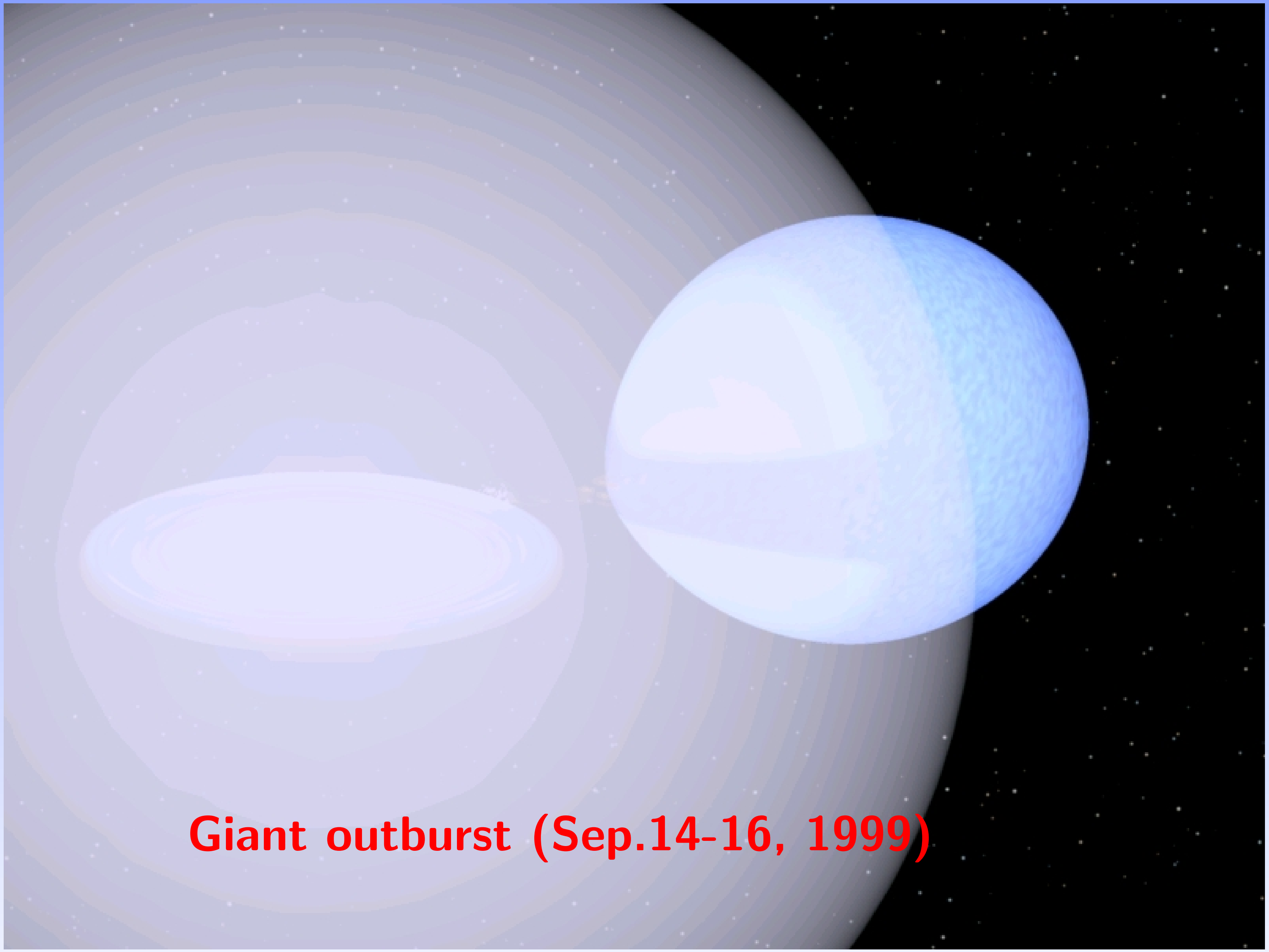
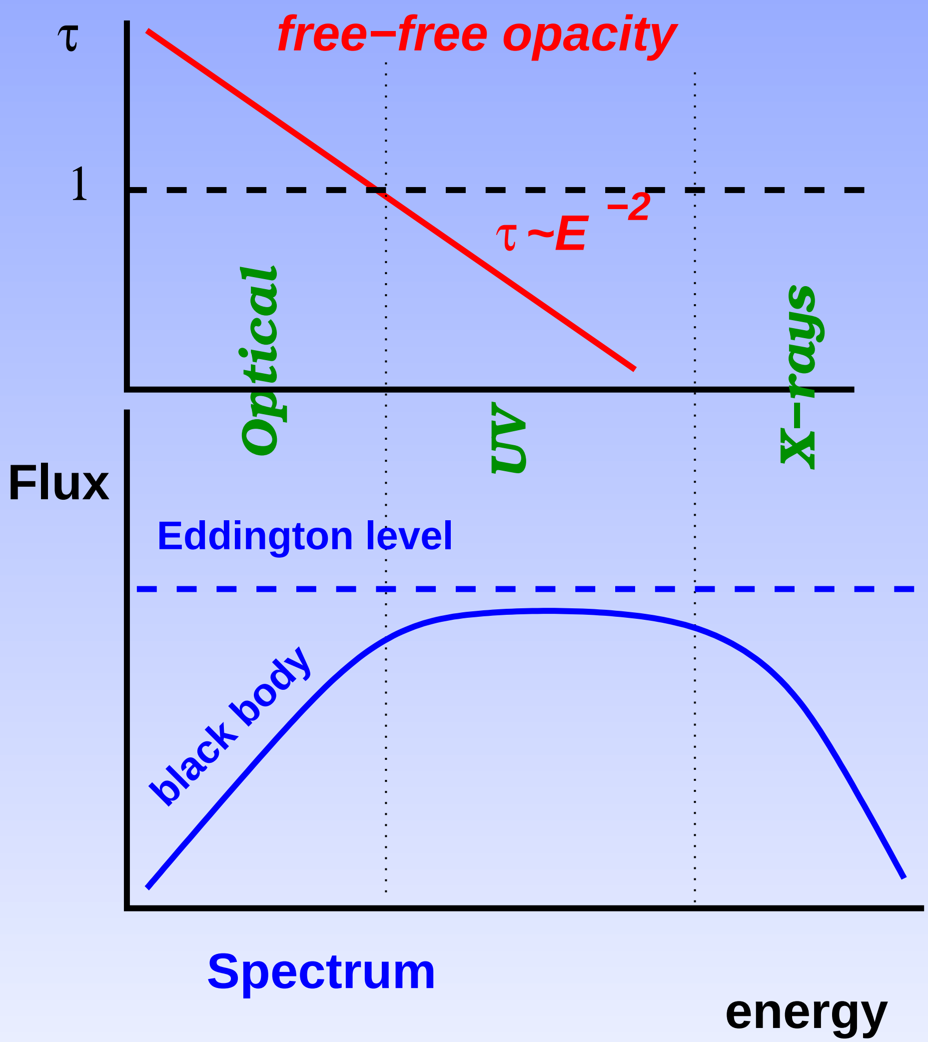

Giant outburst (Sep.14-16, 1999)

Radiation of the envelope



- **Free-free opacity $\tau \propto \nu^{-2}$ (if $h\nu << kT$) $\rightarrow \tau_{\text{free-free}}$ is deacreasing from optical to UV**

We need $\tau \sim 1$ at the boundary between optics and UV

$$\tau \sim \frac{4.1 \cdot 10^{-23}(1 - \exp(-x))}{T^{7/2}x^3} n^2 R = 1$$

$x = h\nu/kT$. **Substituting the parameters we get $n^2R \sim 10^{39}$, $n \sim 10^{13} - 10^{14}$ cm^{-3}**

Luminosity of such a cloud

$L_{bremss} \sim 2 \cdot 10^{-27} T^{1/2} n^2 V \sim 10^{38}$ **erg/sec**

Mass: $\sim 10^{23-25}$g

Envelope needs energy supply

Taking the bremsstrahlung cooling;

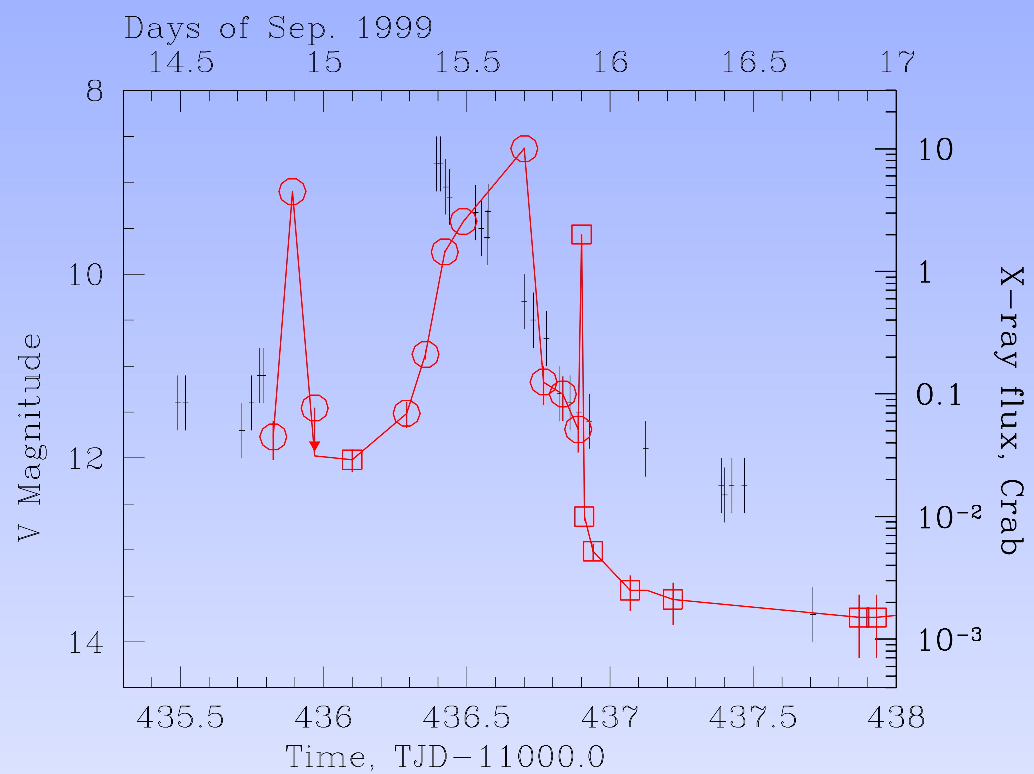
$$L_{bremss} \sim \int 2 \cdot 10^{-27} T^{1/2} n^2 dV \sim 2 \cdot 10^{-27} T^{1/2} n^2 V \ erg/s$$

Brightness temperature at the maximum of the optical light curve $T \sim 3 \cdot 10^5$ **K.**

$$t_{cool} \sim 6.9 \cdot 10^{10} T^{1/2}/n = 10^{14} n^{-1} \ \ sec$$

Large envelope needs the energy supply.

May be this energy comes from the X-rays?



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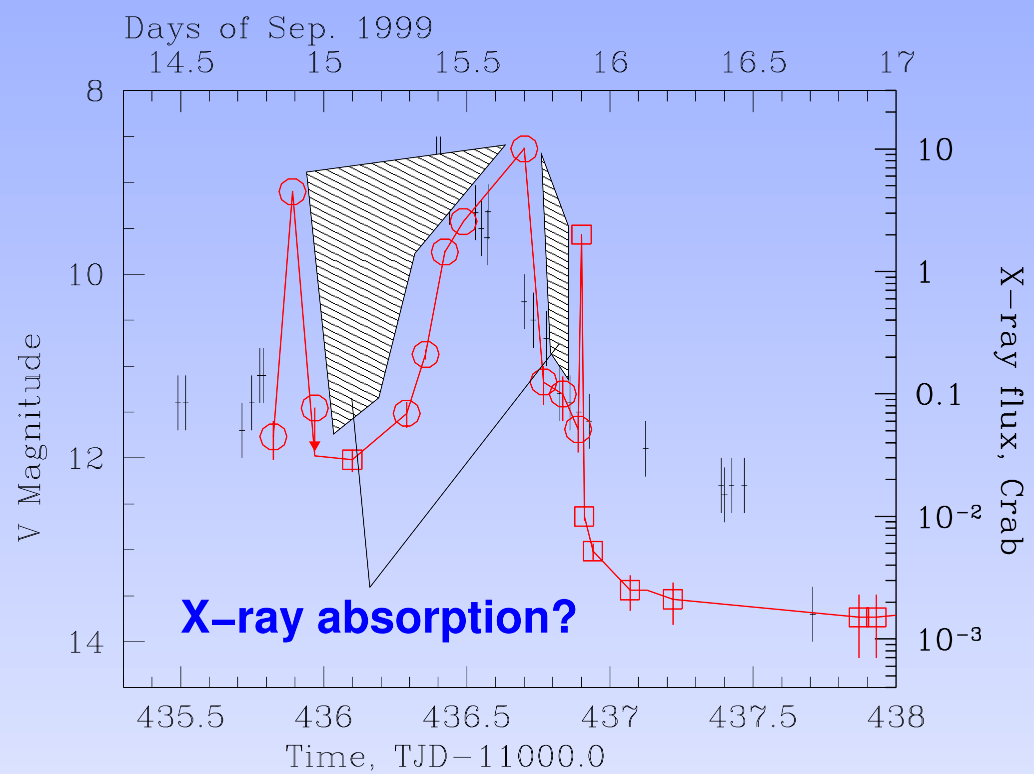
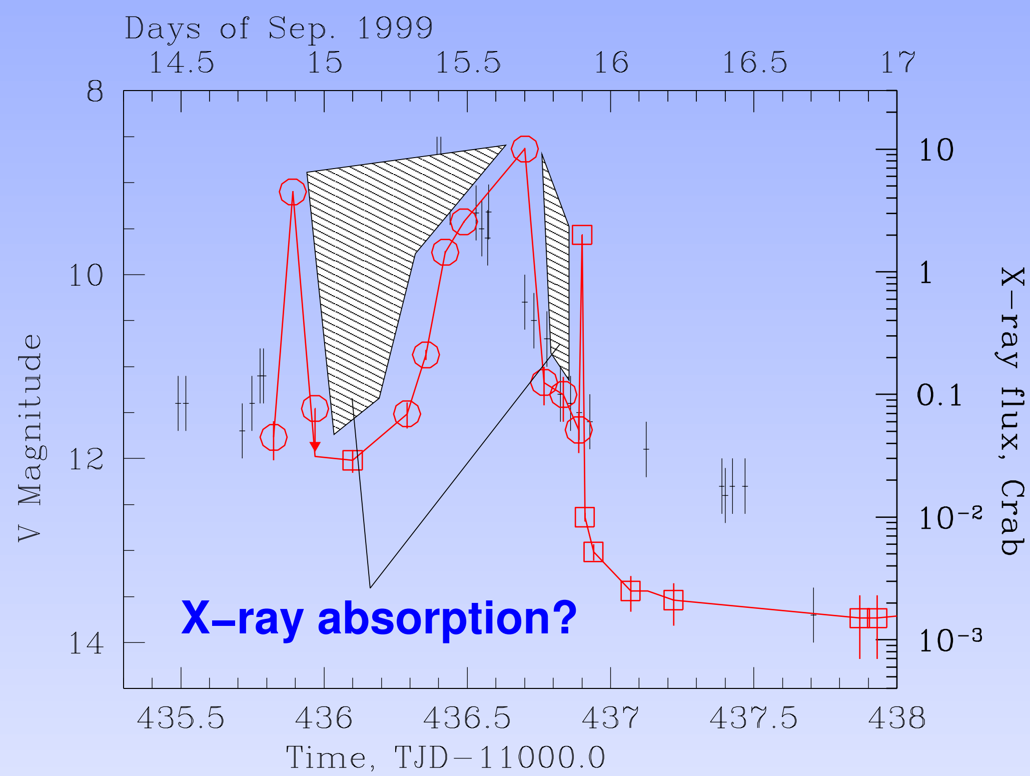

Days of Sep. 1999
14.5
15
15.5
16
16.5
17
8
10
12
14
V Magnitude
10
1
0.1
10⁻²
10⁻³
X−ray flux, Crab
X−ray absorption?
435.5
436
436.5
437
437.5
438
Time, TJD−11000.0

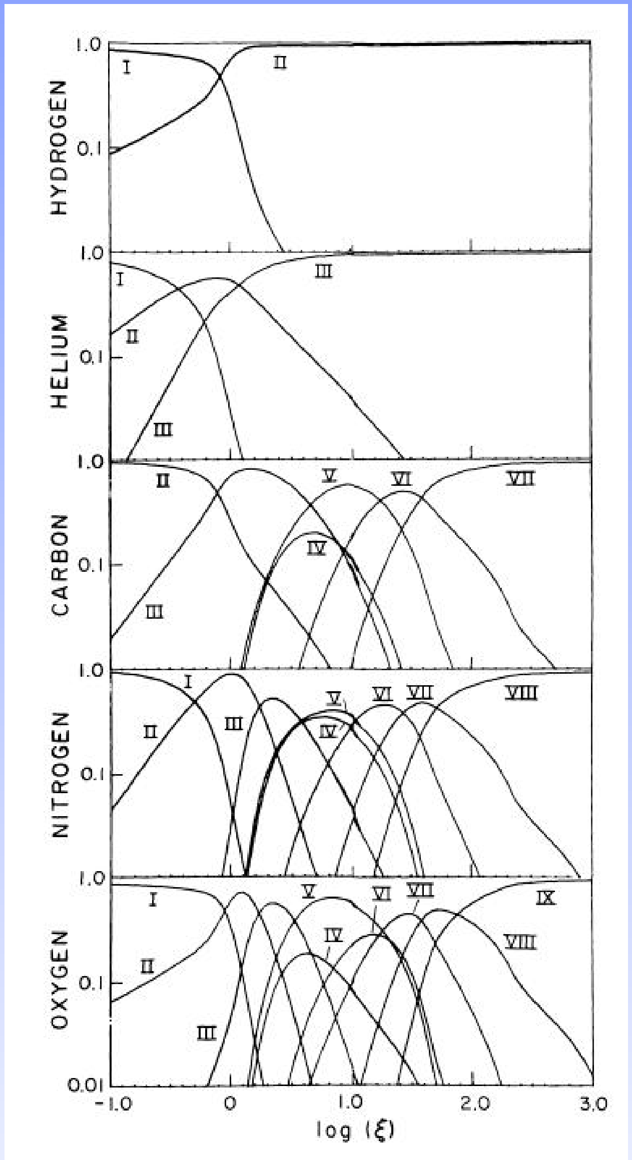


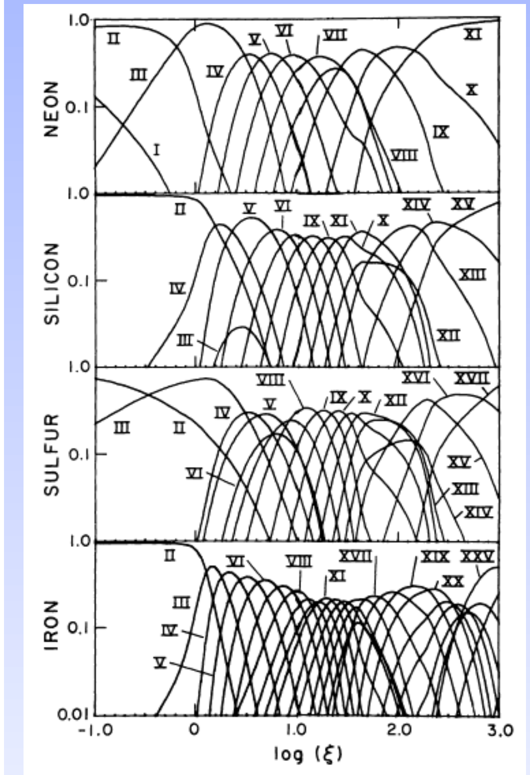
To absorb X-rays one need the column

$$N_H L \sim 10^{24} - 10^{25}\ cm^{-2}$$

Radius of the envelope $R_{env} < R_{Roche} \sim 5 \cdot 10^{11}$ cm.
Then the density in the envelope can not be smaller than $\sim 10^{13} - 10^{14}$ cm^{-3}.
It ok with our previous estimates!

Ionization (very naive view)





Kallman, McCray

Lines are very important!

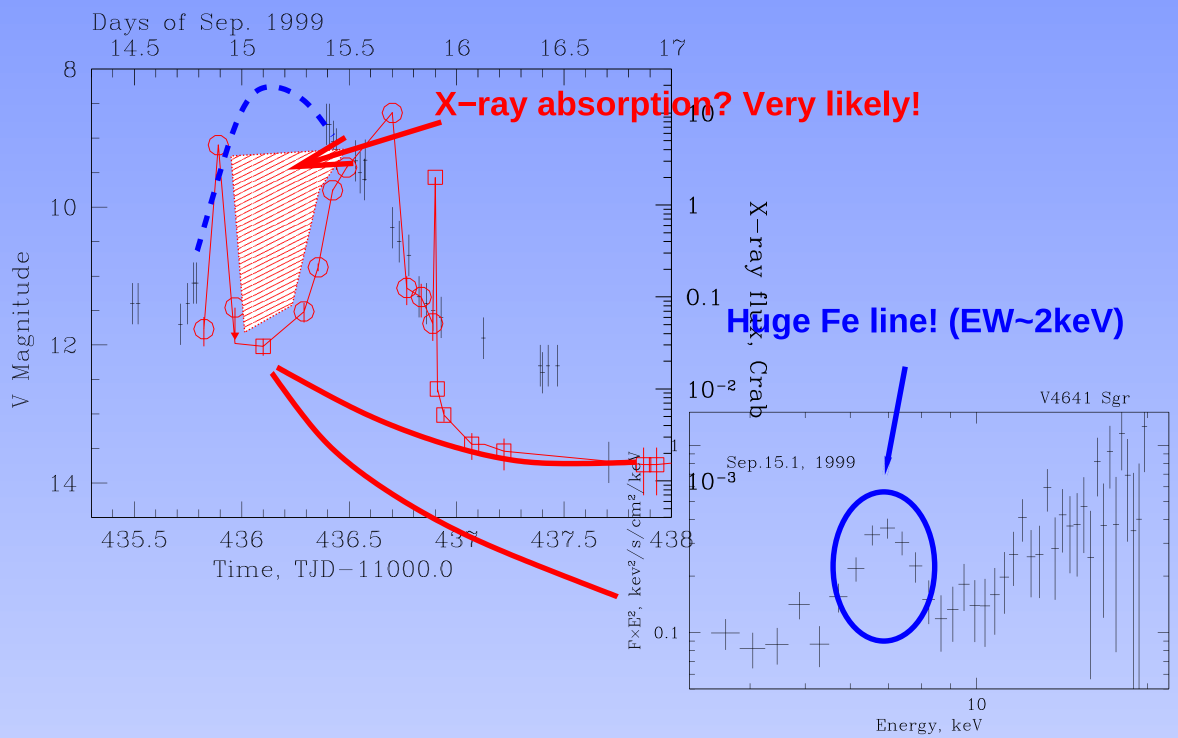
- **Simple ionization parameter**

$$\xi \sim L/nR^2 \sim 10^{16-17} n^{-1}$$

$\xi \sim 10^{2-4}$ **for** $n \sim 10^{13-14}$

- **It means that almost all elements are fully ionized**

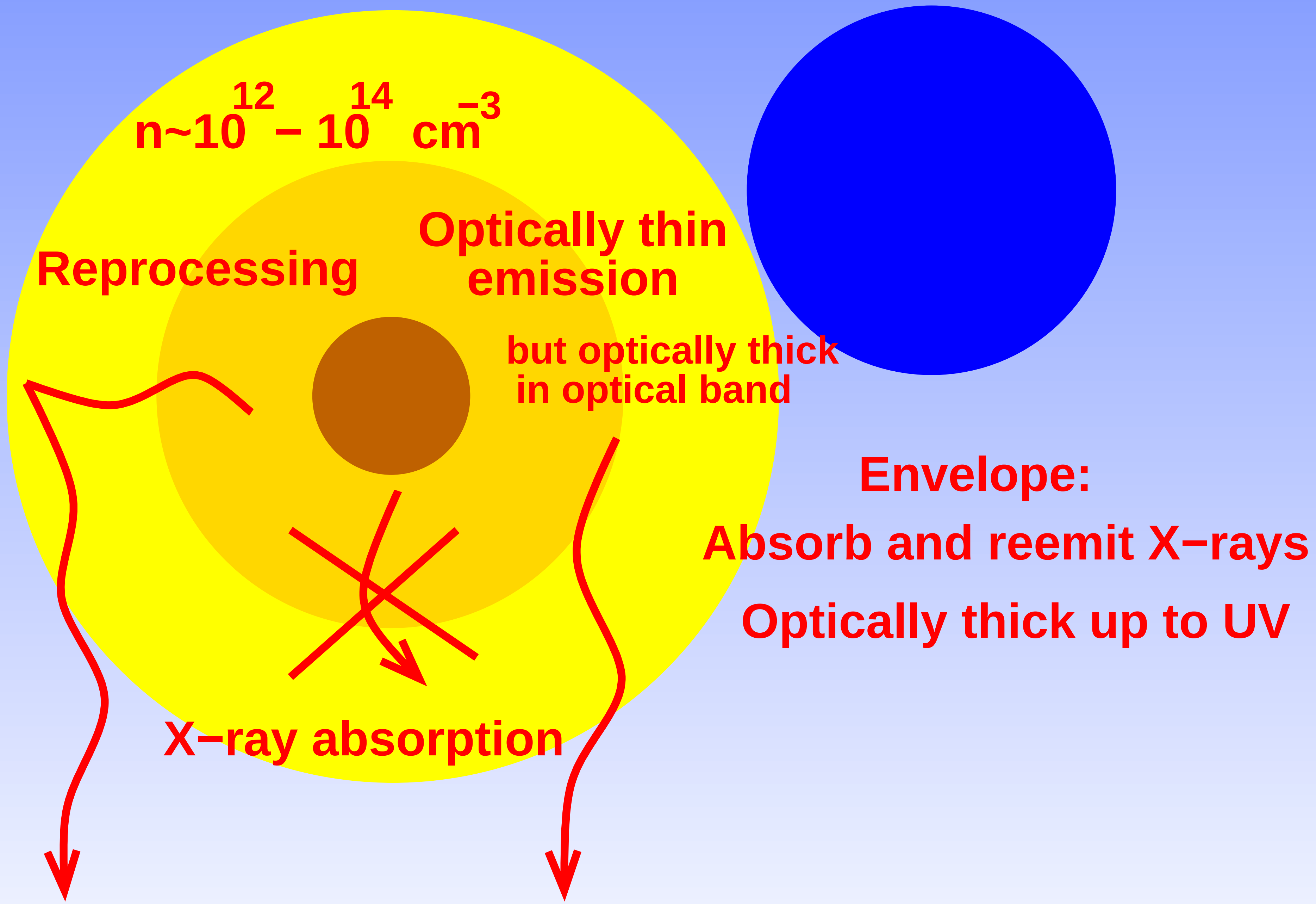
- **Some fraction of heavy elements could be non-ionized, providing us the X-ray absorption**



At this moment we (presumably) do not see the direct emission from the inner accretion disk.

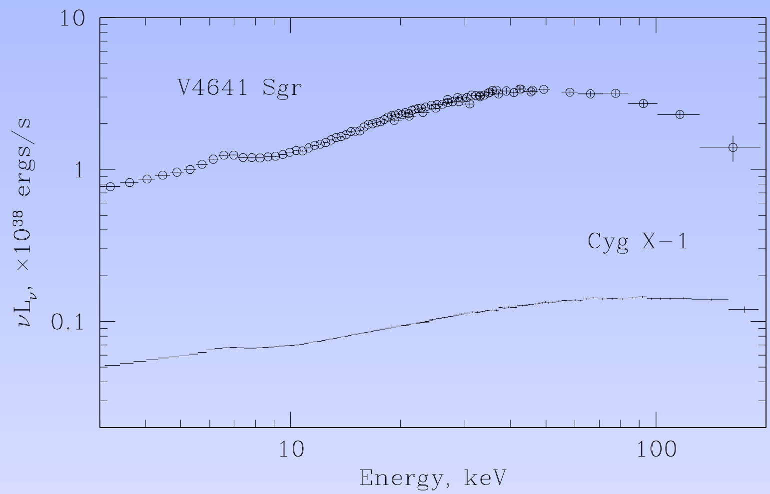
May be inner parts of the envelope are hotter and emit that Fe line via optically thin emission?

To explain this line we need $\int n^2 dV \sim 10^{60}$. With $n \sim 10^{13-14}$ cm^{-3} we need $R \sim 10^{10-11}$ cm.

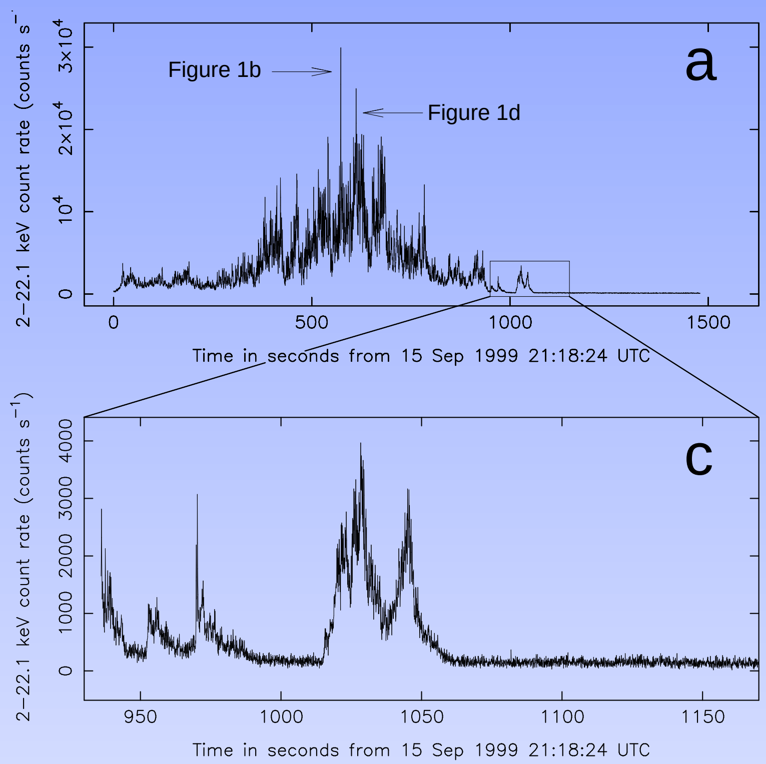

n~10^12 − 10^14 cm^−3
Reprocessing
Optically thin
emission
but optically thick
in optical band
Envelope:
Absorb and reemit X−rays
Optically thick up to UV
X−ray absorption

Pointed X-ray observation

- **X-ray flux is highly variable**
- **At the peak - the spectrum of the source is similar to Cyg X-1**



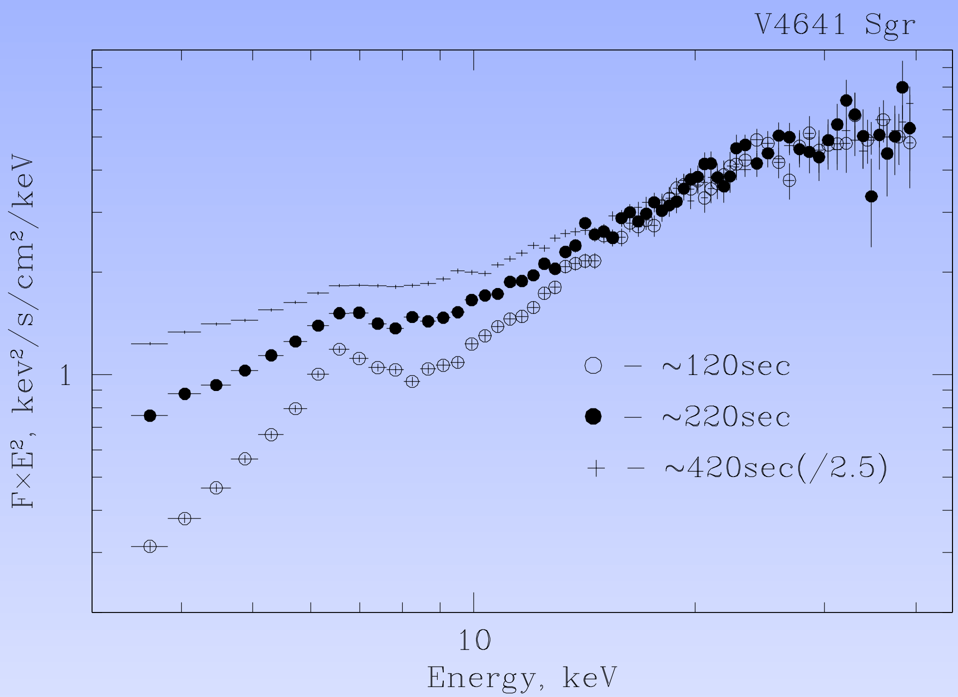
from Revnivtsev et al. 2002

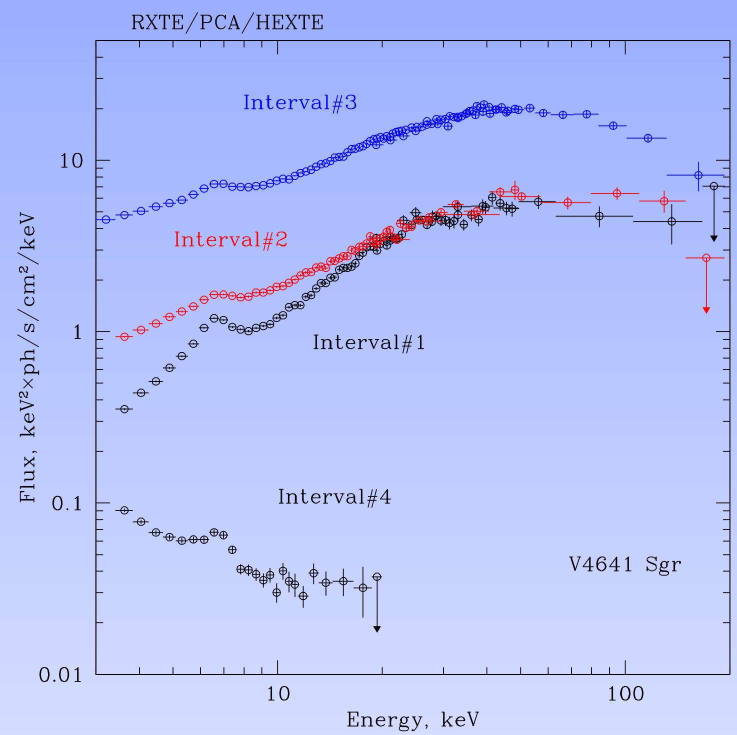


from Wijnands& van der Klis 1999

Variations of the spectral shape

- **Spectral variability looks like change in the absorption column**

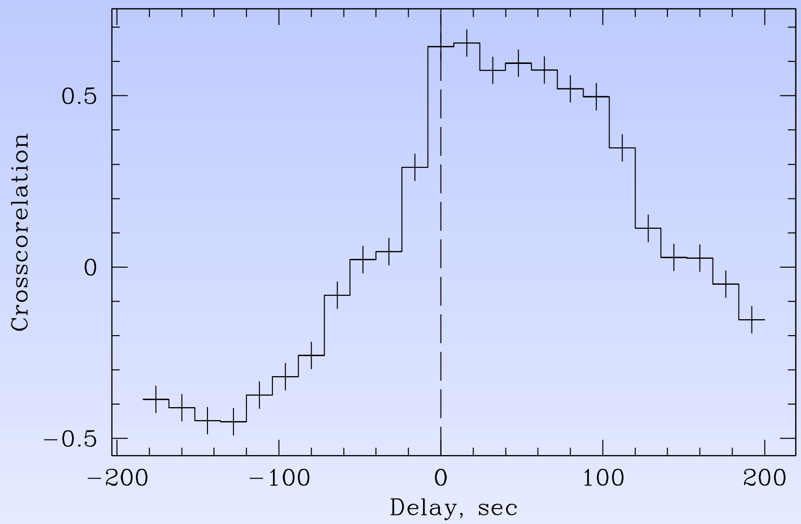


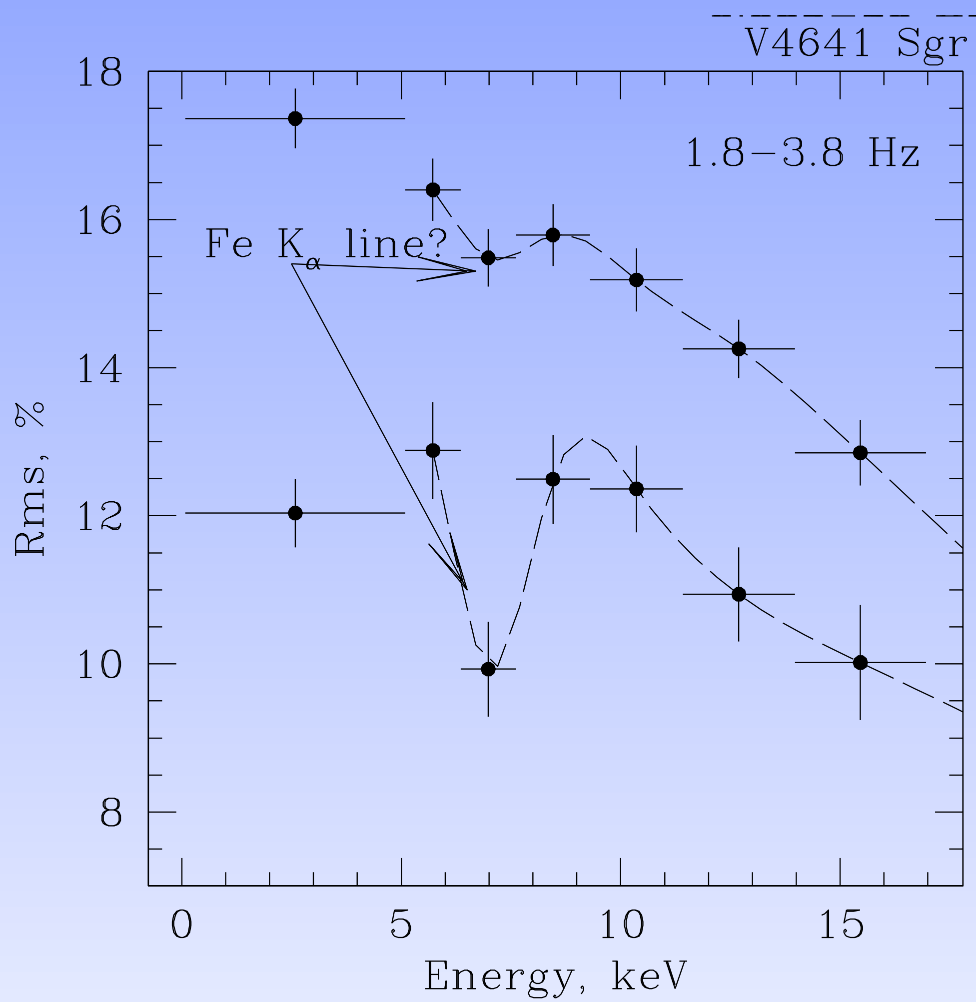


Fe line variability

- **The line flux is less variable than the continuum – could be smearing in the reprocessing region?**

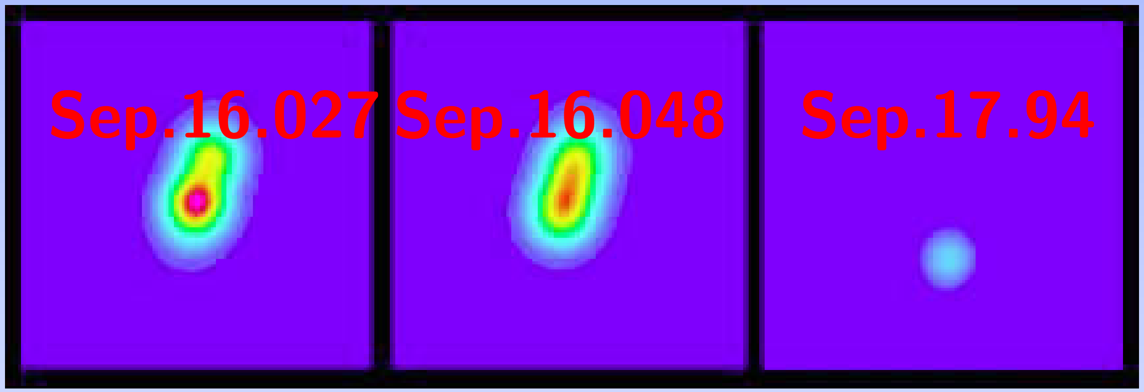
- **There is an indication that the line flux is delayed with respect to the continuum flux**





Radio activity

First big X-ray flare – Sep.14.9, 1999



Hjellming et al. 1999

Size of the source ∼0.25"∼2000 AU!

- **Almost immediately after the giant X-ray burst an extended radio emission was observed**
- **Superluminal motion was assumed**
- **However, 9.5 kpc distance makes it very suspicious. Apparent velocity $v_{app} > 9c$?**

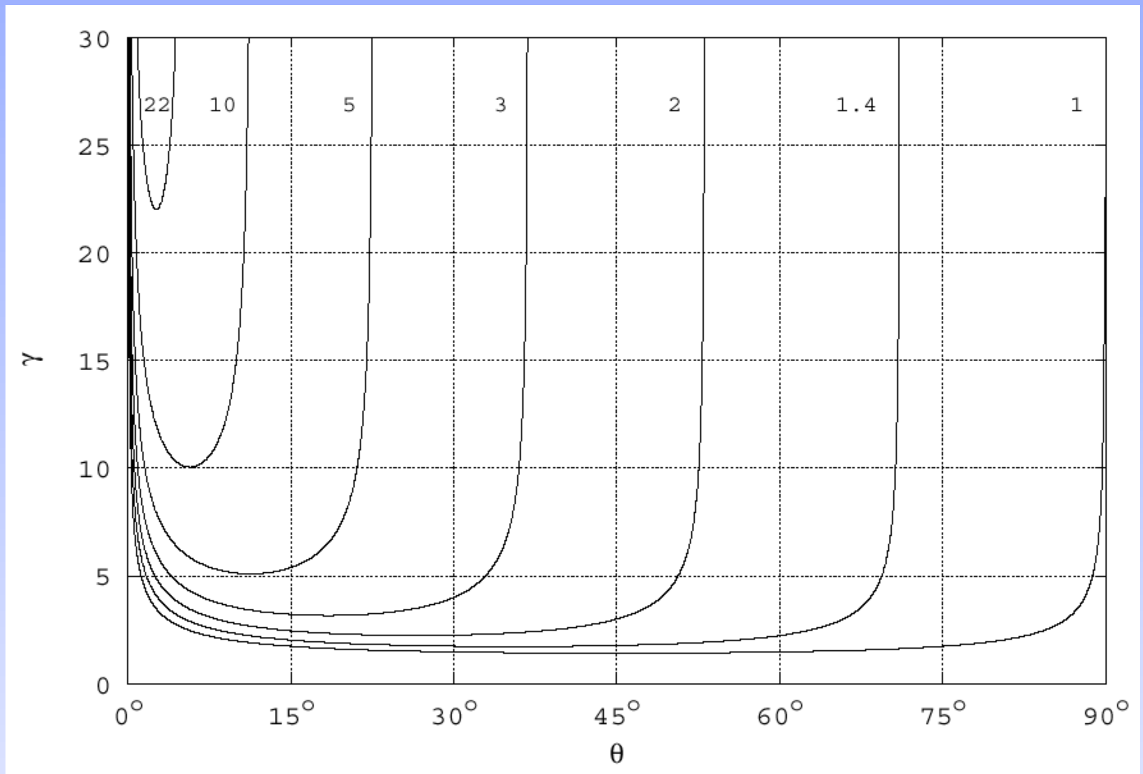
9c apparent velocity?

- **Apparent velocity was not directly observed. Its estimation based on the assumption of the jet ejection time**

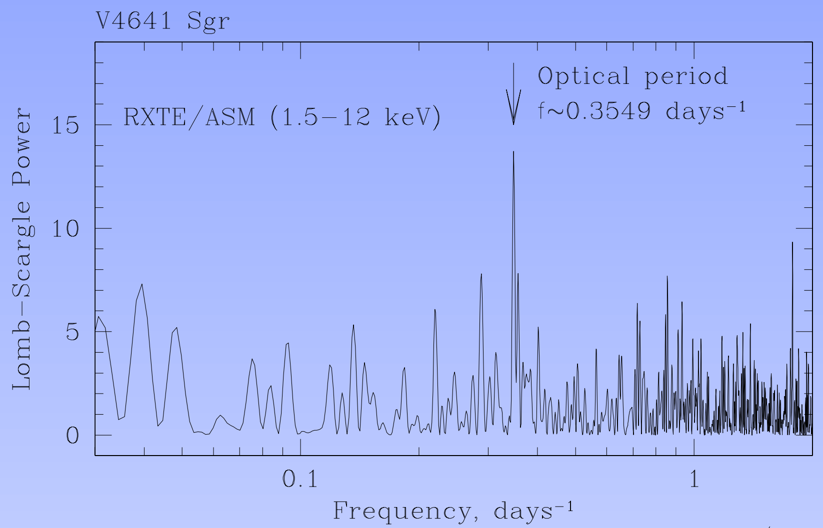
- **If time of big X-ray event is the time of the jet launch, then $v_{app} > 9c$**

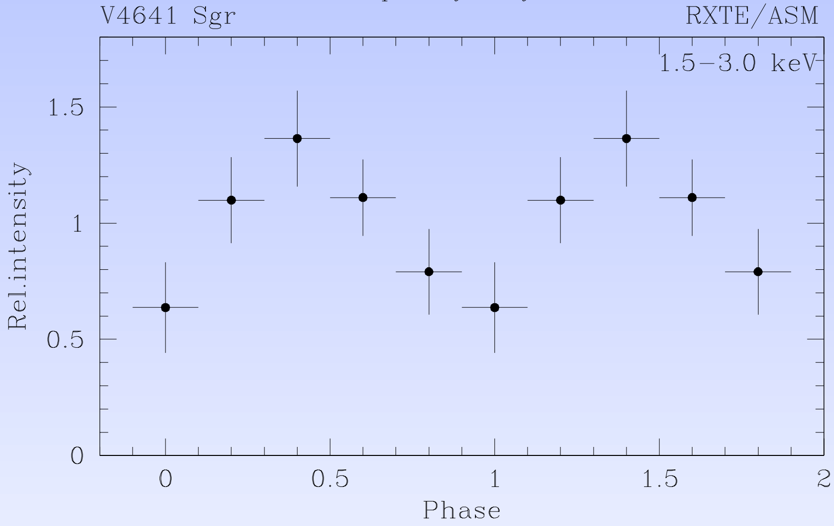
- **It is very hard to make such apparent velocities: large γ and small θ, it contradicts to the measured i**

- **May be jet was launched 2 weeks earlier ($v_{app} \sim c$)?**



X-ray period confirms that $i \sim 70^{\circ}$





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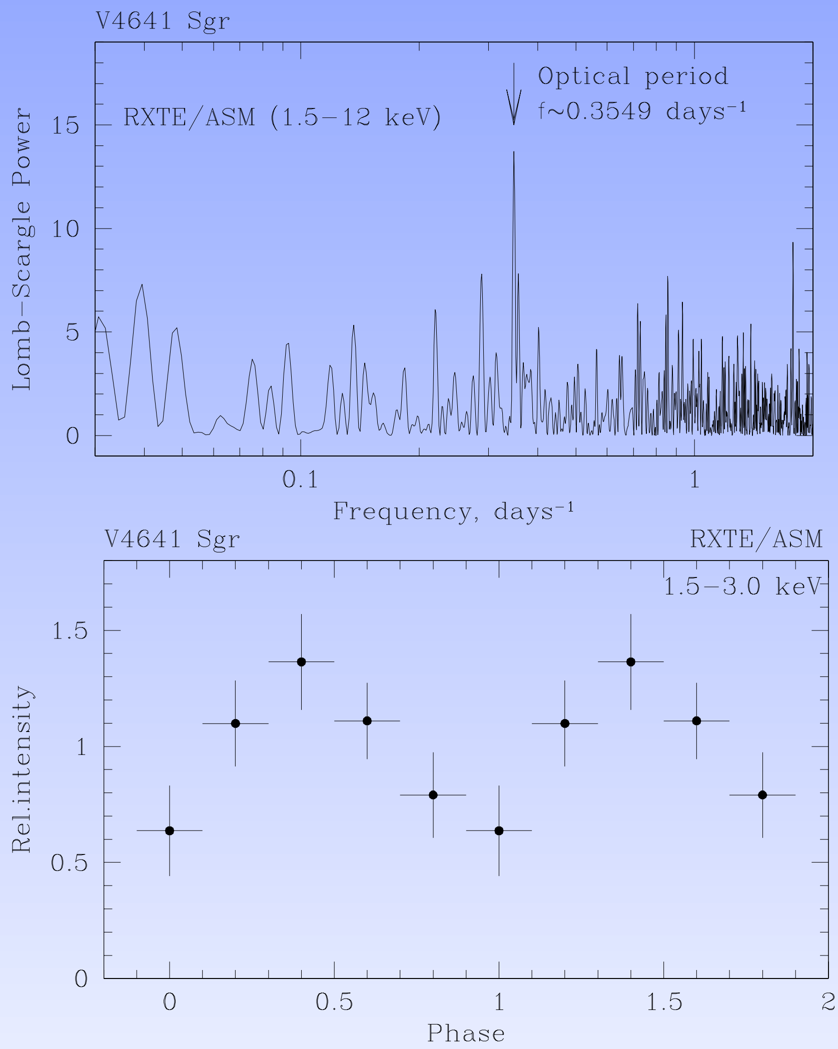

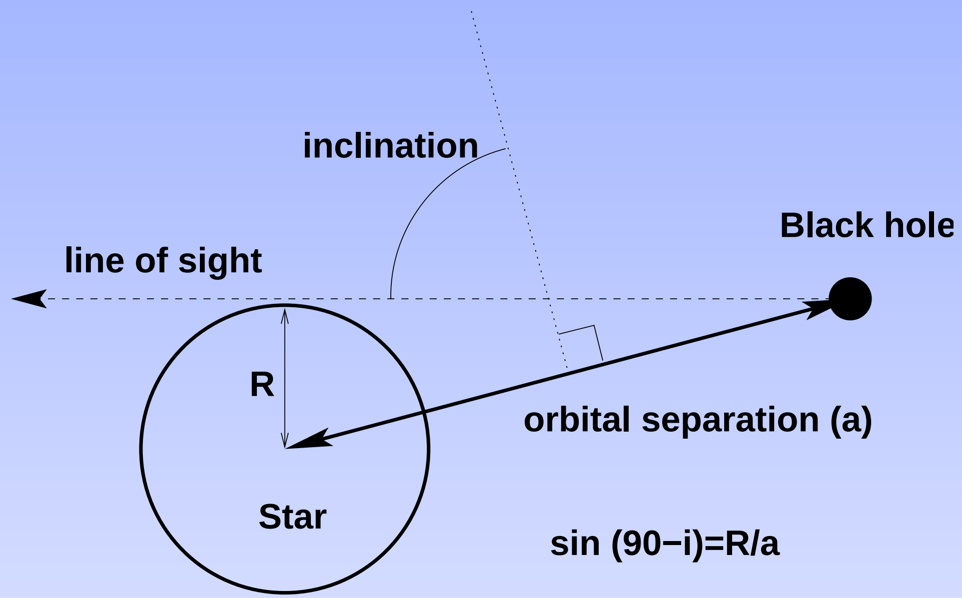

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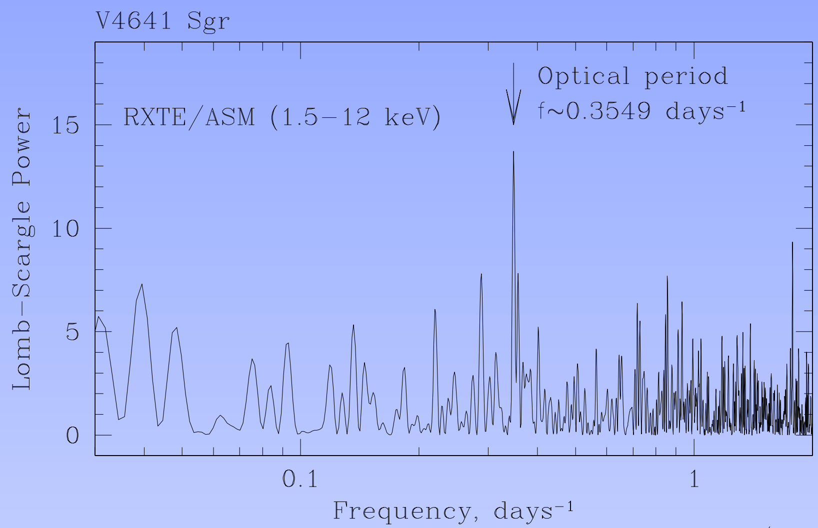
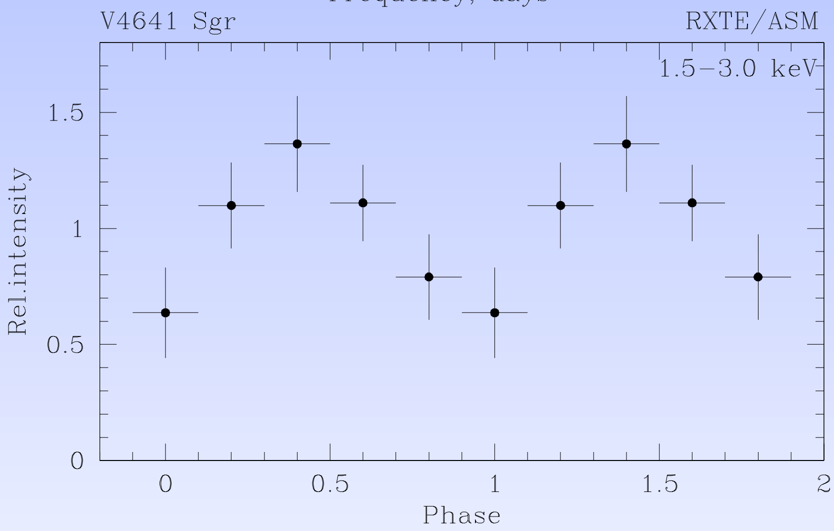
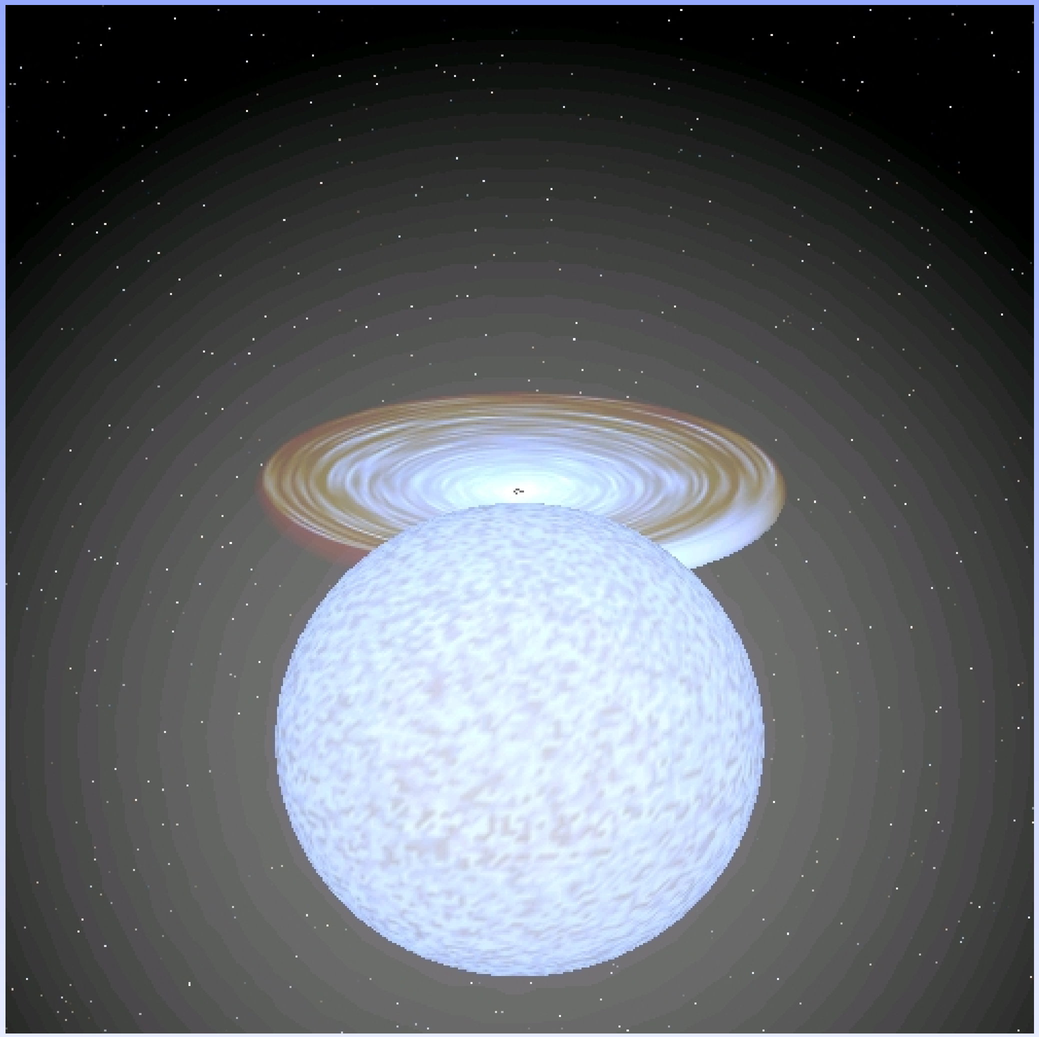
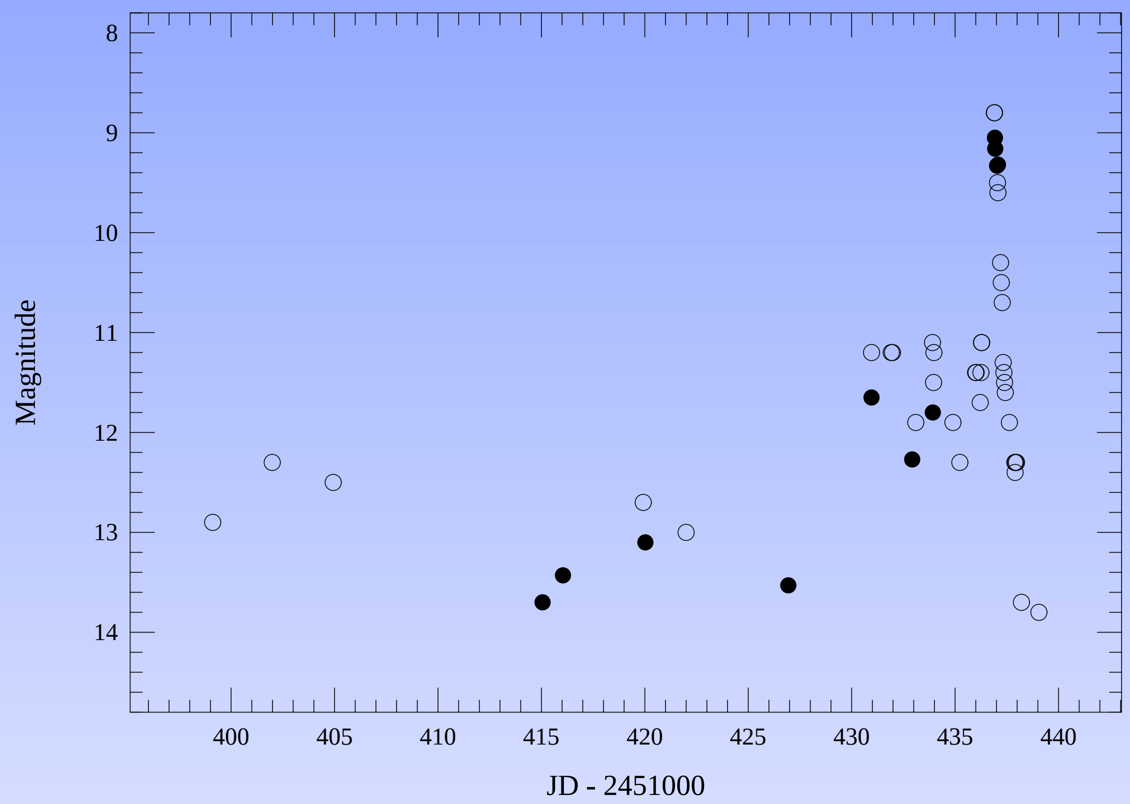




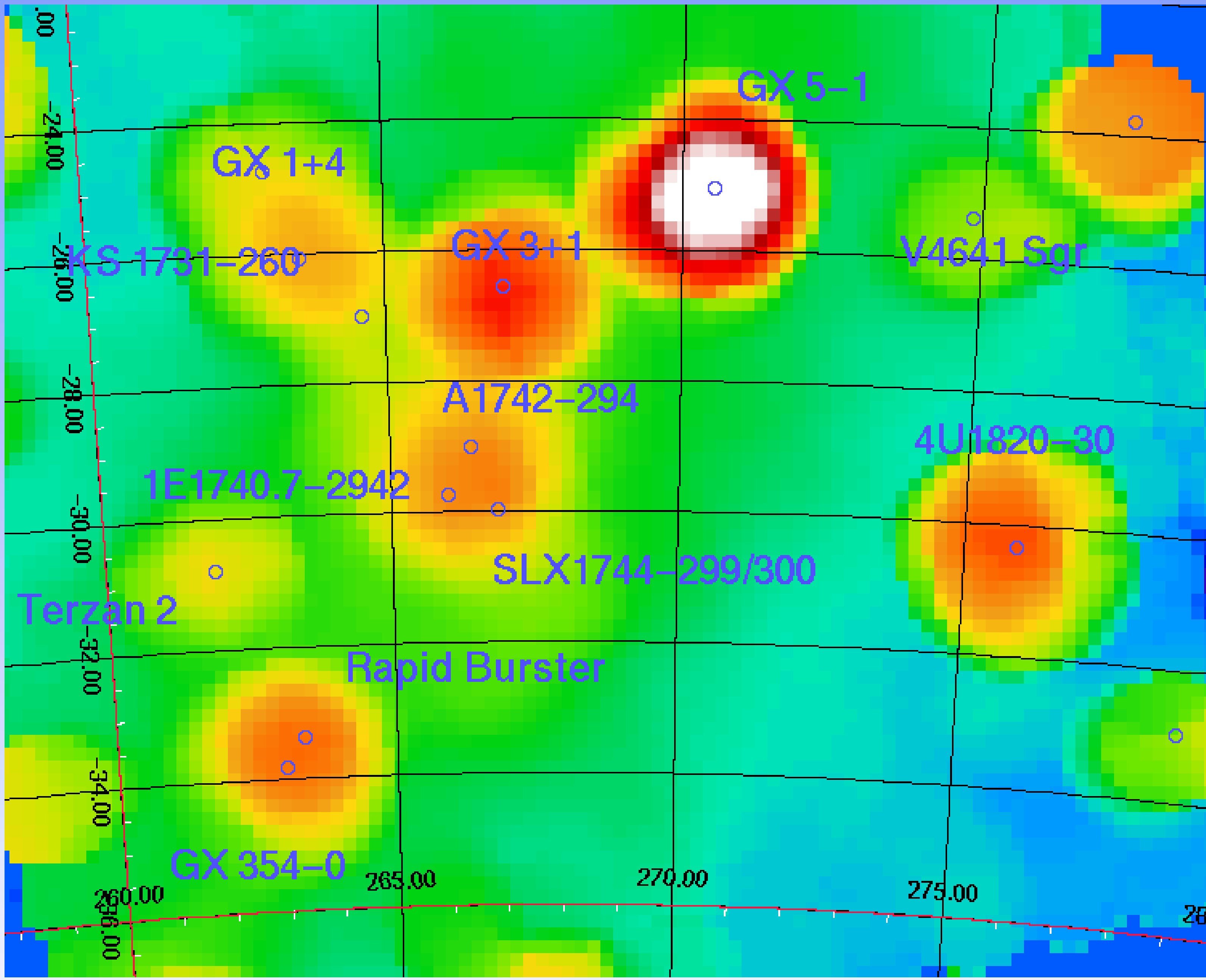


Optical activity

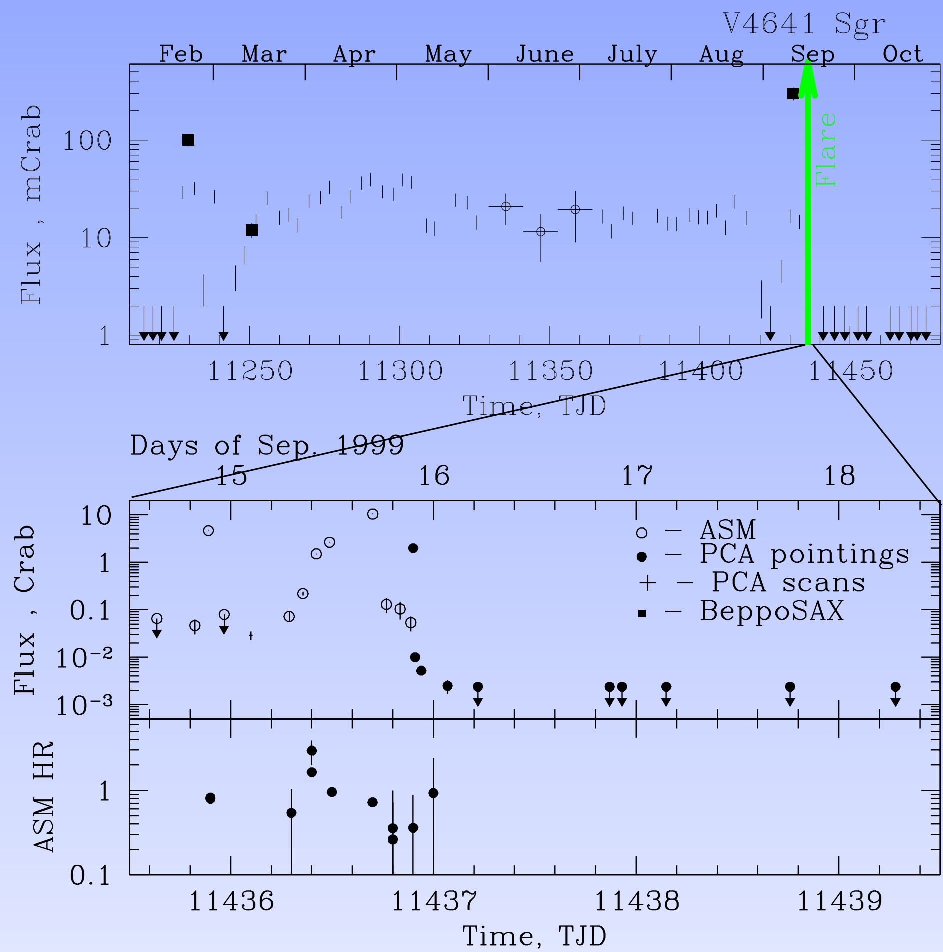


from Kato et al. 1999 (VSNET data)

- **Quiescent optical flux** $m_v \sim 14$
- **At the beginning of Sep. 1999 increase by** $\Delta m_v \sim 2$
- **Maximum optical flux** $m_v \sim 8.5$**. Observed increase** $\Delta m_v \sim 5$

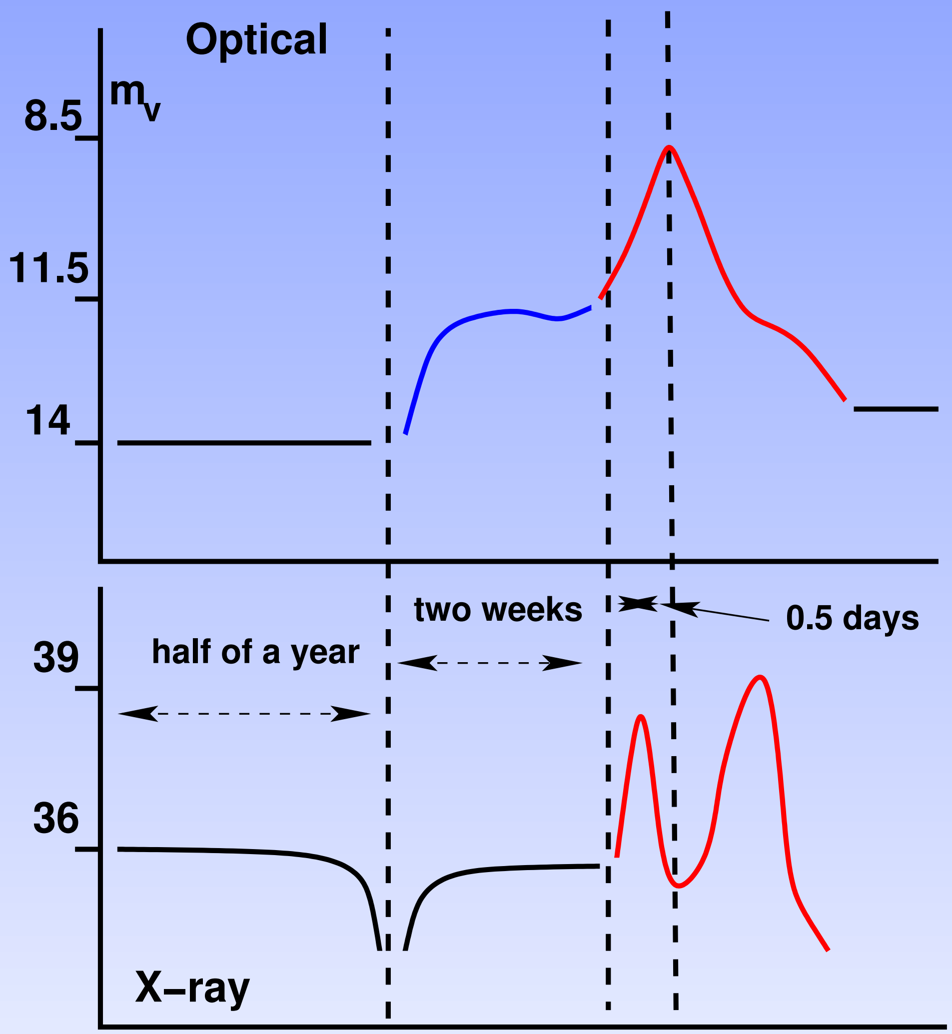

GX 5−1
GX 1+4
KS 1731−260
GX 3+1
V4641 Sgr
A1742−294
4U1820−30
1E1740.7−2942
SLX1744−299/300
Terzan 2
Rapid Burster
GX 354−0
265.00
270.00
275.00
260.00
-24.00
-26.00
-28.00
-30.00
-32.00
-34.00
-36.00

X-ray activity

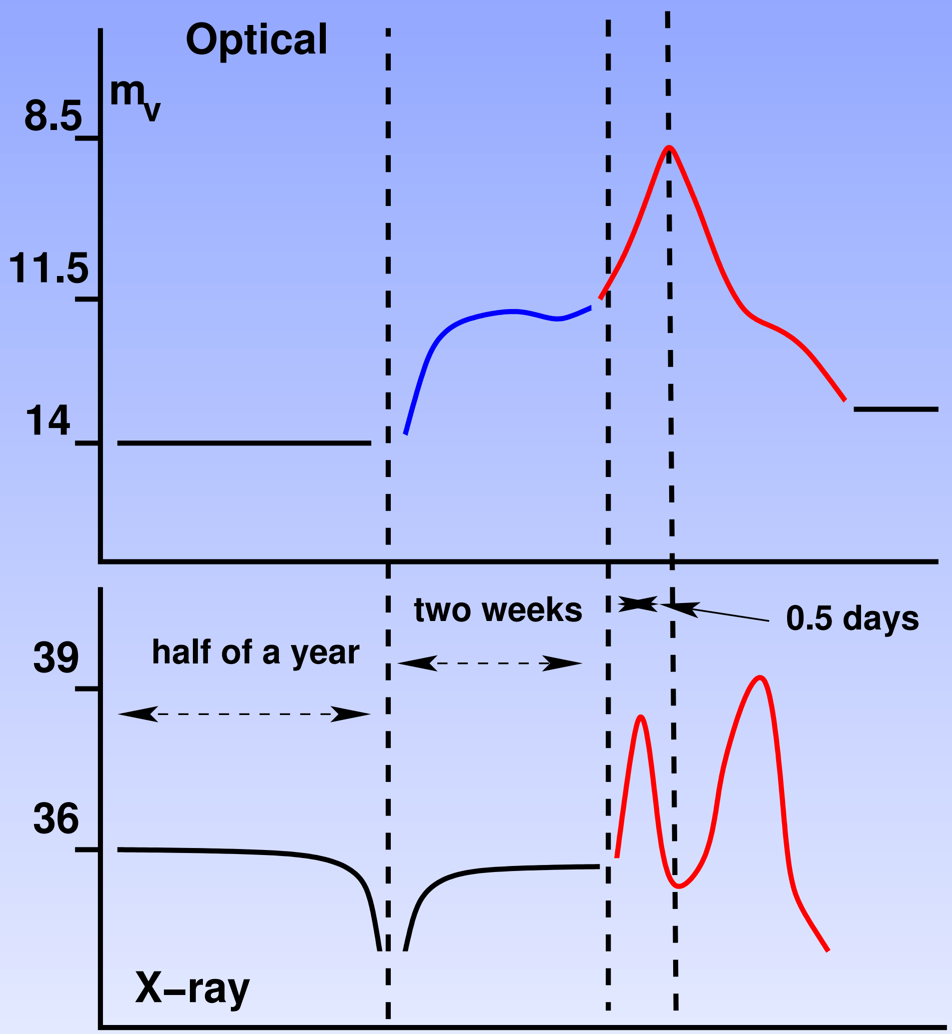


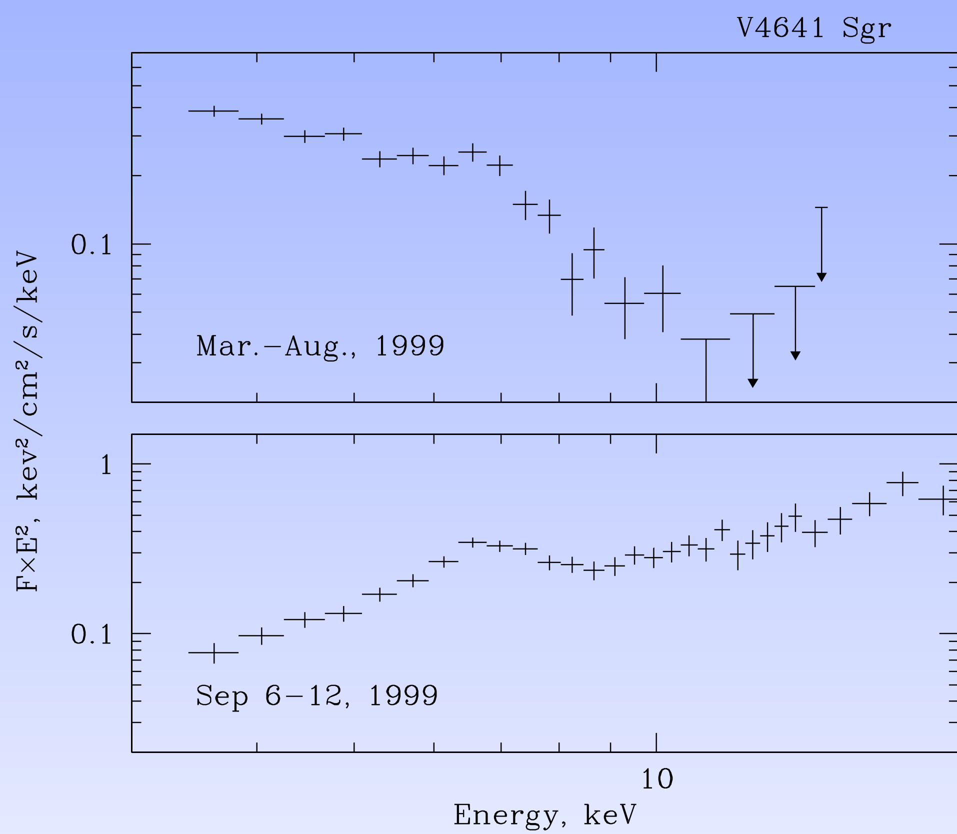
- **X-ray flux is ∼10–30 mCrab since Feb.1999 till Sep. 1999**
- **X-ray "dip" ∼ 2 Sep. 1999**
- **Huge flares ∼14–16 Sep. 1999. Flux rose to 12 Crabs**
- **Disappeared after Sep.16, 1999. Upper limit <1–2 mCrabs**

Long-term history picture/scheme



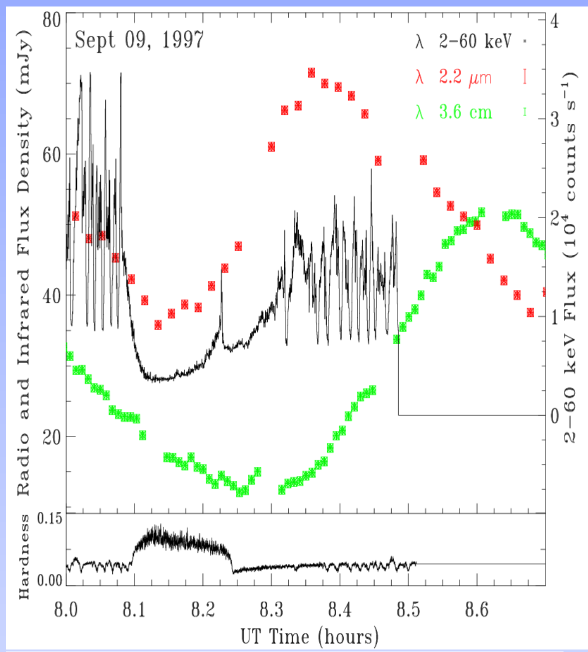
Long-term history picture/scheme

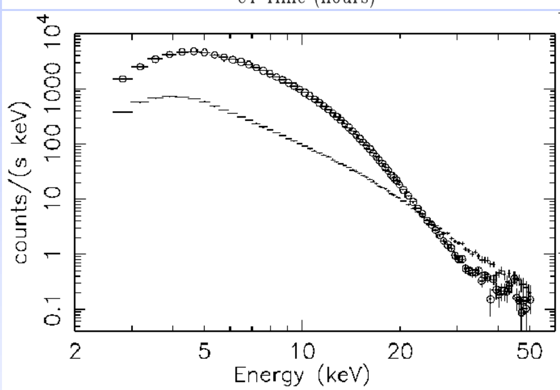


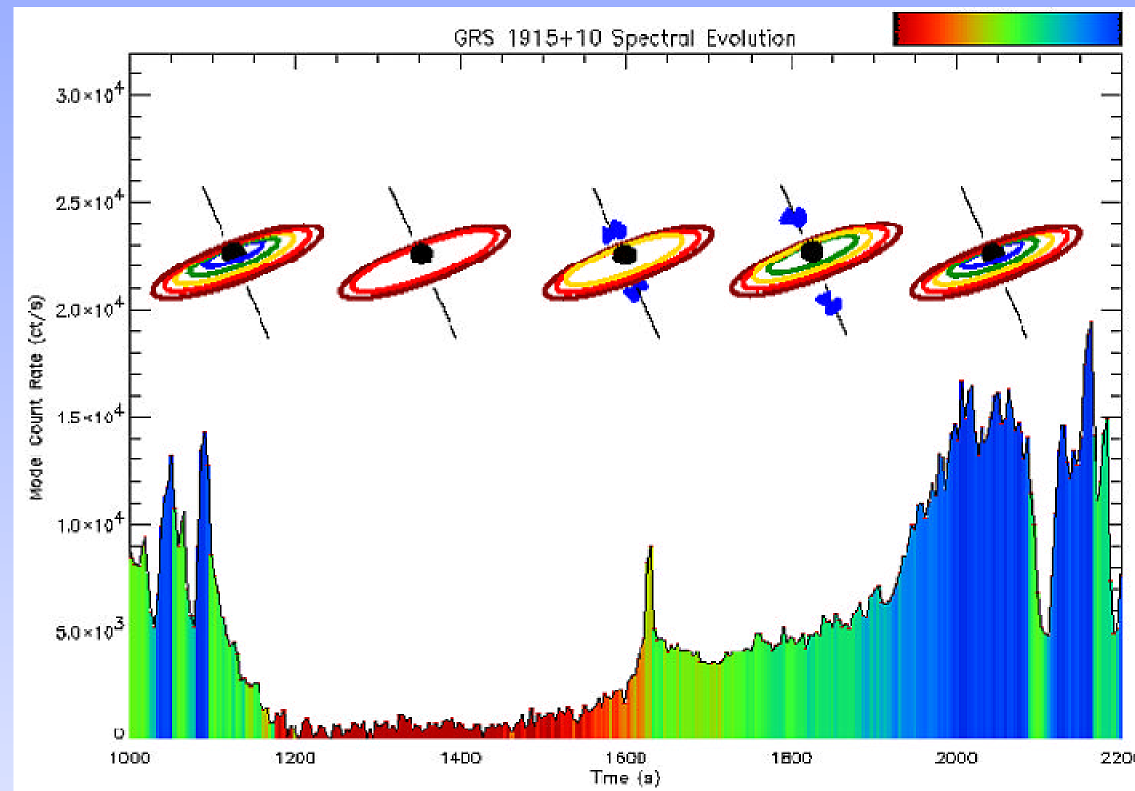


May be jet was ejected two weeks before the giant outburst?

Similarity to GRS 1915+105?







Disappearance of the inner disk is accompanied by the jet ejection. Infrared, radio flares were observed

Belloni et al.

Conclusions

- Source is extremely complicated. We can not explain all observational features. But we think that we understand some points
- We argue that V4641 Sgr in Sep. 1999 demonstrated an episode of super-Eddington accretion
- During this episode a powerful expended evelope was formed
- When the accretion rate decreased the envelope vanished
- X-ray observations support this picture: we have detected the change in the X-ray absorption column, smeared and probably delayed variability of fluorescent Fe line
- Source is also interesting from the point of view of unusually high L_{opt}/L_x ratio. Synchrotron emission mechanisms are under consideration (Uemura, et al. 2002)