The role of the disk irradiation in the outbursts of the Rapid Burster

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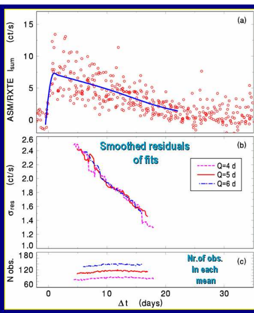
Abstract

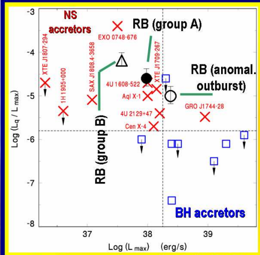
We analyze a specific group of intense outbursts with strong persistent emission (group A) in the unique low-mass X-ray binary Rapid Burster. We interpret them in terms of irradiation of the disk by X-rays strong enough to ionize all of the disk without self-shadowing. We argue that the parameters of irradiation underwent a large and rapid change in the subsequent group B. We interpret the irradiation in terms of the slim accretion disk region. The vertical dimension of the irradiating source, and hence its ability to irradiate the disk, decreases with the increasing luminosity of outbursts with the exponential decays in soft X-ray transients of a comparable orbital period, and is exceptionally small in the Rapid Burster. The difference between the intensities and profiles of the group A and group B outbursts is not caused by a different absorption. We argue against a significant role of the propeller effect in the Rapid Burster.



Merged light curves of group B

Folded light curves of 12 outbursts smoothed by code HEC13 (Vondrak 69, 77; Harmanec).

Residuals then smoothed by two-sided moving averages for the semi-interval width Q=5 d.



Maximum luminosity L_{max} vs. ratio of max. and quiescent luminosity L_q of SXTs

Rapid Burster:
L_q=2.4x10^{33} erg/s
(0.7-12 keV; d=8 kpc)
ASCA observations (Asai et al. 96)

Rapid Burster: position consistent with NS SXTs: propeller effect not important; relatively weak magnetic field of NS – another support to Lewin et al. (96) that this field is weaker than in another type II burster GRO J1744–28.

Rapid Burster (RB) (MXB 1730-335) – remarkable LMXB in globular cluster Liller 1 (Liller 77)

Unique in displaying two types of X-ray bursts:

Type I – thermonuclear runaway of accreted matter on the neutron star (NS)

Type II – spasmodic accretion (e.g. Lewin et al. 93, 95; Spruit & Taam 93; Mahasena et al. 03). It is not clear what ingredients and system parameters are needed to produce type II bursts.

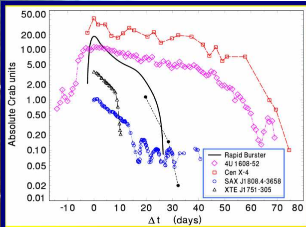
RB is distinguished from both `atoll' and `Z' sources (Rutledge et al. 95)

Recent outbursts in RB – similar to those in soft X-ray transients (SXTs), strong persistent emission, initially without type II bursts (Guerriero et al. 99; Masetti 02)

Outbursts of SXTs – thermal instability of accretion disk (e.g. Chen et al. 97; King & Ritter 98; Dubus et al. 01)

Subjects of our analysis focused on the group of intense outbursts:

- nature and physical processes in the disk
- comparison of the parameters of outbursts in the RB with a group of outbursts in SXTs (putting them into a system of outbursts)



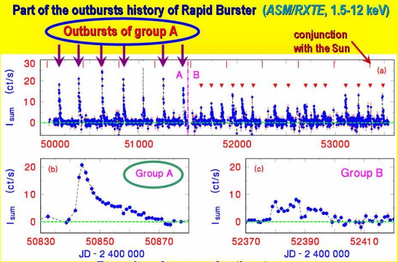
Outbursts with exponential decaying branches in neutron star (NS) SXTs

Smooth curve – fit to the mean profile of group A.
Closed circles – final decline of the 1998 outburst of the Rapid Burster (Masetti et al. 2000). Δt denotes the time interval with respect to the moment of the peak intensity. Intensities are in Absolute Crab Units (i.e. calculated for the distance of the source).

RESULTS

- We interpret the exponential decay of the group A outbursts as arising from irradiation of the disk by X-rays strong enough to keep all of the disk in the ionized state out to its outer edge without self-shadowing (using models by King & Ritter 98 and Truss et al. 02).
- Parameters of irradiation remained stable with a relatively high degree of consistency for all 6 events of group A, but they underwent a large and rapid change in 12 outbursts of subsequent group B.
- We argue that the observed change of the outburst profile (from the A to the B type) was due to a change of the conditions for the disk irradiation.

Part of the outbursts history of Rapid Burster (*ASM/RXTE*, 1.5-12 keV)



Examples of groups of outbursts.
Data are one-day means, connected by lines for convenience.

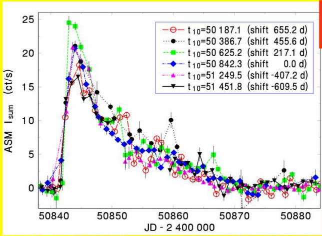
Neutron star SXTs and their outbursts with the exponential decaying branches

P_{orb} ...orbital period; LC...X-ray light curve; Max. I_{ACU} ...maximum intensity of outburst in Absolute Crab Units (intensity in Crabs recalculated for the distance and extinction); τ_d...decay time scale (e-folding time) of outburst.

System	P_{orb} (hr)	d (kpc)	Source of LC	Max. I_{ACU}	τ_d (day)	E range (keV)
Rapid Burster		8.0 [1]		18.4	8.2	1.5-12
4U1608-52	12.89 [2]	3.6 [3]	[4]	11.4	40	1.5-12
Cen X-4	15.1 [5]	1.2 [6]	[7]	42	38	3-12 [7]
SAX J1808-36	2.014 [8]	3.5 [9]	[10]	1.05	11.3	2-16 [10]
XTE J1751-305	0.71 [11]	(8.5) [12]	[10]	3.66	8.6	2-16 [10]

References:
1...Ortolani et al. (96); 2...Wachter et al. (02); 3...Nakamura et al. (89); 4...Simon (04); 5...Chevalier et al. (89); 6...Kaluzienski et al. (80); 7...Chen et al. (97); 8...Chakrabarty & Morgan (98); 9...Galloway & Cumming (06); 10...Wijnands (06); 11...Markwardt et al. (02); 12...Gierlinski & Poutanen (05).

- We observationally confirm the statement of the model by King & Ritter (98) that τ_d depends on P_{orb} – outbursts of SXTs with longer P_{orb} decay more slowly. We show that the luminosity on the exponential branch at a given moment elapsed from the moment of the peak light largely differs even for SXTs with similar P_{orb} (at least for ultra-compact SXTs) – this implies large differences in the irradiating sources.
- Vertical dimension of the irradiating source is smaller for the brighter outbursts: the decay profile changes from the exponential to a linear at a higher luminosity for the outbursts with higher peak luminosity L_{max}.
- Vertical dimension of the irradiating source, and hence its ability to irradiate the disk, decreases with the increasing luminosity of outbursts with exponential decays in NS SXTs of a comparable orbital period length (the transition from an exponential decay to the linear one occurs at a higher luminosity for the more luminous outbursts)–this dimension is exceptionally small in the Rapid Burster.

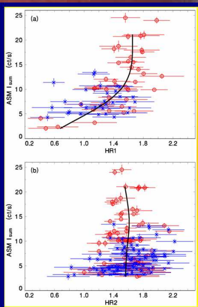


Outbursts of group A

Type FRED (fast rise, exponential decay)

Truncation limit of uncertainty I_{sum}, σ_q, was set at 2 ct/s.

Outbursts shifted along time axis to match the rising branch of the template at I_{sum} = 10 ct/s (i.e. t_{10}) (template: shift 0.0 d). t_{10} is given in JD – 2400000. Points are one-day means, connected by line for convenience.



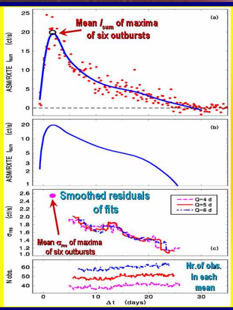
Spectral evolution during outbursts

Hardness ratios:
$HR1$=I_B(3-5 keV) / I_A(1.5-3 keV)
$HR2$=I_C(5-12 keV) / I_B(3-5 keV)

Dependence of HR1 and HR2 on the intensity in the Rapid Burster:
Open circles – group A
Crosses – group B
Smooth curve – HEC13 fits for group A
Group B data display no systematic shift in *HR* with respect to those of group A.

Truncation limit of uncertainty of *HR1* and *HR2*, σ_q, was set to be 2 ct/s.

- The group A outburst profiles indicate that the Rapid Burster is an ultra-compact system.
- The difference between the intensities and profiles of the group A and group B outbursts is not caused by a different absorption.
- We find a very stable mean X-ray spectrum in the 3-12 keV passband, with the profile almost identical for both groups for I_{sum} > 9 ct/s. Luminosity of group B gets close to the limit when the irradiation is too weak to keep the entire disk ionized.
- Evolution of the fluctuations of the outburst profile displays regularities not only inside each group, but also between both groups (both the rapid variability (time scale of a few days) and systematic changes of the decay rate of the individual outbursts contribute).



Merged light curves of group A

Folded light curves of 6 outbursts smoothed by code HEC13 (Vondrak 69, Vondrak 77; Harmanec).

Residuals were then smoothed by two-sided moving averages for the semi-interval width Q=5 days.

Systematics of group A outbursts:

- L_{max} of group A: ~0.53 L_{Edd} – typical for outb. of set of SXTs (NS, BH) of Chen et al. (97). Among about one third of the most luminous SXTs.
- Ratio of max. and quiescent luminosity: ~4x10^4 – typical for NS SXTs.
- rise time τ_r, decay time τ_d – the Rapid Burster is among SXTs with the fastest outbursts.
- Total energy radiated during outburst: E_{tot} ~ 7x10^{43} ergs (group A) – middle of range of outbursts in SXTs on logarithmic scale of E_{tot}.
- Parameters of group A fall into ensemble of outbursts in SXTs of Chen et al. (97); compatible with the thermal instability of the disk.

- The largest fluctuations occur at the outburst peak flux, which cannot be accounted for by a variable absorption caused by the accreting matter in the initial phases of the individual outbursts or its gradual decrease during outburst.
- We explain the fluctuations as the mass inflow rate onto the NS from the disk attaining the highest fluctuations at the outburst peak – it takes several days after the onset of outburst for the conditions for the irradiation of the disk to stabilize. The spiral arms do not reach the disk center at the moment of the outburst peak (Truss et al. 02), and hence they cannot cause the observed fluctuations at this outburst phase.
- We argue in favor of a relatively weak magnetic field of the NS in the Rapid Burster and against a significant role of the propeller effect.