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X-ray bursters

Course on Compact Objects
Niels Bohr Institute (KU)
29 May 2007

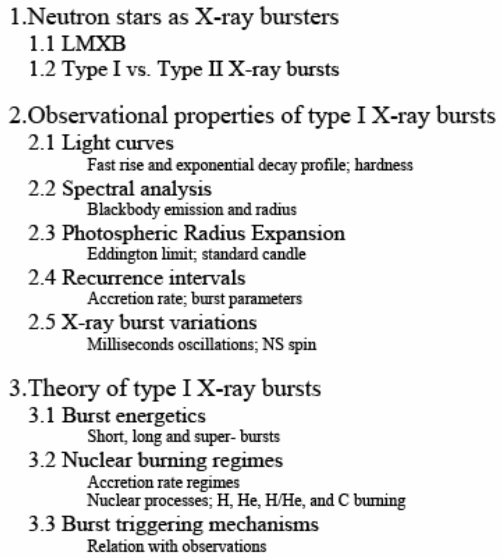
Jérôme Chenevez

OVERVIEW

INTRODUCTION

OBSERVATIONS

EXPLANATIONS



1. Neutron stars as X-ray bursters
   - 1.1 LMXB
   - 1.2 Type I vs. Type II X-ray bursts
2. Observational properties of type I X-ray bursts
   - 2.1 Light curves
     - Fast rise and exponential decay profile; hardness
   - 2.2 Spectral analysis
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   - 3.2 Nuclear burning regimes
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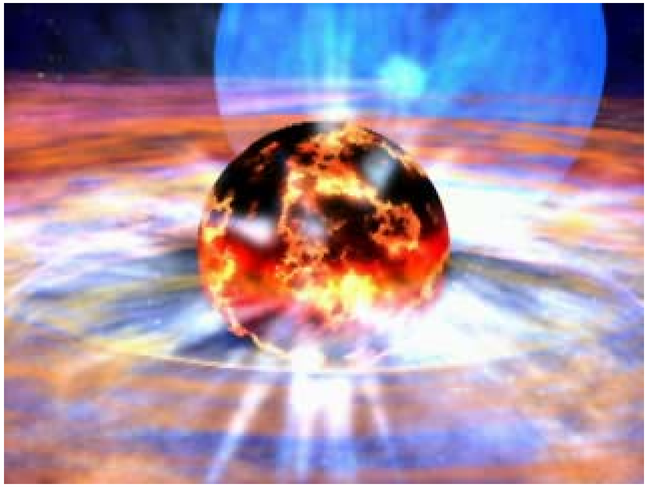
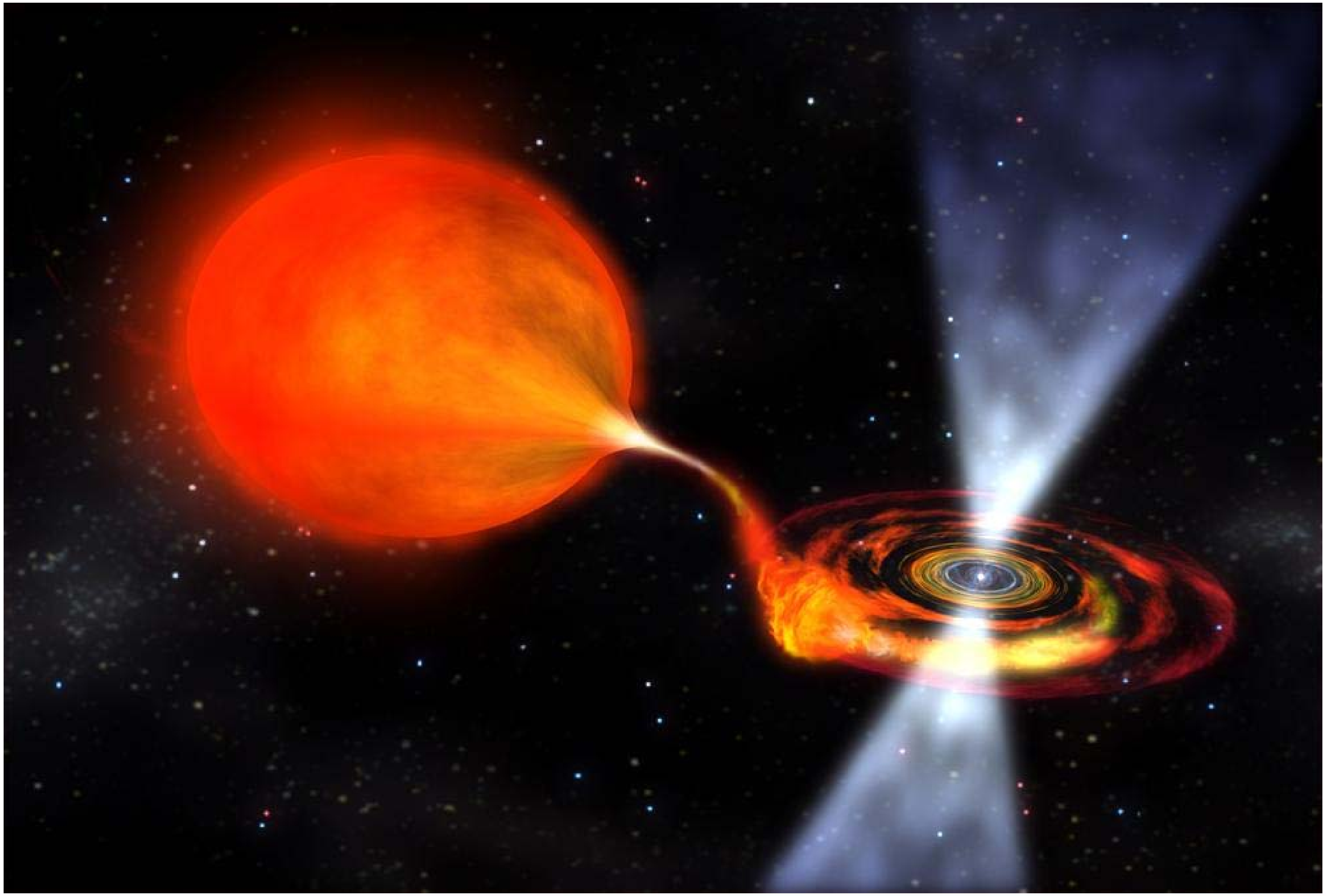
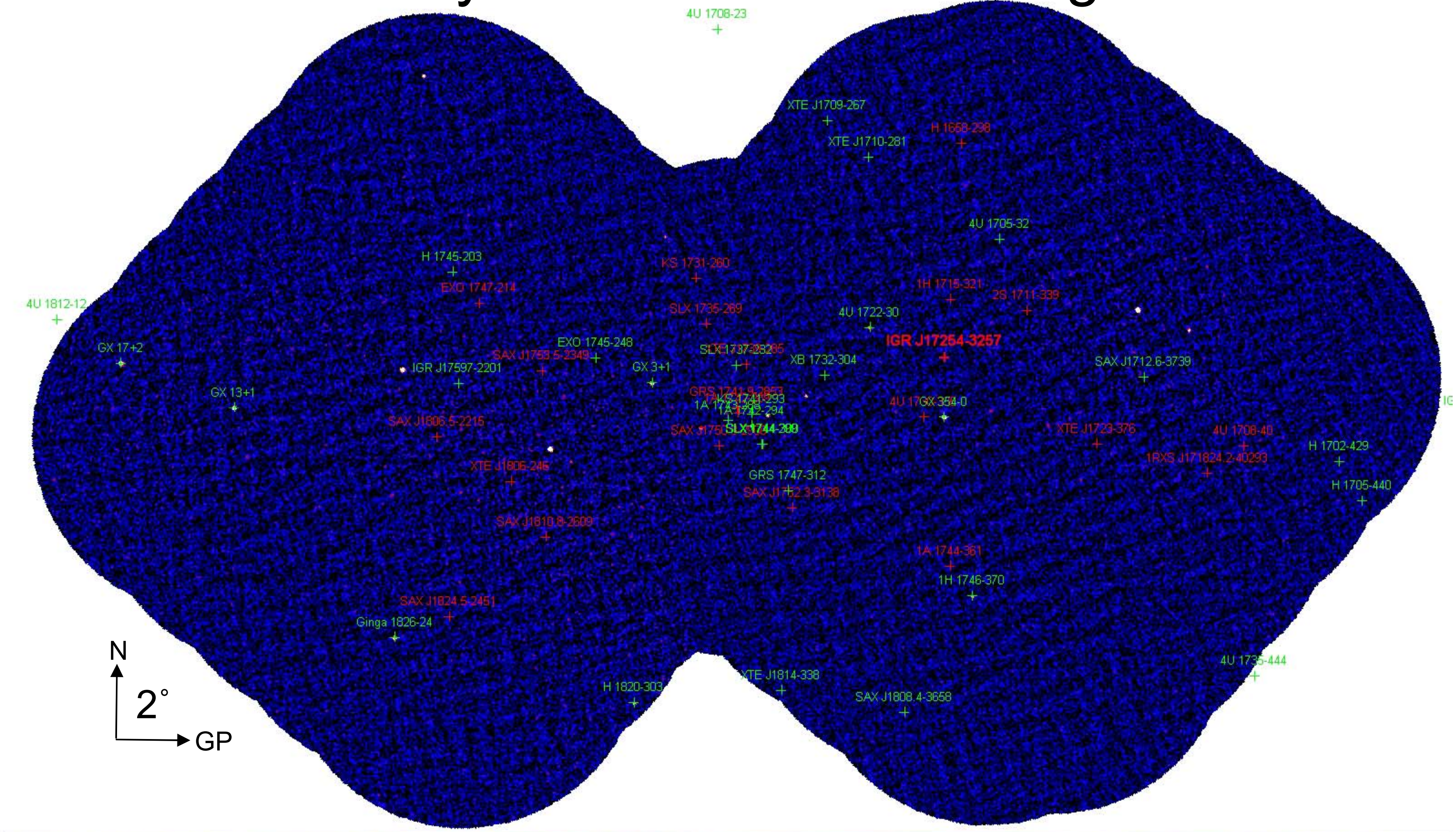
     - Relation with observations



X-ray binaries



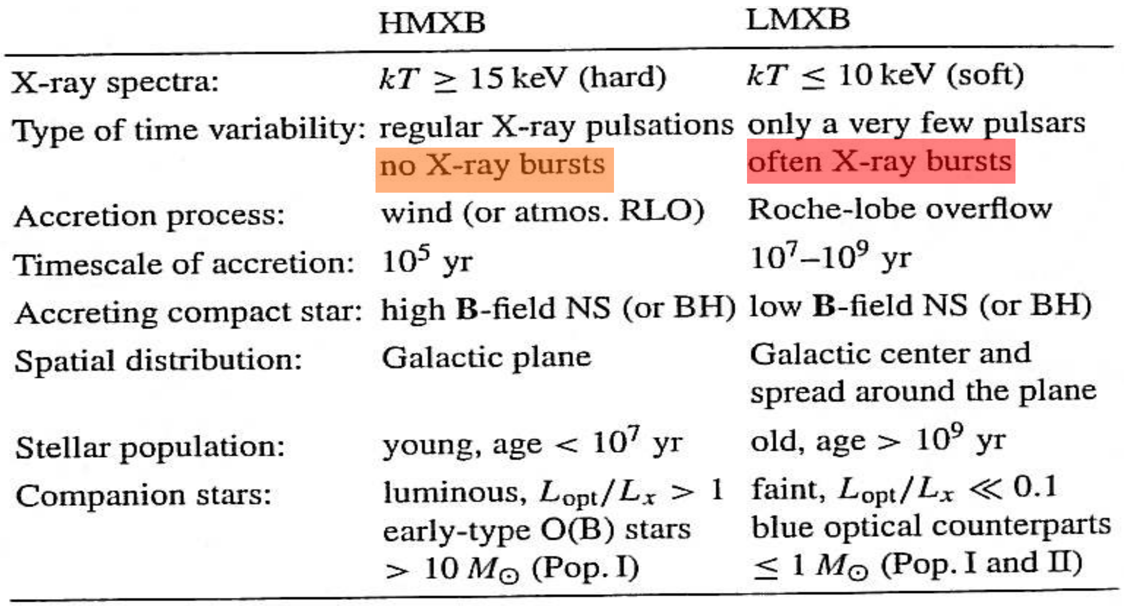
X-ray binaries in the GC region



84 type I X-ray bursters known to date; ~2/3 located in the Galactic Bulge

Classification after the mass of the companion

Characteristics

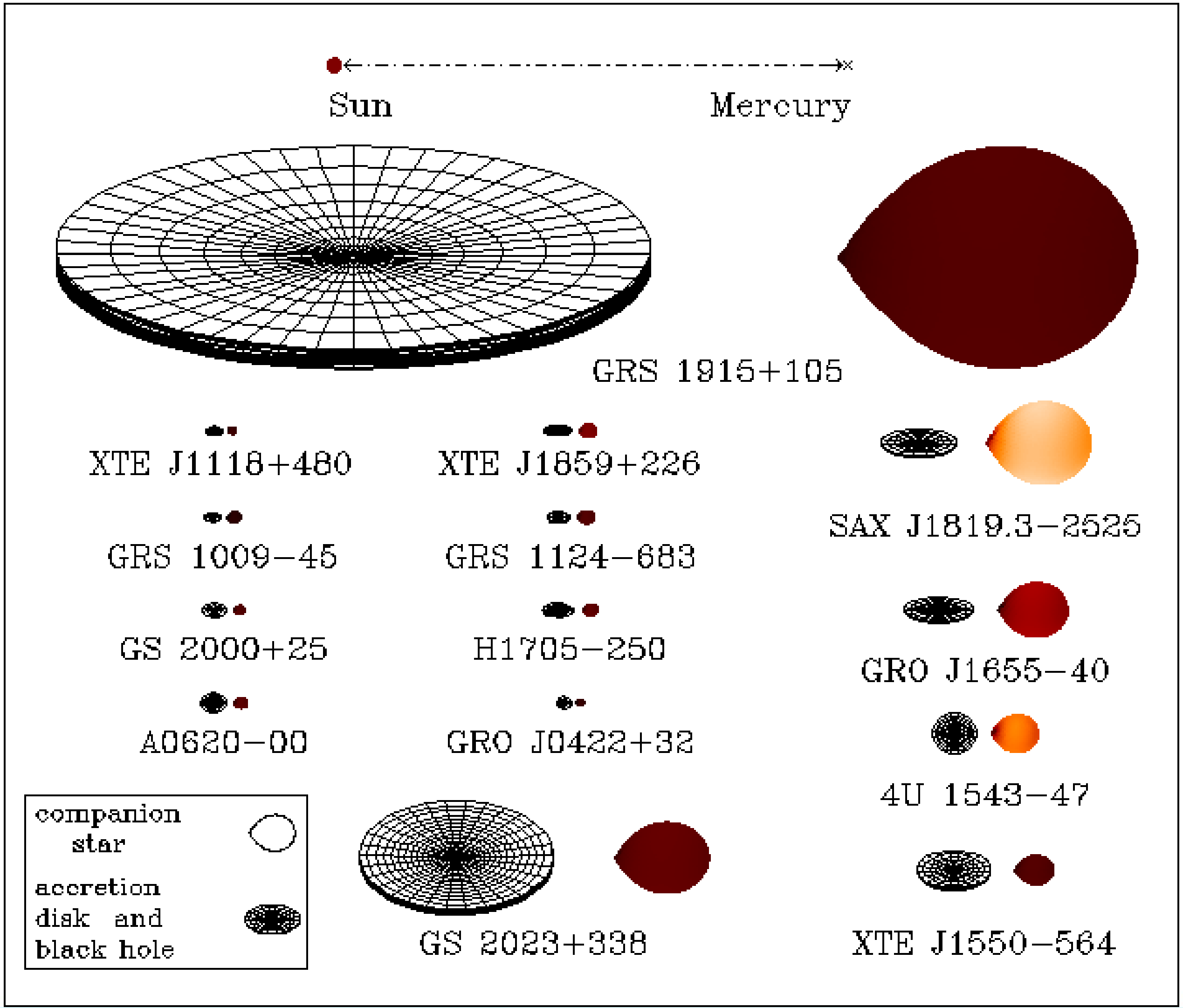


	HMXB	LMXB
X-ray spectra:	$kT \geq 15$ keV (hard)	$kT \leq 10$ keV (soft)
Type of time variability:	regular X-ray pulsations no X-ray bursts	only a very few pulsars often X-ray bursts
Accretion process:	wind (or atmos. RLO)	Roche-lobe overflow
Timescale of accretion:	10^5 yr	10^7–10^9 yr
Accreting compact star:	high **B**-field NS (or BH)	low **B**-field NS (or BH)
Spatial distribution:	Galactic plane	Galactic center and spread around the plane
Stellar population:	young, age $< 10^7$ yr	old, age $> 10^9$ yr
Companion stars:	luminous, $L_{\rm opt}/L_x > 1$ early-type O(B) stars $> 10\, M_\odot$ (Pop. I)	faint, $L_{\rm opt}/L_x \ll 0.1$ blue optical counterparts $\leq 1\, M_\odot$ (Pop. I and II)

$M_{Comp} > M_{CO}$ $M_{Comp} < M_{CO}$

IMXB: Intermediate-Mass X-ray Binaries (M_{comp} 1-10 $M_\odot$)

Black Holes have no surface ⇒ no X-ray bursts!



X-ray bursters

RXTE Puffed Accretion Disk
Version 2 with NO Wobble

Animation by
Dana Berry
SkyWorks Digital Animation
310-441-1735

Type I X-ray bursts are thermonuclear explosions in the surface layers of a neutron star accreting H and/or He from the envelope of a companion star. Their emission is described by blackbody radiation with peak temperature ~2 keV and X-ray softening during the decay.

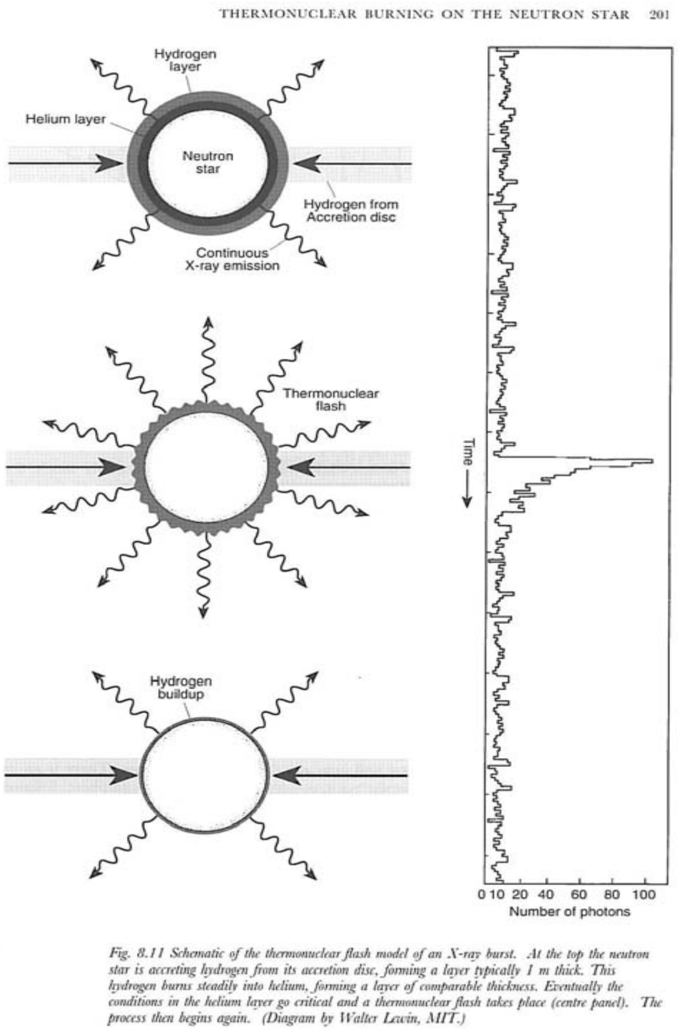


Fig. 8.11 Schematic of the thermonuclear flash model of an X-ray burst. At the top the neutron star is accreting hydrogen from its accretion disc, forming a layer typically 1 m thick. This hydrogen burns steadily into helium, forming a layer of comparable thickness. Eventually the conditions in the helium layer go critical and a thermonuclear flash takes place (centre panel). The process then begins again. (Diagram by Walter Lewin, MIT.)

TYPE I

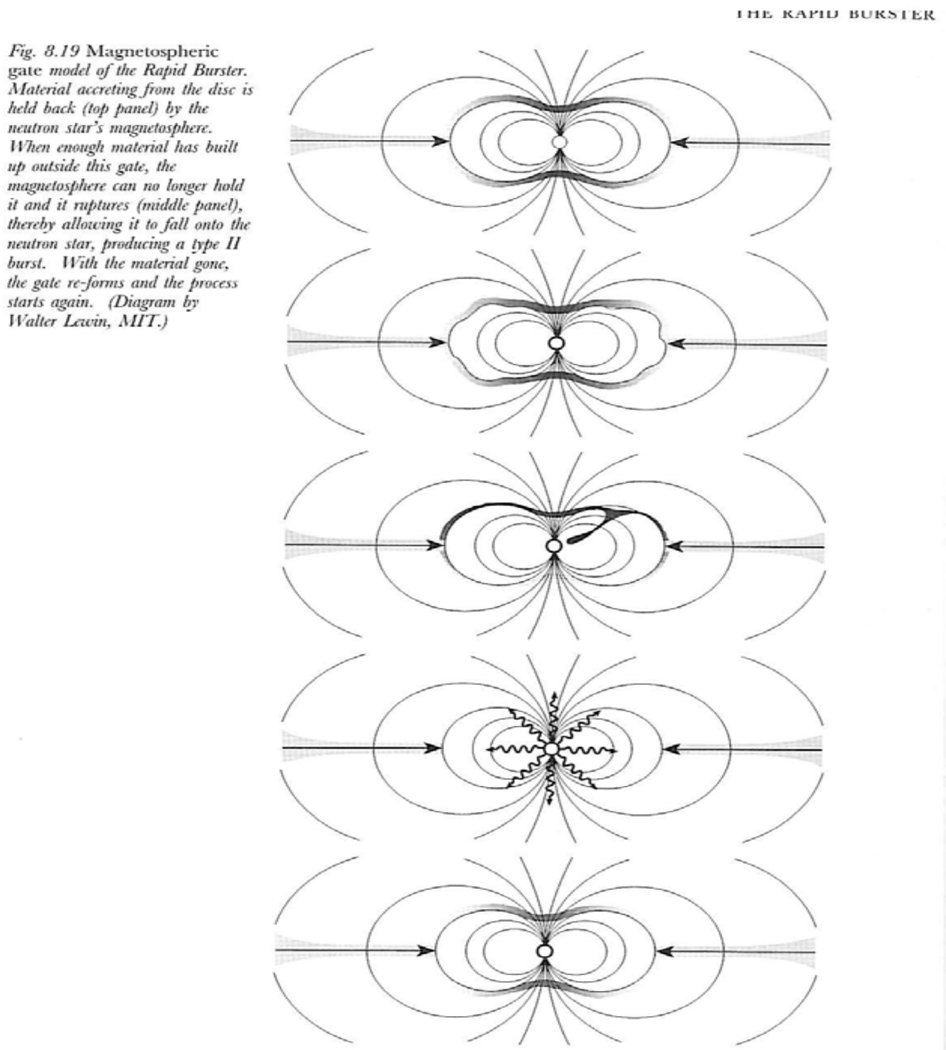
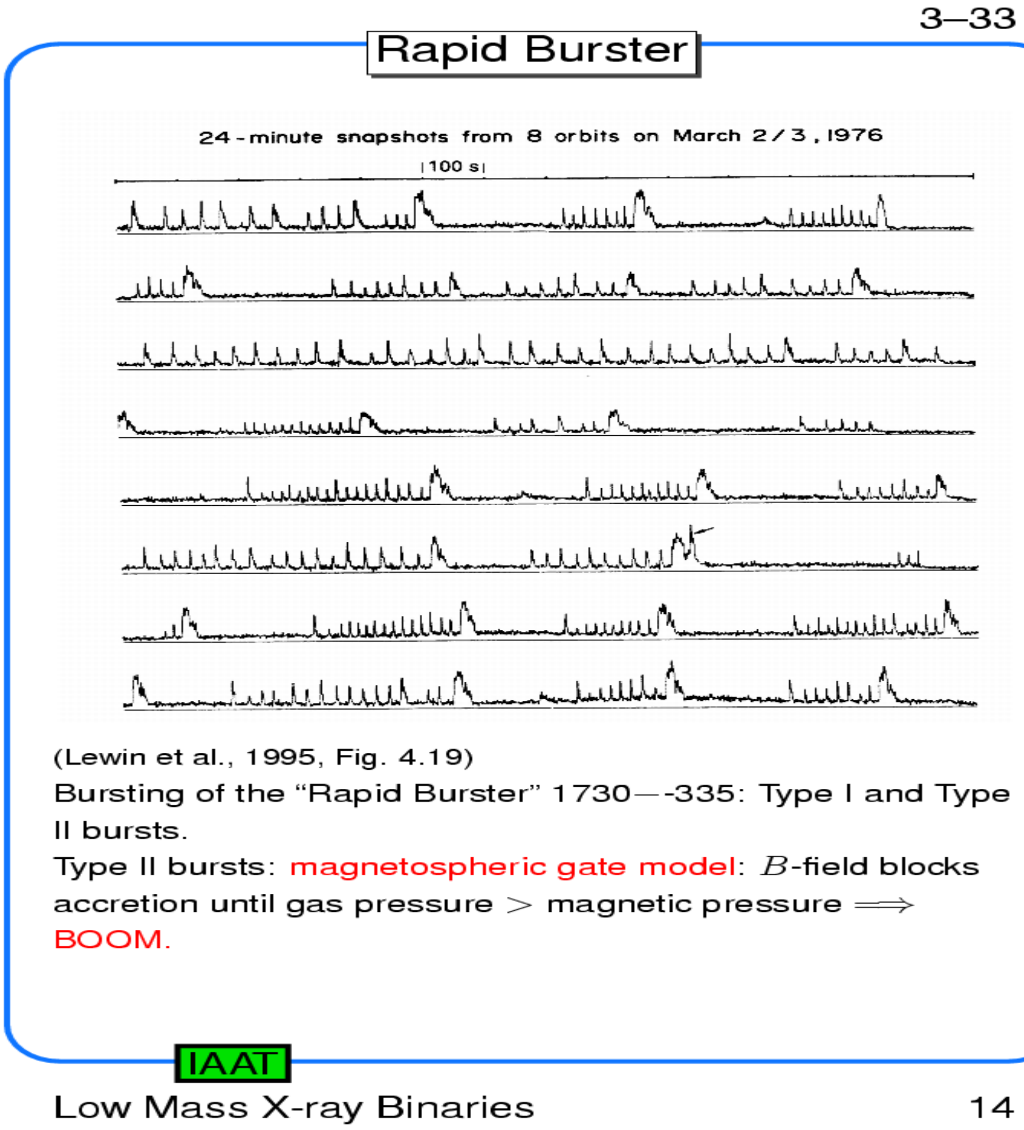


Fig. 8.19 Magnetospheric gate *model of the Rapid Burster. Material accreting from the disc is held back (top panel) by the neutron star's magnetosphere. When enough material has built up outside this gate, the magnetosphere can no longer hold it and it ruptures (middle panel), thereby allowing it to fall onto the neutron star, producing a type II burst. With the material gone, the gate re-forms and the process starts again. (Diagram by Walter Lewin, MIT.)*

TYPE II

Only 2 Type II X-ray bursters known so far:
MXB 1730-335 (Rapid Burster) and the Bursting Pulsar
GRO J1744-28 (no type I).



3–33

Rapid Burster

(Lewin et al., 1995, Fig. 4.19)

Bursting of the “Rapid Burster” 1730—-335: Type I and Type II bursts.

Type II bursts: magnetospheric gate model: B-field blocks accretion until gas pressure $>$ magnetic pressure $\Longrightarrow$ BOOM.

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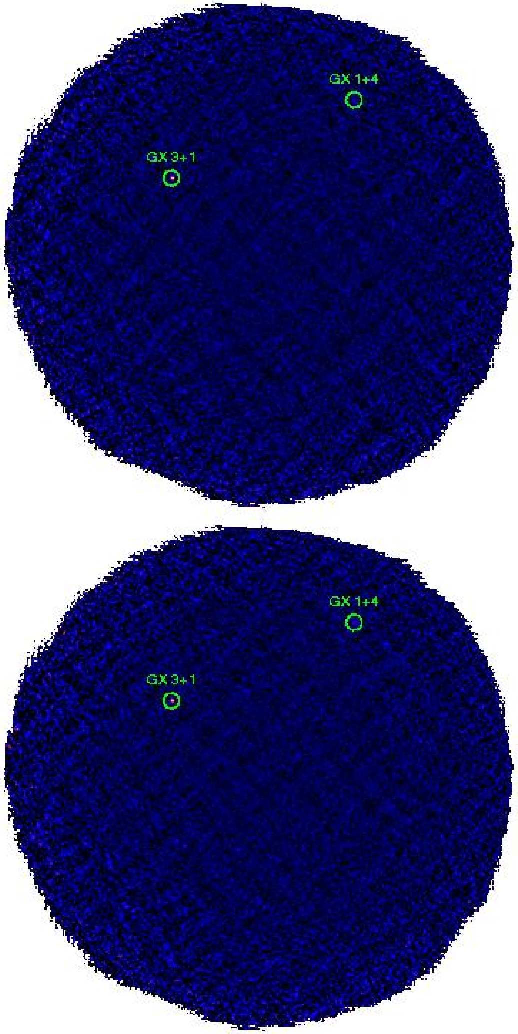
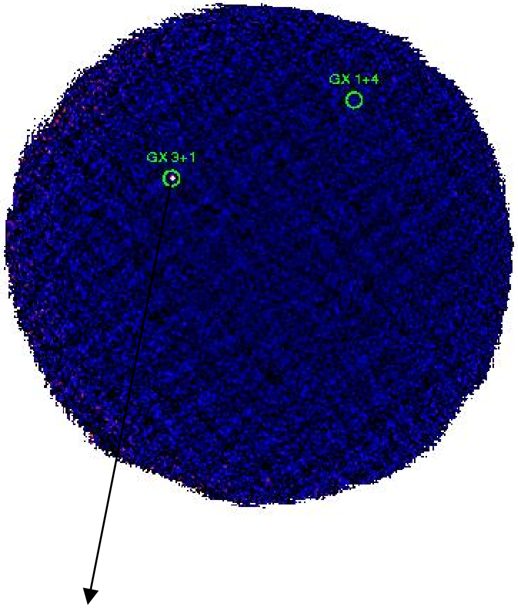
Low Mass X-ray Binaries 14

OBSERVATIONS

Example 1: X-ray burst detection in JEM-X images

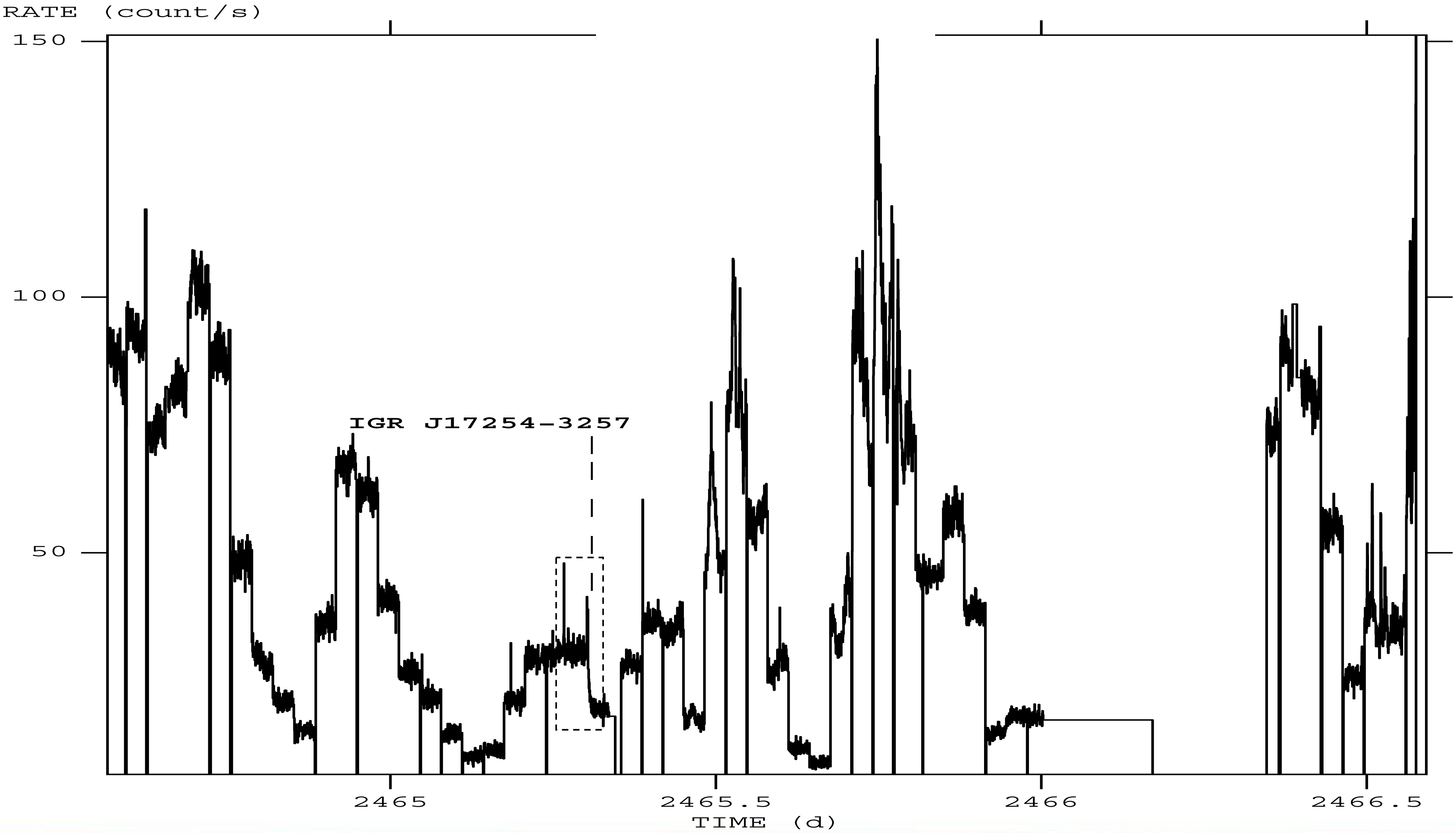


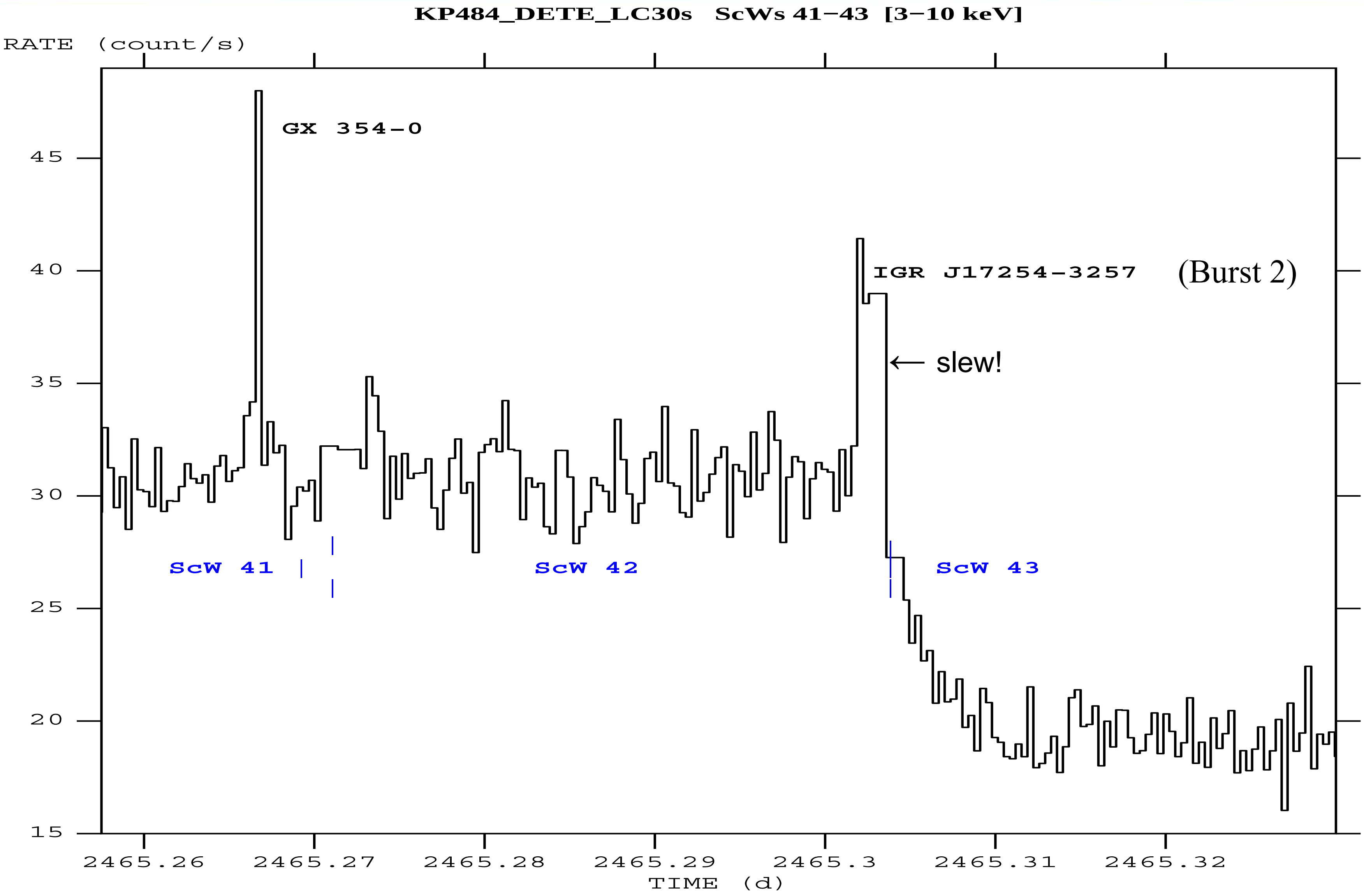


GX3+1 XrB 20040831 (ScW 0230009)

400s exposure 3-10 keV

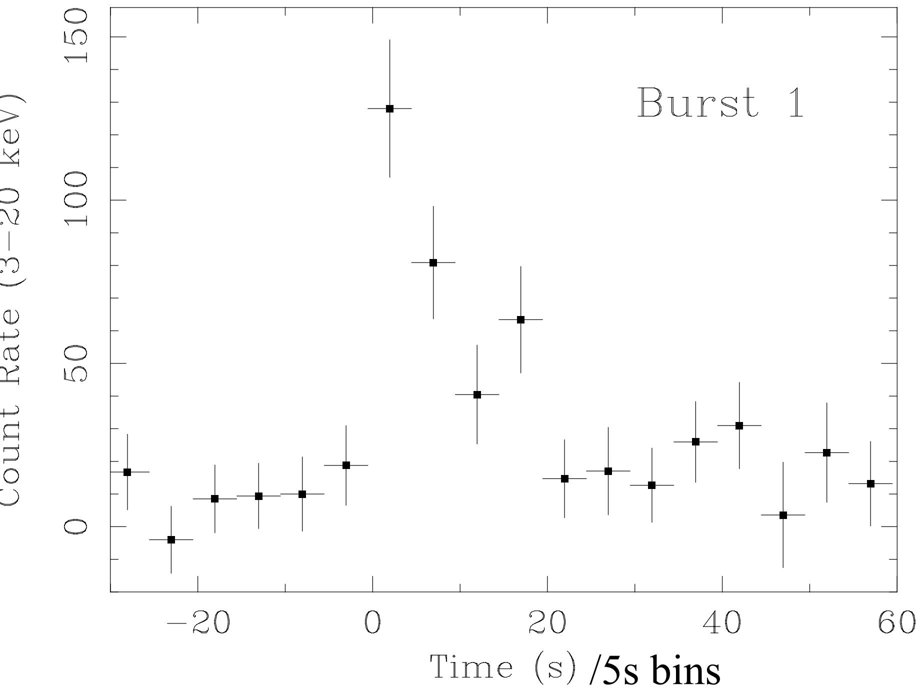
Example 2: JEM-X detector light curve (30s bins)




KP484_DETE_LC30s ScWs 41−43 [3−10 keV]
RATE (count/s)
45
40
35
30
25
20
15
GX 354−0
IGR J17254−3257
(Burst 2)
← slew!
ScW 41
ScW 42
ScW 43
2465.26
2465.27
2465.28
2465.29
2465.3
2465.31
2465.32
TIME (d)

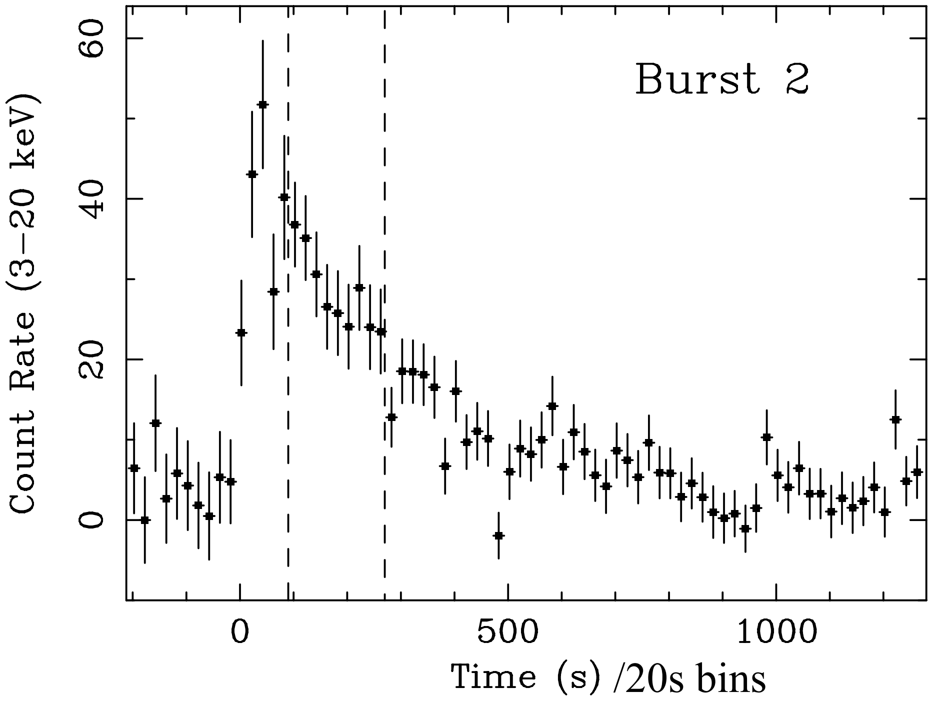
IGR J17254-3257 X-ray burst light curves

Short burst



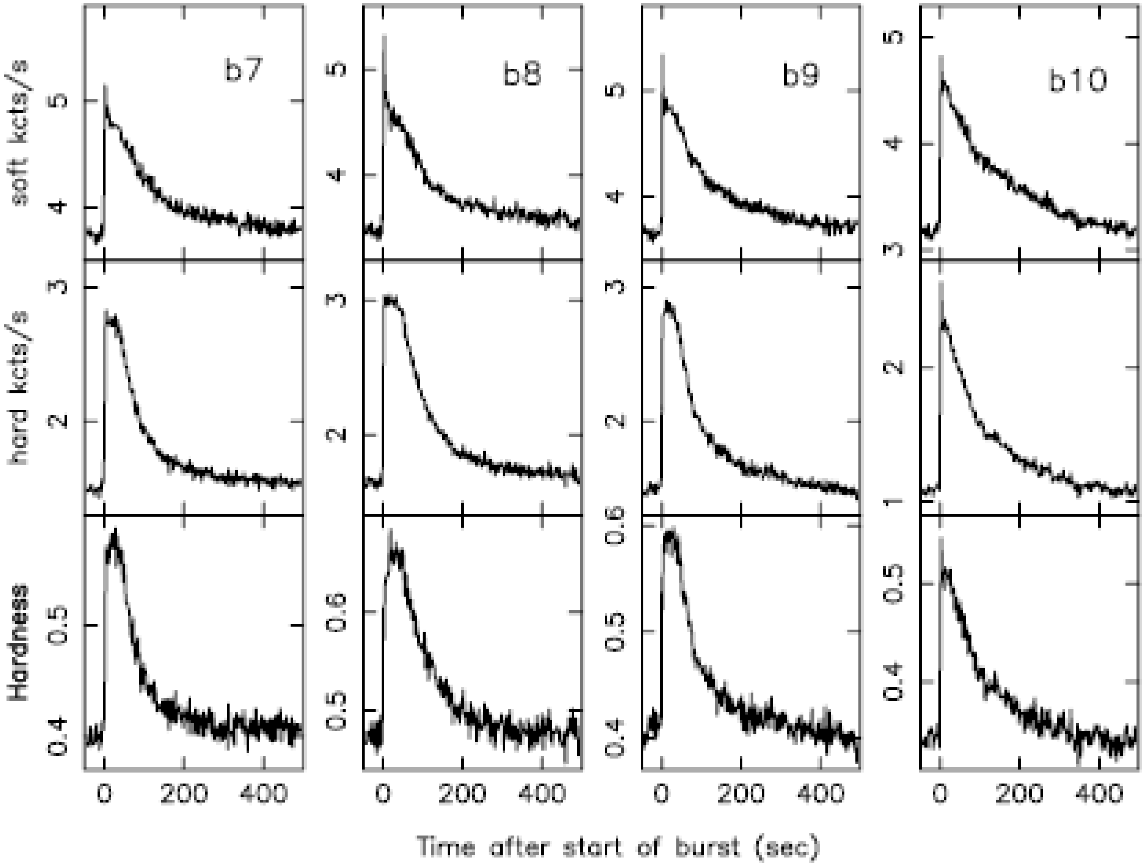
17 February 2004

Long burst



1 October 2006

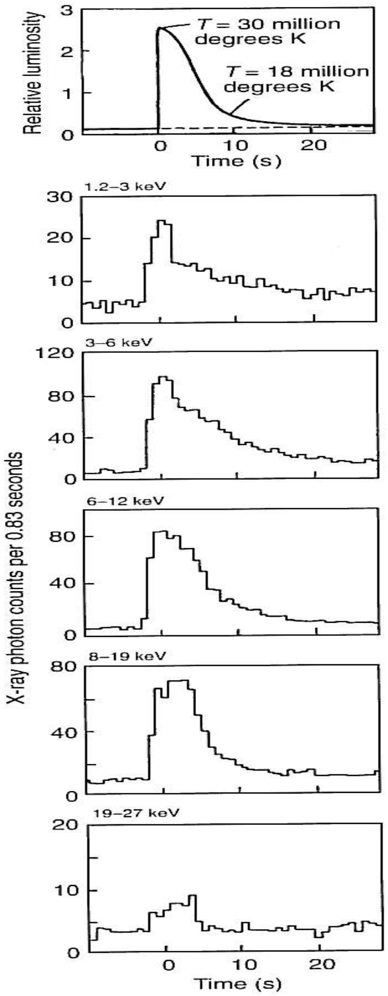
Light curves and hardness profiles



GX 17+2 (Kuulkers et al., 2002)

Hardness = hard flux / soft flux

Fig. 8.9 X-ray burst profiles observed by SAS-3 in different energy bands from MXB1728–34. Note how in the lowest energies the burst persists for much longer (it has a tail), which does not happen at higher energies. This is because the radiating material cools significantly during the burst, as indicated in the theoretical burst profile shown at top. (Original diagram by Walter Lewin, MIT.)



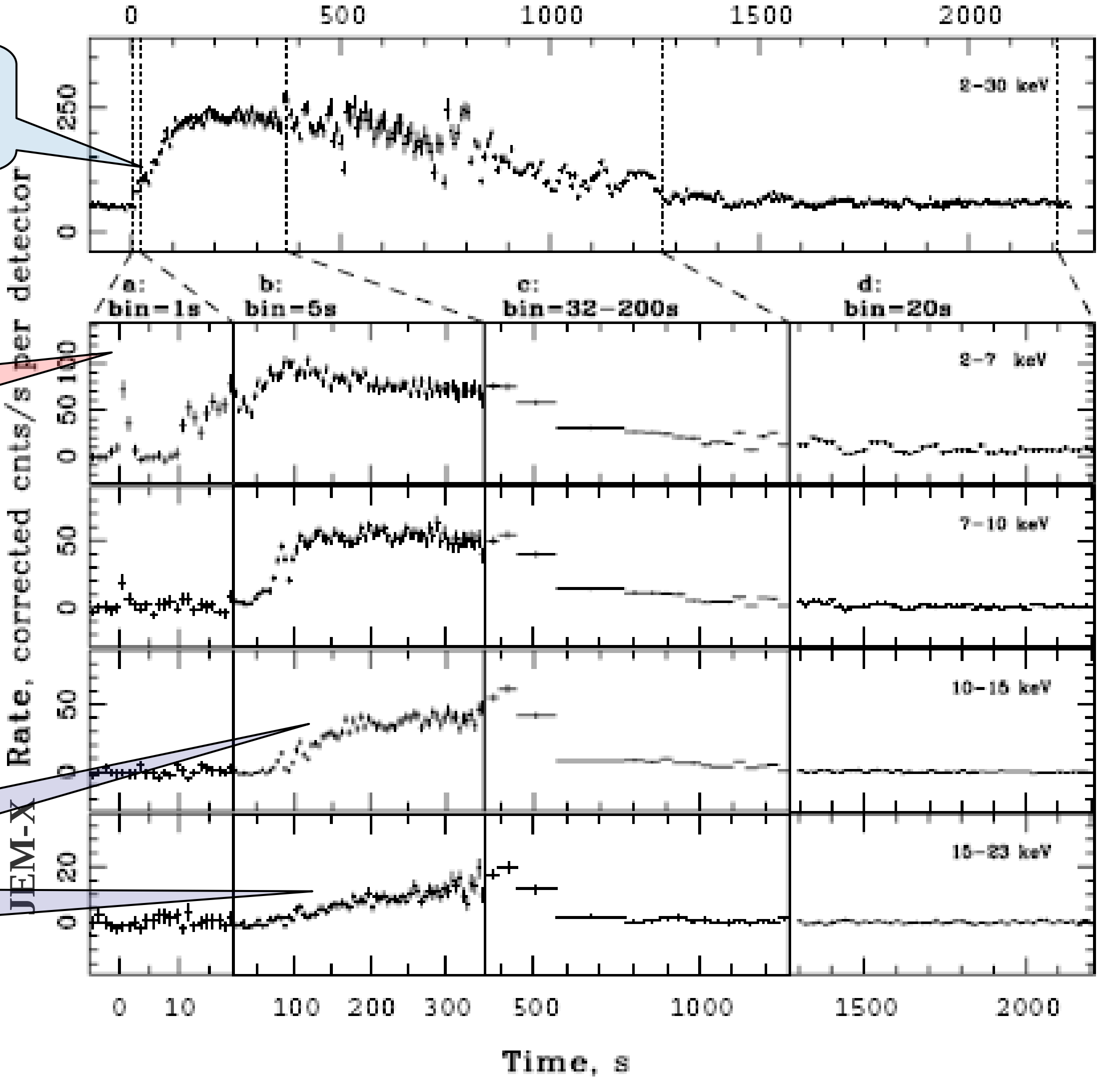
Shorter tails at harder energies:
Softening

Exponential decay (e-folding time: τ)
due to thermal conduction (Newton's law)
$\Rightarrow$ Cooling

Fluence: $E_b = \int_0^T F_{bol}(t)\,dt$

$\Rightarrow E_b = F_p \times \tau\left(1 - e^{-T/\tau}\right)$ (bolometric)

S. Molkov et al.: INTEGRAL detection of a long powerful burst from SLX 1735-269 (2005)



Long rise

Soft precursor

Very soft emission (UV)
due to cooling
caused by large radius expansion
followed by contraction.

Progressive hardening

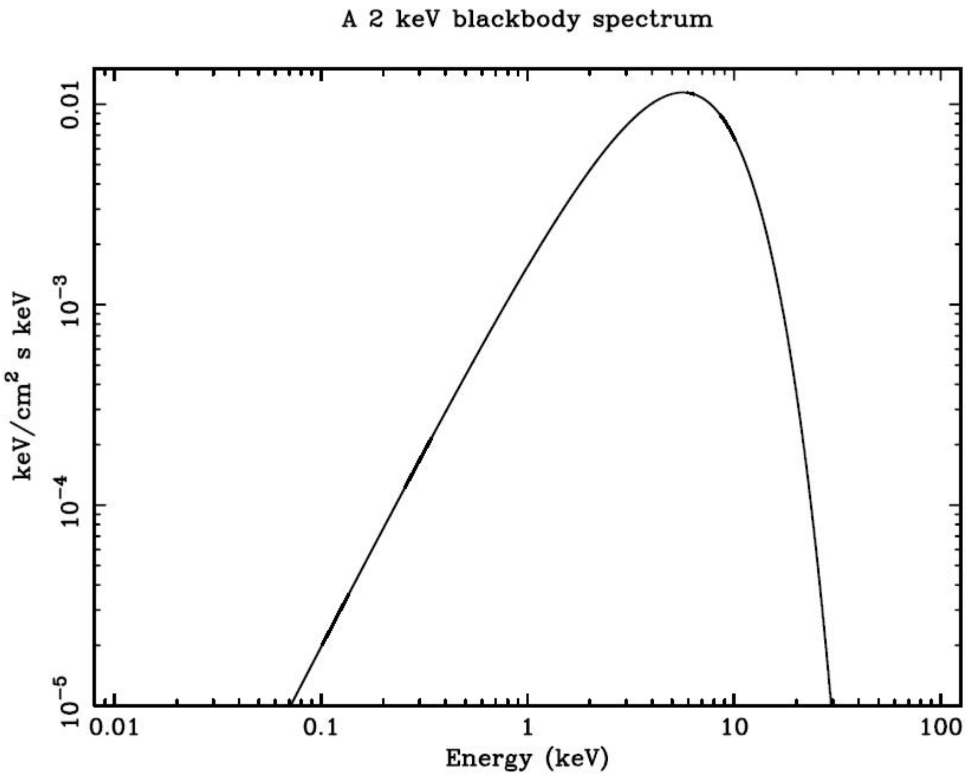
Investigation method

Time resolved spectral analysis

- Standard method: modelling of the net burst emission by blackbody (BB)
- 2-component method: modelling of the total burst emission by BB+PL
  (PL is fixed by pre-burst persistent emission)

Blackbody radiation

Type I X-ray bursts are characterized by a ≈2 keV (T ≈ 25·10^6 K) blackbody emission and exponential decay with cooling.



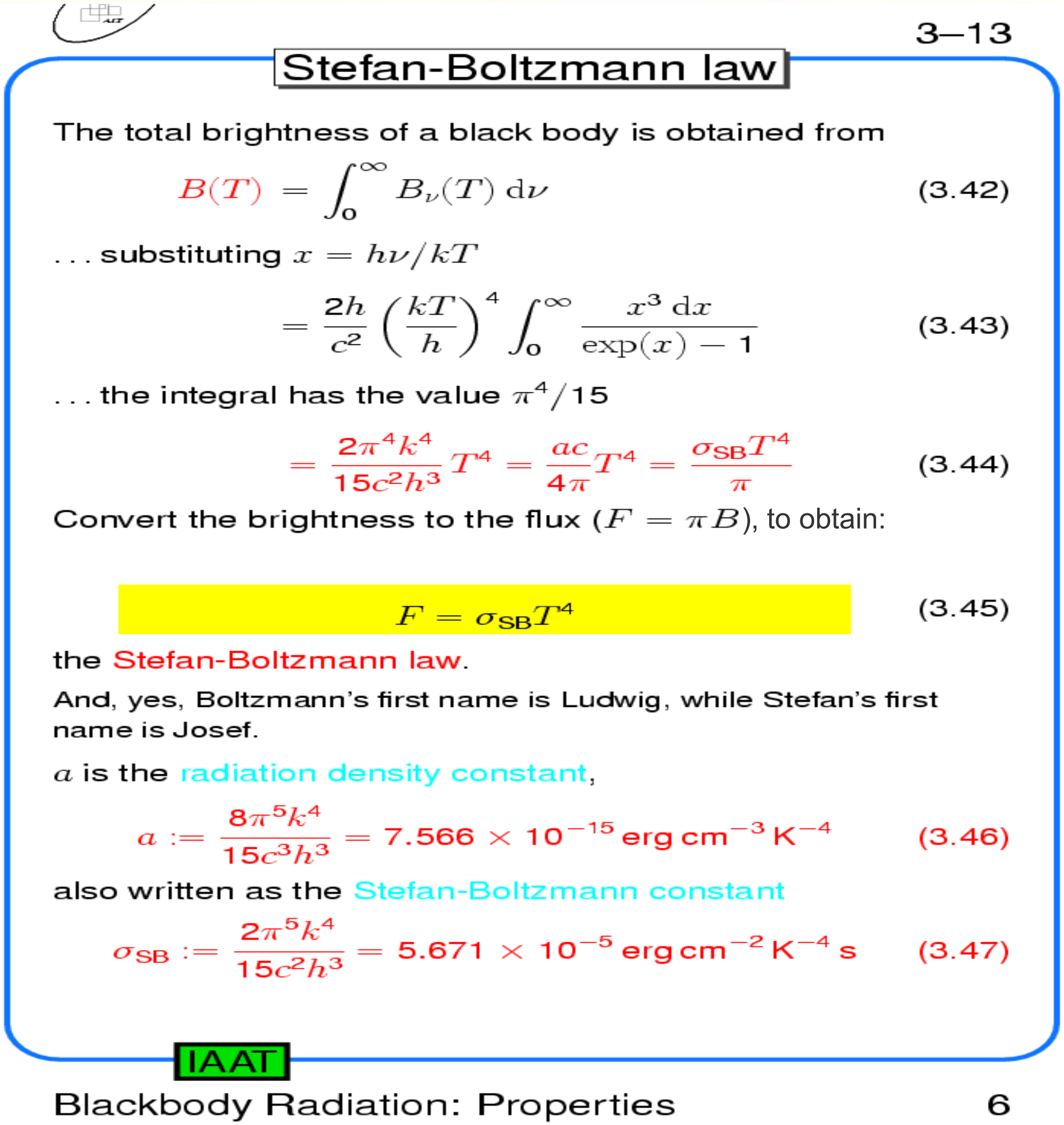
Spectral intensity ≡ Planck Function:

$$I_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$

Wien displacement law: $h\nu_{\mathrm{Max}} = 2.82\,kT$

⇓

Maximum burst emission (5-6 keV) in JEM-X



Stefan-Boltzmann law

The total brightness of a black body is obtained from

$$B(T) = \int_0^\infty B_\nu(T)\,\mathrm{d}\nu \qquad (3.42)$$

. . . substituting $x = h\nu/kT$

$$= \frac{2h}{c^2}\left(\frac{kT}{h}\right)^4 \int_0^\infty \frac{x^3\,\mathrm{d}x}{\exp(x)-1} \qquad (3.43)$$

. . . the integral has the value $\pi^4/15$

$$= \frac{2\pi^4 k^4}{15c^2h^3}T^4 = \frac{ac}{4\pi}T^4 = \frac{\sigma_{\mathrm{SB}}T^4}{\pi} \qquad (3.44)$$

Convert the brightness to the flux ($F = \pi B$), to obtain:

$$F = \sigma_{\mathrm{SB}}T^4 \qquad (3.45)$$

the Stefan-Boltzmann law.

And, yes, Boltzmann's first name is Ludwig, while Stefan's first name is Josef.

a is the radiation density constant,

$$a := \frac{8\pi^5k^4}{15c^3h^3} = 7.566 \times 10^{-15}\,\mathrm{erg\,cm^{-3}\,K^{-4}} \qquad (3.46)$$

also written as the Stefan-Boltzmann constant

$$\sigma_{\mathrm{SB}} := \frac{2\pi^5k^4}{15c^2h^3} = 5.671 \times 10^{-5}\,\mathrm{erg\,cm^{-2}\,K^{-4}\,s} \qquad (3.47)$$

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Blackbody emission from a neutron star

Flux conservation: L = Φ

$$\Leftrightarrow 4\pi R_{BB}^{2}\,\sigma\,T_{eff}^{4} = 4\pi\,d^{2}F_{BB}$$ (Stefan's law)

$$\Leftrightarrow R_{BB} = \frac{d}{T_{eff}^{2}}\sqrt{\frac{F_{BB}}{\sigma}}$$

Caveats:

Burst emission is assumed isotropic (ξ=1)

Gravitational redshift effects $\begin{cases} L = L_{\infty}(1+z)^{2} \\ T = T_{\infty}(1+z) \\ R = R_{\infty}(1+z)^{-1} \end{cases}$

What is actually observed is a "colour temperature"…

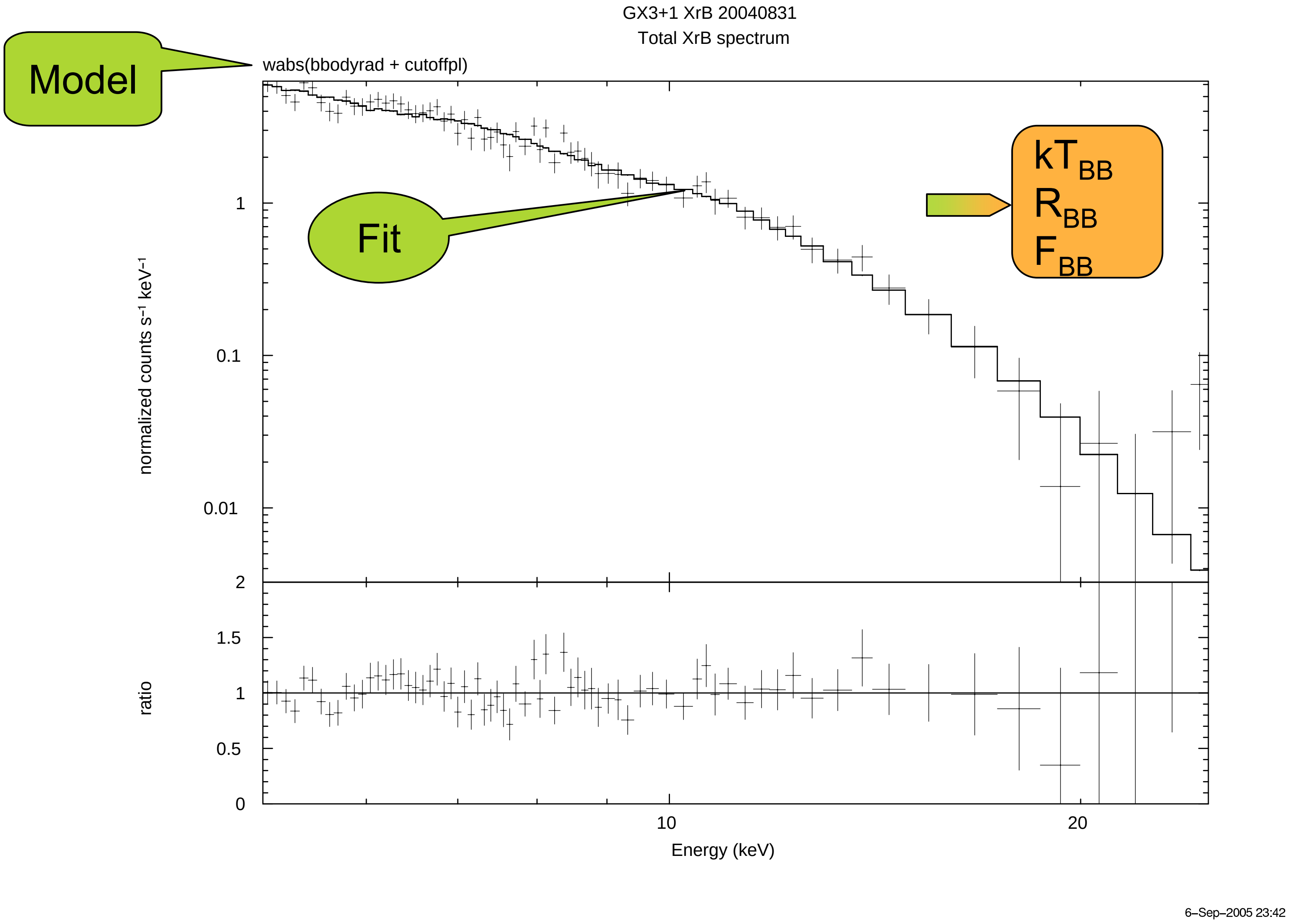
Deviations from blackbody emission of hot neutron stars ($kT > kT_{Edd} \approx 2.4$ keV)

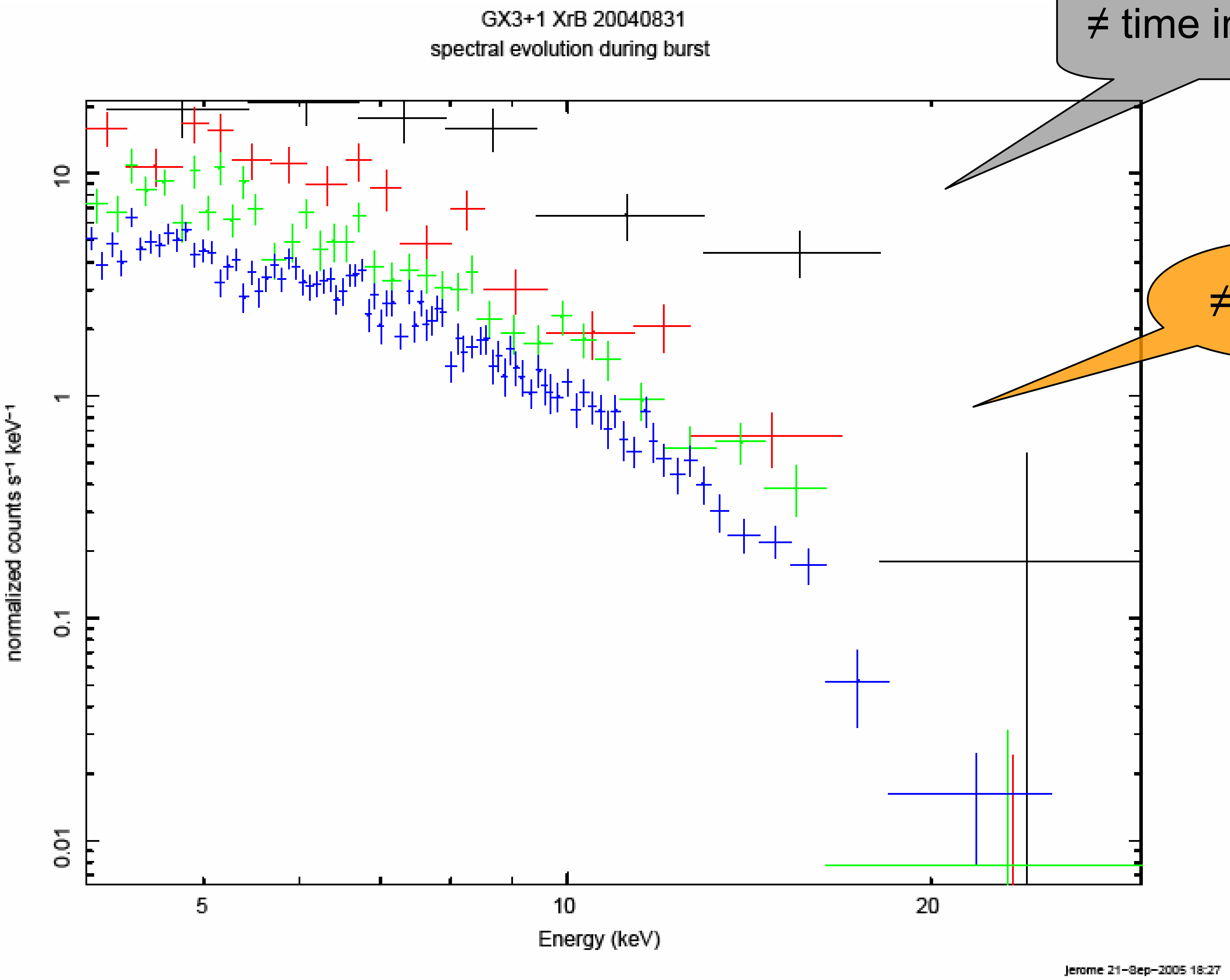
- Nakamura et al., 1989:
  High energy tail due to comptonization of photons in a hot plasma around NS

- Lewin et al., Space Sci. Rev. 62 (1993):
  Modification of BB emission by electron scattering in the atmosphere of NS

► $T_{col} \approx 1.5\ T_{eff} \Rightarrow$ R understimated by factor ≈ 2

- Strohmayer & Brown, ApJ 566 (2002):
  Reflection from accretion disk of 4U 1820-30
  [suggested by Day & Dove, MNRAS 253 (1991)]


GX3+1 XrB 20040831
Total XrB spectrum
wabs(bbodyrad + cutoffpl)
Model
Fit
kT_BB
R_BB
F_BB
normalized counts s⁻¹ keV⁻¹
1
0.1
0.01
2
1.5
1
0.5
0
ratio
10
20
Energy (keV)
6–Sep–2005 23:42

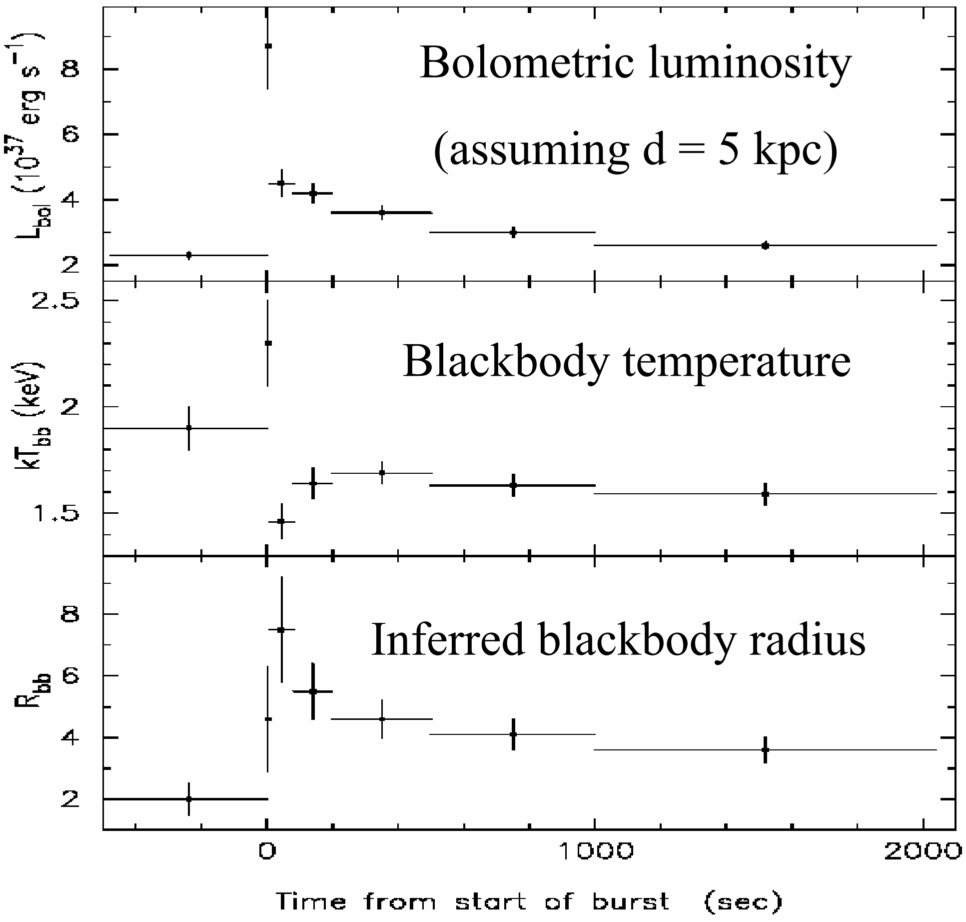


≠ time intervals

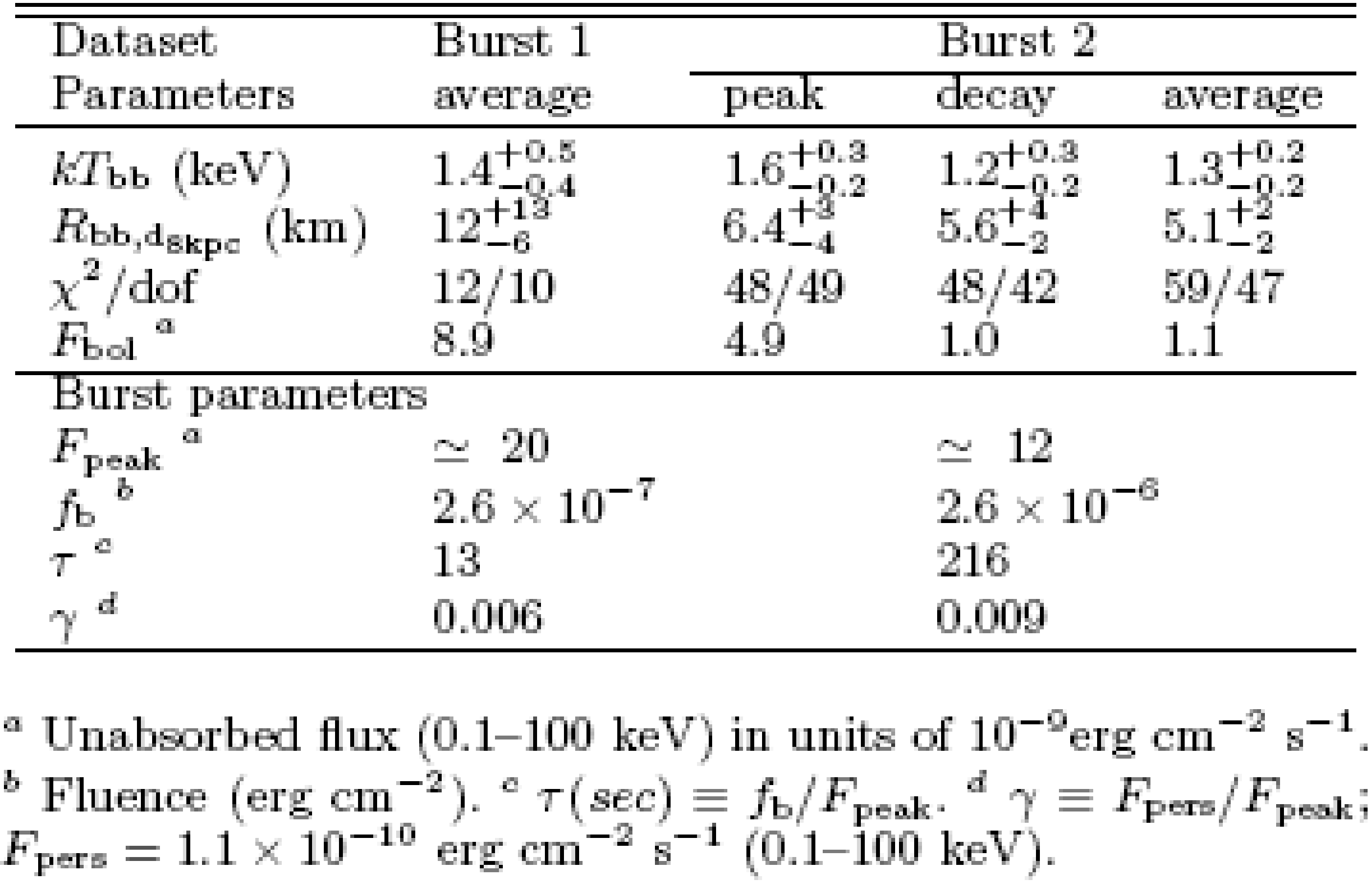
≠ kT_{BB}…

Results (Example 1)

The time resolved spectral analysis of GX 3+1 long X-ray burst reveals variations in the temperature and inferred blackbody radius which indicate expansion and contraction of the emission region.



Example 2: IGR J17254-3257 X-ray burst spectral analysis



Dataset	Burst 1	Burst 2		
Parameters	average	peak	decay	average
kT_{bb} (keV)	$1.4^{+0.5}_{-0.4}$	$1.6^{+0.3}_{-0.2}$	$1.2^{+0.3}_{-0.2}$	$1.3^{+0.2}_{-0.2}$
$R_{\mathrm{bb,d_{8kpc}}}$ (km)	12^{+13}_{-6}	6.4^{+3}_{-4}	5.6^{+4}_{-2}	5.1^{+2}_{-2}
χ^2/dof	12/10	48/49	48/42	59/47
F_{bol} [a]	8.9	4.9	1.0	1.1
Burst parameters				
F_{peak} [a]	$\simeq$ 20		$\simeq$ 12	
f_{b} [b]	2.6×10^{-7}		2.6×10^{-6}	
τ [c]	13		216	
γ [d]	0.006		0.009	

[a] Unabsorbed flux (0.1–100 keV) in units of 10^{-9}erg cm^{-2} s^{-1}.
[b] Fluence (erg cm^{-2}). [c] $\tau(sec) \equiv f_{\mathrm{b}}/F_{\mathrm{peak}}$. [d] $\gamma \equiv F_{\mathrm{pers}}/F_{\mathrm{peak}}$; $F_{\mathrm{pers}} = 1.1 \times 10^{-10}$ erg cm^{-2} s^{-1} (0.1–100 keV).

Photospheric Radius Expansion

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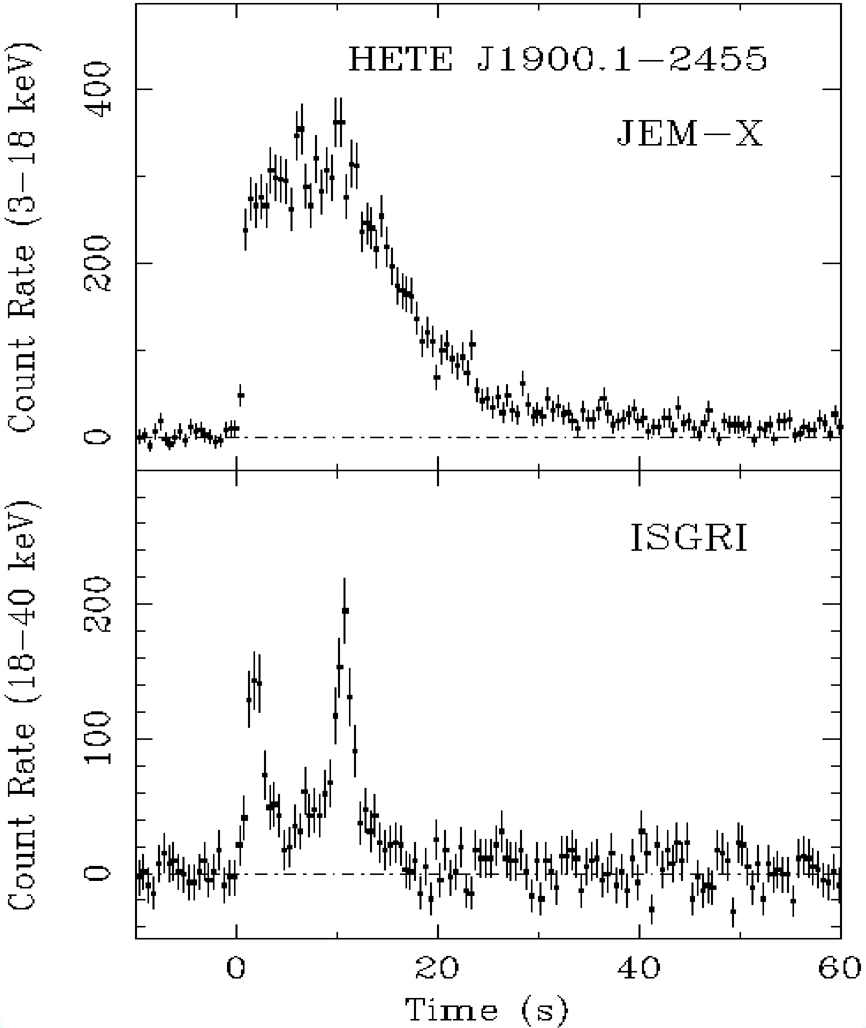
Radius expansion burst from GX 354-0 observed by INTEGRAL (Falanga et al., 2006)



Radius expansion burst from GX 3+1 (Kuulkers & van der Klis, 2000)

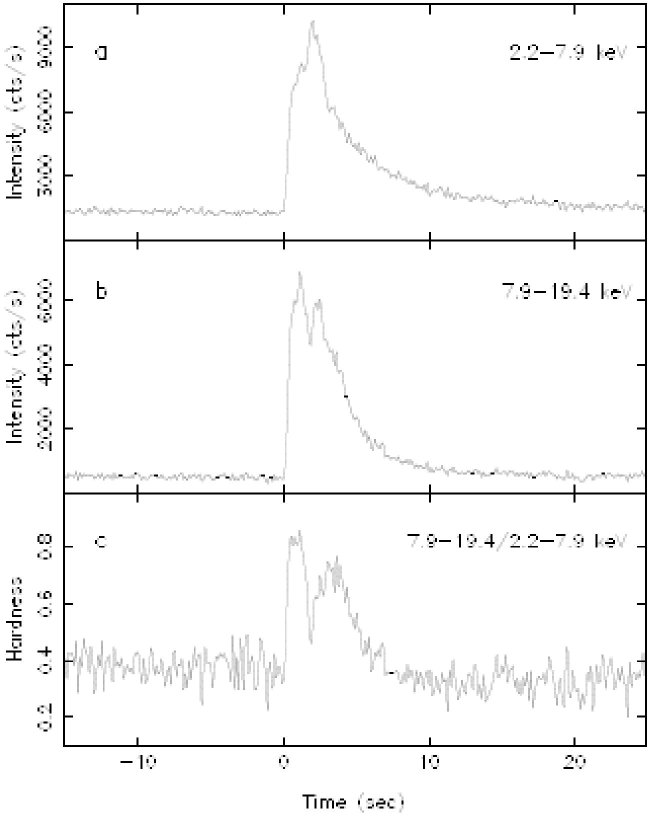


Fig. 2. The X-ray burst light curve at low (a.) and high (b.) energies and the corresponding hardness curve (c.), all at a time resolution of 0.125 sec. T=0 s corresponds to 1999 August 10, 18:35:53.5 UTC.

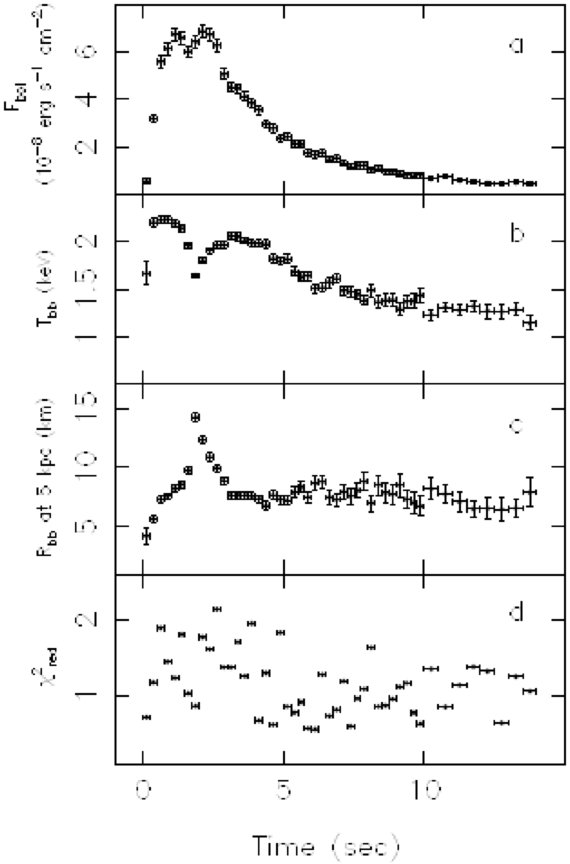


Fig. 3. Spectral fit results during the burst: (a) bolometric black-body flux, $F_{\rm bol}$, (b) black-body temperature, $T_{\rm bb}$, (c) effective black-body radius, $R_{\rm bb}$, at 5 kpc, and (d) goodness of fit expressed in reduced χ^2.

Blackbody cooling track and Stefan's law: $F \sim S \times T^{4}$

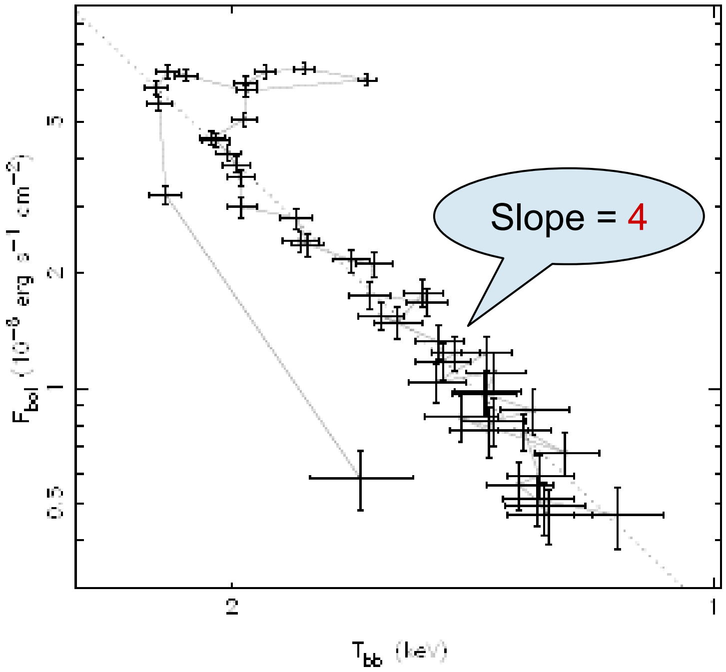
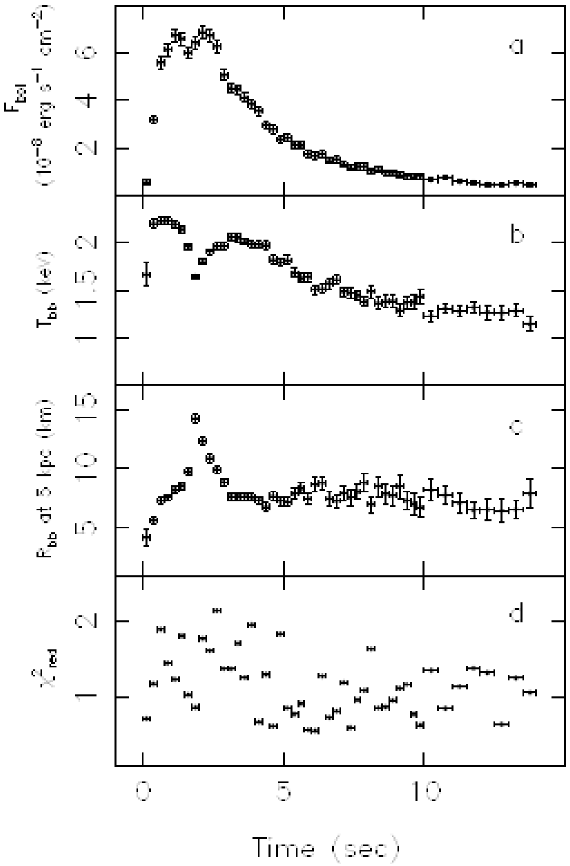
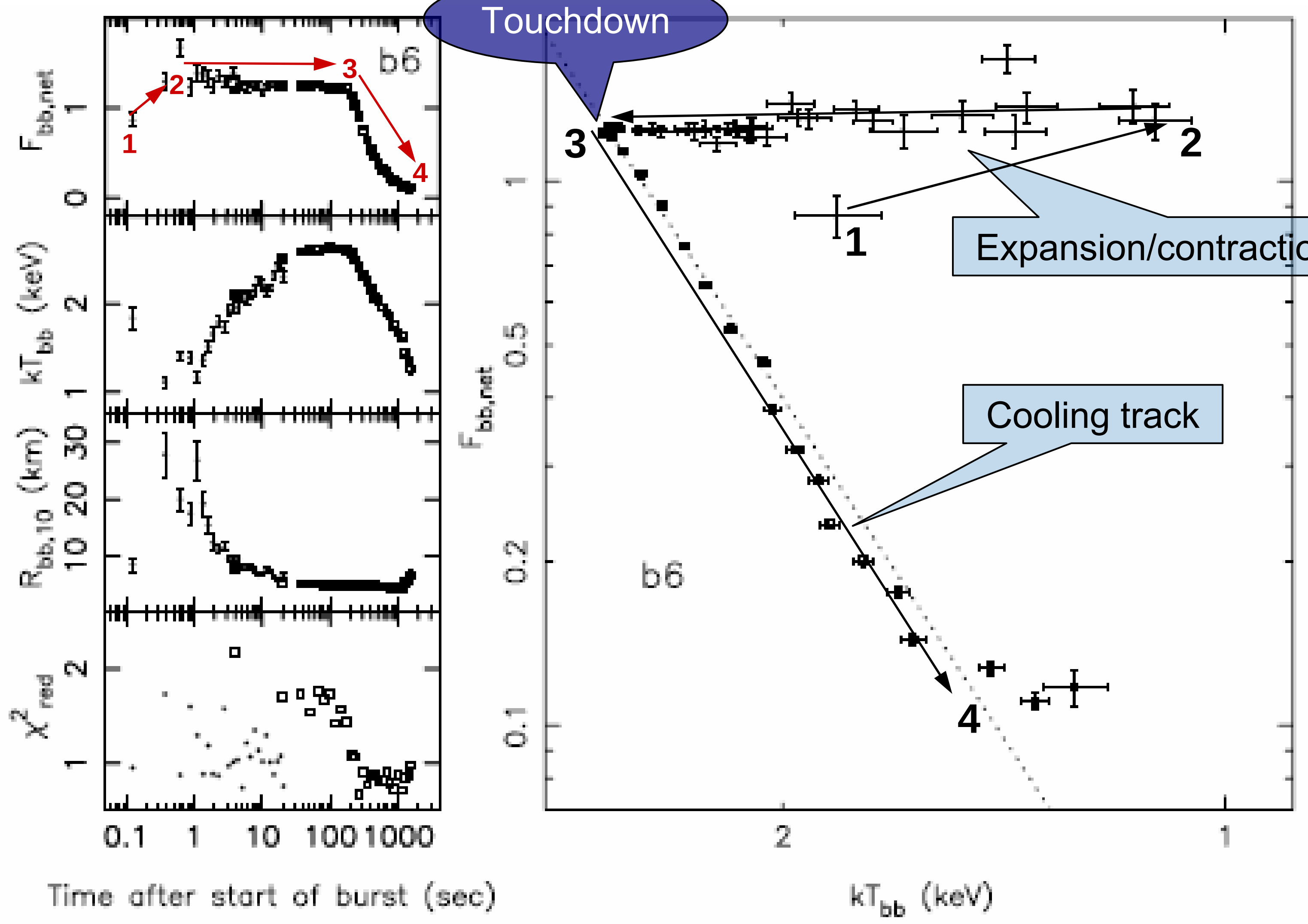


Fig. 4. Bolometric black-body flux (F_{bol}) versus black-body temperature (T_{bb}) for the first 14 s of the burst. Data points are connected for clarity. The dotted line represents the fit to the cooling track of the burst, see text. Note that T_{bb} runs from right to left.



Long radius expansion burst from GX 17+2 (Kuulkers et al., 2002)



Touchdown

Expansion/contraction phase

Cooling track

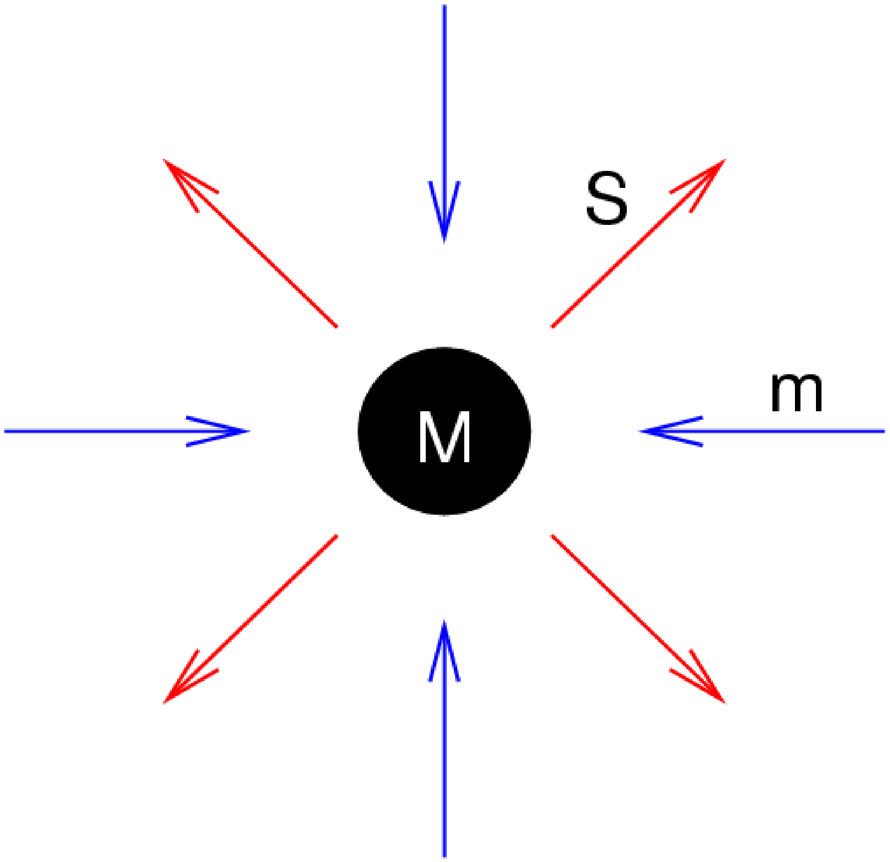
Eddington Limit

For any luminous object, there is a maximum luminosity beyond which radiation pressure will overcome gravity, and material outside the object will be forced away from it rather than falling inwards.

For canonical NS parameters (R_{NS}= 10 km, M_{NS}= 1.4 $M_{\odot}$)

- Eddington luminosity
- Eddington temperature
- Eddington accretion rate

Eddington luminosity, IV

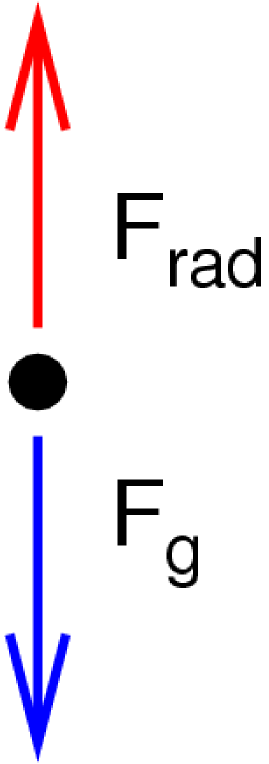


Assume mass M spherically symmetrically accreting ionized hydrogen gas.

At radius r, accretion produces energy flux S.

Important: Interaction between accreted material and radiation!

Eddington luminosity, VIII



Force balance on accreted electrons and protons:

Inward force: gravitation:

$$F_g = \frac{GMm_p}{r^2} \tag{4.5}$$

Outward force: radiation force:

$$F_{rad} = \frac{\sigma_T S}{c} \tag{4.6}$$

where energy flux S is given by

$$S = \frac{L}{4\pi r^2} \tag{4.7}$$

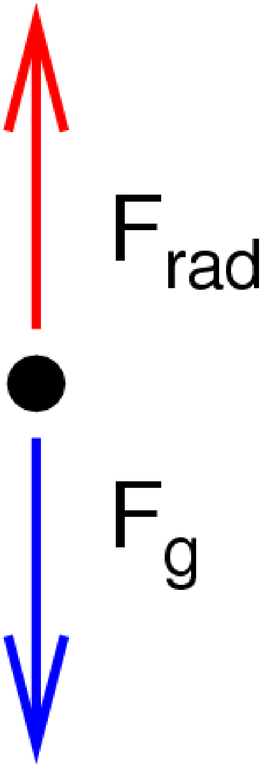
where L: luminosity.

Note: $\sigma_T \propto (m_e/m_p)^2$, so negligable for protons.

But: strong Coulomb coupling between electrons and protons

$\Longrightarrow$ F_{rad} also has effect on protons!

Eddington luminosity, IX



Accretion is only possible if gravitation dominates:

$$\frac{GMm_{\text{p}}}{r^2} > \frac{\sigma_{\text{T}} S}{c} = \frac{\sigma_{\text{T}}}{c} \cdot \frac{L}{4\pi r^2} \tag{4.8}$$

and therefore

$$L < L_{\text{Edd}} = \frac{4\pi GMm_{\text{p}}c}{\sigma_{\text{T}}} \tag{4.9}$$

or, in astronomically meaningful units

$$L < 1.3 \times 10^{38}\,\text{erg}\,\text{s}^{-1} \cdot \frac{M}{M_\odot} \tag{4.10}$$

where L_{Edd} is called the Eddington luminosity.

But remember the assumptions entering the derivation: spherically symmetric accretion of fully ionized pure hydrogen gas.

For pure He: $L_{\text{Edd}} = 2.9\text{x}10^{38}$ erg s^{-1}

Eddington luminosity, X

Characterize accretion process through the accretion efficiency, $\eta = \frac{GM}{Rc^2}$:

$$L = \frac{GM}{R}\frac{dM}{dt} \Rightarrow \quad L = \eta \cdot \dot{M} c^2 \tag{4.11}$$

where $\dot{M}$: mass accretion rate (e.g., $\mathrm{g\,s^{-1}}$ or $M_\odot\,\mathrm{yr}^{-1}$).

Therefore maximum accretion rate ("Eddington rate"):

$$\dot{M}_{Edd} = \frac{L_{\mathrm{Edd}}}{\eta c^2} \sim 2 \times 10^{-8} \quad M_\odot\,\mathrm{yr}^{-1} \tag{4.12}$$

(for $\eta = 0.2$)

Per unit area: $\dot{m}_{Edd} = \frac{\dot{M}_{Edd}}{4\pi \mathrm{R}^2} = 10^5\ \mathrm{g\ cm^{-2}\ s^{-1}}$

Peak Temperature (at "touchdown"): $T_{Edd} = \left(\frac{L_{Edd}}{4\pi R_{NS}^2\ \sigma}\right)^{1/4}$

Applications

Relativistic formula for L_{Edd} :

$$L_{Edd} = 1.9 \cdot 10^{38} \times \frac{M}{M_\odot} \times \frac{1+(\alpha T)^{0.86}}{1+X} \times \frac{1.31}{1+z(R)} \text{ erg/s}$$

$$z(R) = \left(1 - \frac{2\,G\,M_{NS}}{R\,c^2}\right)^{-1/2} - 1 \;=\; 0.31 \quad @\, R = \mathrm{R}_{\mathrm{NS}}$$

X : H fraction, $\alpha \approx 2.2\text{x}10^{-9}\ \text{K}^{-1}$: e^- scattering opacity coefficient of the atmosphere

Observationally (globular clusters): $L_{Edd} \approx 3.8\text{x}10^{38}$ erg/s (Kuulkers et al., 2003)

- Determination of the redshift z ⇒ M_{NS}
- X-ray bursts as standard candles: if $L = L_{Edd}$ ⇒ d

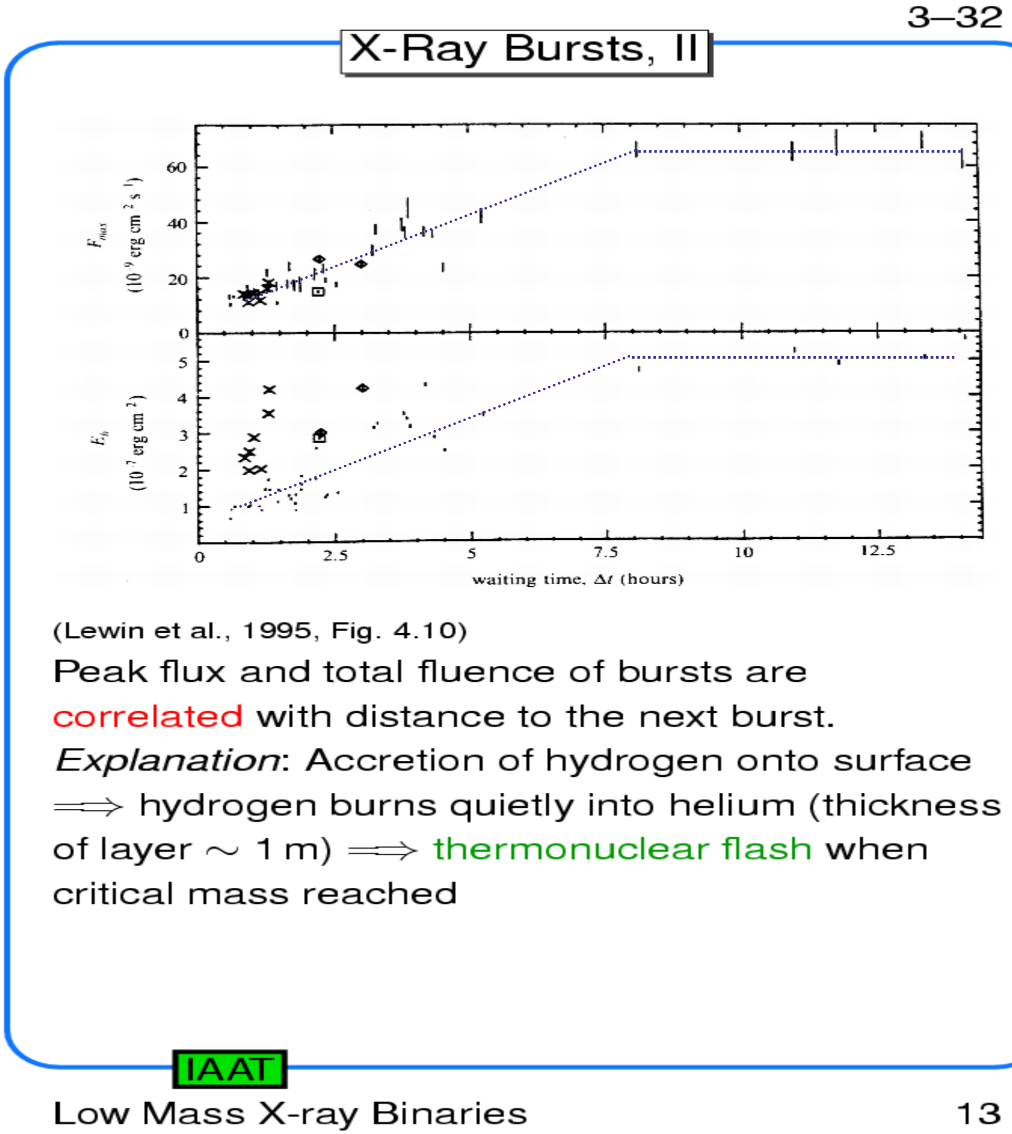
$$L \le L_{Edd} \Leftrightarrow 4\,\pi\,d^2\,F \le L_{Edd}$$

$$\Leftrightarrow d \le \sqrt{\frac{L_{Edd}}{4\pi\,F}}$$

: upper limit to distance

Burst intervals and burst energy

The released energy is limited by PRE and indicates limited nuclear fuel due to steady nuclear burning between bursts.



3–32

X-Ray Bursts, II

(Lewin et al., 1995, Fig. 4.10)

Peak flux and total fluence of bursts are correlated with distance to the next burst.

Explanation: Accretion of hydrogen onto surface $\Longrightarrow$ hydrogen burns quietly into helium (thickness of layer $\sim$ 1 m) $\Longrightarrow$ thermonuclear flash when critical mass reached

IAAT

Low Mass X-ray Binaries 13

Recurrence time

1. Bursts are fuelled by accreted material at rate $\frac{dM}{dt} = \dot{M}$

Energy

2. Mass burned during a burst is given by: $M_b = \frac{E_b}{\varepsilon}(1+z)$; ε : burning efficiency $[\mathrm{erg} \cdot \mathrm{g}^{-1}]$
3. Recurrence time between bursts is then: $\Delta t = \frac{M_b}{\dot{M}} = \frac{E_b}{L_{pers}} \times \frac{\eta c^2}{\varepsilon} \times (1+z)$

$\Delta t \propto (L_{pers})^{-1}$ should reflect the time needed to accumulate the nuclear burning fuel

But things are not that simple…

Burst parameters

$$\alpha = \frac{F_{pers}}{E_b}\Delta t$$ $10<\alpha<10^3$: a measure of burst energetics

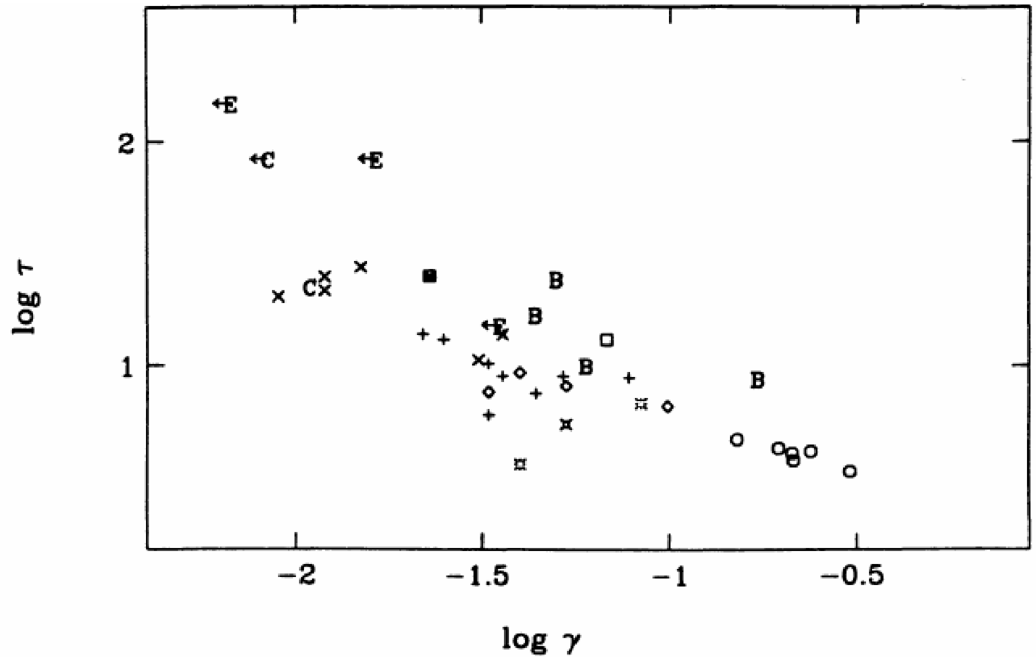
Fluence

$$\gamma = \frac{F_{pers}}{F_{peak}}$$: burst strength relative to persistent emission

Effective burst duration: $$\tau = \frac{E_b}{F_{peak}}$$ ~ e-folding decay time

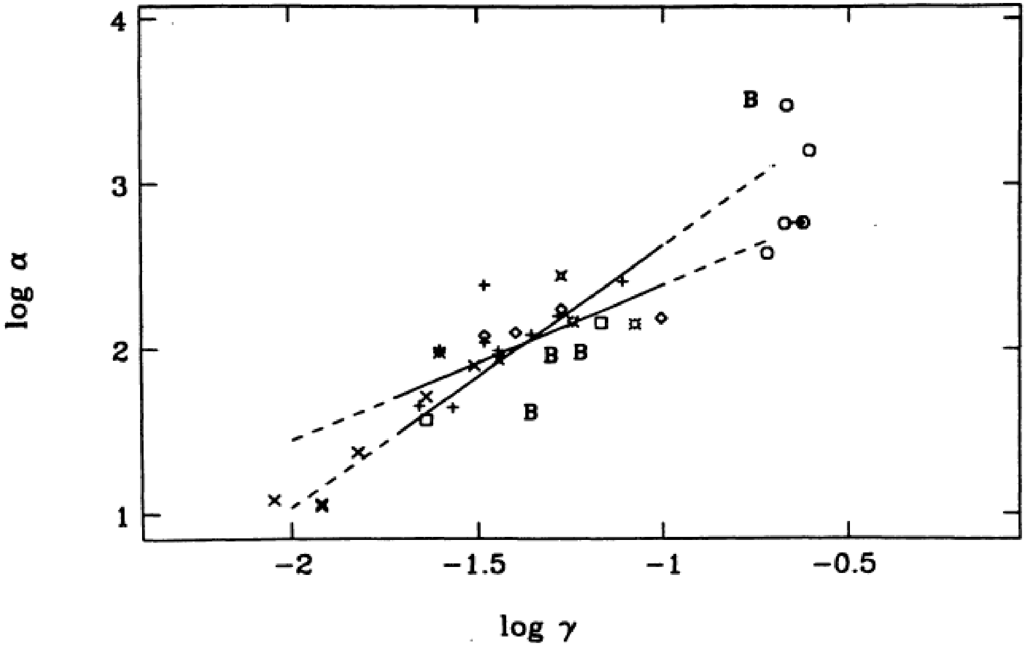
Note: $$\frac{\alpha\tau}{\gamma} = \Delta t$$

Burst parameter relationships: τ vs. γ



The decrease of burst duration with persistent luminosity indicates that hydrogen becomes less important in the energetics of the burst as the mass accretion rate increases (Van Paradijs et al, 1988).

Burst parameter relationships: α vs. γ

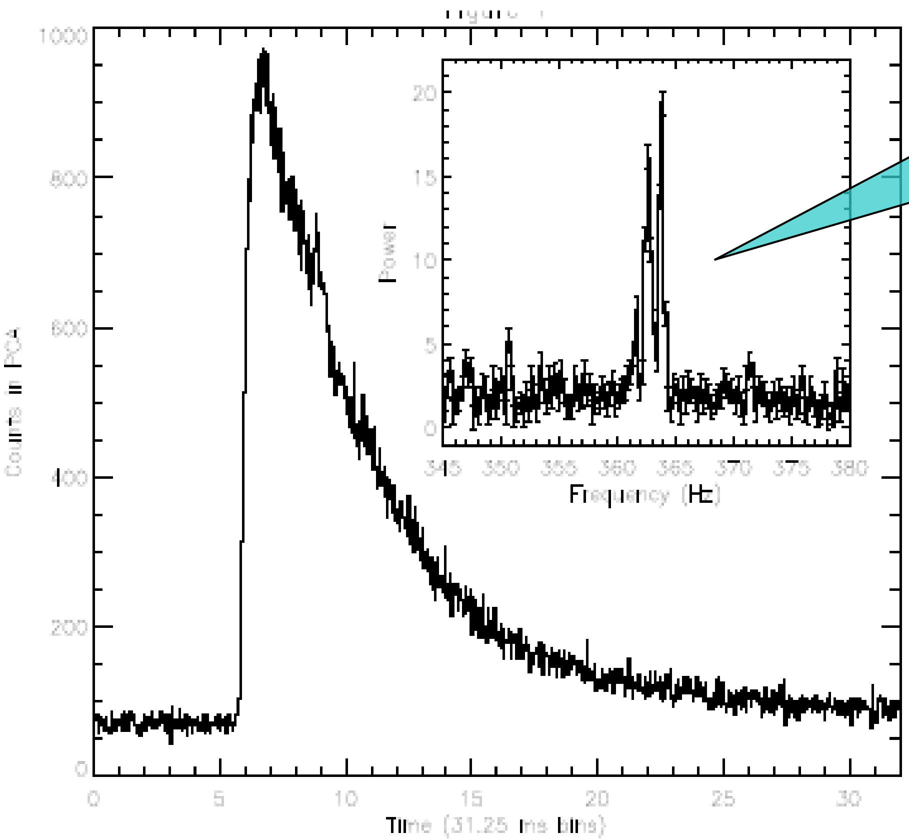


The correlation of α with γ is consistent with previous conclusion and seems to indicate that steady nuclear burning limiting the burst energy release does increase with accretion rate (Van Paradijs et al, 1988).

Preliminary interpretation

- The previous records seem to indicate a transition between two nuclear burning regimes.
- Evidences of increasing time between bursts as persistent emission increases may indicate an increase of the accretion area implying that the local accretion rate per unit area, $\dot{m}$, actually decreases with the accretion rate $\dot{M}$.
- The influence of the accretion rate per unit area is an indication that only a fraction of the NS is covered by freshly accreted fuel.

X-ray burst oscillations



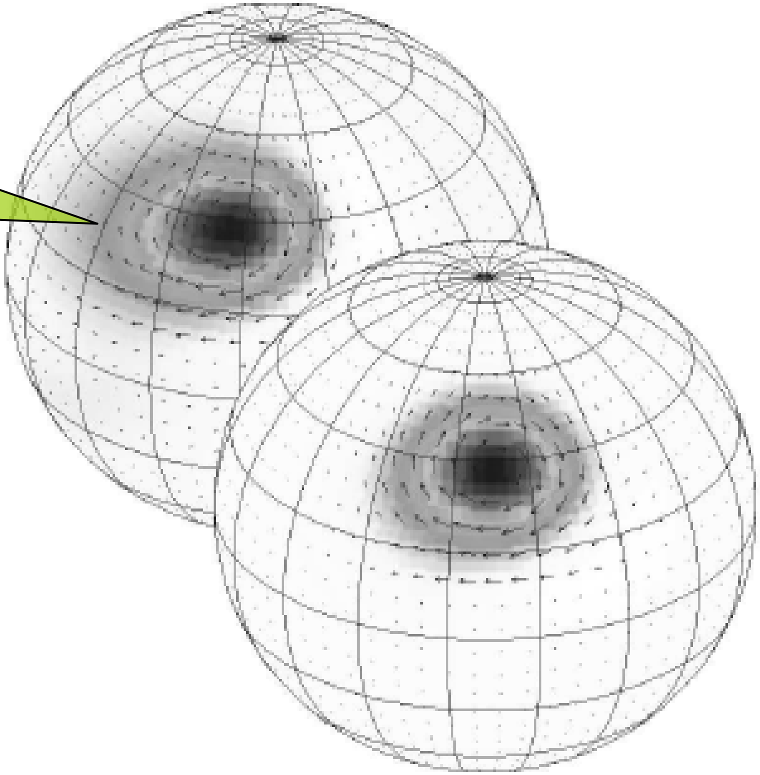
Power spectrum showing millisecond variability during X-ray bursts

Fig. 3.6. An X-ray burst from 4U 1728–34 observed with the PCA onboard RXTE. The main panel shows the X-ray counts observed by the PCA in (1/32) s bins. The inset panel shows the power spectrum in the vicinity of 363 Hz (after Strohmayer et al. 1996).

Recently, Kaaret et al. (2007) has observed a record breaking oscillation at 1122 Hz in the tail of an X-ray burst from XTE J1739-285, previously identified as a burster by the JEM-X team.

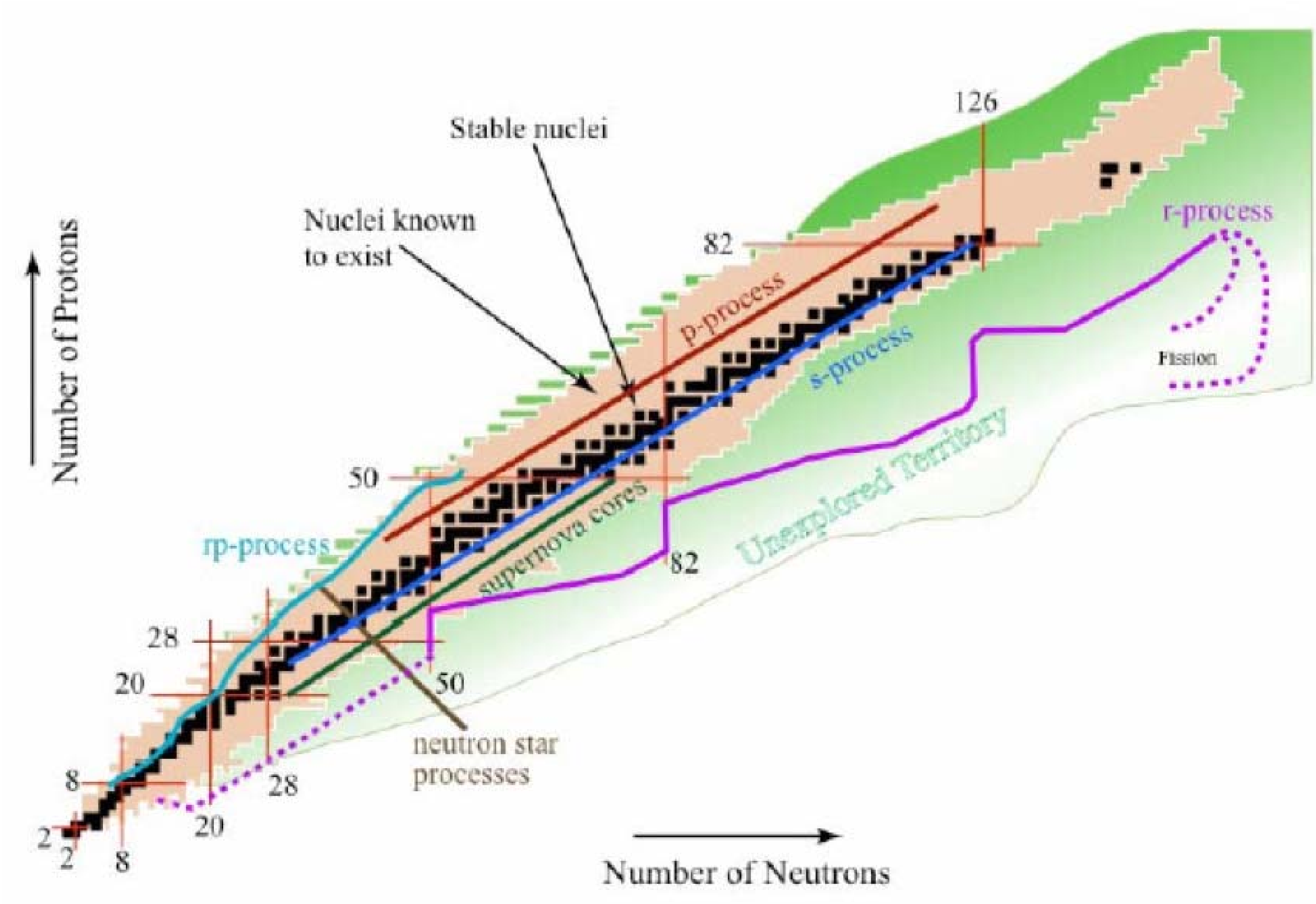
Spin modulation

Oscillations are associated with a hot spot expanding on the NS surface like a deflagration flame and modulated by the NS rotation.

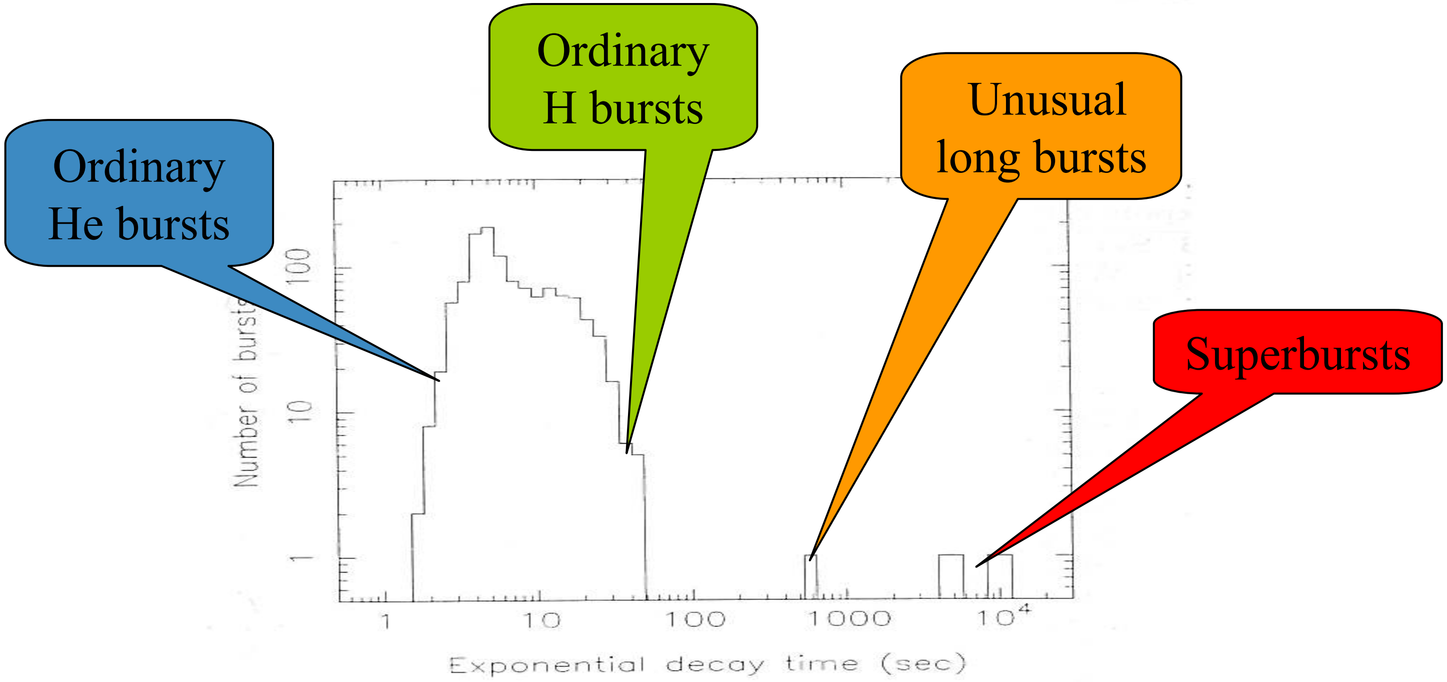


Coriolis forces

THEORY


126
Stable nuclei
Nuclei known
to exist
82
p-process
r-process
s-process
Fission
Number of Protons
50
rp-process
supernova cores
82
Unexplored Territory
28
20
50
neutron star
processes
8
28
2
2
20
8
Number of Neutrons

More or less long bursts



Ordinary He bursts

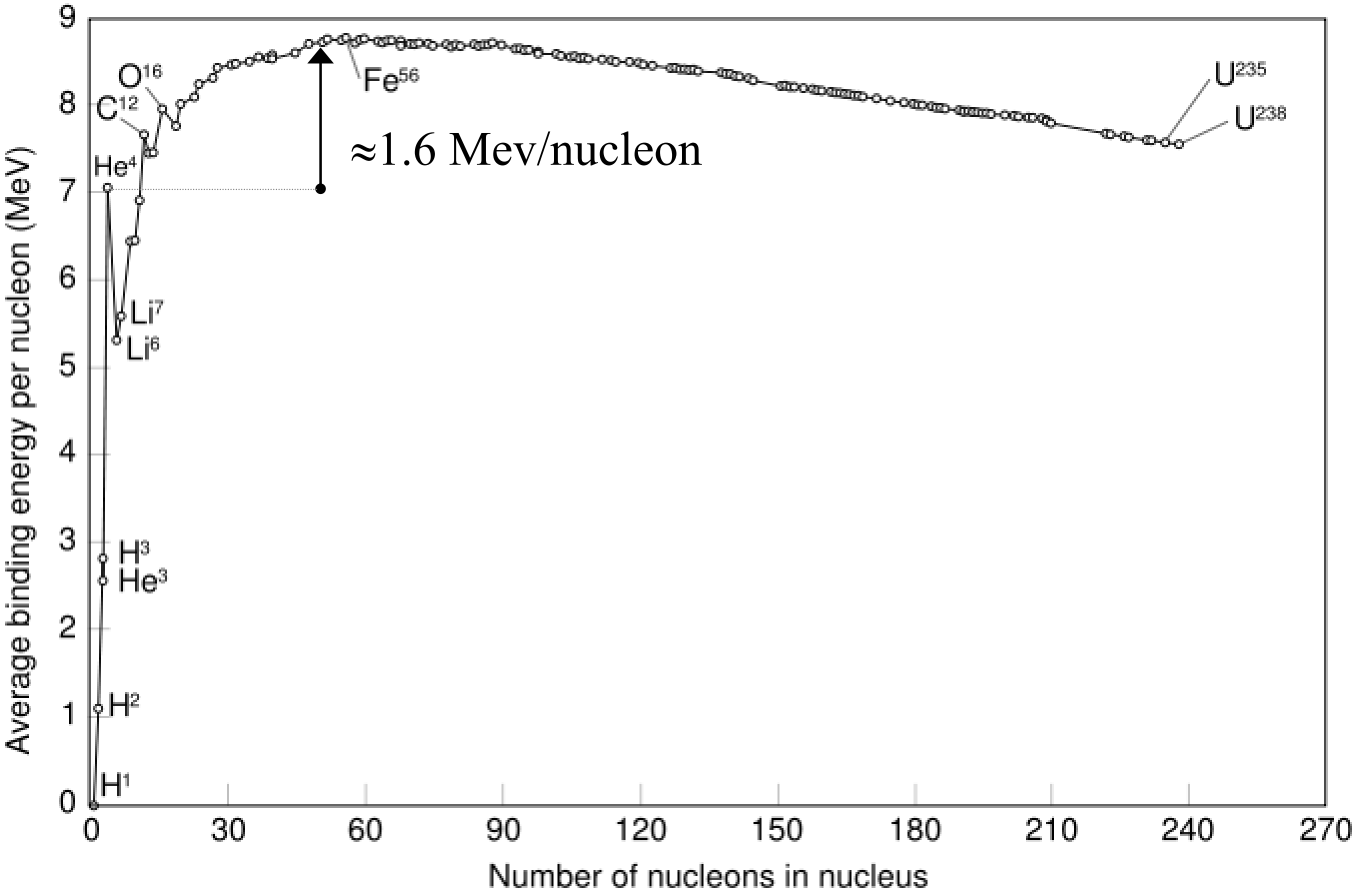
Ordinary H bursts

Unusual long bursts

Superbursts

Figure 1. The distribution of the decay times of 1158 X-ray bursts seen by the *BeppoSAX*/WFCs. The decay times are determined from exponential fits to the burst decay profiles. Courtesy: the *BeppoSAX*/WFC team at SRON/Utrecht and CNR/Rome.

Burst Energetics



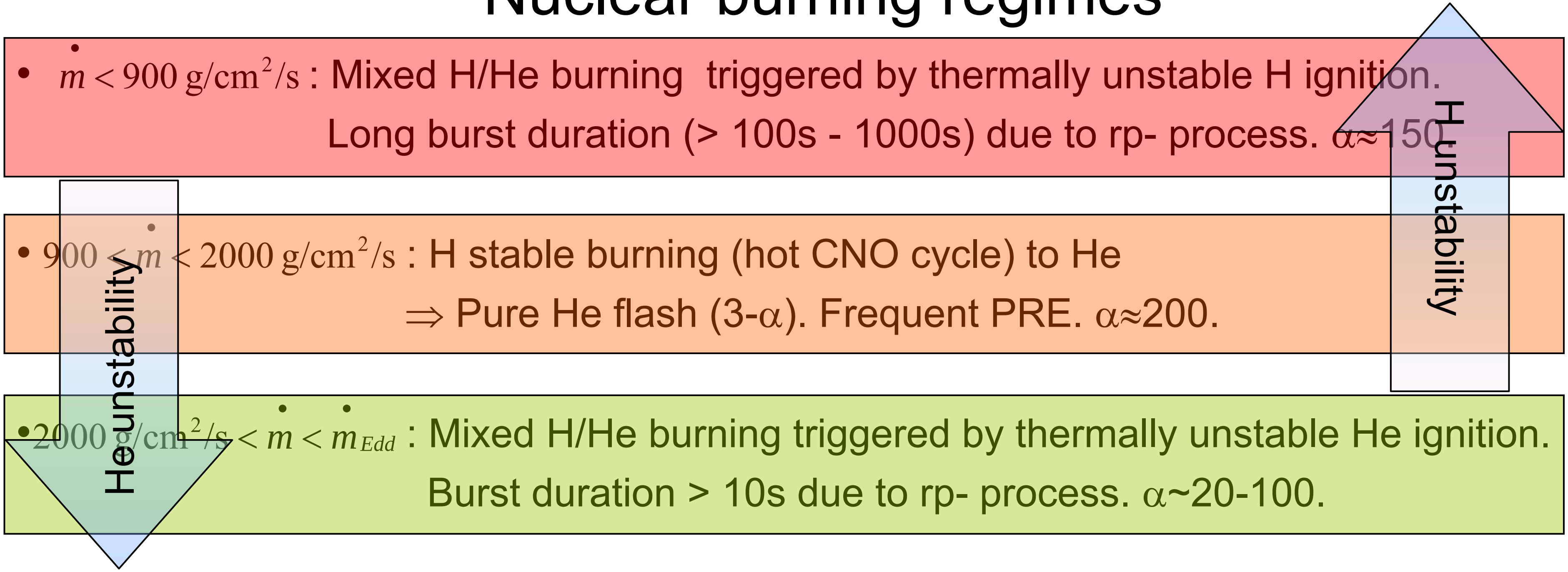
Nuclear vs. gravitation

Power of accretion: $\frac{GM_{NS}m_p}{R_{NS}} \approx$ 200Mev/nucleon

Energy release of nuclear burning to heavy elements is
≈1.6 Mev/nucleon for pure He and
≈5 Mev/nucleon for solar composition material

⇒ Ineffective process compensated by accumulation

Nuclear burning regimes

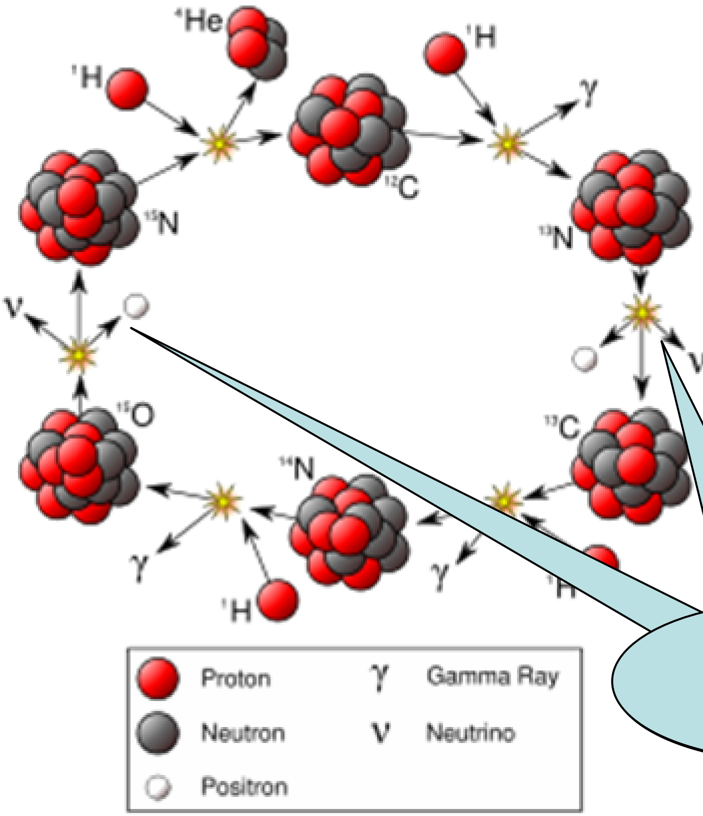


- $\dot{m} < 900\ \mathrm{g/cm^2/s}$: Mixed H/He burning triggered by thermally unstable H ignition.
  Long burst duration (> 100s - 1000s) due to rp- process. $\alpha \approx 150$
- $900 < \dot{m} < 2000\ \mathrm{g/cm^2/s}$: H stable burning (hot CNO cycle) to He
  $\Rightarrow$ Pure He flash (3-α). Frequent PRE. $\alpha \approx 200$.
- $2000\ \mathrm{g/cm^2/s} < \dot{m} < \dot{m}_{Edd}$: Mixed H/He burning triggered by thermally unstable He ignition.
  Burst duration > 10s due to rp- process. $\alpha \sim 20\text{-}100$.
- $\dot{m} \geq \dot{m}_{Edd}$: No bursts (e.g. pulsars).

- Pure He accretion (e.g. from white dwarf) $\Rightarrow$ powerful pure He bursts.
- Deep Carbon burning in superbursts.

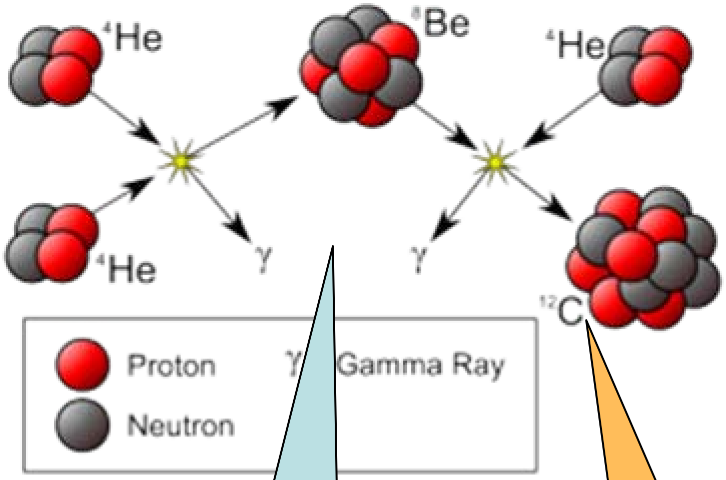
Nucleosynthesis

CNO cycle



Waiting points

3-α

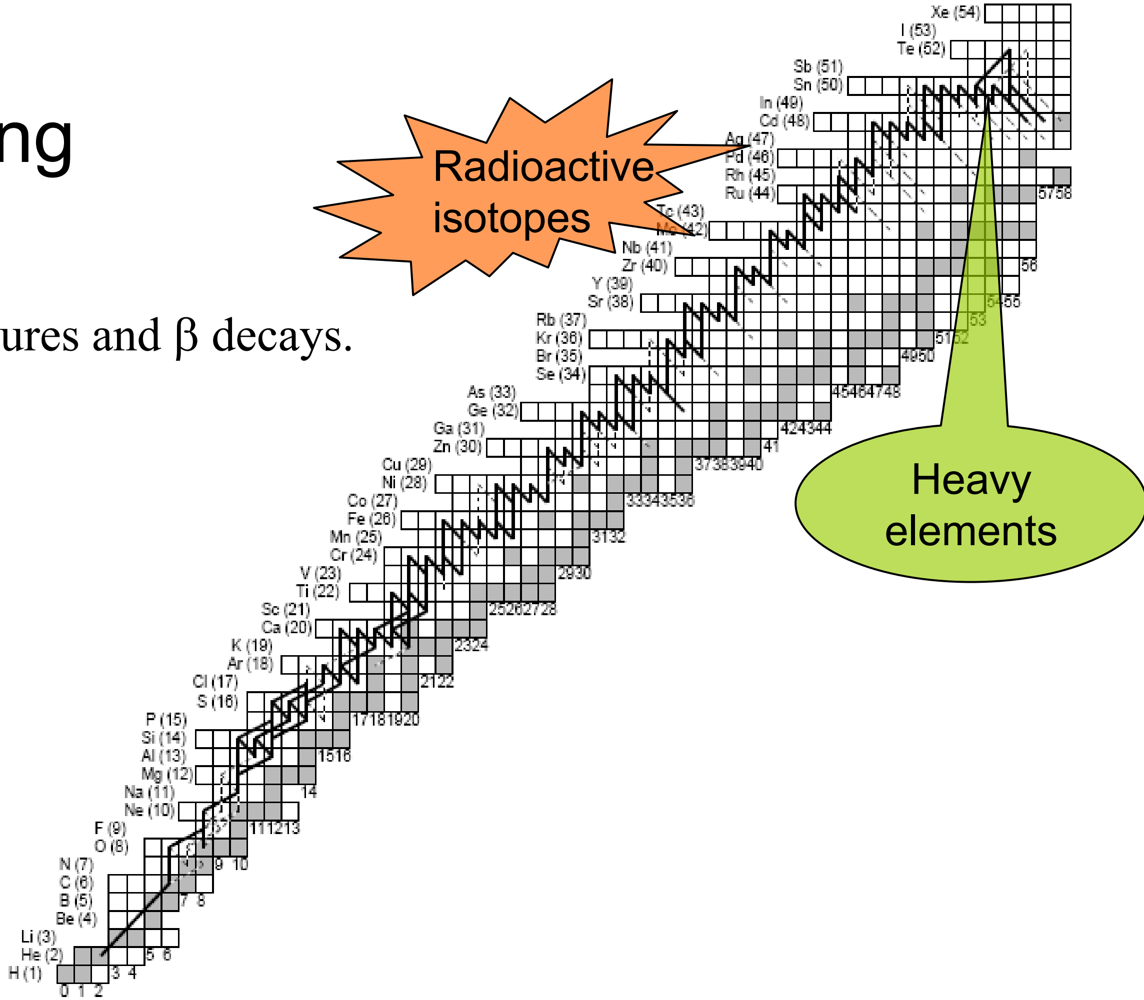


No β-decay
⇒ He flash

Final product

Burst nuclear burning

The rp- process: series of proton captures and β decays.



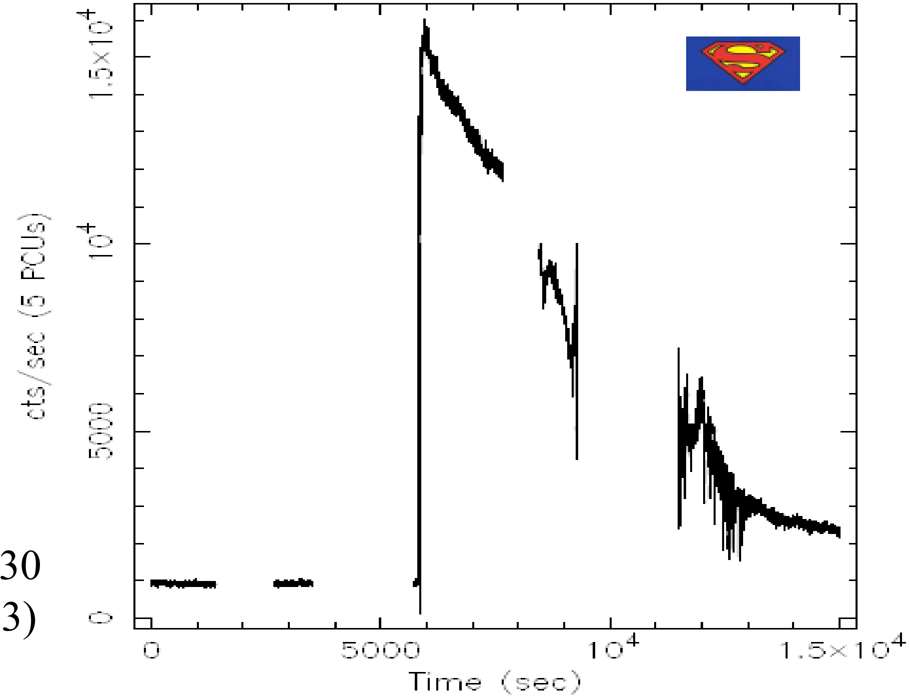
Radioactive isotopes

Heavy elements

Fig. 3.1. Schematic showing the dominant pathways of the nuclear reaction flows during the rp process. Elements far beyond ^{56}Fe can easily be reached. Filled squares denote stable nuclides (after Schatz et al. 2001).

Superbursts

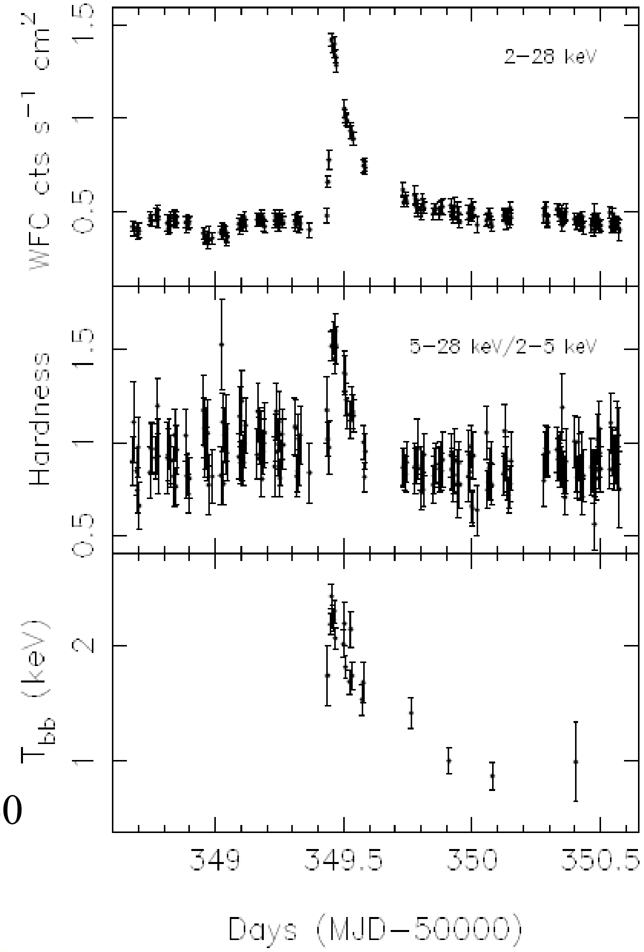
Compared to normal type I X-ray bursts, superbursts are ~1000 times more energetic ($E_b \approx 10^{42}$ ergs), ~1000 times longer (from hours to half a day), and have recurrence times of the order of years. They are very rare, only 13 such events having been found from 8 sources.



Superburst from 4U 1820-30 on 9/9/1999 (Kuulkers, 2003)

Superbursts II

Superbursts display the same properties as usual type I X-ray bursts.
They are thought to arise from Carbon shell flashes in the layers where heavy elements have previously been produced through the rp-process of H/He bursts.
Their duration is explained by a deep ignition column below the surface.



Superburst from KS 1731-260

Unusually long bursts

Only 8 known bursts have shown a duration of a few tens of minutes

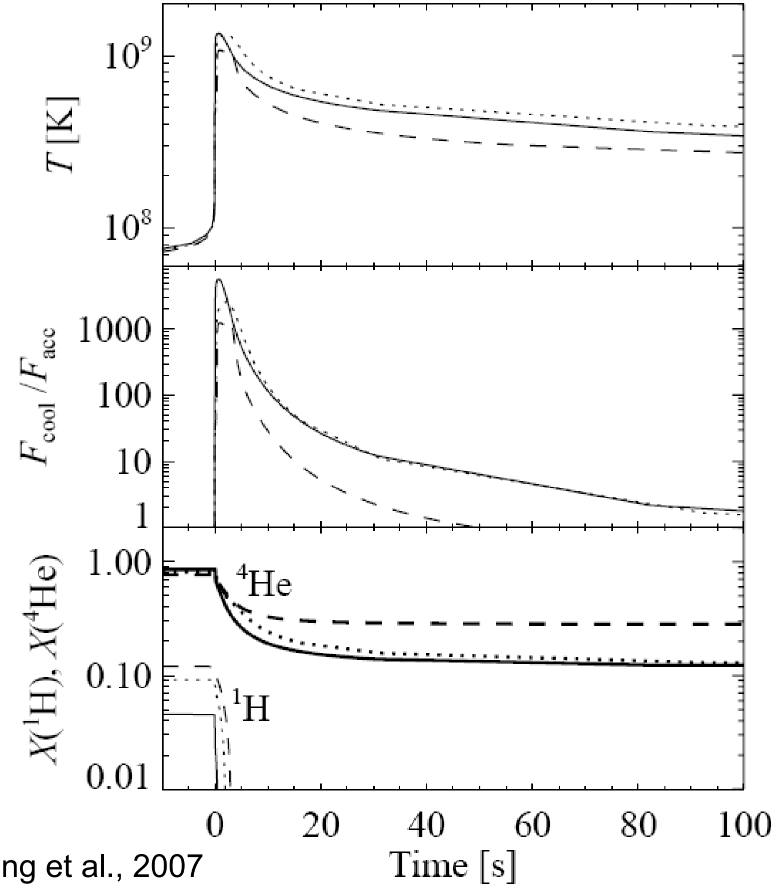
Unusually long bursts seem generally to be associated with mixed H/He burning at low accretion rate.

Depending on the actual accretion rate, either the burning of a large amount of H is triggered by an He flash, or a large column of He is triggered by H ignition.

Long pure He bursts involving an even larger column depth are also possible, especially if no H is accreted.

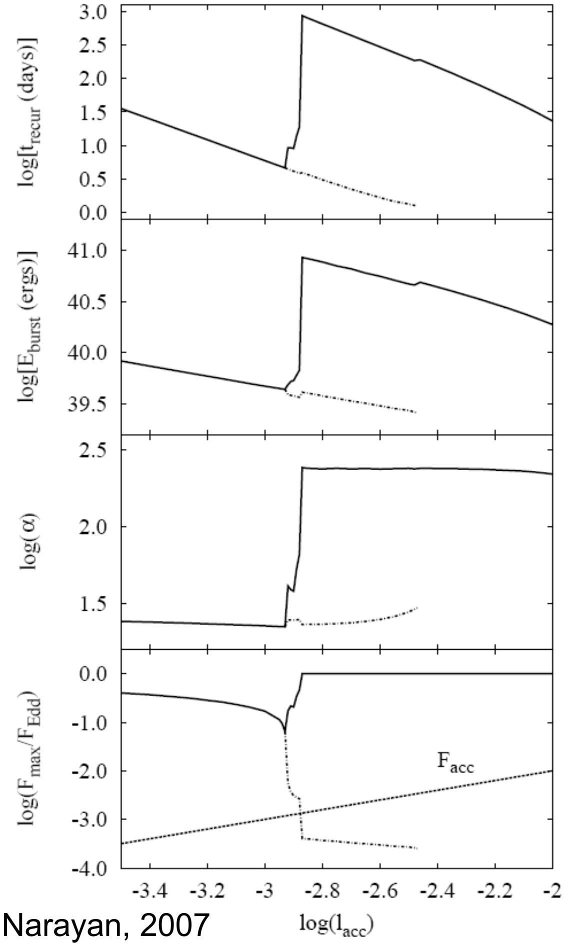
An aborted superburst due to the premature ignition of a carbon layer triggered by an He detonation may also be considered.

Burst triggering Mechanisms



Peng et al., 2007

FIG. 6.— One-zone burst calculation following unstable H ignition for three mass accretion rates: $\dot{m}/\dot{m}_{\rm Edd} = 9.1 \times 10^{-4}$ (*solid lines*), 1.1×10^{-3} (*dotted lines*) and 2.3×10^{-3} (*dashed lines*), respectively. Top panel: temperature evolution; Middle panel: the ratio of one-zone cooling flux to the accretion flux; Bottom panel: mass fraction of hydrogen (*thin lines*) and ^{4}He (*thick lines*), respectively. Diffusion and sedimentation is included. This category of H ignition triggers helium ignition and produces strong x-ray burst.

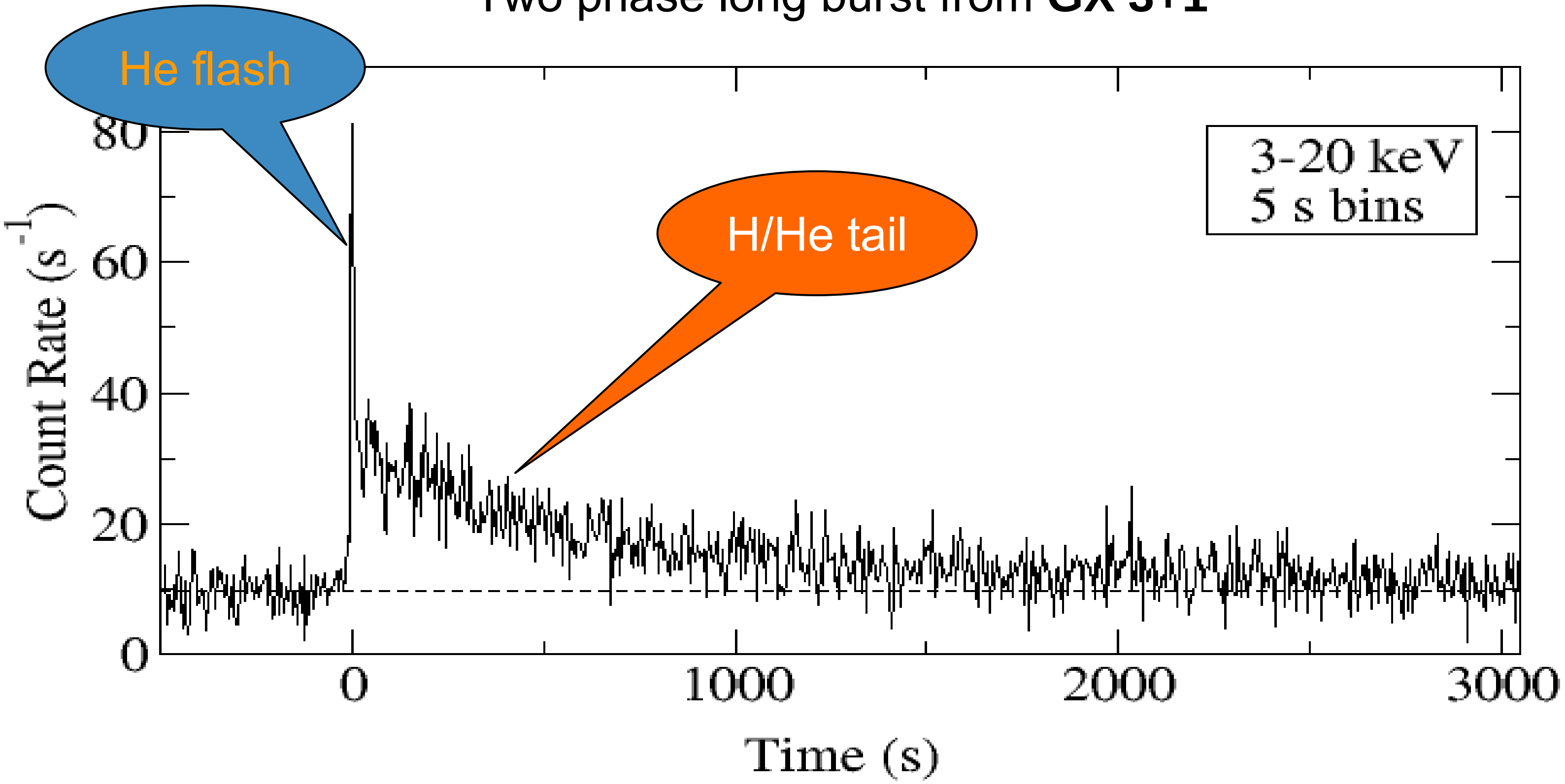


Cooper & Narayan, 2007

FIG. 7.— Recurrence time, burst energy, ratio of accretion to burst energy α, and peak flux of type I X-ray bursts as a function of $l_{\rm acc}$, from top to bottom. For $-2.9 \lesssim \log(l_{\rm acc}) \lesssim -2.5$, both energetic pure helium flashes and weak hydrogen flashes occur. In this case, the solid line denotes the burst properties of the helium flashes and the dot-and-dashed line denotes the burst properties of the hydrogen flashes. The chaotic behavior discussed in §4 and Fig. 5 causes the sudden jumps in the panels that occur in the range $-2.93 < \log(l_{\rm acc}) < -2.87$. The dashed line in the bottom panel denotes the luminosity due to accretion. Note that the peak flux during most weak hydrogen flashes is much less than the accretion luminosity.

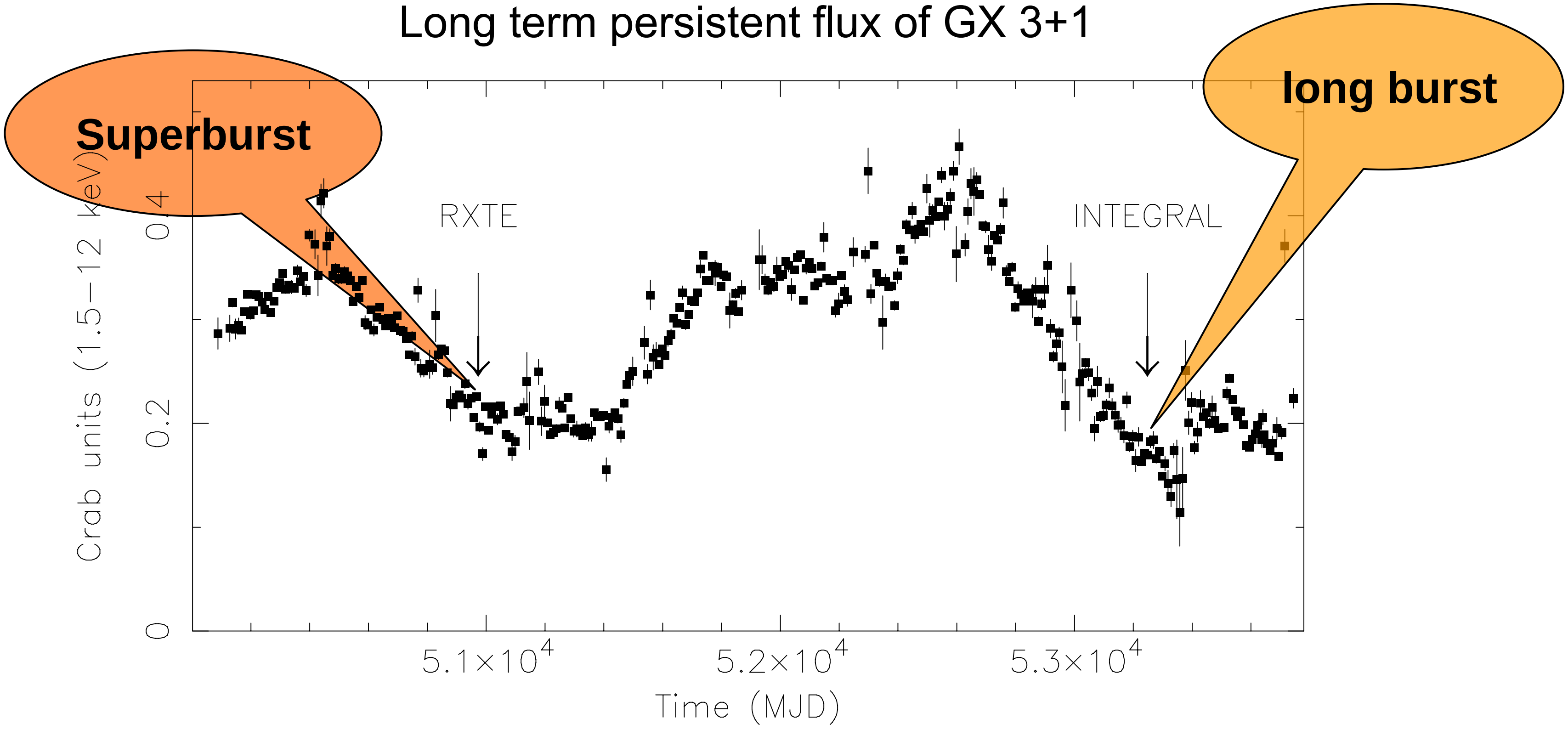
Back to observations

Two phase long burst from **GX 3+1**



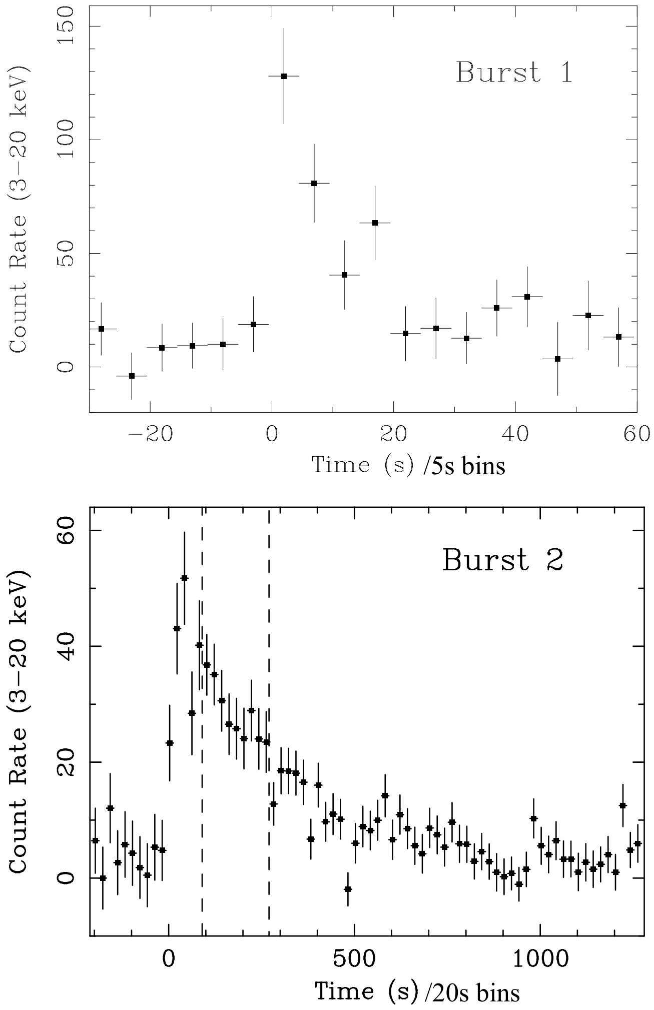
Relation with accretion rate

Long term persistent flux of GX 3+1

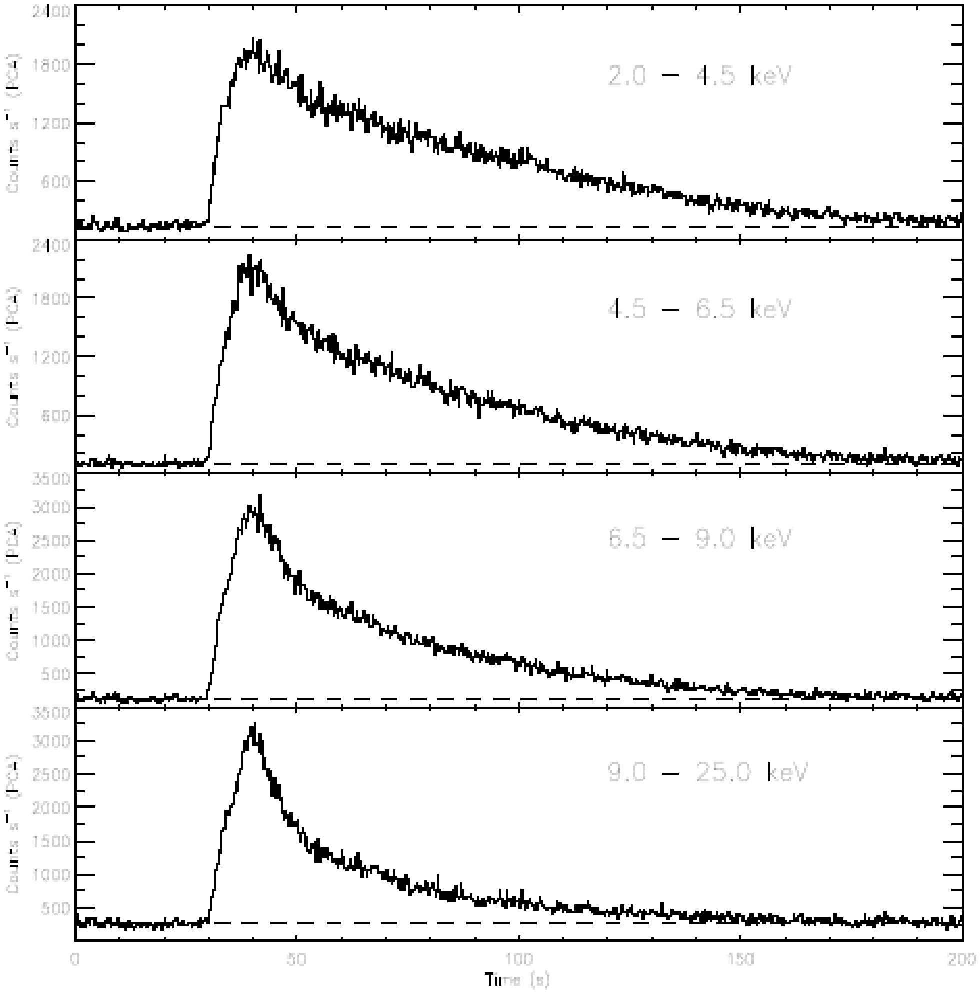


IGR J17254-3257 short and long bursts

Different lasting bursts from IGR J17254-3257 can be explained by a transition between two slightly different accretion rates. Burst 1 is a mixed H/He burst triggered by a weak H flash, while burst 2 is the result of the burning of a large He pile at a slightly higher accretion rate.



Practical example: GS 1826-24



Usual X-ray burst from GS 1826-238. The long rise time and total duration are indicative of the delayed energy release from the rapid proton process.

$F_{pers} = 2{\cdot}10^{-9}$ erg/cm2/s

$\Delta t \approx 5.7$ h

$F_b \Rightarrow \alpha \approx 40$

Some calculations (1/3)

$$\dot{m} = \frac{\dot{M}}{4\pi R_{NS}^{2}}$$

$$\dot{M} = \frac{L_{pers}}{\eta c^{2}}$$

$$L_{pers} = 4\pi d^{2} \xi_{p} F_{pers}$$

$\xi_p \approx 1$: anisotropy

$$\dot{m} = \left(\frac{d}{R_{NS}}\right)^{2} \frac{F_{pers}}{\eta c^{2}} = 10^{4} \text{ g cm}^{-2} s^{-1}$$

: Mixed H/He burning triggered by He ignition

$0.1 \dot{m}_{Edd}$

Ignition column depth: $y = \dot{m} \Delta t$

$$y = 2 \times 10^{8} \text{ g cm}^{-2}$$

Some calculations (2/3)

$$\left.\begin{aligned} \alpha &= \frac{\mathrm{F}_{\mathrm{pers}}}{\mathrm{F}_{\mathrm{b}}}\Delta \mathrm{t} \\ \Delta \mathrm{t} &= \frac{E_{\mathrm{b}}}{L_{\mathrm{pers}}}\frac{\eta\, c^2}{\varepsilon}(1+z) = \frac{\xi_b}{\xi_p}\frac{\mathrm{F}_{\mathrm{b}}}{\mathrm{F}_{\mathrm{pers}}}\frac{\eta\, c^2}{\varepsilon}(1+z) \end{aligned}\right\} \quad \alpha = \frac{\xi_b}{\xi_p}\frac{\eta\, c^2}{\varepsilon}(1+z) \Leftrightarrow \varepsilon = \frac{\xi_b}{\xi_p}\frac{\eta\, c^2}{\alpha}(1+z)$$

$$\varepsilon \approx 5\times 10^{18}\ \mathrm{erg\ g^{-1}} \qquad \mathrm{for:}\ \frac{\xi_b}{\xi_p} \approx 0.85$$

Energy efficiency: $\varepsilon = Q_{nuc} \times 10^{18}$ erg g^{-1}

$Q_{nuc} \approx 1.6 + 4X$ Mev/nucleon

$\Rightarrow Q_{nuc} \approx 5$ Mev/nucleon $\Leftrightarrow$ X ≈ **0.8** : H-rich burst

Indeed!

Some calculations (3/3)

Mass burned: $m = 4\pi R_{NS}^{2}\, y = 2.5 \times 10^{21}\, g$

Burst energy release: $E_{\mathrm{b}} = \dfrac{m}{1+z}\varepsilon$

$$E_{\mathrm{b}} \approx 10^{40}\, ergs$$

OUTLOOK

X-ray bursts as probes of:

- Compact object as neutron star
- Neutron stars properties (M_{NS}, R_{NS}, T_{NS}, spin)
- Accretion rate
- Evolutionary state (H/He) of the companion

Future prospect: • Nuclear lines

THE END