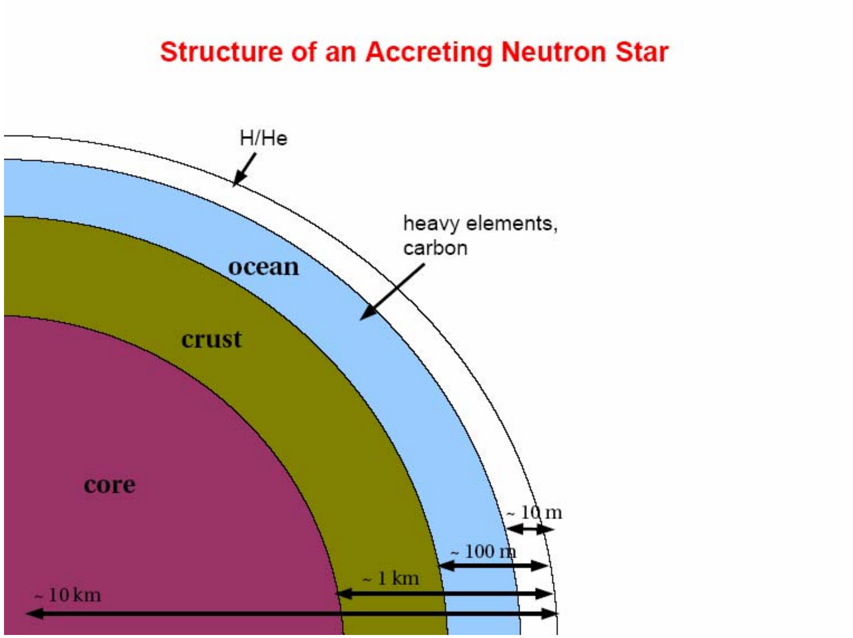
Thermonuclear shell flashes I: on NSs

1. Thermonuclear runaway
2. Flash profiles & spectra
3. Energetics
4. Effects of super-Eddington fluxes
5. Superbursts
6. Burst oscillations

Literature:

- **Lewin, van Paradijs & Taam: SSRv 62, 223 (1993)**
- **Bildsten: astro-ph/9709094**
- **Strohmayer & Bildsten: astro-ph/0301544**

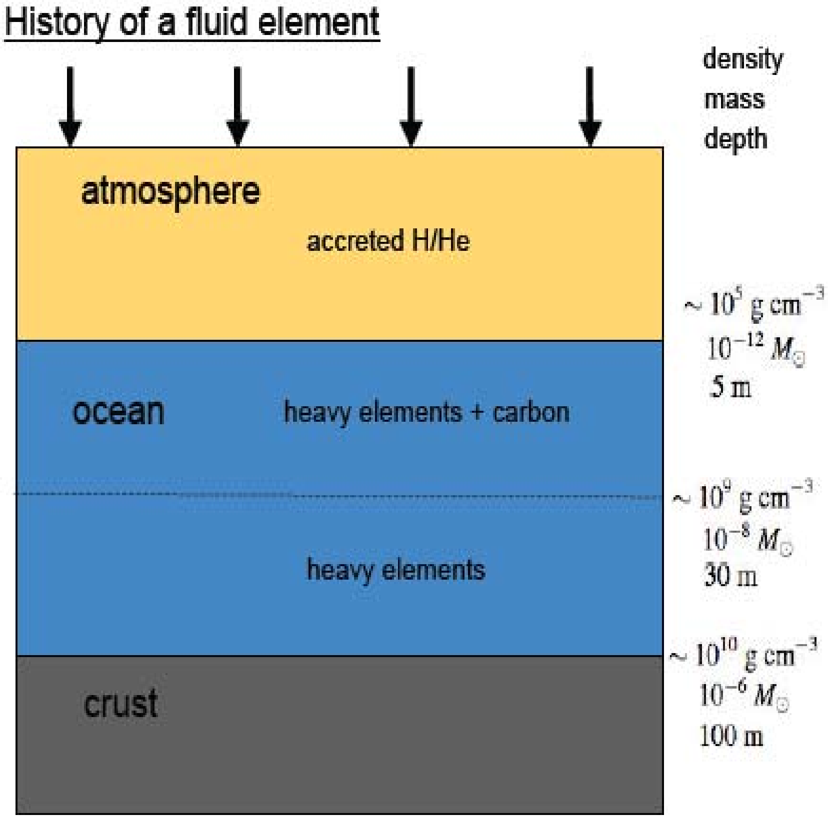
Neutron star structure



- Density of nuclear matter ρ_0
- Core: 10-15 ρ_0, nature of matter not really determined but probably neutrons, electrons and muons. Distinction between outer and inner core (<>2 ρ_0). Inner core truly undetermined
- Crust: starts at 0.5 ρ_0, containing neutron-rich isotopes, free neutron, degenerate electrons. Mass 0.01 $M_\odot$

NS order-of-magnitude numbers

- mass 1.4 $M_\odot$ = 3 x 10^{33} g
- radius 10 km = 10^5 cm
- density $\rho \sim 10^{14}$ g cm^{-3}
- surface g ~ 10^{14} cm s^{-2}
- typical ignition column densities $y \sim 10^8$ g cm^{-2}
- typical ignition pressure $P \sim 10^{22}$ erg cm^{-3}
- typical ignition density $\rho \sim 10^5$ g cm^{-3}



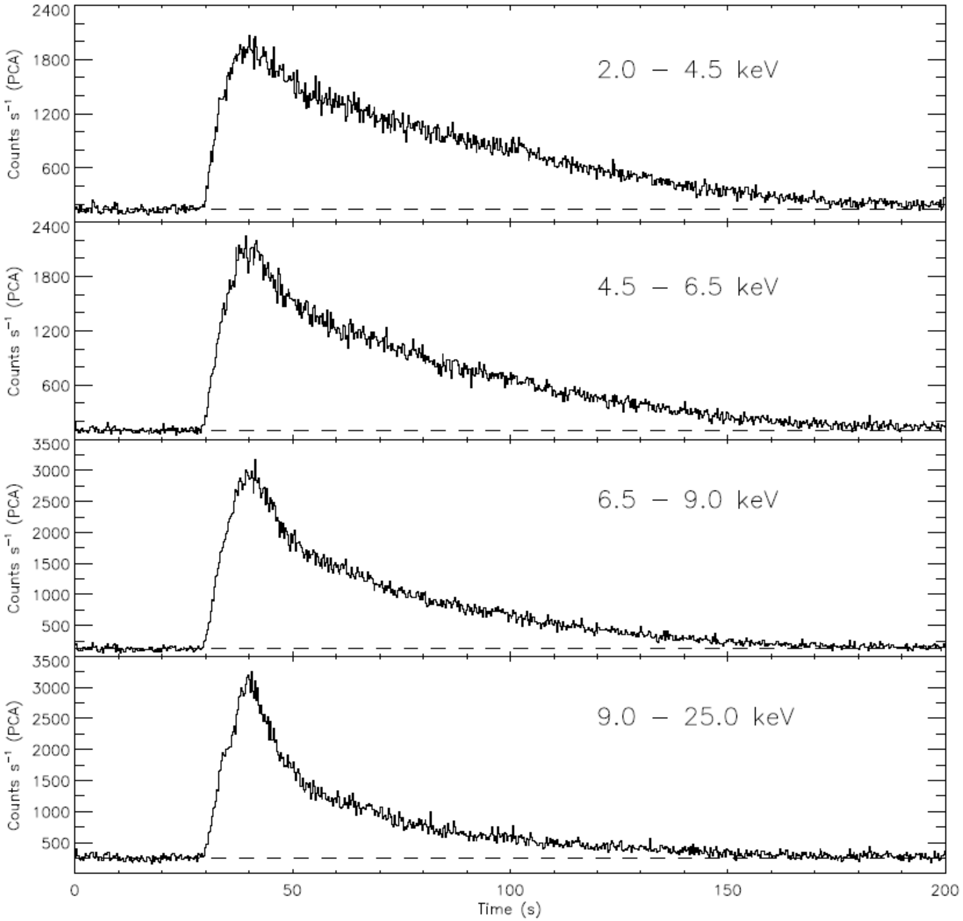
Simple model for ignition

- The thermal energy generated by the accretion (adiabatic compression) is radiated away immediately at the NS surface. It does NOT heat up the NS
- But, accreted matter undergoes 1) pycnonuclear nuclear burning at extreme high densities $\rho > 10^9$ g cm^{-3} in the crust (nuclear barriers are penetrated due to vibrations in a lattice) and 2) electron capture processes. These DO heat up the whole NS at a rate of ~2 MeV per nucleon (the crust at time scales of probably months and the core at ~10^4 yr)
- Due to accretion, pressure builds up at the base of accreted layer while the temperature slowly adjusts to the crust value
- If ρ and T become high enough, thermonuclear burning initiates → T rises while ρ remains constant (due to thin shell; scale height $H = kT/mg \ll R_{NS}$ with m mean molecular weight) → if heating goes faster with T than radiative cooling, runaway process or “thermonuclear shell flash” occurs
- If fuel refreshment is high enough, burning keeps going. Otherwise, flash stops when fuel is exhausted
- What we see is the photosphere, not the burning layer despite that’s only ~1 m thick → X-ray burst

X-ray burst = what we see of the flash in the photosphere. General shape: fast rise, exponential decay (FRED)

Rise usually shorter than 1 sec = time when flash is progressing underneath photosphere

Peak temperature is ‘only’ 2.5 keV (10^7 K). Compare with peak temperature in burning shell: 10^9 K



Decay results from cooling of heated layer. These light curves clearly show cooling, because decay grows longer towards smaller energies. Decay is usually exponentially shaped, but can be modeled by power law

Thermonuclear runaway on neutron stars

- runaway if $d\varepsilon_{nuc}/dT > d\varepsilon_{cool}/dT$ with ε in erg g^{-1} s^{-1}
- heating is by nuclear fusion of hydrogen ([hot] CNO cycle; ε_{nuc} (:) T_8^{17}) and helium (triple-α; ε_{nuc} (:) $\exp(-44/T_8)/\ T_8^{3}$)
- cooling is by radiation through surface ε_{cool} (:) T^4.
- Ignition conditions can be calculated through:

hydrostatic balance

$$P = \frac{GM}{R^2}\frac{\Delta M}{4\pi R^2}$$

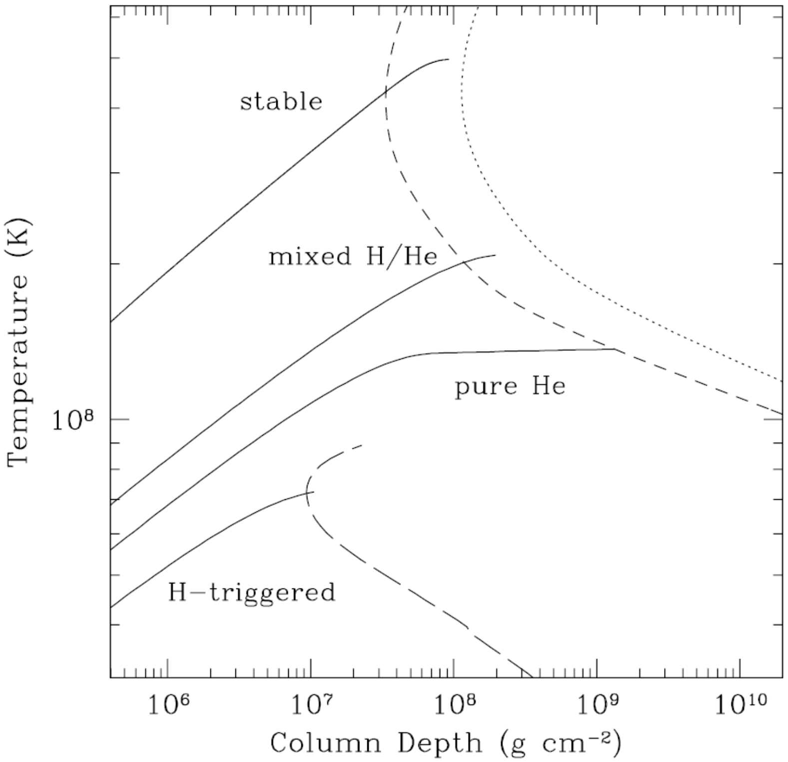
entropy

$$c_P\frac{\partial T}{\partial t} = \varepsilon - \varepsilon_\nu - \frac{1}{\rho}\frac{\partial F}{\partial r}$$

heat flux

$$F = F_C - \frac{4acT^3}{\kappa\rho}\frac{\partial T}{\partial r}$$

Ignition conditions



Important nuclear reactions in X-ray bursts

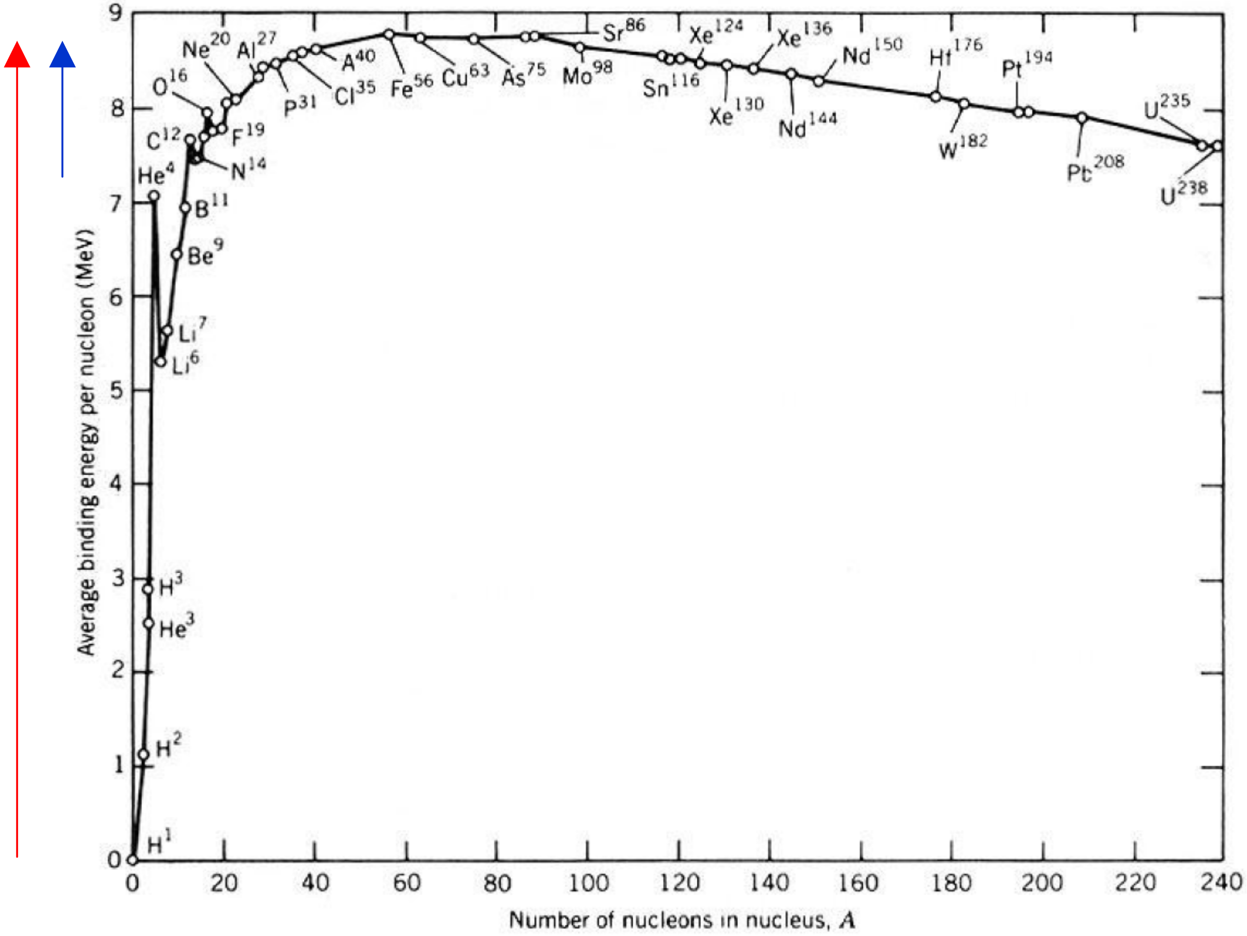
$T_6 = T/10^6$ K

- ^1H -> ^4He
  (-proton-proton (pp) cycle: most important for $T_6 < 15$; eg, Sun, NOT in X-ray bursts)
  - CNO cycle: $15 < T_6 < 80$ (7 MeV/nucleon yield)
    ε_{nuc} (:) T^{17}
  - hot CNO: $T_6 > 80$ (NB: T-independent)
- ^4He -> ^{12}C
  - 3α: $T_6 > 100$ (1.6 MeV/nucleon yield)
    ε_{nuc} (:) $T^{-3} \exp(-44/T)$
- ashes 3α -> ^{108}Te
  - rp process: $T_6 > 500$ (7 MeV/nucleon yield)

Average binding energy per nucleon in atomic nucleus

H-burning releases at maximum 8.8 MeV/nucleon. If burned till He4, 7 MeV/nucleon

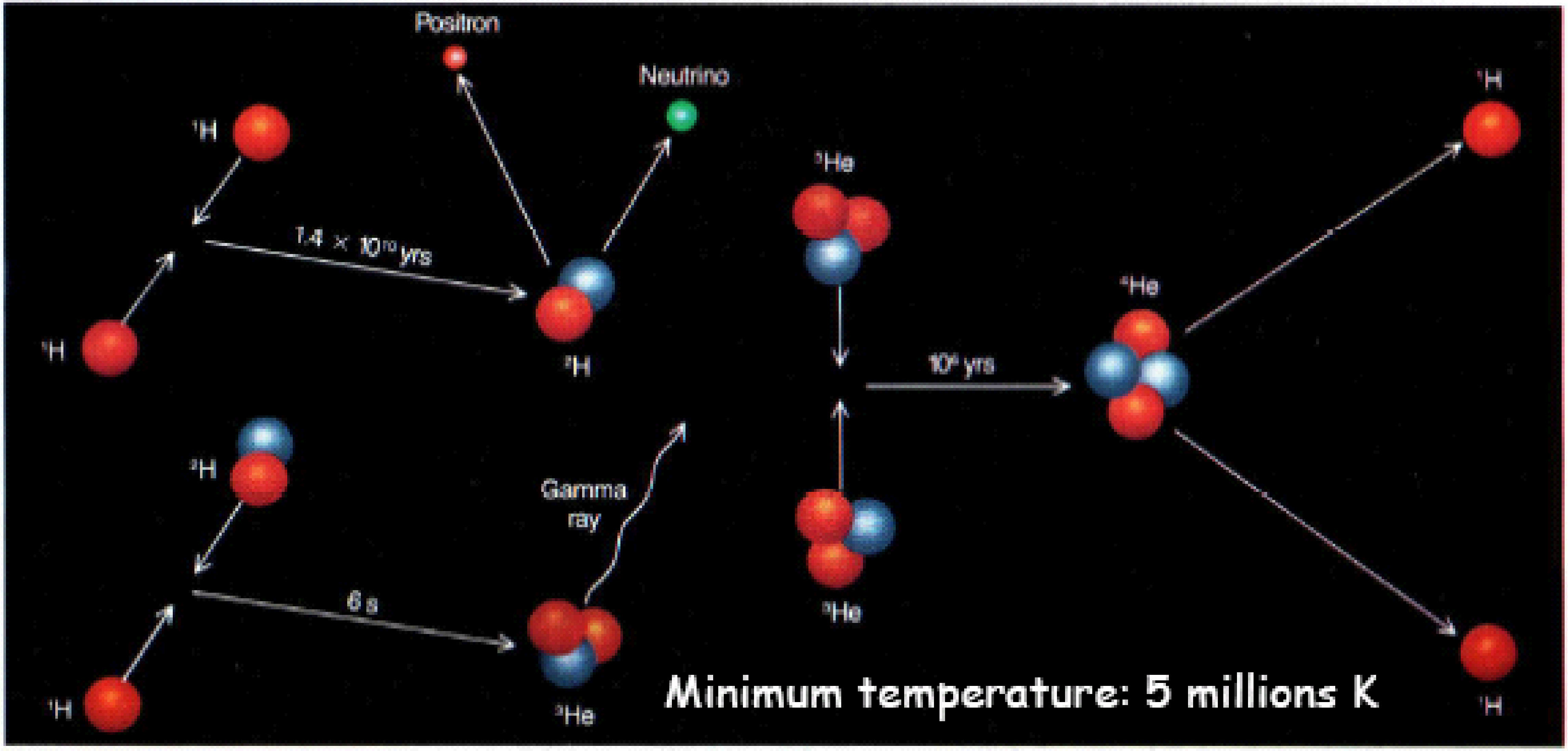
He-burning releases at maximum 1.7 MeV/nucleon. If burned till C12, 0.6 MeV/nucleon



The Power of the Star: The Proton-Proton Cycle

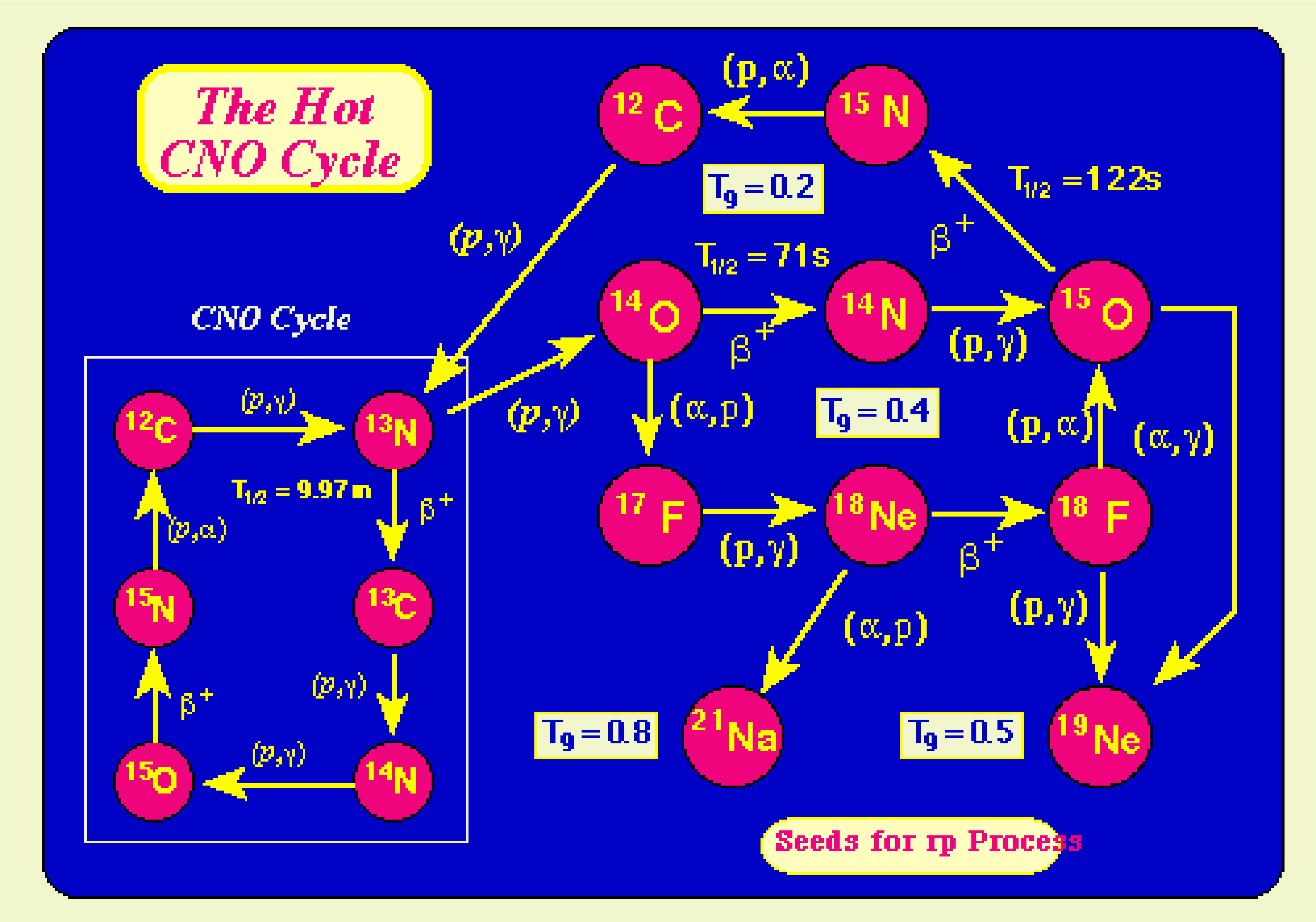
This is the primary source of energy for <u>main sequence</u> stars

In this reaction cycle, 4 protons are transformed in one He nucclei, 2 positrons, gamma rays and 2 neutrinos

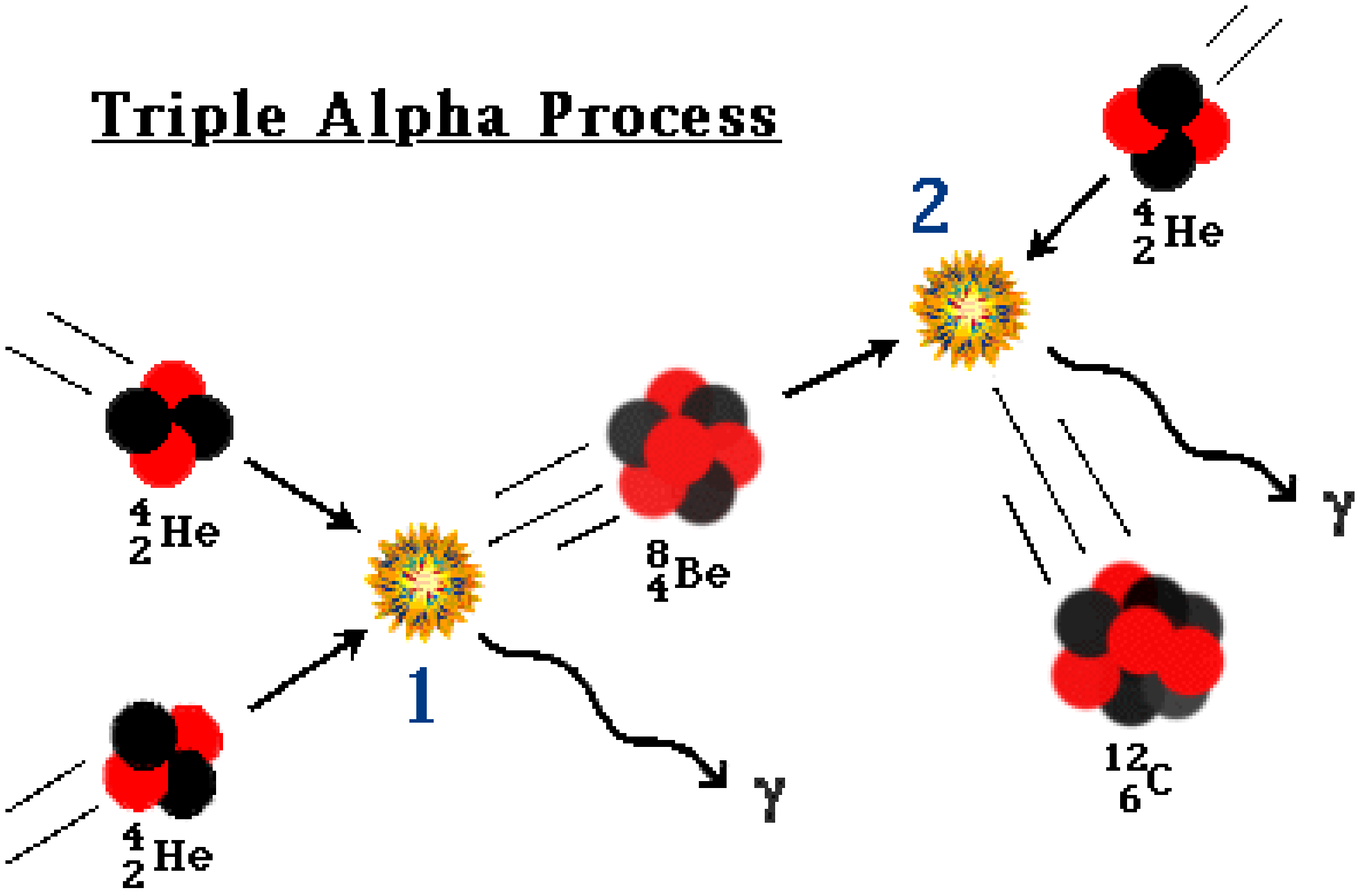


Minimum temperature: 5 millions K

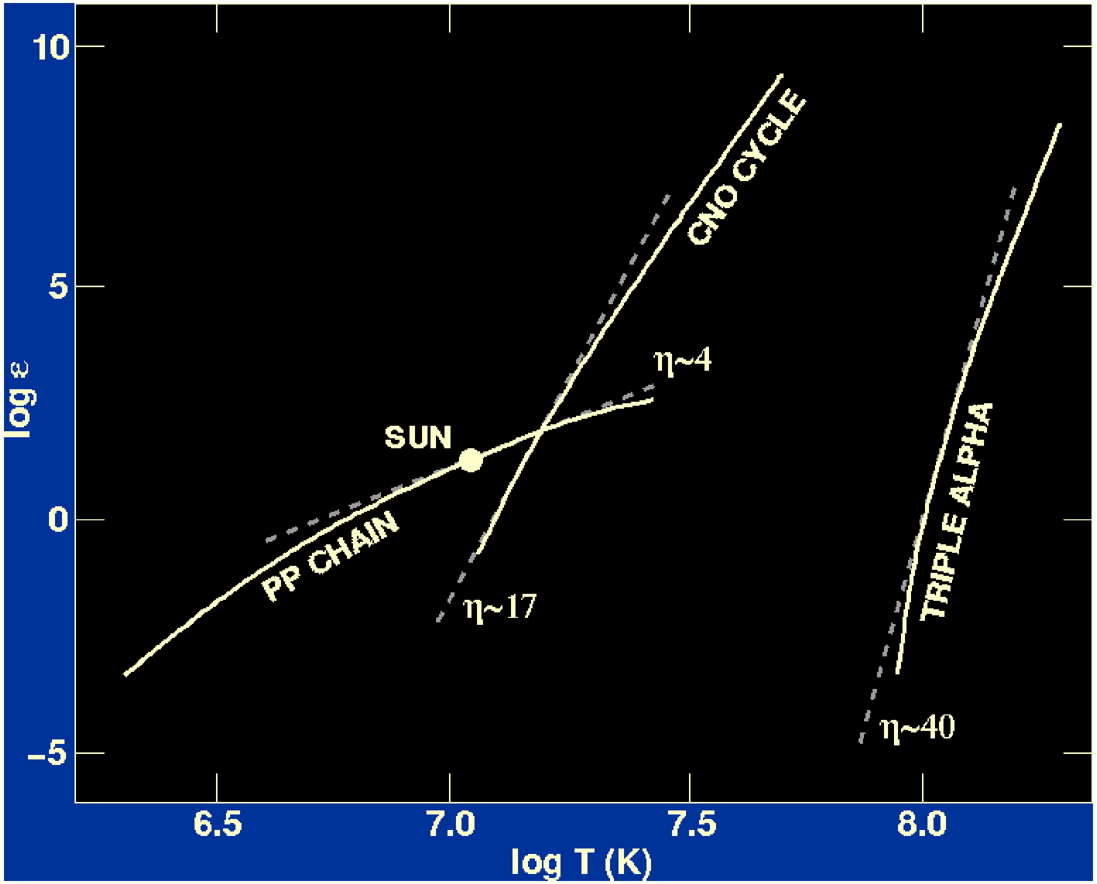
Thermonuclear shell flashes


The Hot CNO Cycle
CNO Cycle
12C
13N
13C
14N
15O
15N
(p,γ)
T1/2 = 9.97 m
β+
(p,γ)
(p,γ)
β+
(p,α)
12 C
15 N
(p,α)
T9 = 0.2
T1/2 = 122s
β+
(p,γ)
(p,γ)
14 O
14 N
15 O
T1/2 = 71s
β+
(p,γ)
(α,p)
T9 = 0.4
(p,α)
(α,γ)
17 F
18 Ne
18 F
(p,γ)
β+
(α,p)
(p,γ)
T9 = 0.8
21 Na
T9 = 0.5
19 Ne
Seeds for rp Process

At T ~ 10^8 K



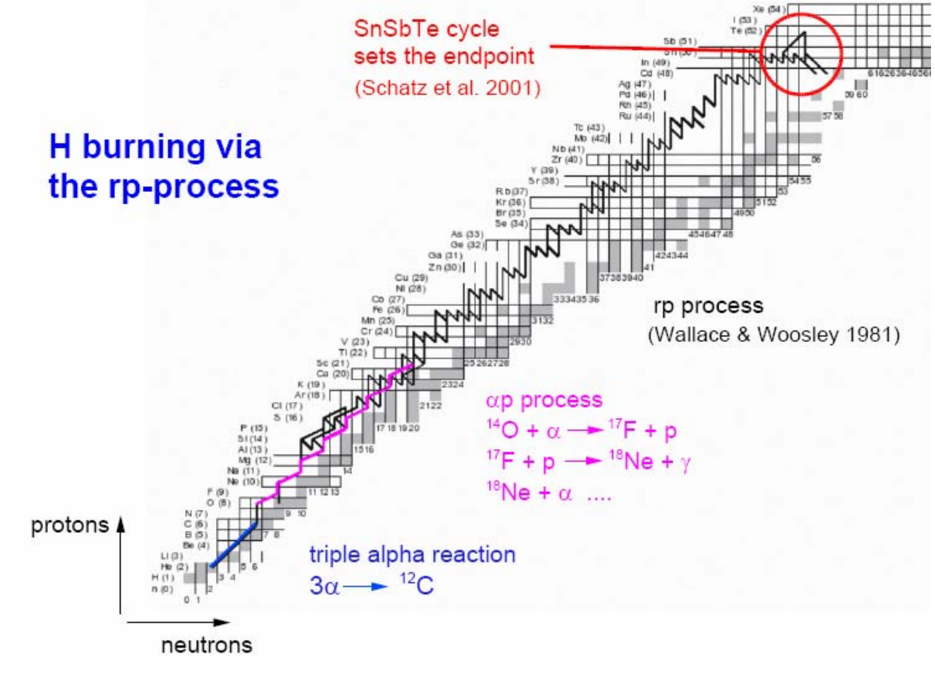
Specific nuclear energy rates as a function of temperature



X-ray burst regime

The rp process

- If the temperature rises above 10^9 K, the ashes of the helium burning will capture protons (=hydrogen from donor) and the resulting isotopes will decay through emission of a positro → rp process
- The higher the temperature, the longer the nuclear chain involved in the rp process, the heavier the isotopes produced, up to antimone (Sb, mass number ~100) which has the most stable isotopes of all elements
- T is proportional to abundance of protons
- Decay rates are relatively slow, but not well measured. Some isotopes have decay times of > 100 s → prolonges burning in a burst considerably
- The extend of the rp process is unique in X-ray bursts
- Model calculations are available as movie on web site

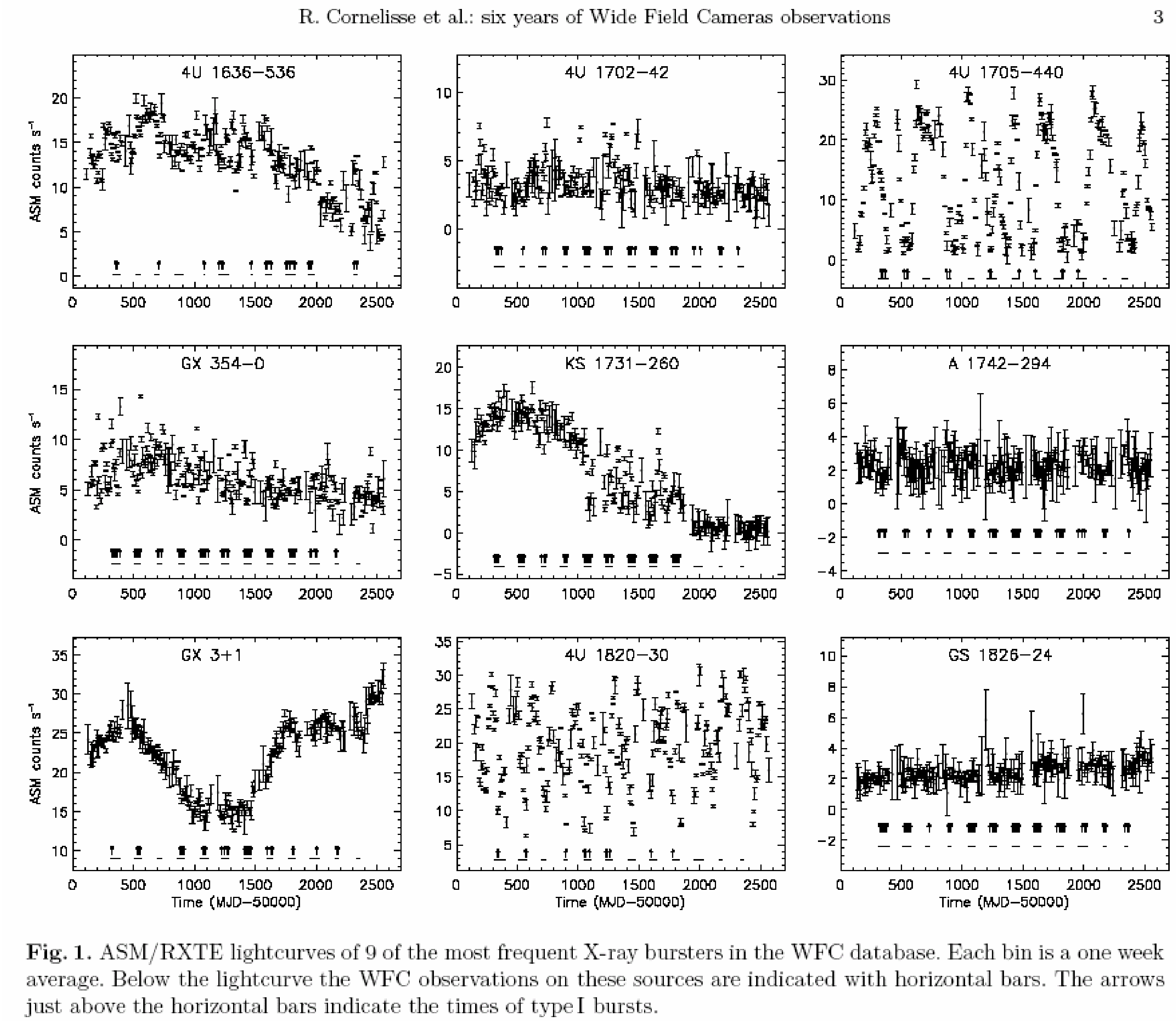


Burst regimes

- Flash ignition depends on T. If the specific mass accretion rate reaches a critical value (900 g s^{-1} cm^{-2} = about 1% of the Eddington limit for NSs), hydrogen will burn continuously in the CNO cycle, giving rise to higher temperatures and increased helium levels (note that the CNO cycle does not burn the helium to heavy elements in the amount as in the rp process). This introduces 2 major burst regimes:
  - If m-dot < 900 g s^{-1} cm^{-2} : mixed H/He flashes, with H igniting first through CNO cycle and the accreted helium burning along
  - If m-dot > 900 g s^{-1} cm^{-2} : stable H (CNO) burning produces a pure He layer which may ignite
    - If the hydrogen burns completely before flash ignition: pure He flashes
    - If m-dot > 2000-5000 g s^{-1} cm^{-2} : the accretion is faster than the hydrogen burning → residual hydrogen in the flash layer → mixed He/H flash, with an active rp process
- If m-dot > 10^5 g s^{-1} cm^{-2} : stable H/He burning; no flashes . Both H and He burn stably

(approximate numbers; threshold depend on Z_{CNO} and are for Z_{CNO}=0.01)

Bursts as a function of M-dot

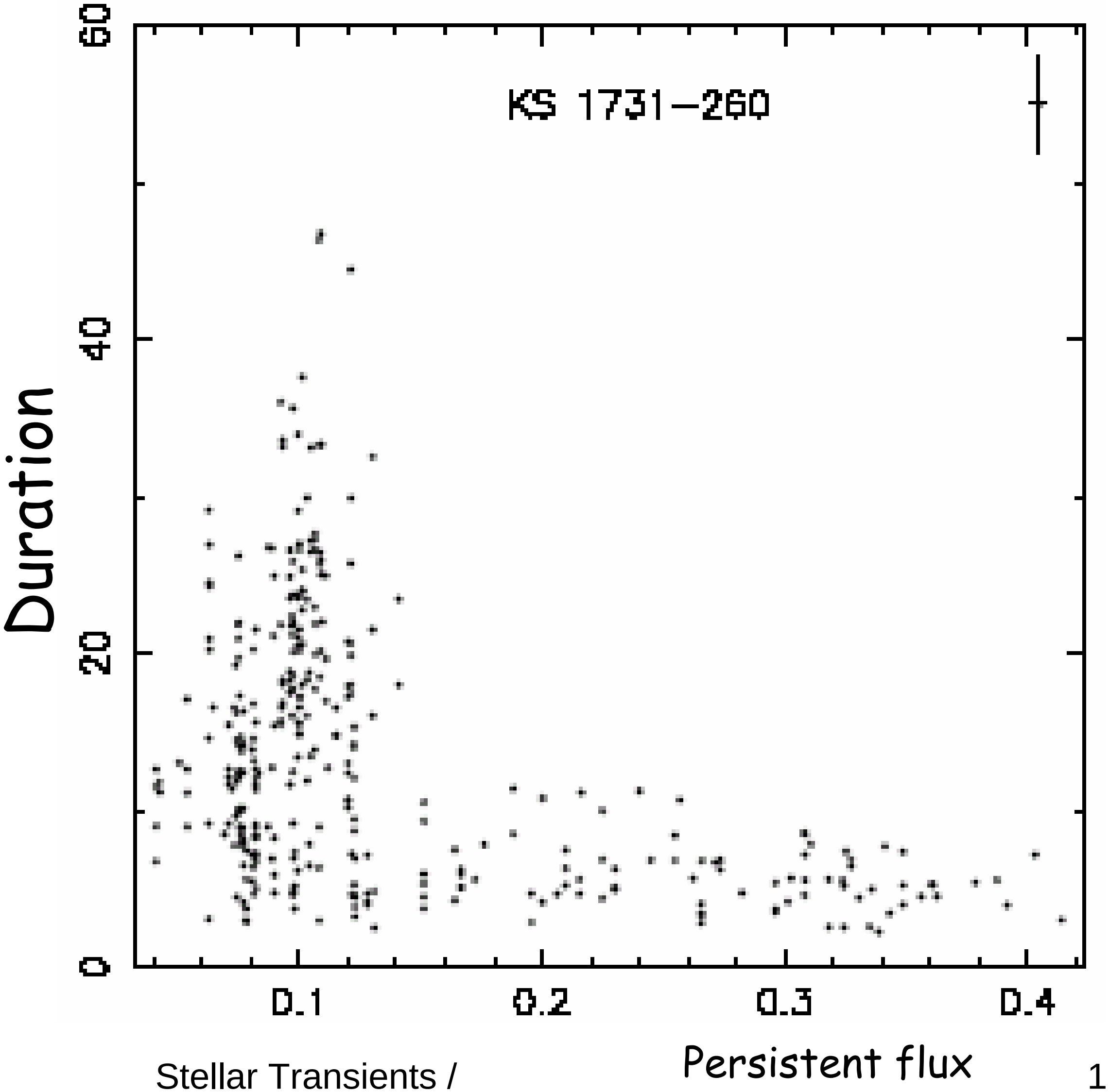


R. Cornelisse et al.: six years of Wide Field Cameras observations 3

Fig. 1. ASM/RXTE lightcurves of 9 of the most frequent X-ray bursters in the WFC database. Each bin is a one week average. Below the lightcurve the WFC observations on these sources are indicated with horizontal bars. The arrows just above the horizontal bars indicate the times of type I bursts.

Example of transition of burst regime

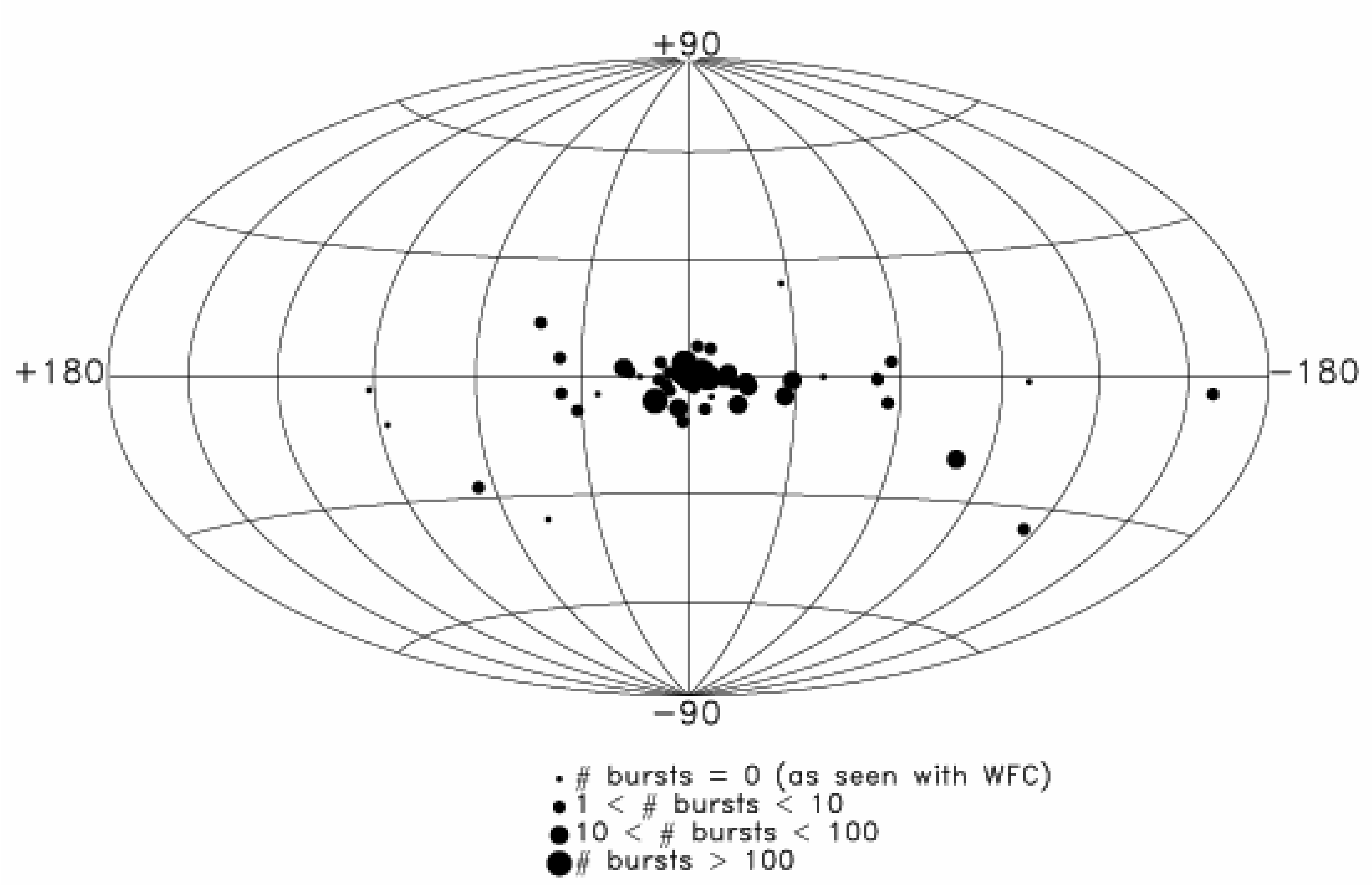
- This diagram shows measurements of burst duration versus accretion rate as measured through the flux outside bursts (='persistent' flux)
- KS 1731-260 is a nice example, because it is a transient that traversed a large range of accretion rates
- There is a discrete transition at a flux of about 0.12. This is equivalent to about 4% of the Eddington limit
- The transition is identified with the threshold for stable hydrogen burning above which pure helium bursts occur and below which bursts are prolonged by rp process (plenty of protons=H-atoms around)



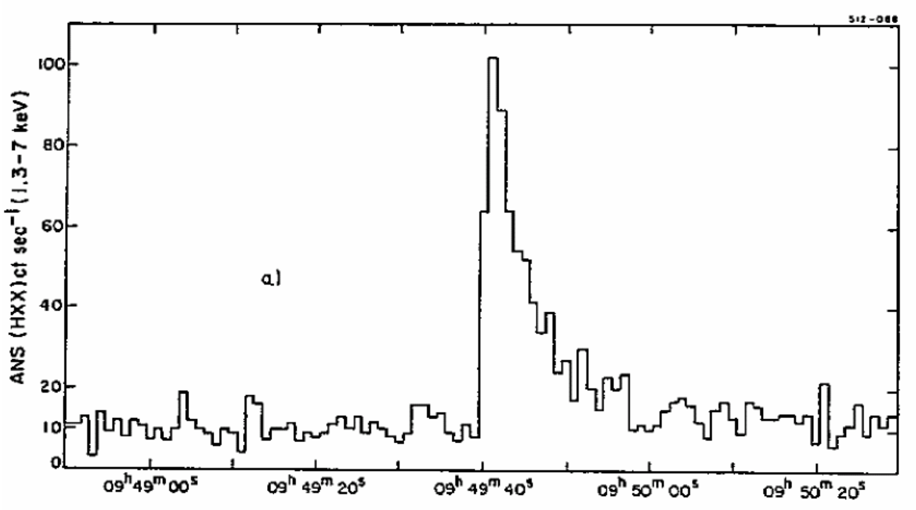
Flashes are only seen in LMXBs

- NSs in HMXBs are usually pulsars. Sometimes magnetic field strength has been measured through cyclotron line → $B \approx 10^{12}$ G
- LMXBs presumably have $B \approx 10^{8}$ G.
- The higher B in HMXBs channels the accretion to small areas at the poles (therefore, we see a pulsar) → while the global accretion rates in LMXBs and HMXBs (in $g\ s^{-1}$) are similar, the specific rates (in $g\ s^{-1} cm^{-2}$) differ by large factors (~100?) → both hydrogen and helium are burned continuously and not in flashes

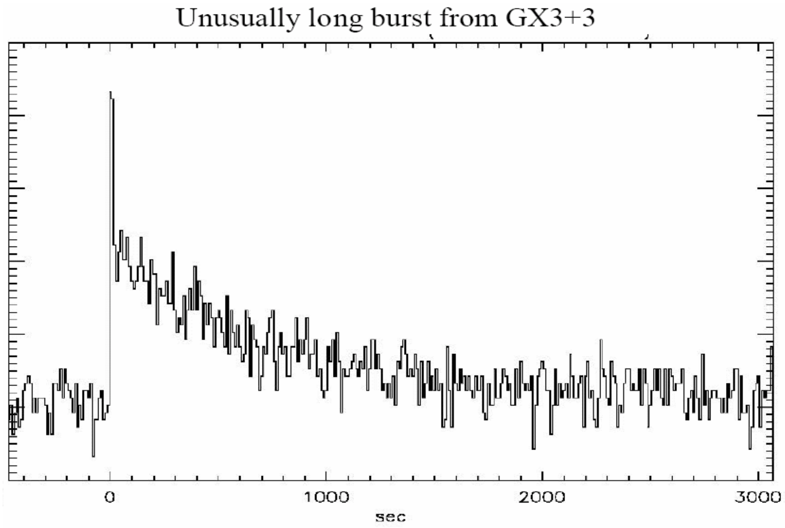
Galactic map of bursters → strong concentration in bulge

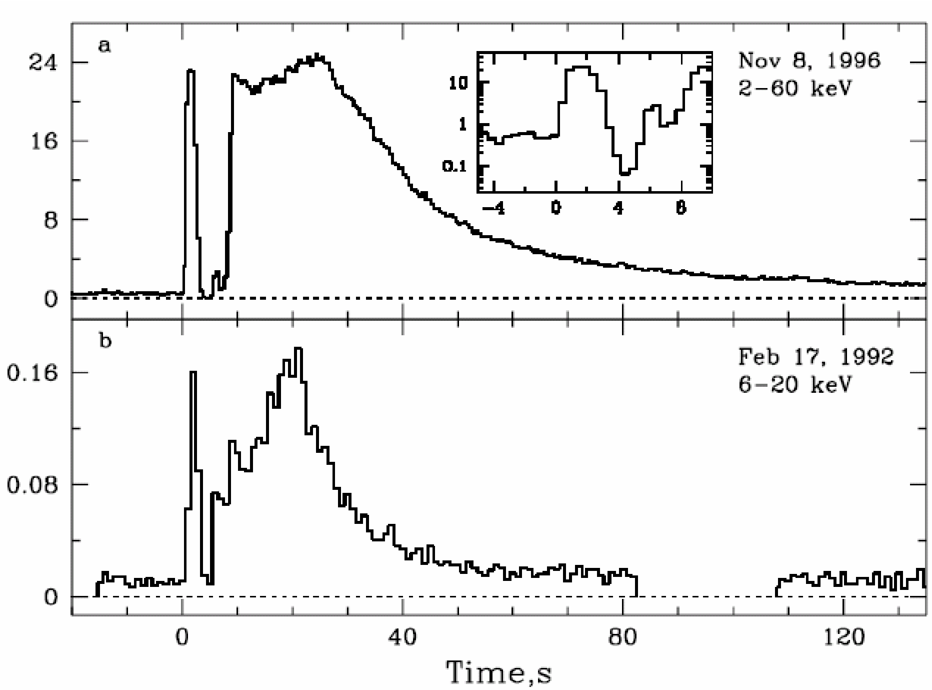


X-ray burst time profiles → mostly FRED with few % exceptions

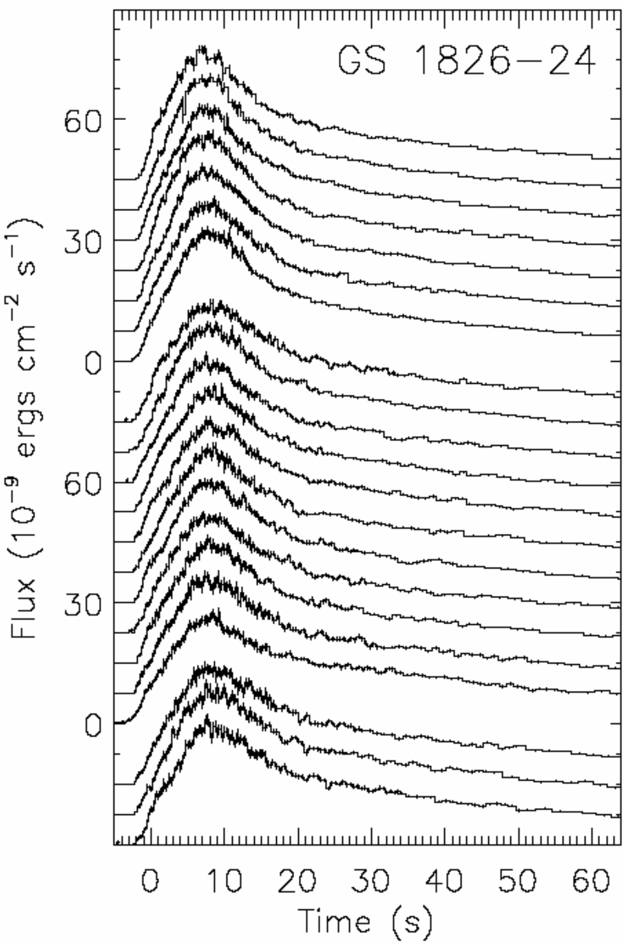


Discovery X-ray burst, detected with Dutch 'ANS' satellite from 4U 1820-303 globular cluster NGC 6624 (Grindlay, Heise et al. 1976)


Unusually long burst from GX3+3

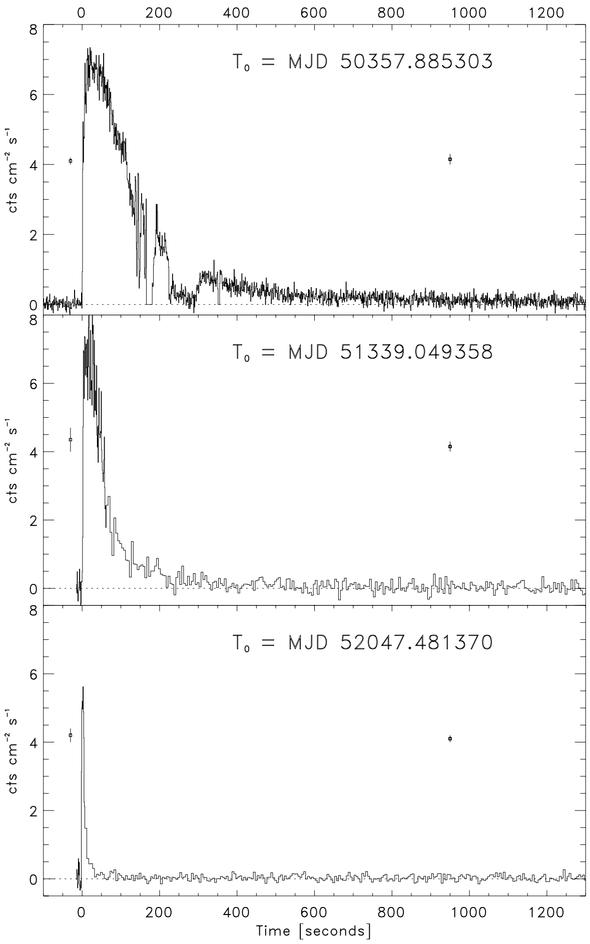


Time profiles (II)



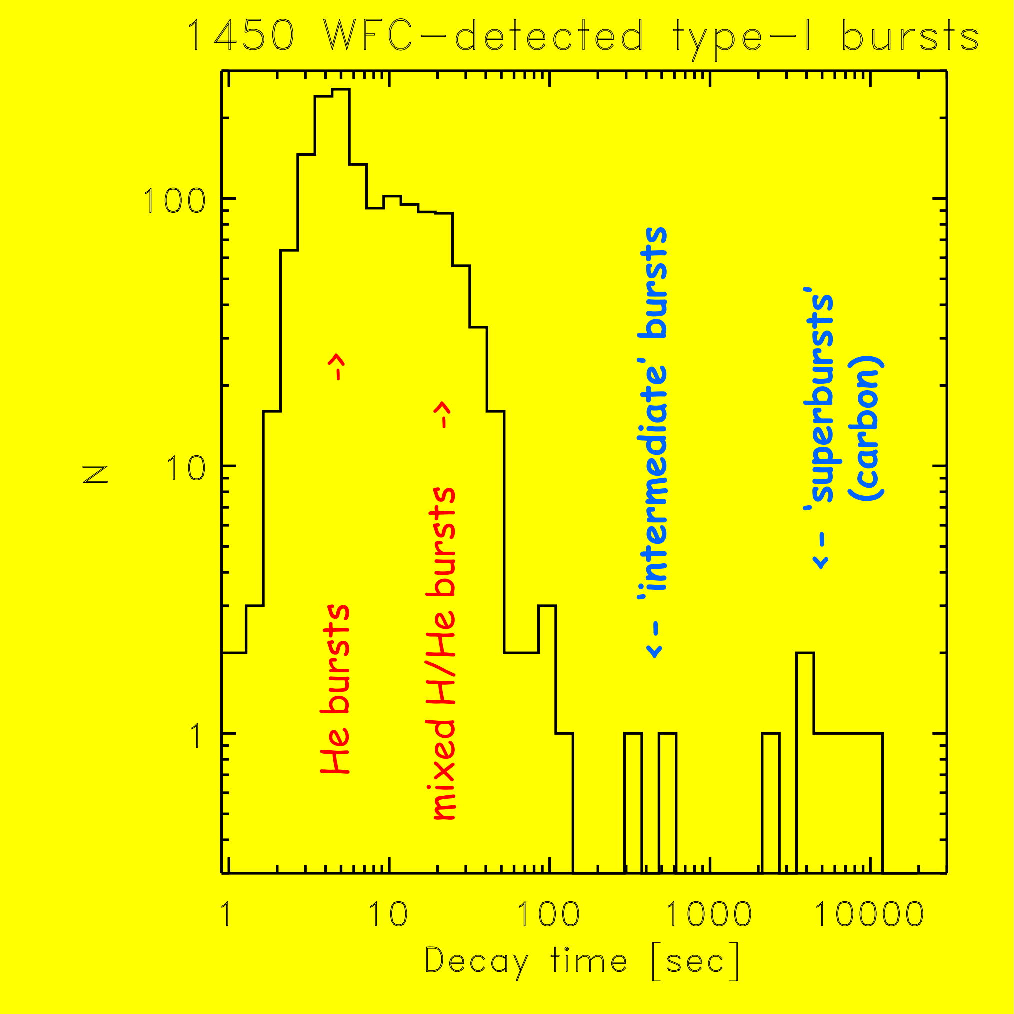
X-ray bursts almost identical in one source <u>for years</u>,

but highly variable in another



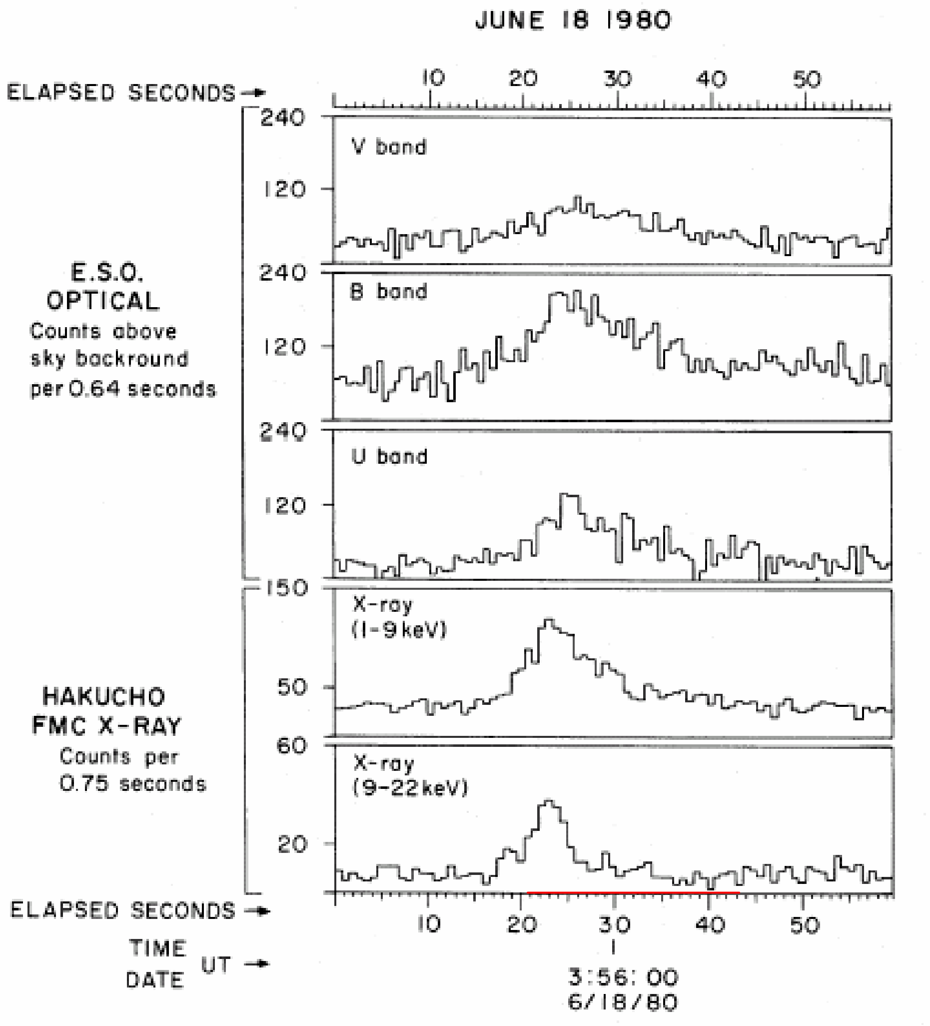
X-ray burst duration histogram

- In the histogram on the right the e-folding decay time of burst tails has been taken as burst duration. Note the logarithmic scales
- Most bursts are short (less than 10 s). These are the pure helium bursts (remember that H-burning is generally slow)
- The next most frequent bursts are mixed H/He bursts
- Very rare kinds of bursts are intermediate bursts from ultracompact X-ray binaries (with H-deficient WDs as donors) and superbursts (see later)



Optical detections

- X-ray bursts are also detected in the optical. Some bursters have even been discovered in the optical
- When simultaneous X-ray measuments are available, the optical emission usually lags by a few seconds and is smeared out by a few seconds
- This is consistent with reprocessing of X-rays emitted at the NS surface by the accretion disk (which has a size of order light-seconds)

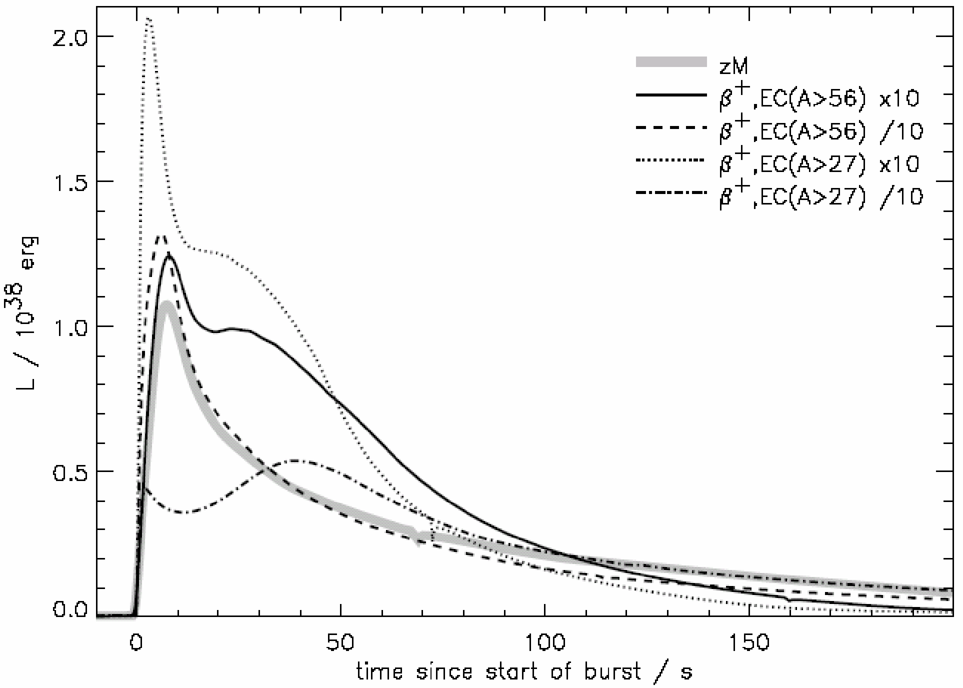


Lawrence et al. 1983

General burst profile dependencies

- 3-alpha process is fast (burns all fuel in less than 1 s)
- rp-process is slow and can prolong burning for hundreds of seconds. Duration depends on amount of H
- pure cooling decay is proportional to the thickness of the flash layer. This thickness depends on ignition condition (-> P and T) and varies between 10 s and thousands of s
- plateau indicative of super-Eddington luminosities -> energy stored higher up in gravitational well and released when flash luminosity has sufficiently diminished -> may endure for minutes
- further complications may arise from convection (e.g., slow rises)
- considerable uncertainties exist in nuclear data, specifically reaction rates in some of the >100 processes in the rp chain

Detailed understanding of profiles is absent



These profiles show model calculations of the same flash layer, but with different rp beta decay rates within experimental uncertainties

Woosley et al. 2003

X-ray spectra

- X-ray spectra are to a high degree consistent with a black body. For bursters for which the distance is independently known (for instance, if they are in globular clusters), the spherical radii determined from the spectral fits (after all Planck says F (:) $R^2 T_{eff}^4$) are consistent with those for NSs (~10 km). This is considered proof that bursts occur on NSs.

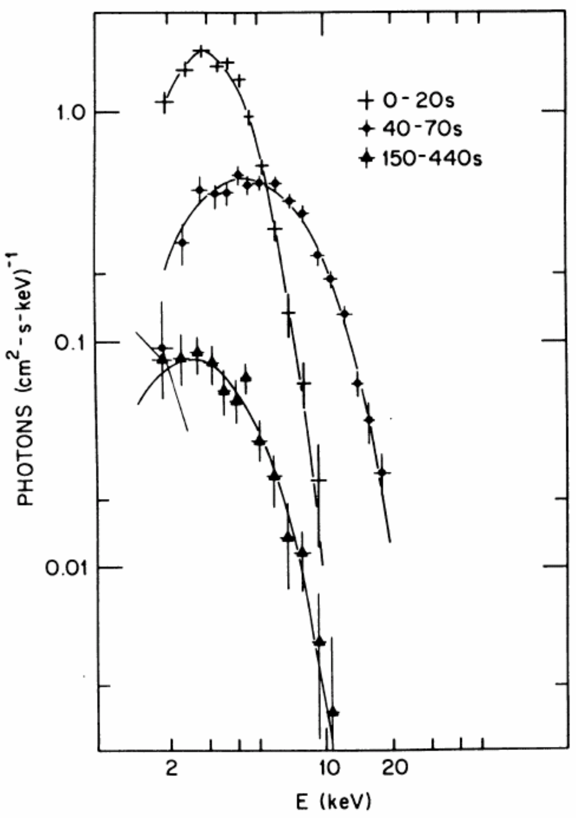


Fig. 3.9. Average spectra, during three time intervals, of a long burst which probably came from 1724–307 in the globular cluster Ter 2. The solid curves are blackbody fits to the data. The values for kT are ~0.9 keV (0–20 s), ~2.3 keV (40–70 s), and ~1.2 keV (150–440 s). For assumed spherical emission and source distance of 10 kpc the blackbody radii were ~100 km during the first 20 s of the burst, and ~15 km thereafter. This figure is from Swank *et al.* (1977).

Spectral shape -> simple black body

Planck function times interstellar absorption:

$$F_{bb}(E)\,\mathrm{d}E = KE^3[\exp(E/kT_{bb}) - 1]^{-1}\exp[-\sigma(E)N_\mathrm{H}]$$

E = photon energy; sigma = cross section per H-atom, taking into account photo-electric absorption of a gas with cosmic abundances; NH = column density of H-atoms per cm^2 in the line of sight

Bolometric correction from bandpass E1-E2:

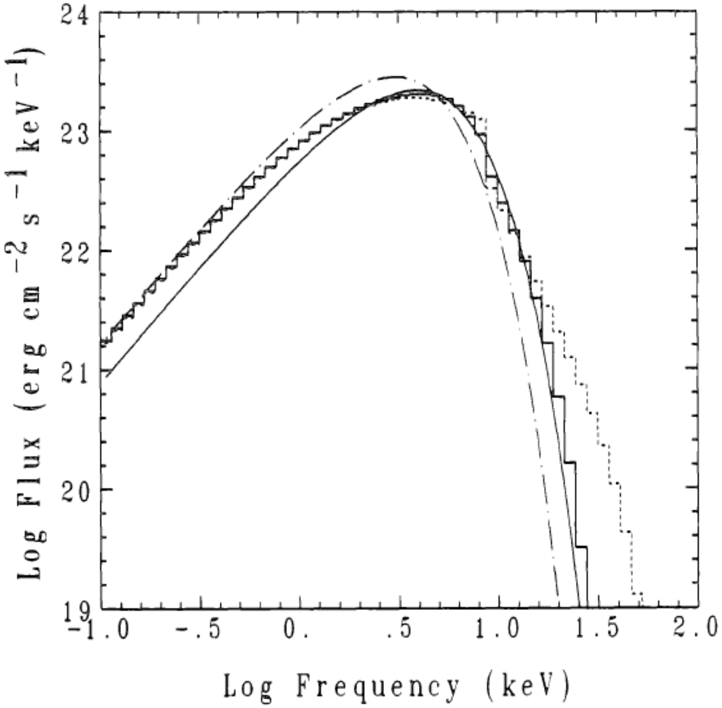
$$\int_0^\infty F_{bb}(E)\,\mathrm{d}E / \int_{E_1}^{E_2} F_{bb}(E)\,\mathrm{d}E$$

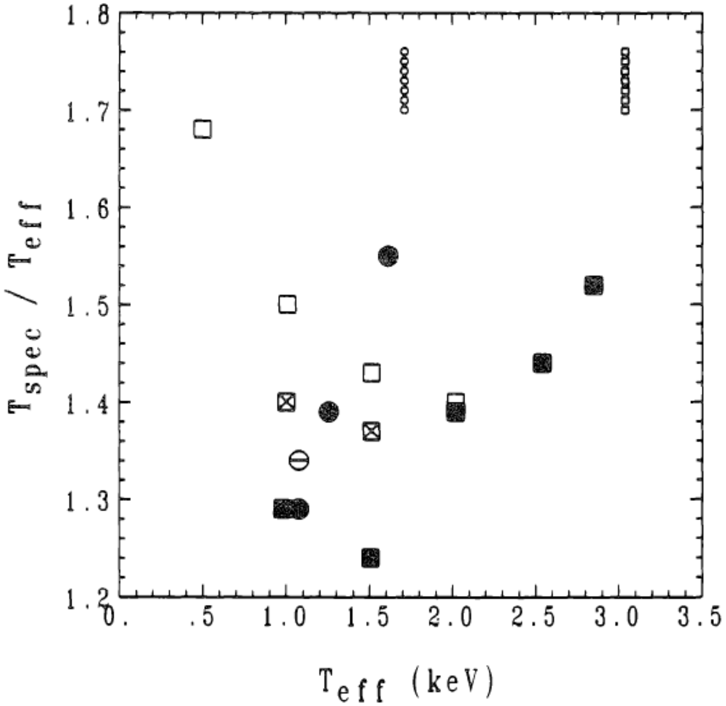
(T,d) -> radius or (T,R) -> d:

$$R_{bb} = d\,(F_\mathrm{bol}/\sigma T^4)^{1/2}$$

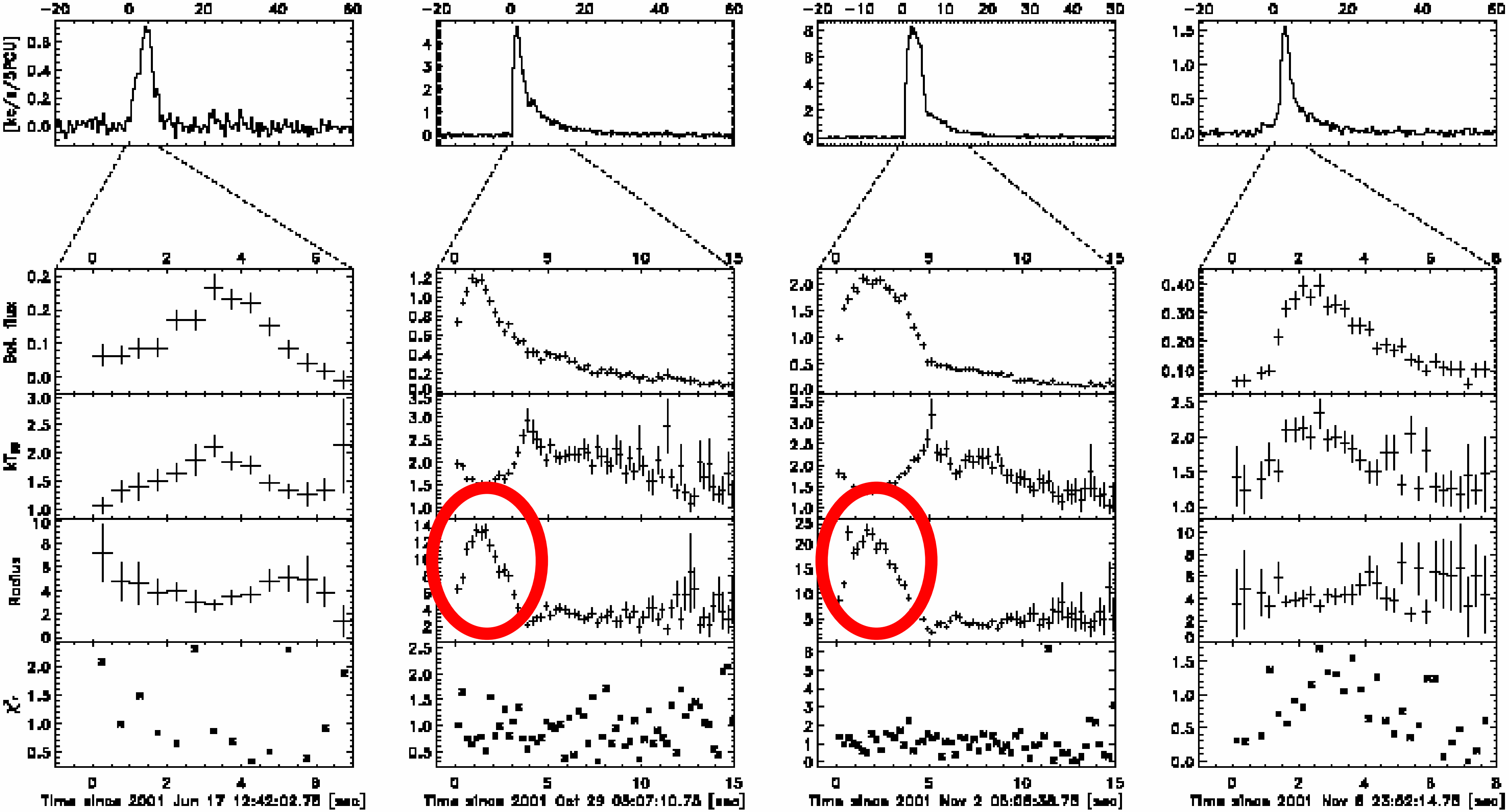
Deviations from black body

In the NS photosphere there is a hot plasma. The flash light is Compton up-scattered by the electrons → measured Teff are not true Teff and the spectrum is hardened → call measured value 'color' temperature. Below are results of model calculations for this effect by London et al. (1984). The plot left shows the effect on the spectrum. The plot right shows T_{color}/T_{eff}





Time-resolved X-ray burst spectroscopy - example of GRS 1747-312



Note clear radius expansion!

Stellar Transients /
Thermonuclear shell flashes

Photospheric radius expansion – an extreme example

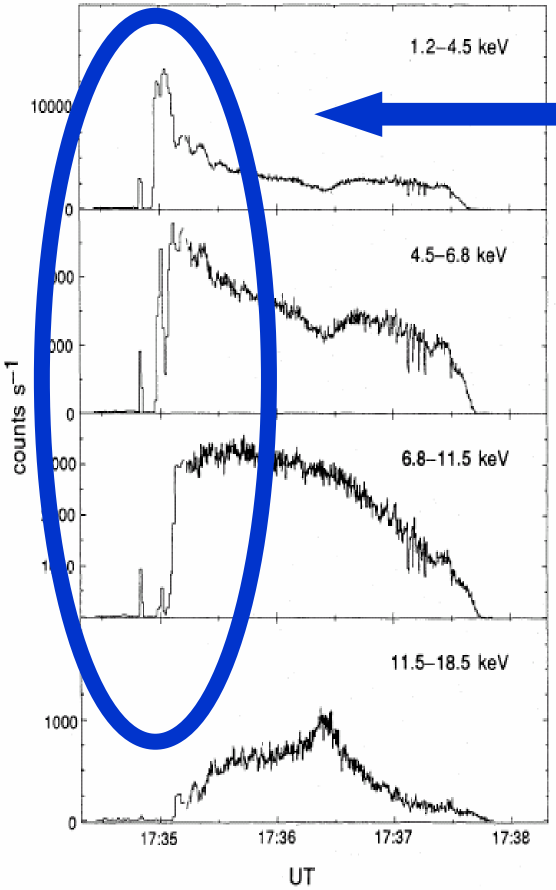
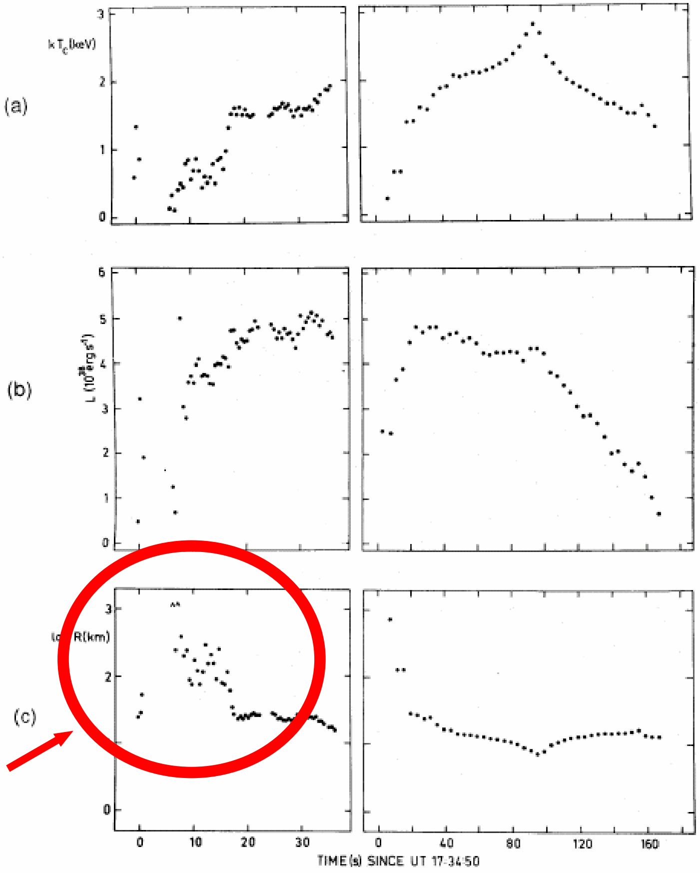


Fig. 3. Intensity profile of the X-ray burst from 2129+11, in four different energy channels. The precursor of the burst occurred near UT 17:34:50; it is separated from the main part of the burst by ~ 6 s in the (1.2–4.5) keV band, and by ~ 17 s in the (11.5–18.5) keV band. During the first ~ 30 s of the burst intensity oscillations occur, which are anticorrelated in the low-and high-energy bands. Near the end of the burst a series of four brief dips occur, which do not show a significant energy dependence. Earth occultation starts at ~ UT 17:37:10.

Expansion at a constant Eddington Luminosity → $F = K R^2 T_{eff}^4$ is constant and R increases, T_{eff} decreases. Sometimes this pushes spectrum to outside X-ray regime and we loose the X-ray signal



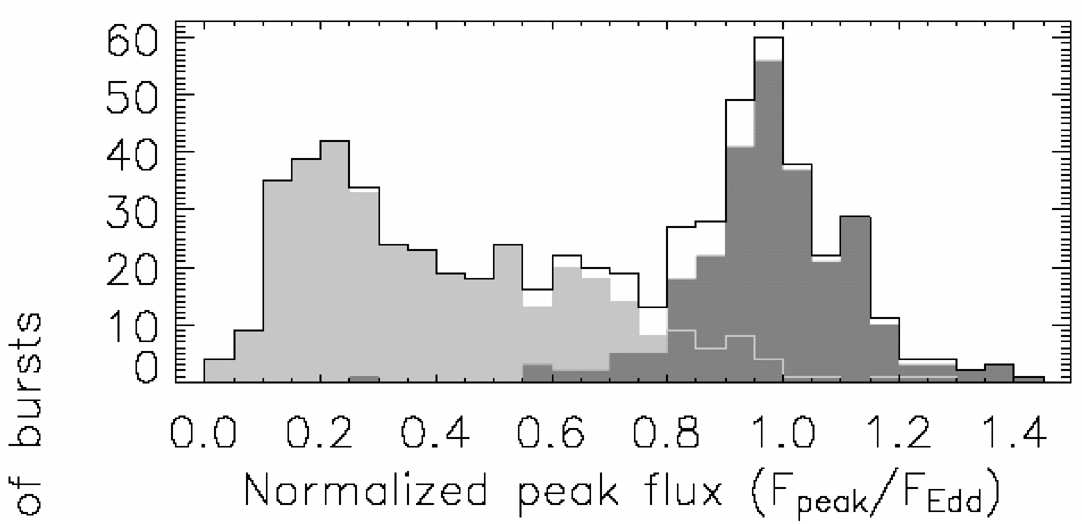
Expansion from 10 km to $>10^3$ km

Fig. 4. (a) Variation of the color temperature $kT_{c\infty}$ (in keV), as obtained from blackbody fits to the burst spectra observed in consecutive 0.5-s time intervals. The intervals are shown at the full 0.5-s time resolution for the initial part of the burst (left panel); in the right panel the results for eight consecutive spectra have been averaged, and are displayed with a time resolution of 4 s. (b) similar as (a), for the (0.01–30 keV) luminosity (see text); the figure is for an assumed distance of 10 kpc. (c) Similar as (b), for the blackbody radius (see equation 2).

van Paradijs et al. 1990

Is burst peak luminosity a standard candle?

- The **Eddington luminosity limit** is
  $L_{edd} = 4\pi GMc/\kappa$ with $\kappa=0.2(1+X)$ cm^2/g
- For now, we forget about the significant curvature of space-time close to the NS surface: $L_{edd,\infty}=L_{edd}/(1+z)$ with redshift factor $1+z=[1-2GM/(Rc^2)]^{-1/2}\approx 1.3$ for a NS
- For $M=1.4\ M_\odot$ and $X=0.734$ (solar hydrogen abundance in mass) this is 2.1×10^{38} erg s^{-1}, for $X=0$ (hydrogen-deficient donor) it is 3.7×10^{38} erg s^{-1}
- The Eddington limit is reached during radius-expansion bursts
- Therefore, one may expect that the peak flux of radius-expansion is a standard candle → constant per source and between 2.1 and 3.7×10^{38} erg s^{-1}



Galloway (2005)

Left is the histogram of burst peak fluxes normalized to the average peak flux of radius-expansion bursts per source. Light grey histogram for non-radius-expansion bursts, dark grey for radius-expansion bursts

→

Peak luminosity of radius-expansion bursts shows a spread with a standard deviation of 15%, approximately a standard candle

Where does 15% spread come from?

- From the perspective of the fixed Eddington luminosity per source, it is odd that there is this spread
- Possible causes:
  - varying X due to varying levels of accretion rate
  - Varying levels of reflection off a warped accretion disk. The left figure shows peak flux as a function of burst number in a prolific burster. The right figure shows the periodogram of the peak flux. There is a suggestion of a periodicity → precession of a warped disk? (this is just a single case)

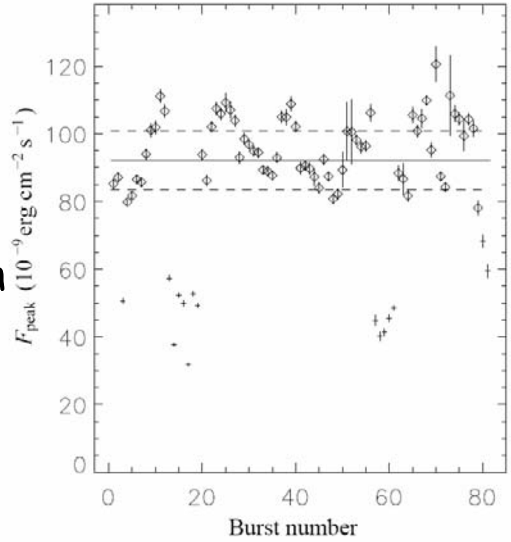


FIG. 3.— The peak fluxes $F_{\rm peak}$ (excluding the pre-burst persistent emission) of 81 X-ray bursts from 4U 1728−34 as a function of burst number, which increases monotonically with time. The horizontal solid line shows the mean peak flux of the radius expansion bursts (diamonds), while the dashed lines show the 1σ limits. Error bars indicate the 1σ uncertainties on each measurement.

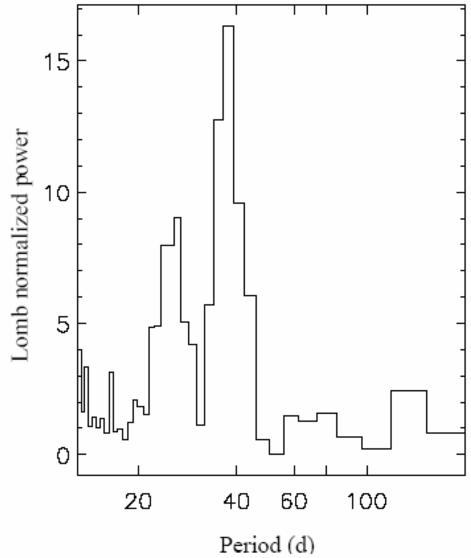
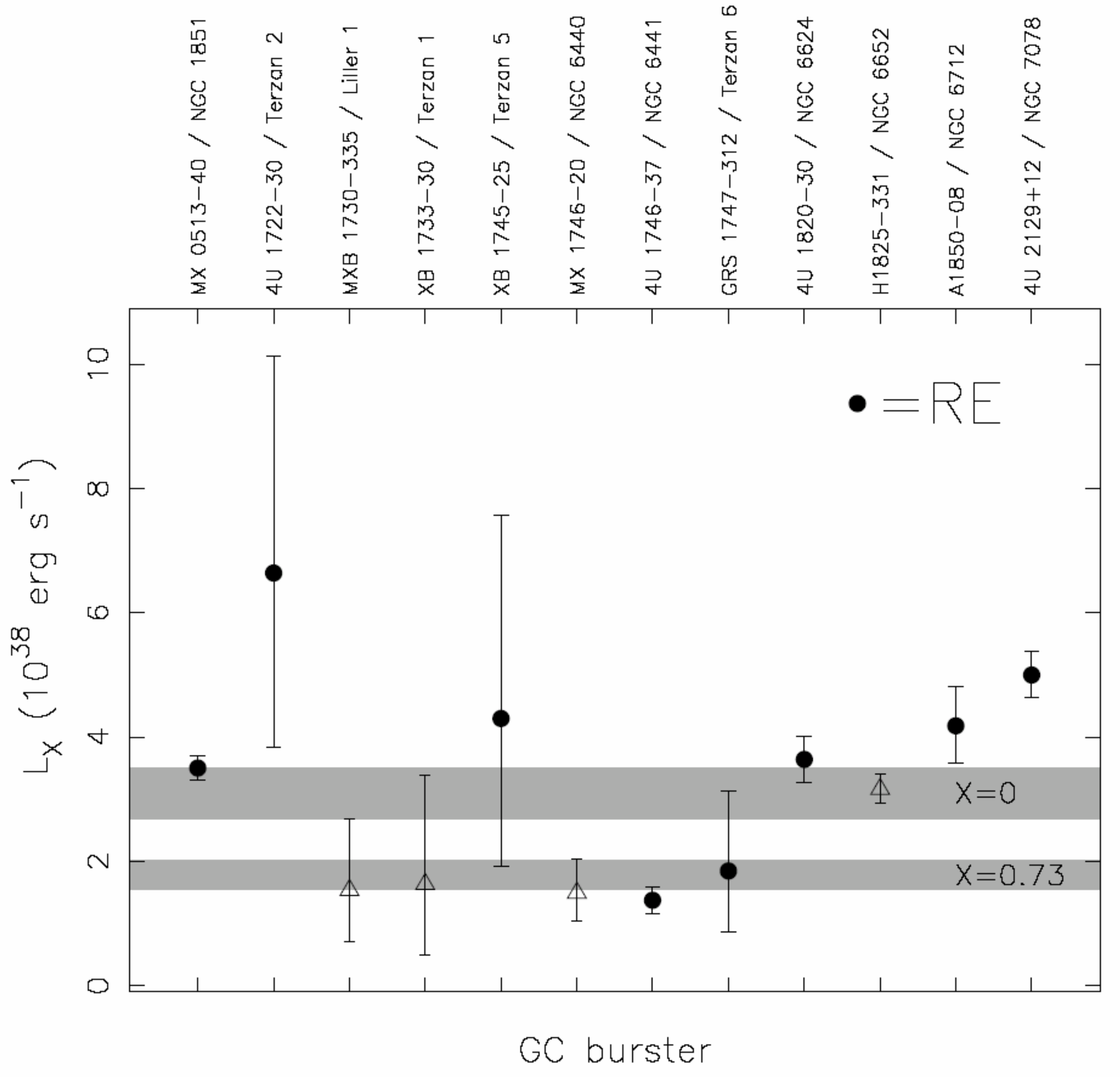


FIG. 4.— The Lomb-normalized periodogram of the time variation of the peak fluxes $F_{\rm peak,RE}$ from 50 radius-expansion bursts occurring before MJD 51500 (of 66 radius expansion bursts in total). Note the indications for excess power between 30–60 d; the most significant peak is at 38 d, with a Lomb power of 16.3.

Galloway et al. 2003

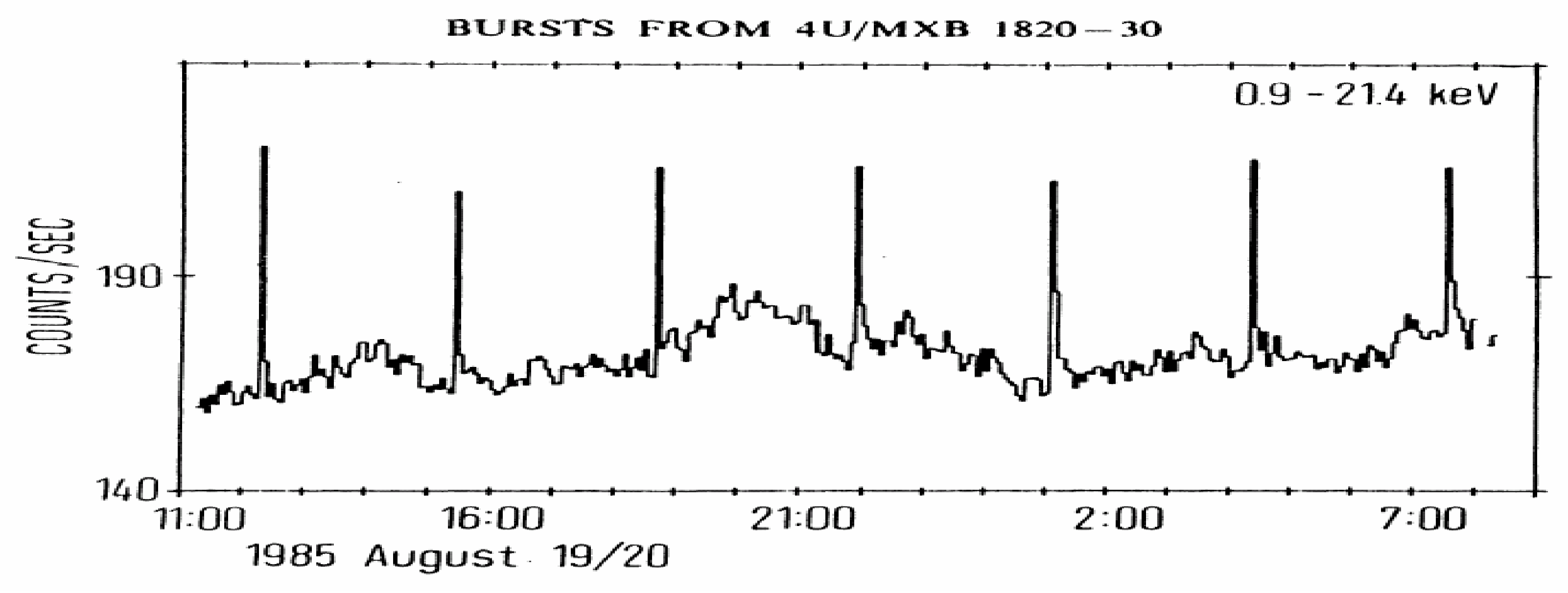
Another standard candle test and distance determinations



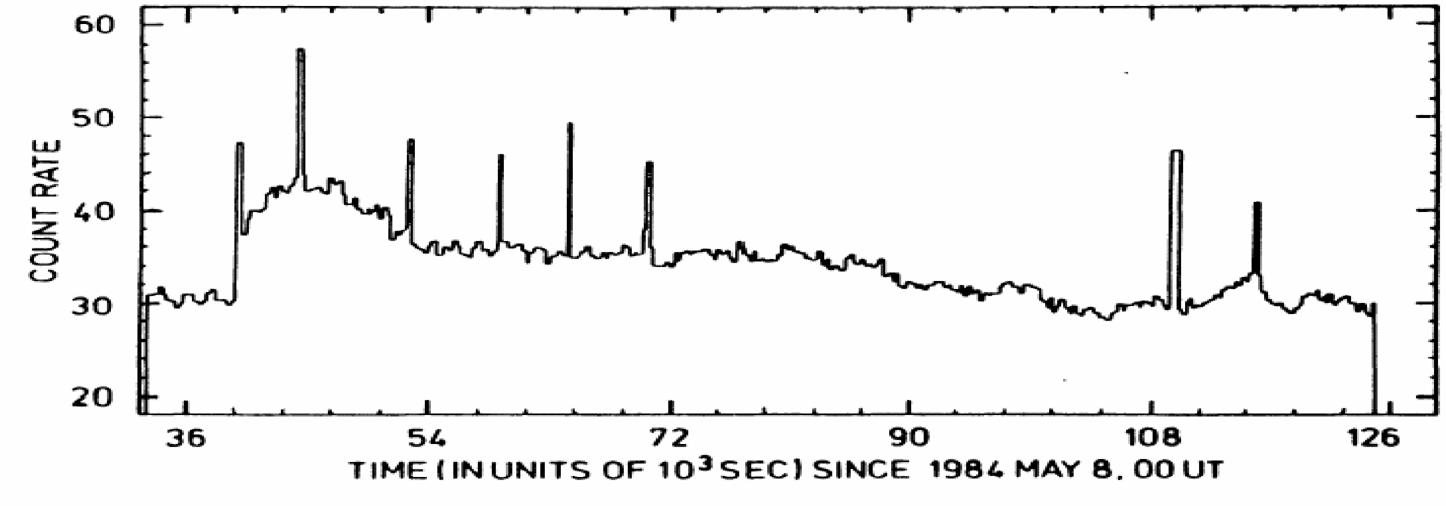
- There are 12 X-ray bursters in globular clusters with independent distance estimates
- Therefore, we can measure the peak luminosity of radius-expansion bursts
- They are roughly consistent with expected values (grey bands)
- So, if we know X and thus L_{edd}, and measure the bolometric peak flux of a radius-expansion burst, we can **determine the distance**: $F_{bol,peak}=L_{edd}/4\pi d^2$ with an uncertainty of roughly 20%

Kuulkers et al. 2003

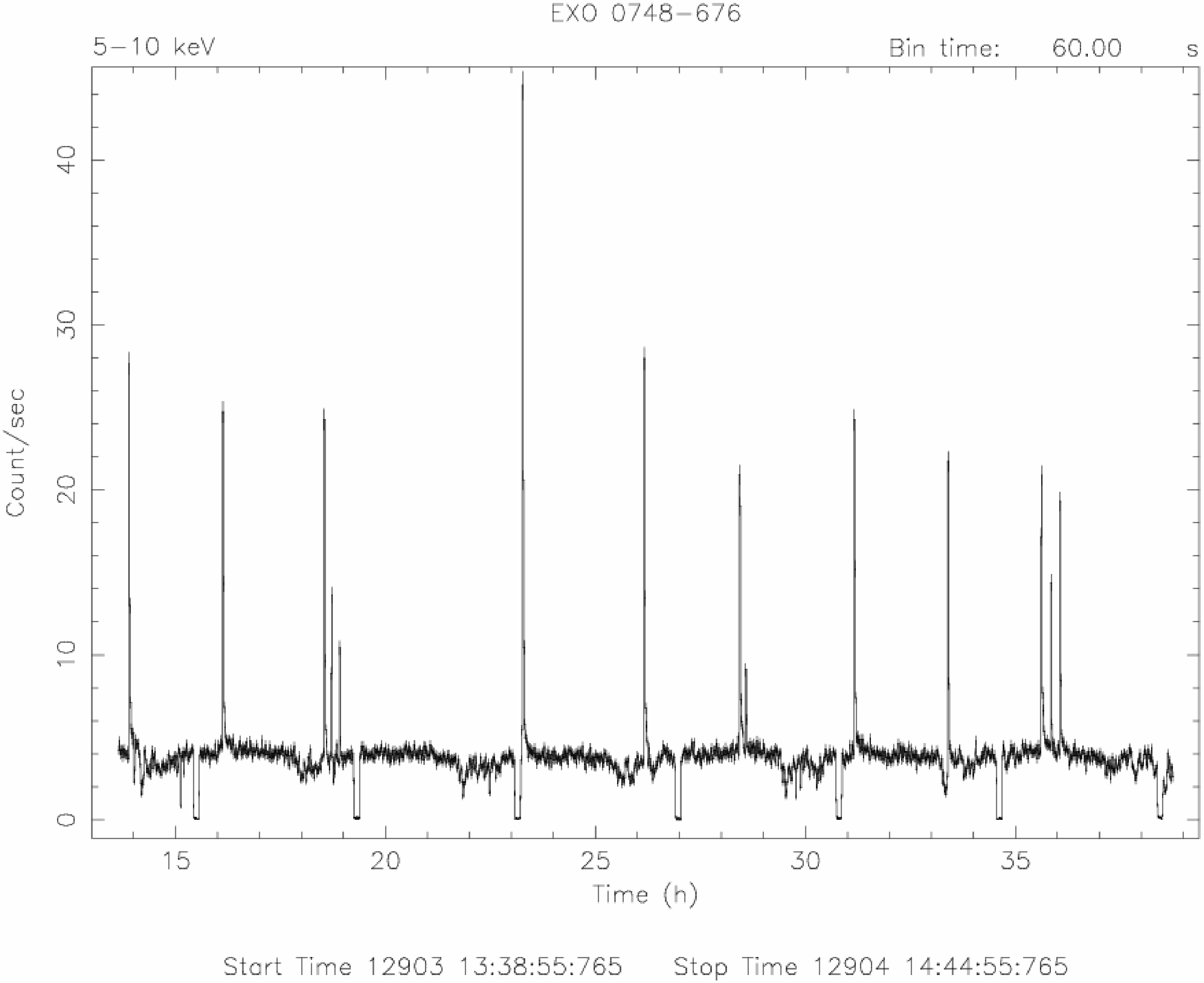
Recurrence, examples 1 and 2



4U 1636-536



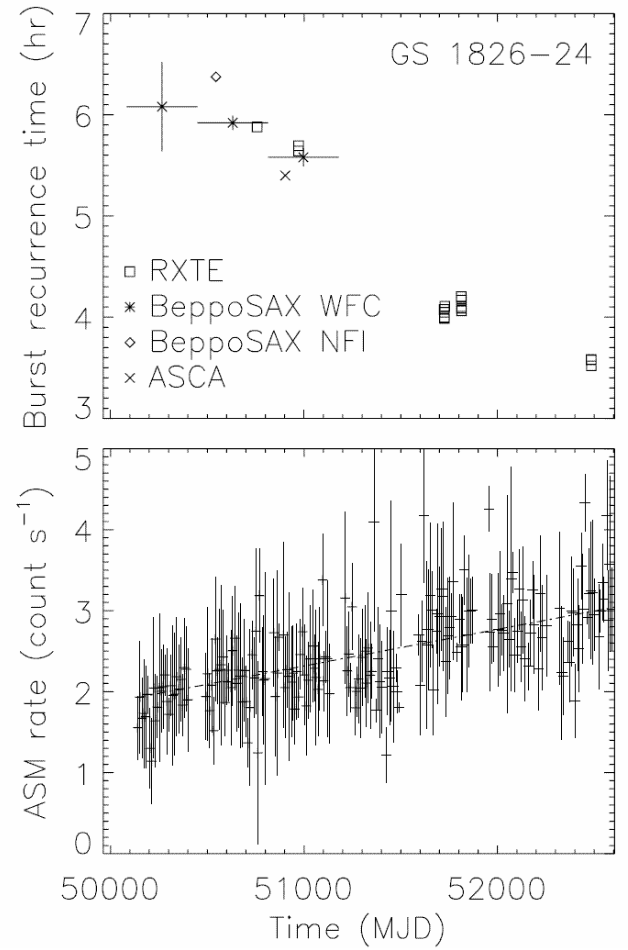
Recurrence, example 3

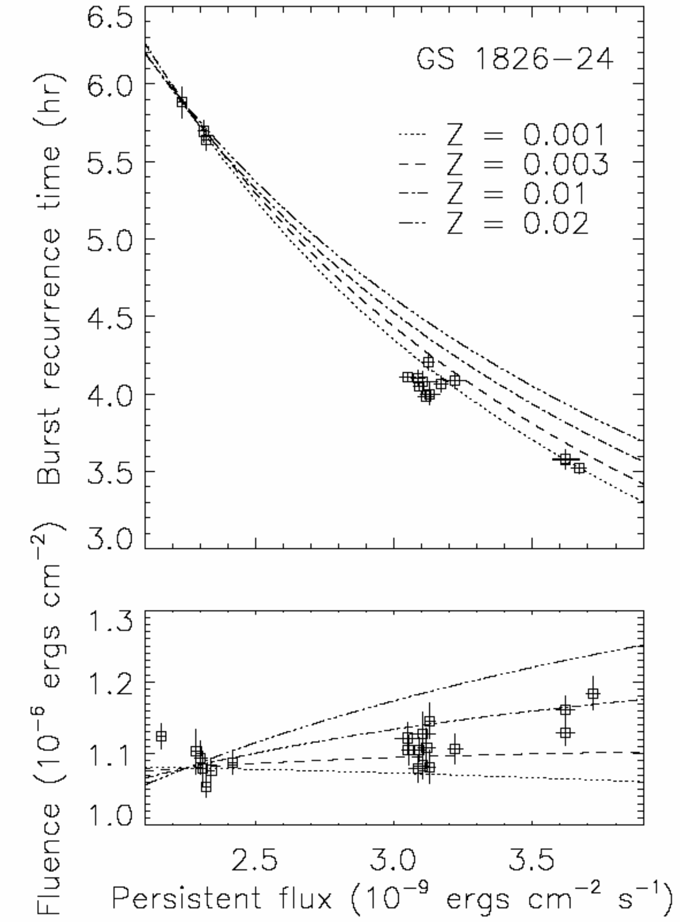


This example shows again recurrence times of a few hours, but also simultaneously very short recurrence times of about 10 mins

Boirin et al. (2007)

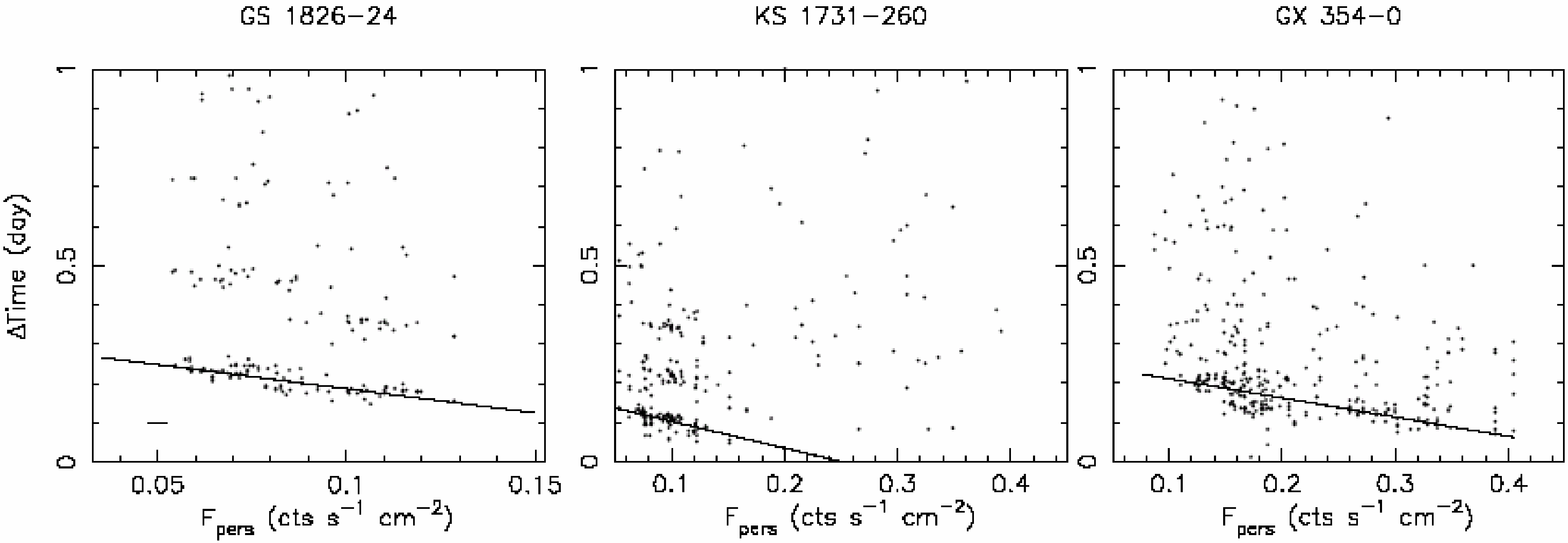
GS 1826-24 – the ‘clocked’ burster -> quasi periodic bursts for many years





Galloway et al. (2004)

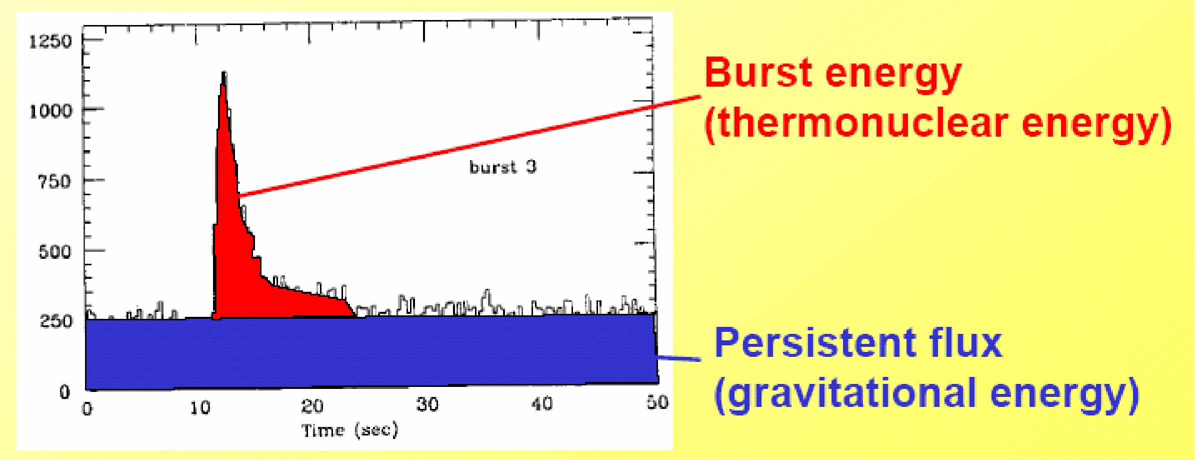
Other ‘clocked’ bursters



From Cornelisse et al. 2003

The alpha parameter

α = fluence in persistent emission since previous burst / fluence in burst → easily measurable

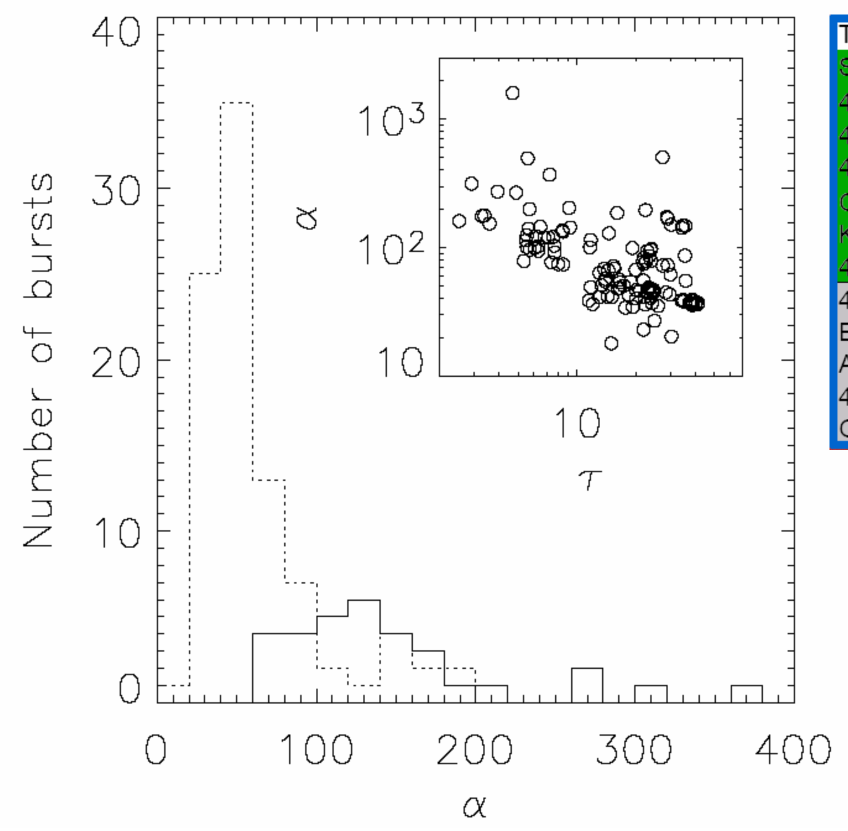


Burst energy (thermonuclear energy)

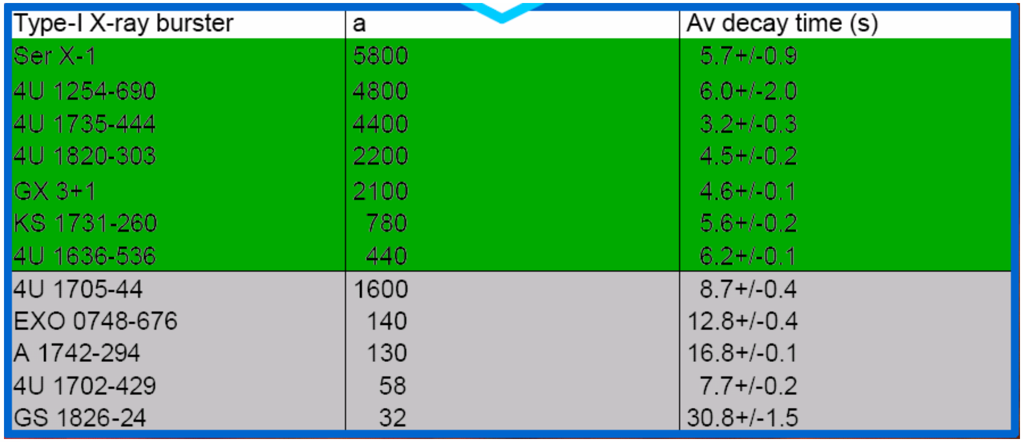
Persistent flux (gravitational energy)

- nuclear energy release per nucleon is 7 MeV for H and 0.6-1.7 MeV for He burning
- gravitational energy release per nucleon is $GM_{NS}m_p/R$=200 MeV
- if gravitational energy is completely liberated as radiation, α parameter indicates kind of fuel (~30 for H burning and ~100-300 for He burning)

The alpha parameter – measurements



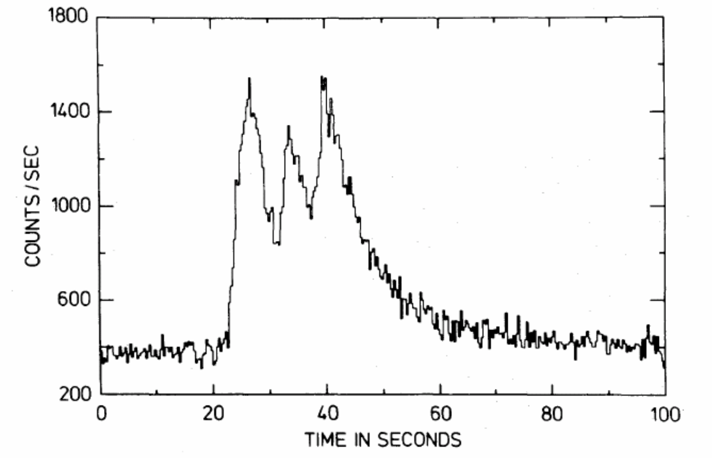
Courtesy D. Galloway (2005)

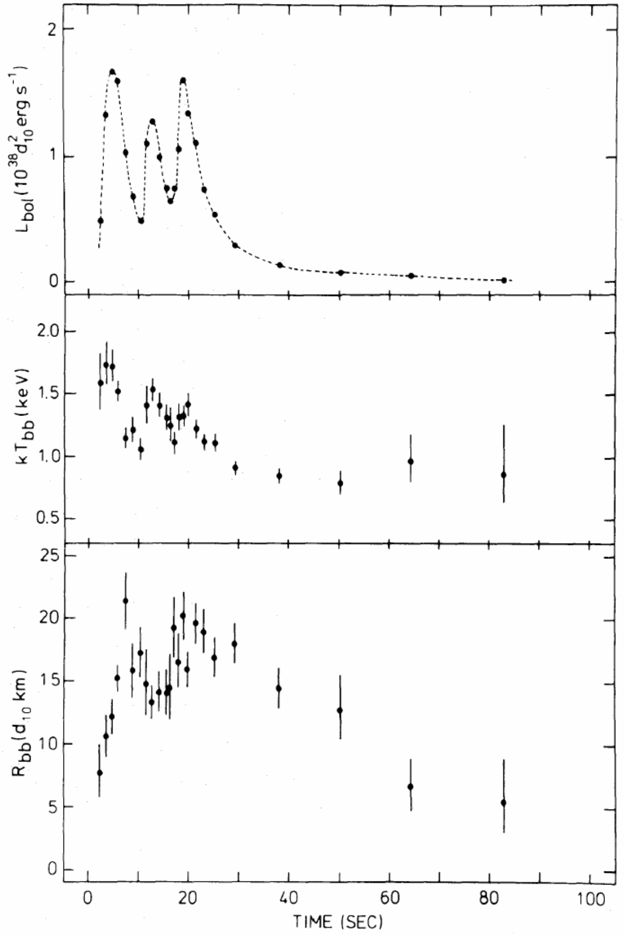


Type-I X-ray burster	a	Av decay time (s)
Ser X-1	5800	5.7+/-0.9
4U 1254-690	4800	6.0+/-2.0
4U 1735-444	4400	3.2+/-0.3
4U 1820-303	2200	4.5+/-0.2
GX 3+1	2100	4.6+/-0.1
KS 1731-260	780	5.6+/-0.2
4U 1636-536	440	6.2+/-0.1
4U 1705-44	1600	8.7+/-0.4
EXO 0748-676	140	12.8+/-0.4
A 1742-294	130	16.8+/-0.1
4U 1702-429	58	7.7+/-0.2
GS 1826-24	32	30.8+/-1.5

sometimes a is much higher than a few 100 → much more fuel is accreted than burnt up in bursts → fuel burnt stably rather than unstably?

Peculiar bursts: triple-peaked burst from 4U 1636-536



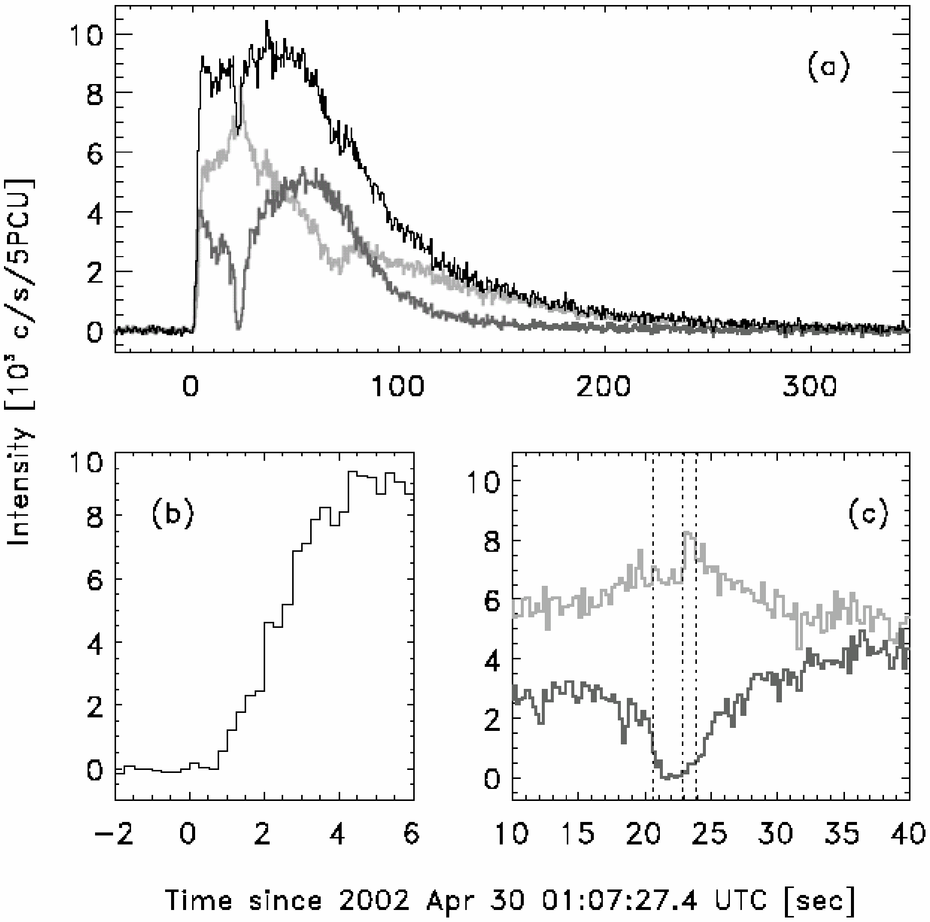


The peaky behavior cannot be ascribed to radius expansion effects. Jury still out on this observation. Suggestion: intermittent nuclear burning

(Van Paradijs et al. 1986)

Peculiar bursts: delayed helium flash from GRS 1747-312

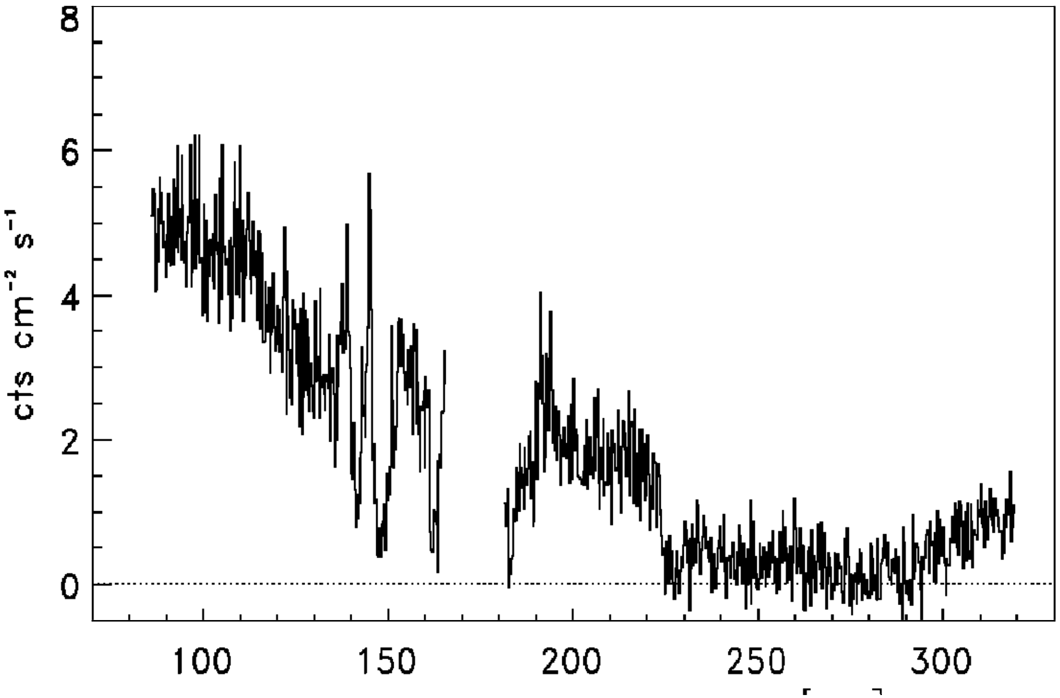
- Panel (a) shows the total observed photon flux in 2-30 keV (upper dark curve), the flux at 2-5 keV (curve with dip) and at 5-30 keV (curve with peak at 20 s)
- Panel (b) zooms in on the burst rise. It is somewhat slow
- Panel (c) zooms on the dip
- Interpretation: in the middle of a Eddington-limited burst another burst goes off on the same NS. Since the maximum peak is already reached, this additional burst pushes the photosphere further out
- The peculiarity is that the second burst is delayed by 20 s, indicating an unexpectedly low thermal conductivity between different fuel layers (mixed H/He and pure He)



(in 't Zand et al. 2002)

Peculiar bursts: dips and oscillations in 2S 0918-549

- This figure shows the lightcurve of a tail of a long burst.
- There are strong oscillations and losses of flux.
- This has been seen in a few other bursts (out of ~8000 bursts detected sofar since the start of X-ray astronomy)
- Again intermittent nuclear burning?
- Limit cycle behavior on the threshold between stable and unstable hydrogen burning?



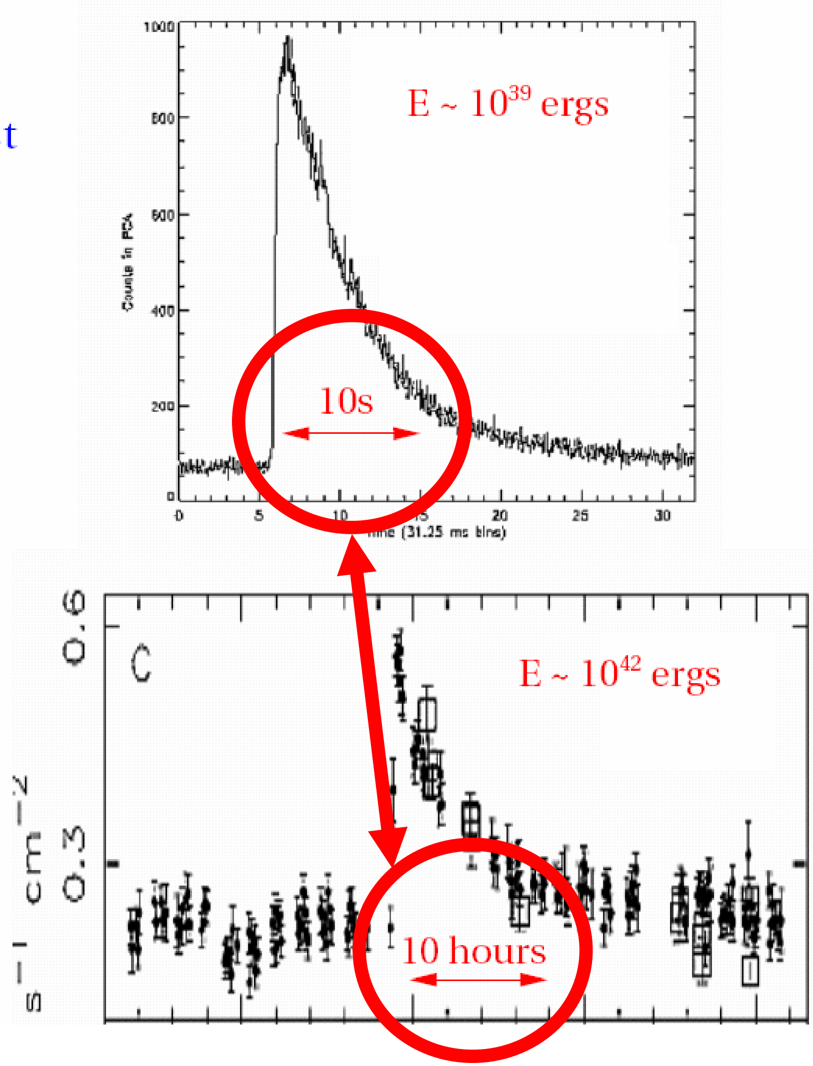
Time (s)

(in 't Zand et al. 2005)

Superbursts: 103 times longer and less frequent

Type I burst

Superburst

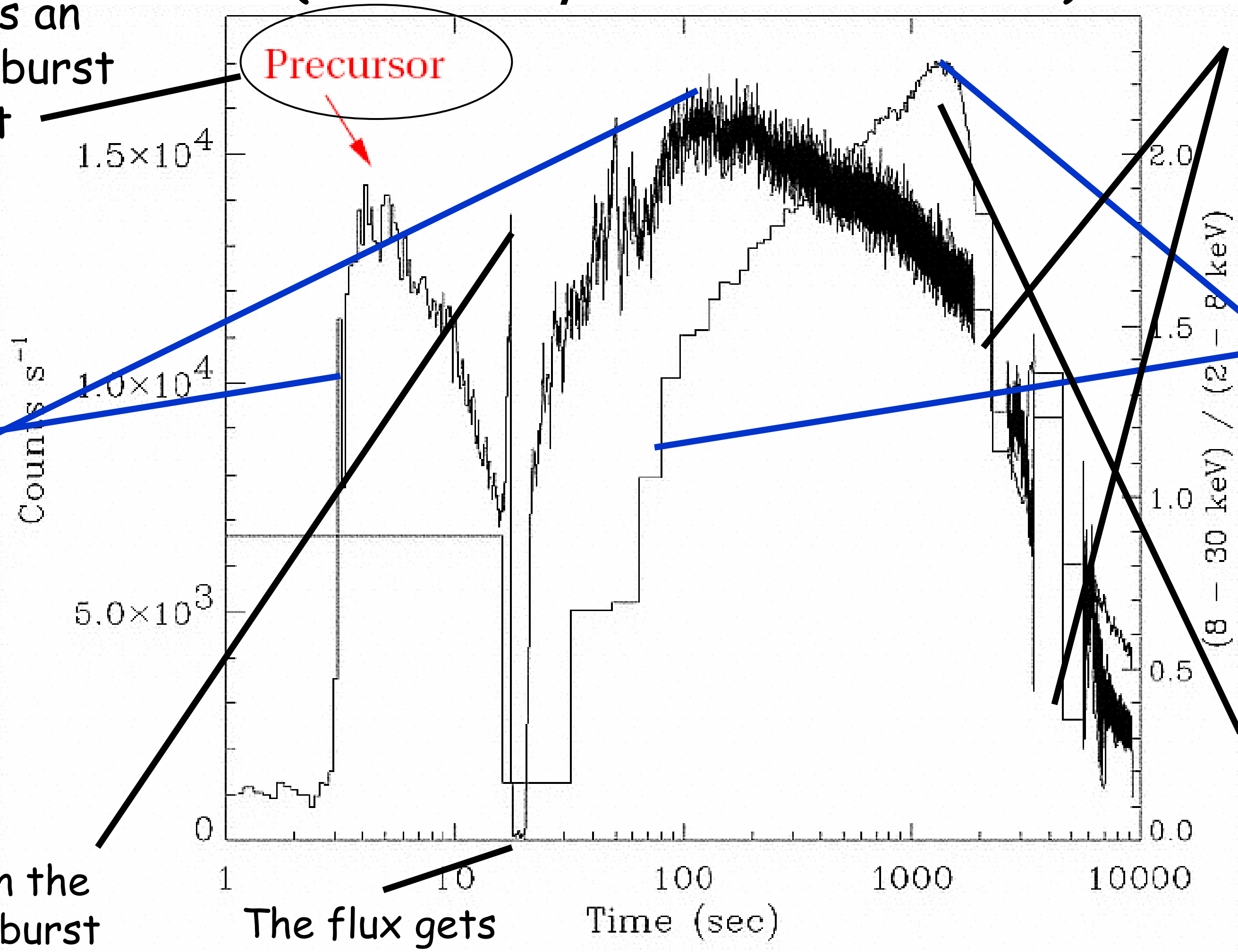


Superburst statistics

- 10 superbursts detected and reported since 2000
- All superbursts are seen from LMXB that exhibit ordinary bursts as well
- all but 2 superbursters accrete at ~10% of Eddington
- all superbursters are normal bursters as well
- 2 superburstser seen to recur, between 30 d for high-L system and 1.7 yr for low-L system; average recurrence about 1 year
- durations between 0.7 and 6 hrs e-folding decay time, peaks ~0.5 L_{edd}
- normal bursting activity ceases for days to weeks after SB
- durations, recurrence times, energetics roughly 10^3 higher than for 'normal' X-ray bursts
- when covered, start of SB coincides with normal burst

Superbursts / best studied cases: 4U 1820-303 (Strohmayer & Brown 2002)

There is an ordinary burst first



4U 1820-30
Strohmayer & Brown (2001)

Time history of photon flux

Data gaps due to earth occultation

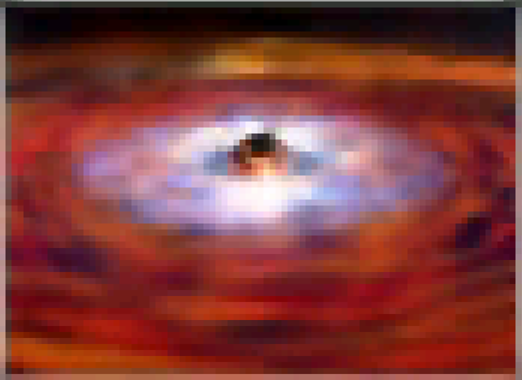
Time history of spectral hardness

End of super-Eddington fluxes, cooling starts

When the superburst starts, the flux becomes super-Eddington

The flux gets lower than the pre-burst level: inner accretion disk blown away

RXTE PUFFED ACCRETION DISK
VERSION 2 WITH NO WOBBLE



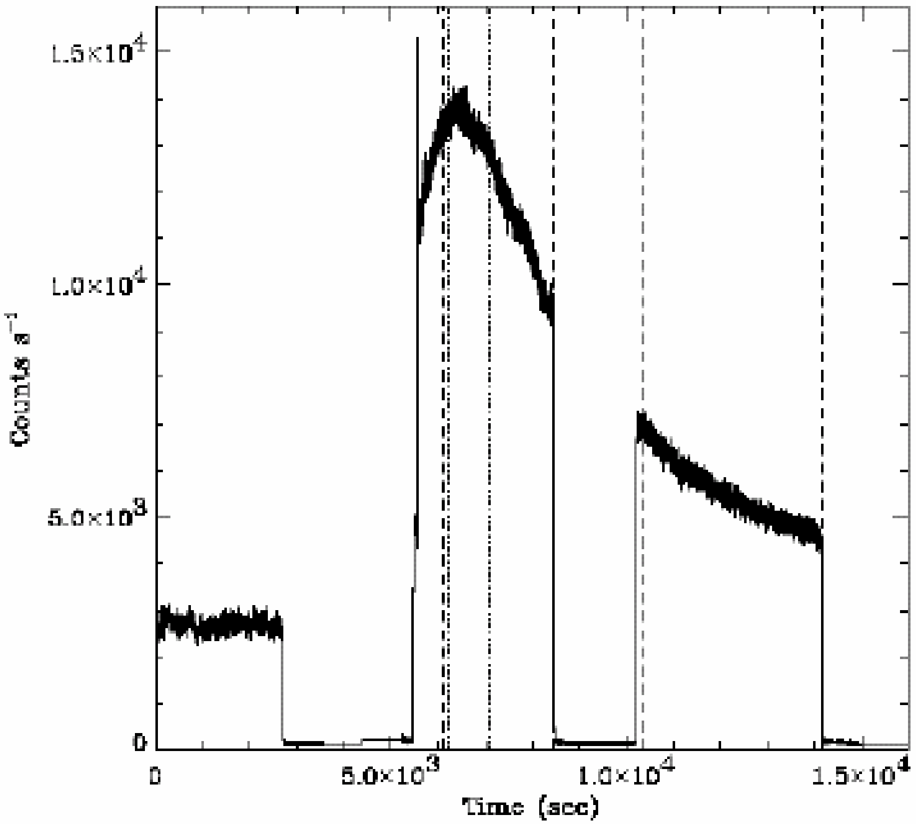
ANIMATION BY

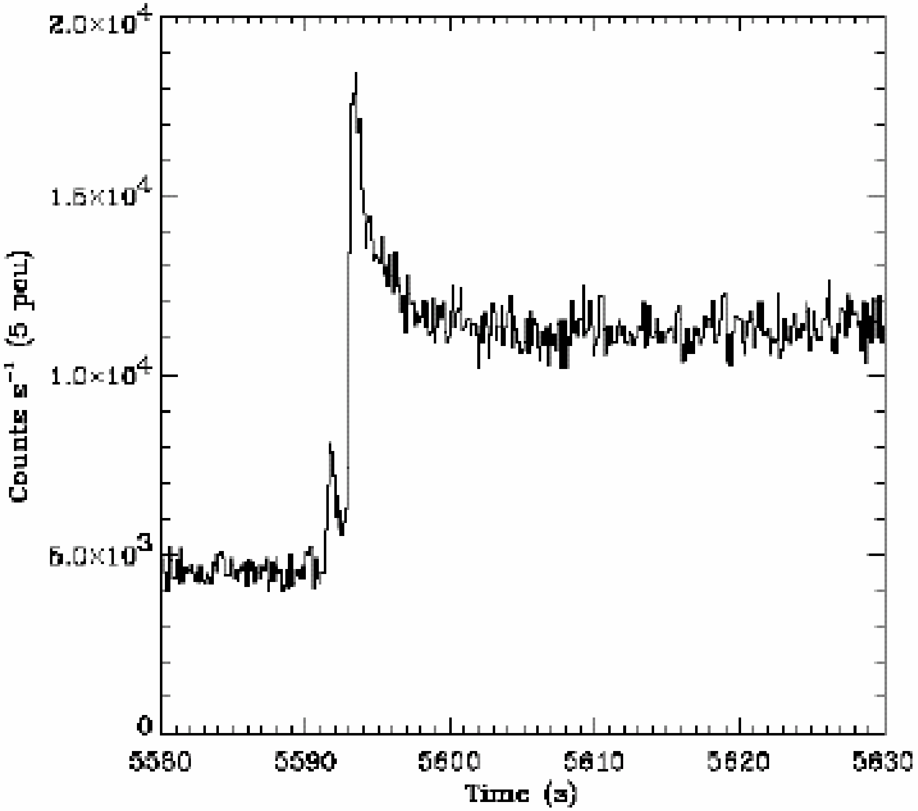
DANA BERRY

SKYWORKS DIGITAL ANIMATION

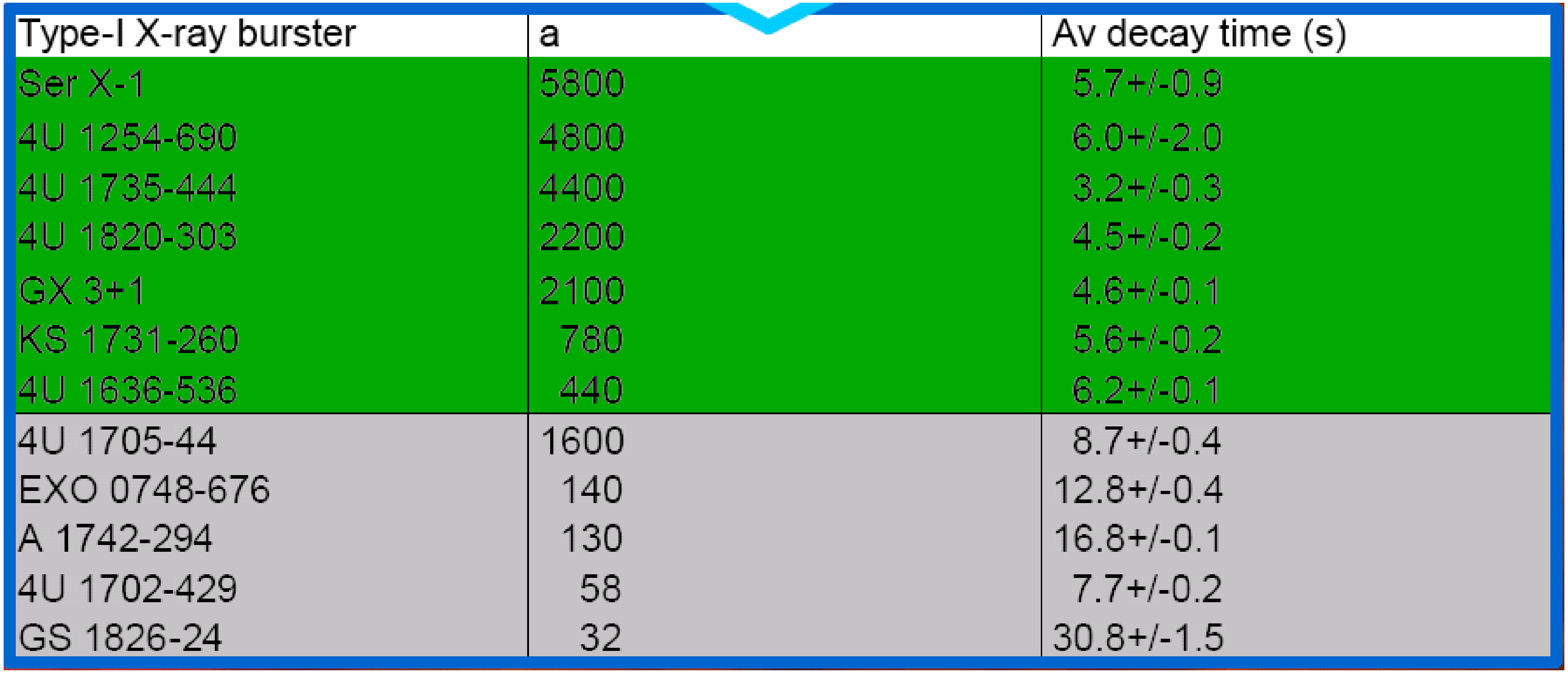
310-441-1735

Superbursts / best studied cases: 4U 1636-536 (Strohmayer & Markwardt 2002)





Superbursters compared to non-superbursters



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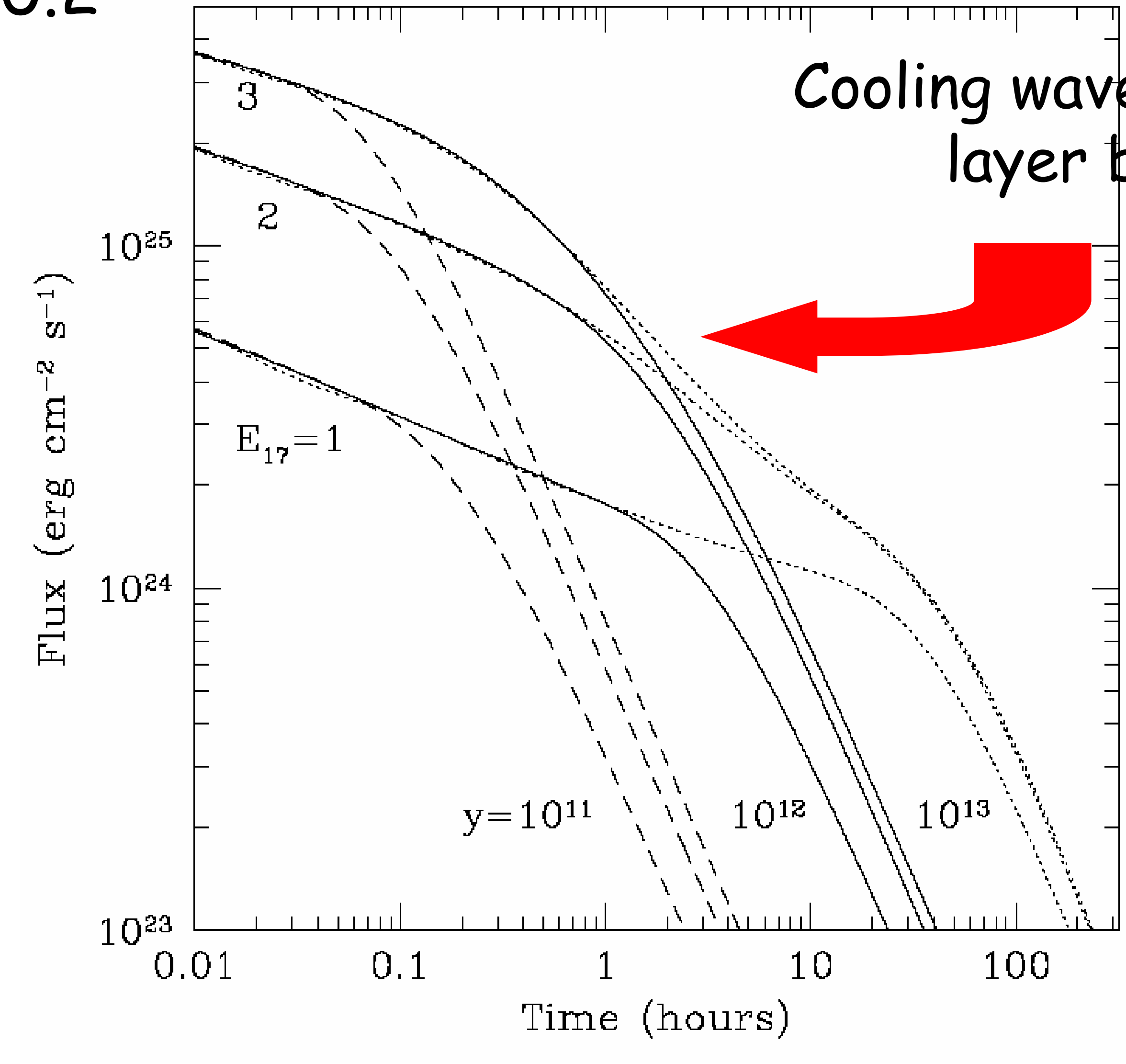
4U 1636-536	440	6.2+/-0.1
4U 1705-44	1600	8.7+/-0.4
EXO 0748-676	140	12.8+/-0.4
A 1742-294	130	16.8+/-0.1
4U 1702-429	58	7.7+/-0.2
GS 1826-24	32	30.8+/-1.5

→ α exceptionally high for SBs -> indicative that stable helium burning is essential for generation of sufficient amounts of Carbon for SB (in ‘t Zand et al. 2003)

Cooling curve models

$t^{-0.2}$



Cooling wave reaches layer base

$t^{-4/3}$

Burst oscillations - discovery

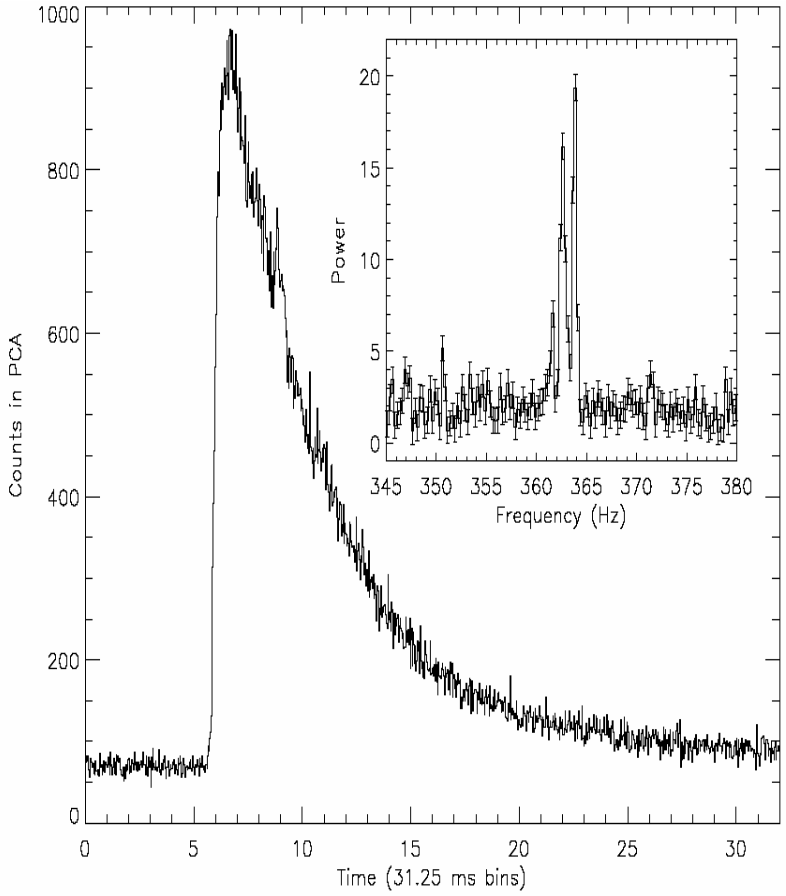


Fig. 3.6. An X-ray burst from 4U 1728–34 observed with the PCA onboard RXTE. The main panel shows the X-ray counts observed by the PCA in (1/32) s bins. The inset panel shows the power spectrum in the vicinity of 363 Hz (after Strohmayer et al. 1996).

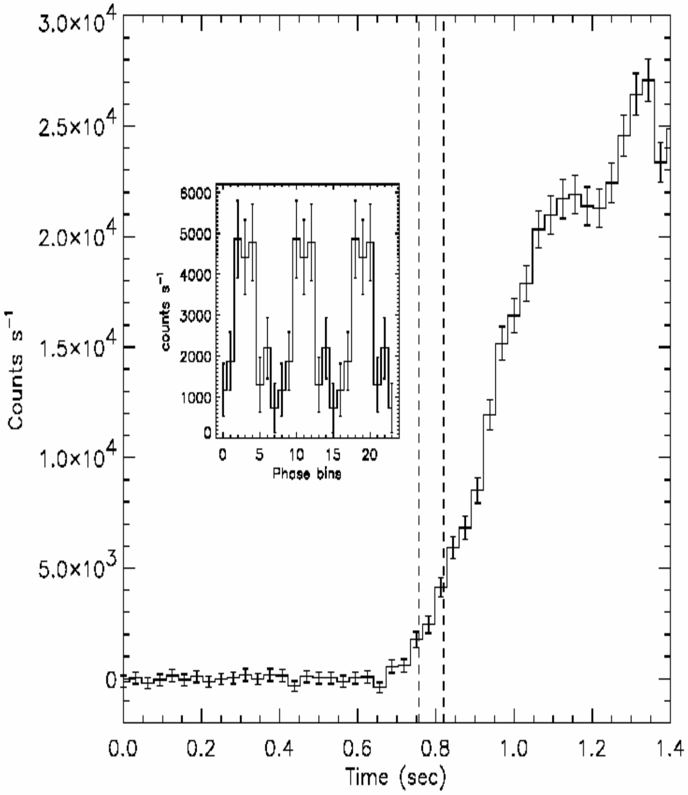


Fig. 3.7. X-ray timing evidence indicating a spreading hot spot at the onset of thermonuclear bursts. The main panel shows a burst from 4U 1636–53 with large amplitude, 581 Hz oscillations on the rising edge of the profile. The inset shows the pulse profile during the interval marked by the vertical dashed lines. The pulse profile is repeated 3× for clarity. Note the large amplitude of the oscillation. (after Strohmayer et al. 1998a).

Burst oscillations - characteristics

- Seen in ~20 bursters
- Do not occur in every burst
- Frequency specific to each source (45, 270-620 Hz)
- Occur at start and in tail of bursts
- Frequencies saturate at asymptotic values (see example at right) that are constant over years
- Sinusoidal profile
- Amplitudes of a few percent, sometimes larger
- Almost everything points to anisotropic emission on NS surface and modulation by NS rotation. Problem: presence in tails, when it is expected that NS surface is emitting isotropically. Magnetic field?
- Next slide shows 6 frames out of movie of model calculations of burst ignition on NS surface.

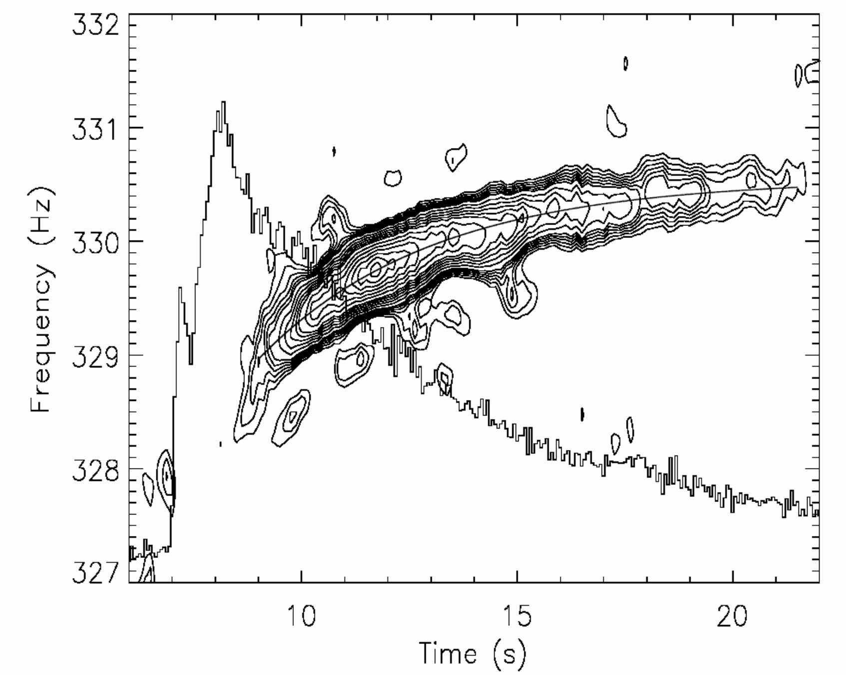
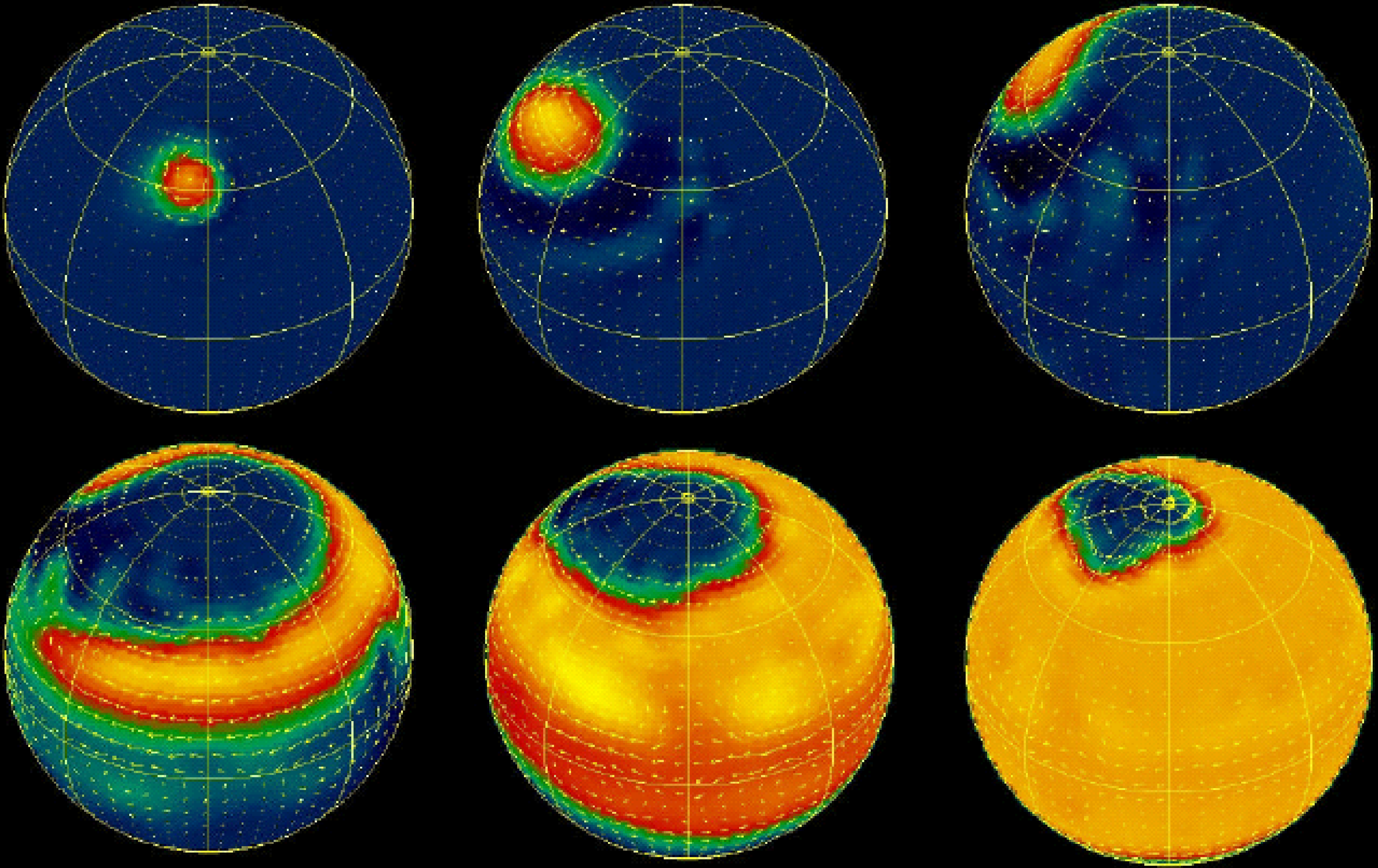


Fig. 3.9. An X-ray burst from 4U 1702–429 observed with the PCA onboard RXTE. Shown are contours of constant power spectral density as a function of frequency and time. The solid curve shows the best fitting exponential model. The burst time profile is also shown (after Strohmayer & Markwardt 1999).

Ignition on a sphere

- 200 turns of 300 Hz star (spherical projection)



Short incomplete history of X-ray burst research

- **1974-75**: launches of first X-ray observatories that performed long observations on individual sources (ANS; SAS; Ariel)
- **1975**: Hansen & Van Horn (1975) suggested possibility of thermonuclear runaway on neutron stars
- **1975**: discovery with the Dutch ANS satellite (Grindlay, Heise et al. 1976) and Vela-5 satellites (Belian et al. 1976)
- **1976**: 20 burst sources detected, mainly with SAS-3 (Lewin, Hoffman et al.), OSO-8
- **1976-77**: Woosley & Taam (1976) and Maraschi & Cavaliere (1977) independently proposed thermonuclear flash model
- **1978-79**: model matured through work by Joss (1978), Taam & Picklum (1979), Wallace & Woosley (1981), Fushiki & Lamb (1987) et al.
- **1984**: establishment of photospheric radius expanion by Tawara et al. (1984) and Lewin, Bacca, & Basinska (1984)
- **1983-86**: ESA's EXOSAT operated at high altitude enabling uninterrupted observations of bursters for ~3 days -> large research effort on recurrence time and relationship to accretion rate by Lewin & Van Paradijs
- **1996**-
  - BeppoSAX WFC picked up rare kinds and enlarged burster population from ~50 to ~75 (Cornelisse, Kuulkers, Heise, Ubertini, in 't Zand, et al.)
  - RXTE timing capabilities enabling detection of burst oscillations (Strohmayer, Swank, Markwardt, van der Klis, Wijnands, et al.)
  - Observations spawn new theoretical effort on various topics (Bildsten, Cumming, Brown, Schatz, et al.)

Burst reference card

- Rise time → composition
- Decay time → layer thickness y
- Fluence → amount of fuel
- Peak luminosity → amount of fuel, ε_{nuc}
- Oscillation → NS spin, M/R
- Absorption line features → M/R
- Alpha & M-dot → Composition