Evidence for a new heat source at low densities in accreting neutron star crusts

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Two parts:

1. What do long Type I X-ray bursts tell us about the thermal state of the neutron star interior ? in’t Zand, Keek, Falanga, Galloway, Page

2. What do the lightcurves of cooling transients tell us about the thermal state of the neutron star interior ?

Brown & Cumming (2008)

Long Type I X-ray bursts as a probe of the neutron star interior

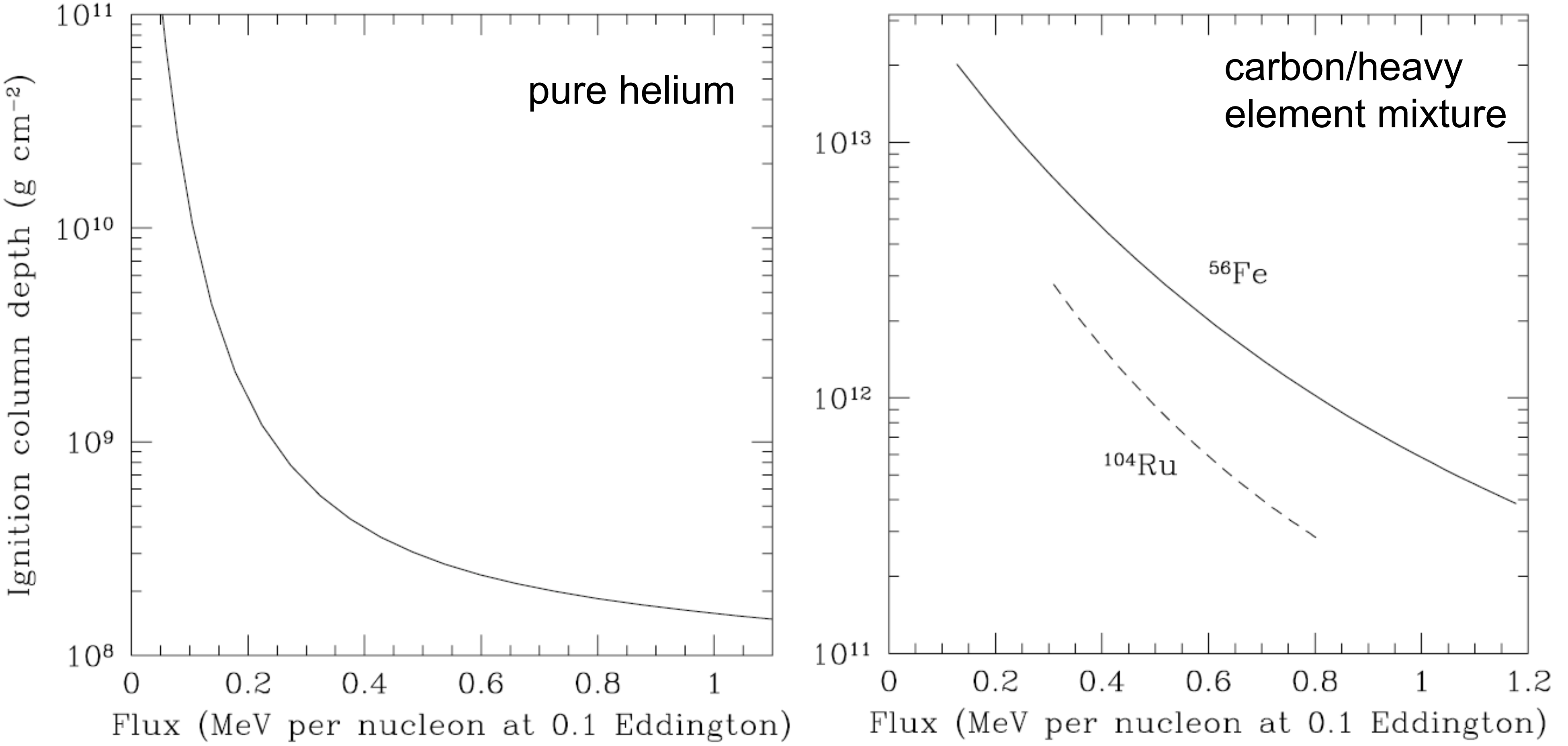
- first suggested by Fujimoto (1987) - but now we have a much larger sample of long XRBs due to long term monitoring

- the ignition conditions for X-ray bursts observed from Atoll and Z sources are set by hydrogen burning by the hot CNO cycle - insensitive to the cooling flux from the neutron star crust

- hydrogen burning is not important if:
  1. burning in a deeper layer - **superbursts** - carbon burning in the deep ocean
  2. burn the hydrogen away and accumulate a pure helium layer - **low mdot accretion**
  3. accrete pure helium - **ultracompact binaries**
  4. **low metallicity** - no significant CNO cycle

(don't know of an example of this last one)

Ignition conditions depend on the flux from the crust



Cumming et al. (2006)

write the flux in terms of Q_b: $F=Q_b\dot{m}$

measure ignition depth => flux heating the layer

How to measure the ignition depth

Two ways:

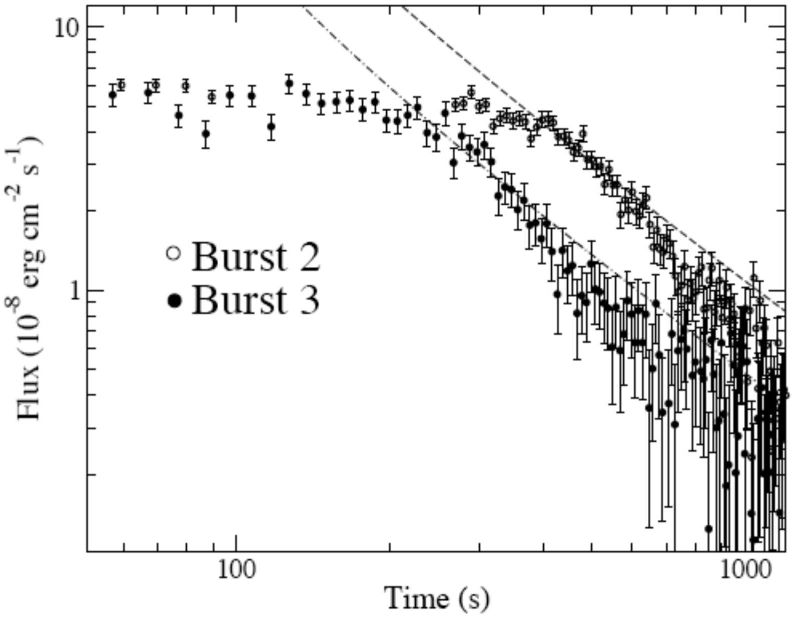
1. **energetics** $E_b = 4\pi R^2 y E_{\rm nuc}$

   doesn't work for superbursts! (neutrino thermostat)

   (Strohmayer & Brown 2002; Cumming & Macbeth 2004)

2. **lightcurve**

   a cooling layer gives a broken power-law lightcurve, whose break time tells you the thermal time of the layer => the thickness



e.g. late time power law cooling in pure helium flashes from SLX 1737-282

Falanga et al. (2008)

3. **recurrence time** at the inferred accretion rate - but this is difficult because long duration bursts are rare

We've done this for:

Superbursts Cumming et al. (2006) (see also Brown 2005, Cooper & Narayan 2005)

- ignition depths inferred from lightcurves are (0.5-2) x 10^{12} g/cm^2
- requires 0.2-0.3 MeV/nucleon at 0.3 Eddington

Helium accretors in ultracompact binaries

4U 1820-30 Bildsten (1995), Cumming (2003)

short duration bursts with 3 hour recurrence times
requires 0.4 MeV/nucleon at 0.3 Eddington

2S 0918-549 in 't Zand et al. (2005)

SLX 1737-282 Falanga et al. (2008)

both are persistent accretors, long ~20 min duration bursts, ~10^{41} ergs
lightcurves consistent with pure He ignition at y~10^{10} g/cm^2
requires Q_b=1 MeV/nucleon at 1% Eddington

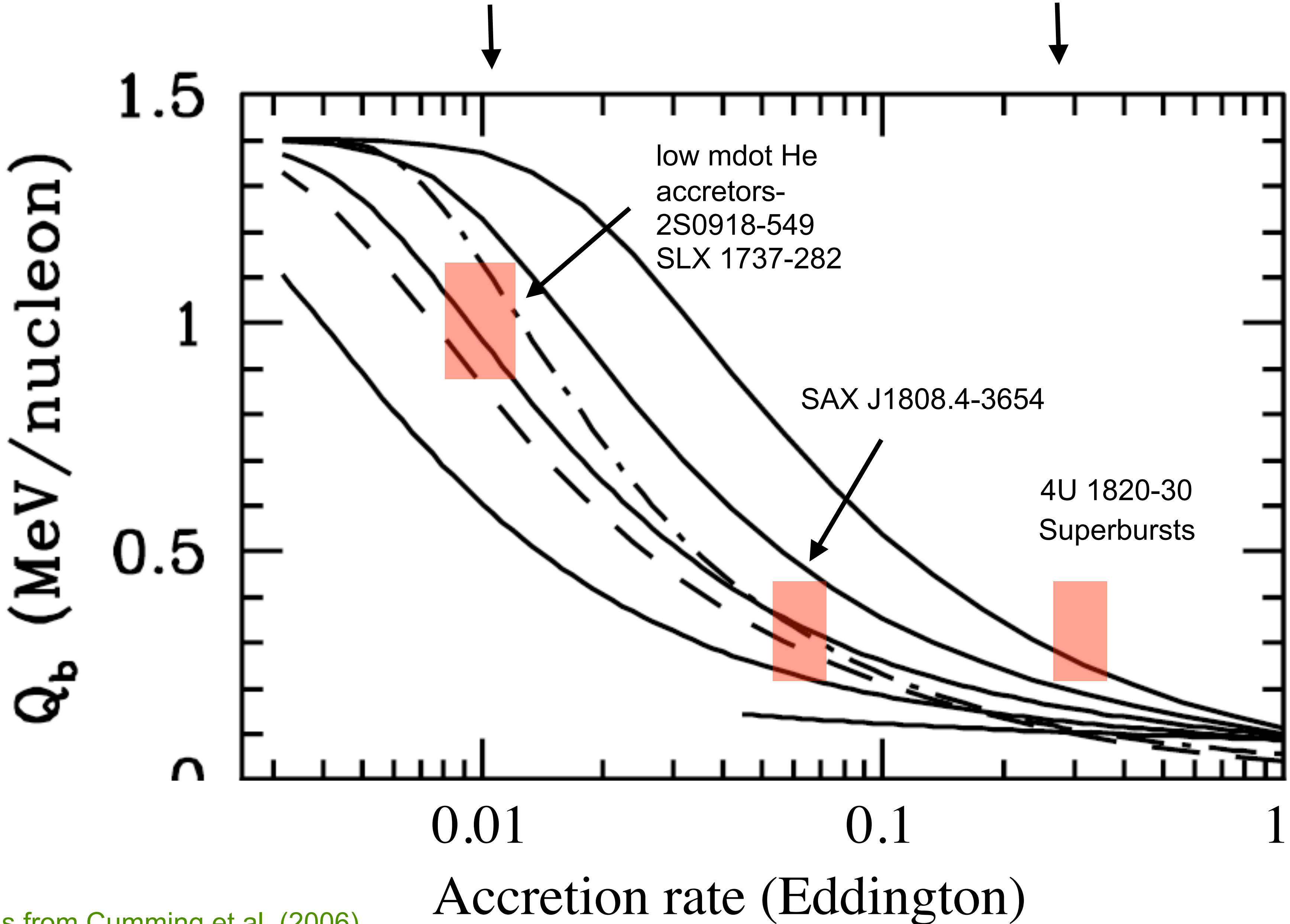
Accreting MSP **SAX J1808.4-3654** Galloway & Cumming (2006)

- burst sequence with ~1 day recurrence time
- complete hydrogen consumption by steady burning, followed by helium ignition in a pure helium layer (first time this regime securely identified)
- need Q_b=0.3 MeV per nucleon at 6% Eddington

Comparison with the flux expected from a deep-heated crust

Most sensitive to core physics

Most sensitive to crust physics



low mdot He accretors- 2S0918-549 SLX 1737-282

SAX J1808.4-3654

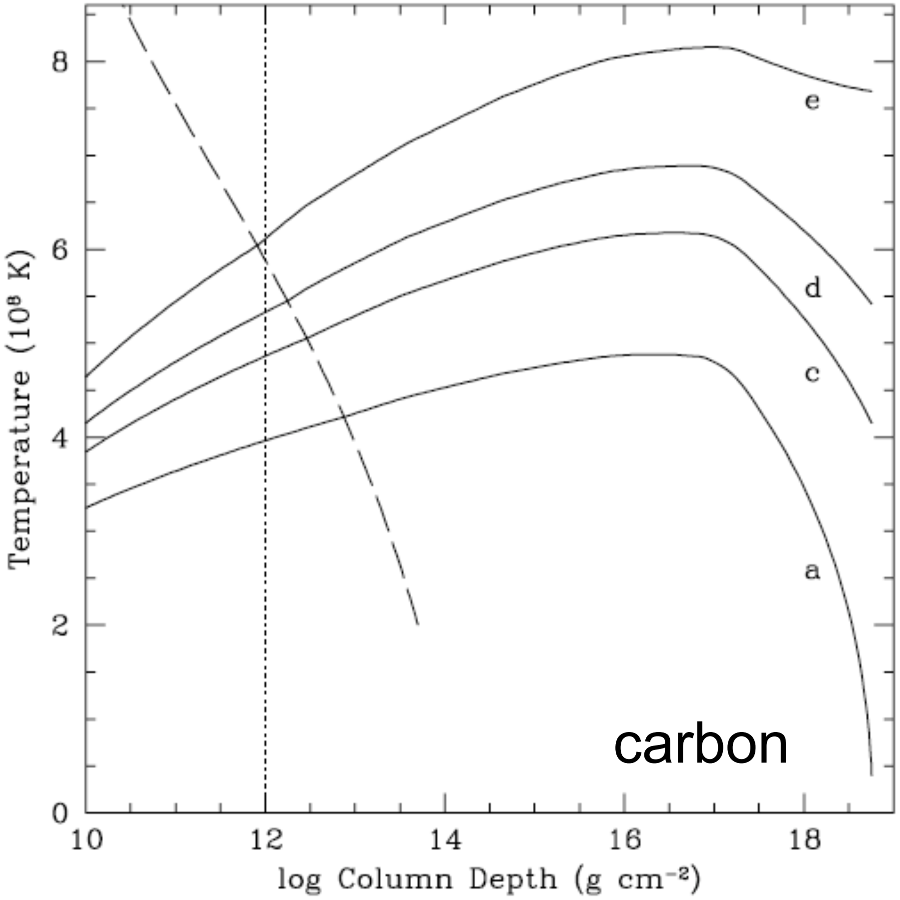
4U 1820-30 Superbursts

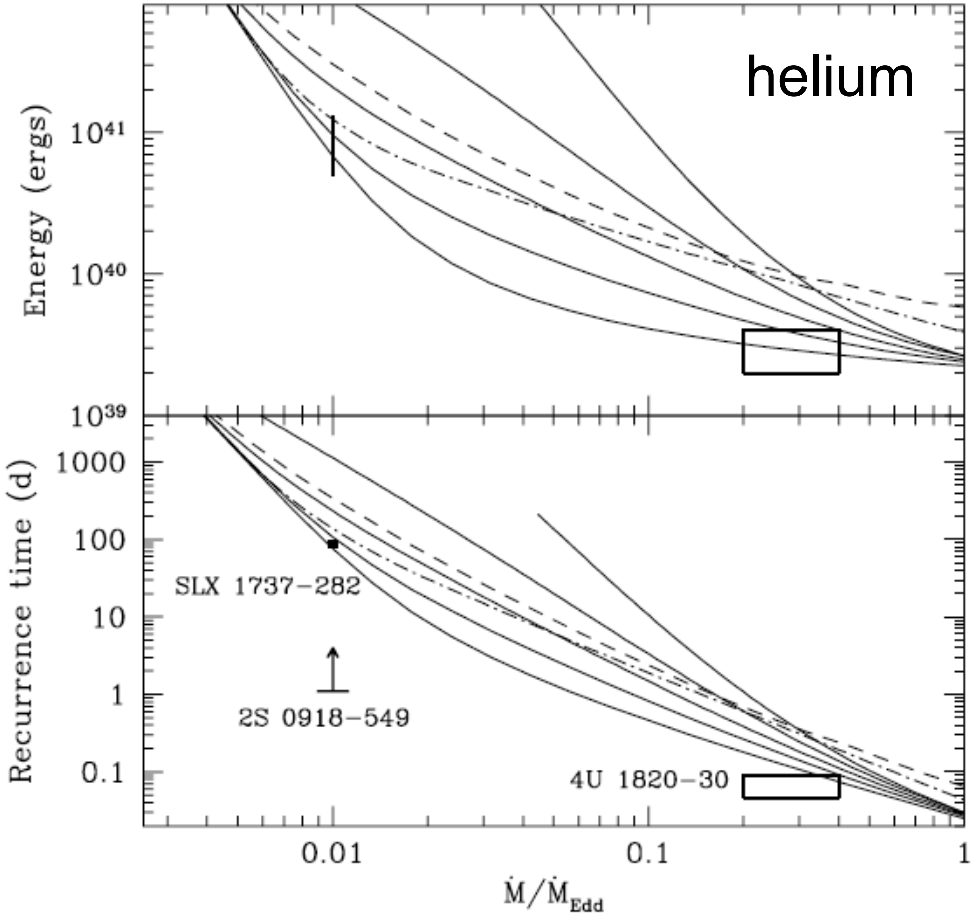
Models from Cumming et al. (2006)

Problems

1. **how to get these Q_b values** with realistic crust and core models - have to turn all the dials to “hot”

e.g. inefficient core neutrino emission
low thermal conductivity crust (amorphous)



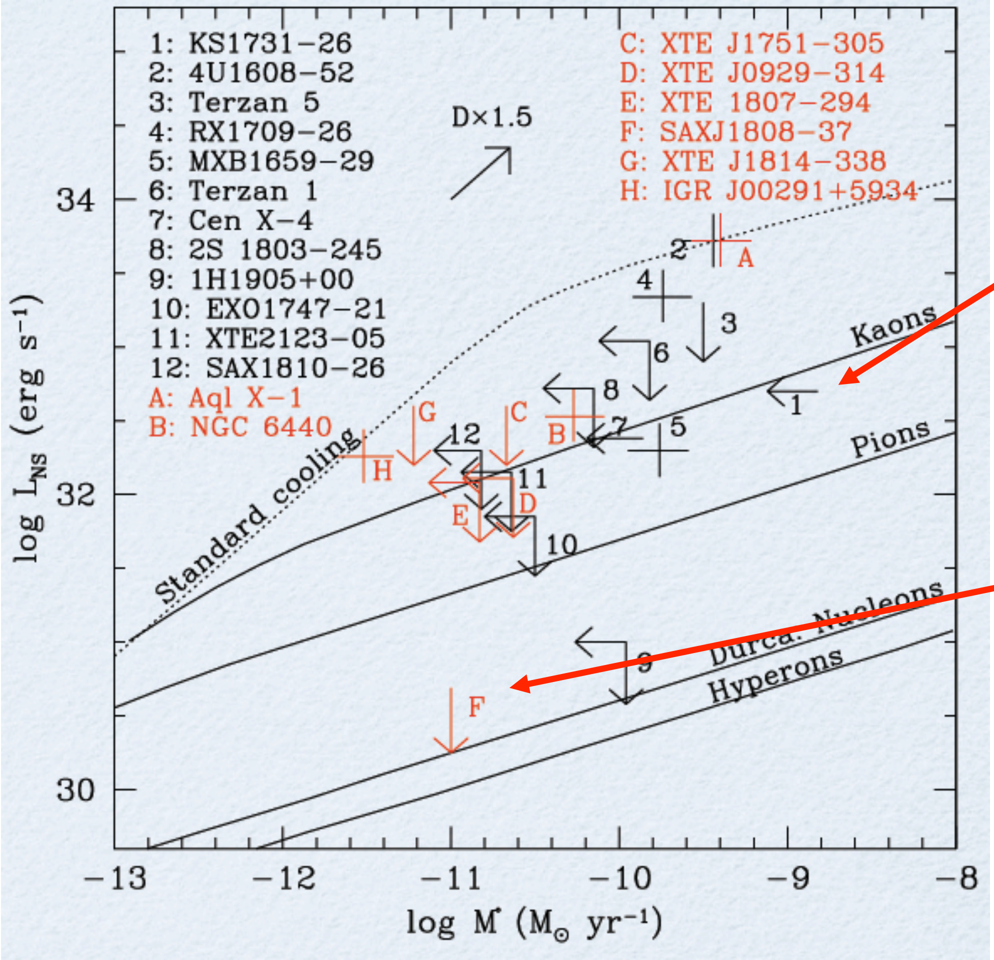


Cumming et al. (2006); see also Gupta et al. (2007)

Problems

1. **how to get these Q_b values** with realistic crust and core models - have to turn all the dials to "hot"

2. **disagreement with the measured quiescent luminosity of transients** - Q_b inferred from bursts is >> measured quiescent luminosity



KS 1731-260
Q_b=0.02 MeV
at 0.1 Edd

(~30 times smaller than needed for the superburst)

SAX J1808
the burst properties need
Q_b=0.3 MeV/nucleon or
L_{crust} = 2 x 10^{34} erg/s

>1000 times greater than quiescent luminosity

Yakovlev et al. (2004), Heinke, Jonker et al (2007)

Problems

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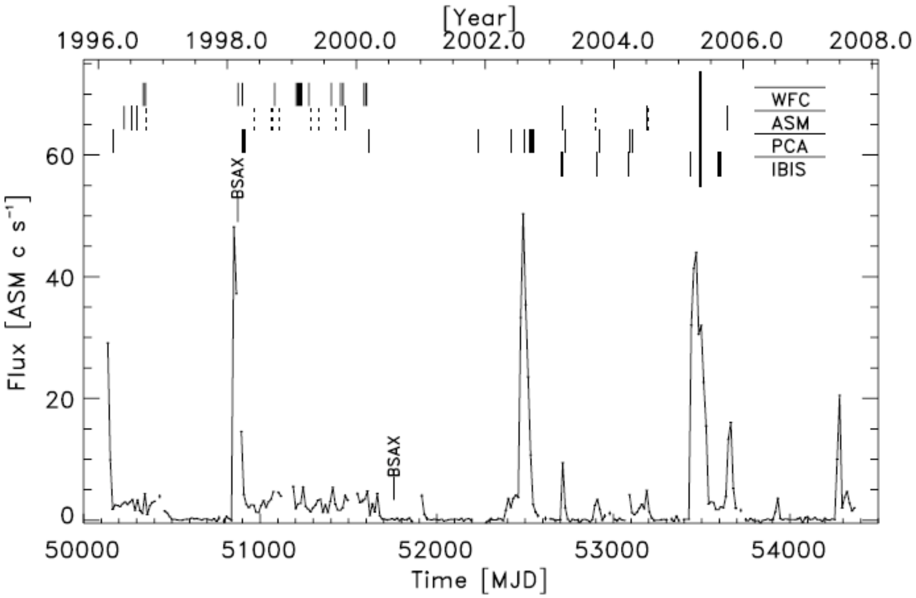
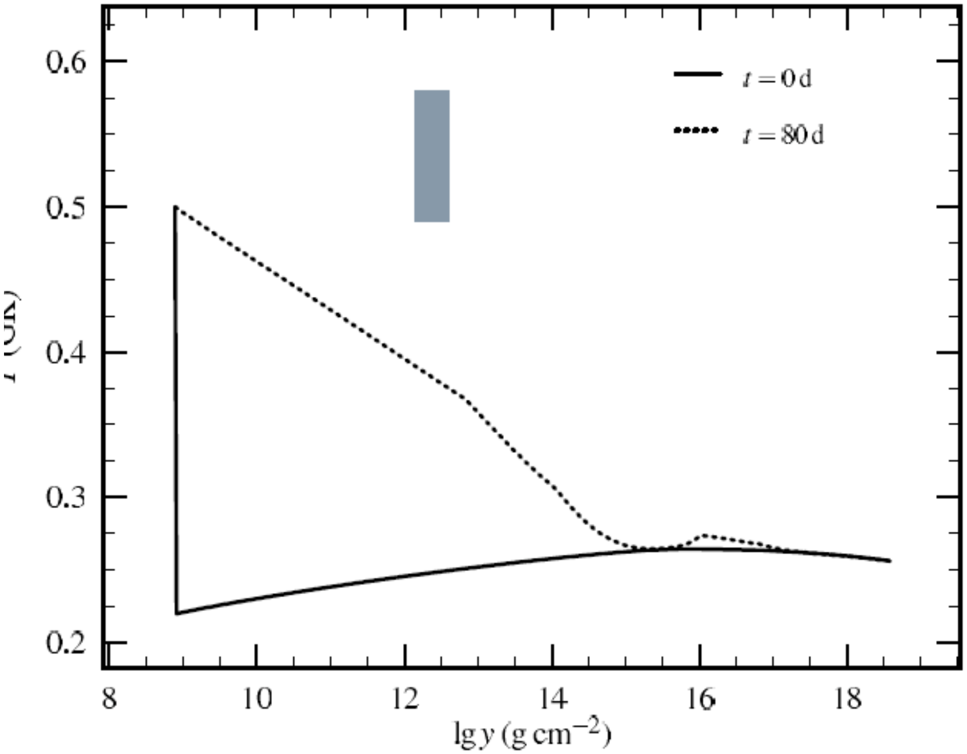
2. **disagreement with the measured quiescent luminosity of transients** - Q_b inferred from bursts is >> measured quiescent luminosity
3. **a superburst was seen from the classical transient 4U 1608-52** - the short outbursts in this source mean that the crust does not reach ignition temperature





Keek et al. (2008)

Problems

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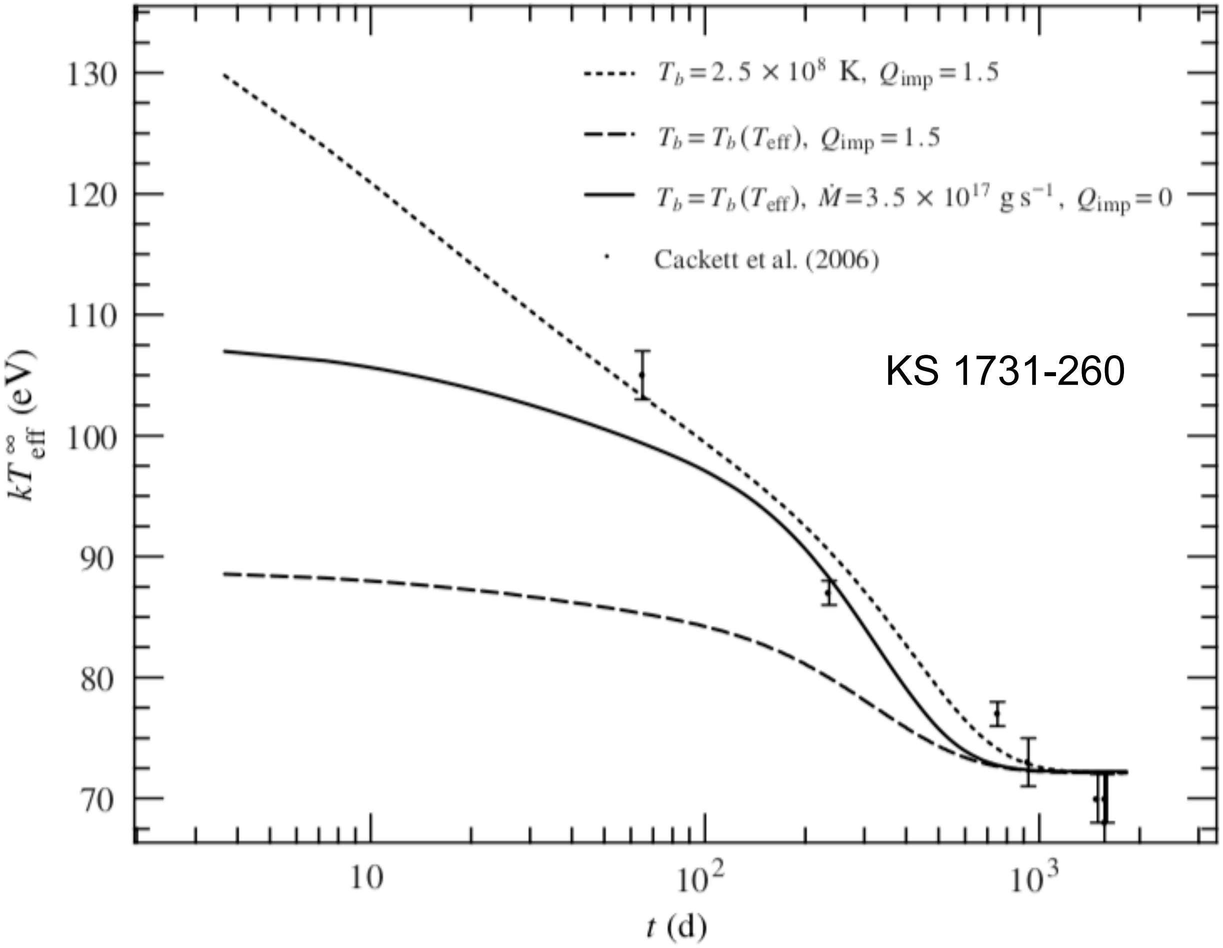
Possible solution

if the ignition physics is right ... then we need an extra heat source, but must put it at low enough density that it cools before we measure the quiescent luminosity!

“shallow crustal heating”

Cooling in quiescence in MXB 1659-29 and KS 1731-260



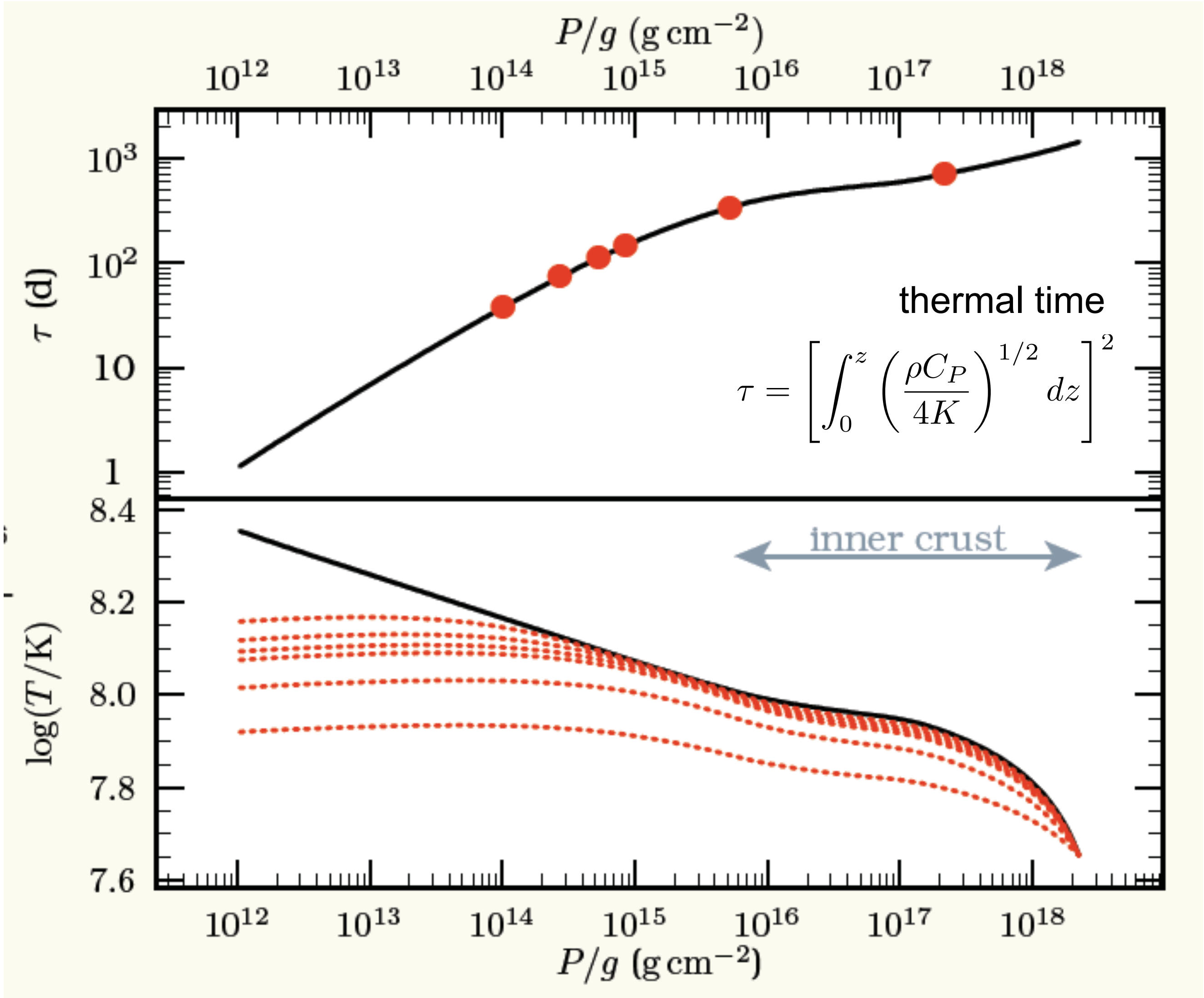
Brown & Cumming (2009)

data from Cackett et al. (2006,2008)

Conclusions:

- the outer crust has an inverted temperature gradient => independent evidence for a heat source at the top of the outer crust/ocean
- tight constraints on the effective impurity fraction “Q” of the crust

Simple understanding of the lightcurve



Brown & Cumming (2008)
see also
Cumming & Macbeth 2004 for SBs
Piro et al,(2005) for DNe

can “invert” the lightcurve to get the initial temperature profile

3 main parameters:

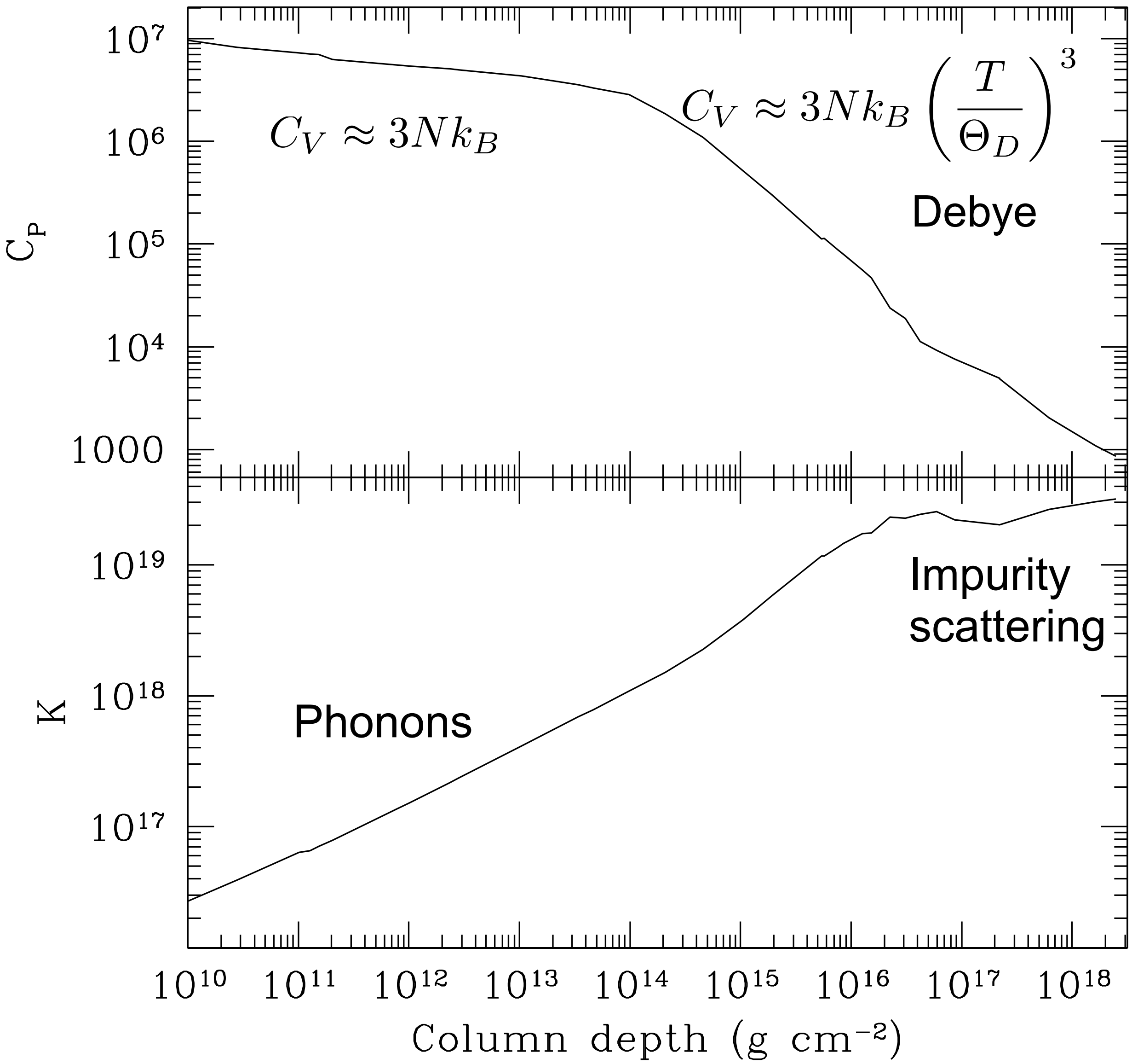
- impurity parameter Q
- core temperature
- temperature at the top

$$\frac{d\ln T_{\mathrm{eff}}}{d\ln t} = \left(\frac{d\ln T_{\mathrm{eff}}}{d\ln T}\right)\left(\frac{d\ln T}{d\ln y}\right)\left(\frac{d\ln y}{d\ln t_{therm}}\right)$$

Heat capacity and thermal conductivity in the crust

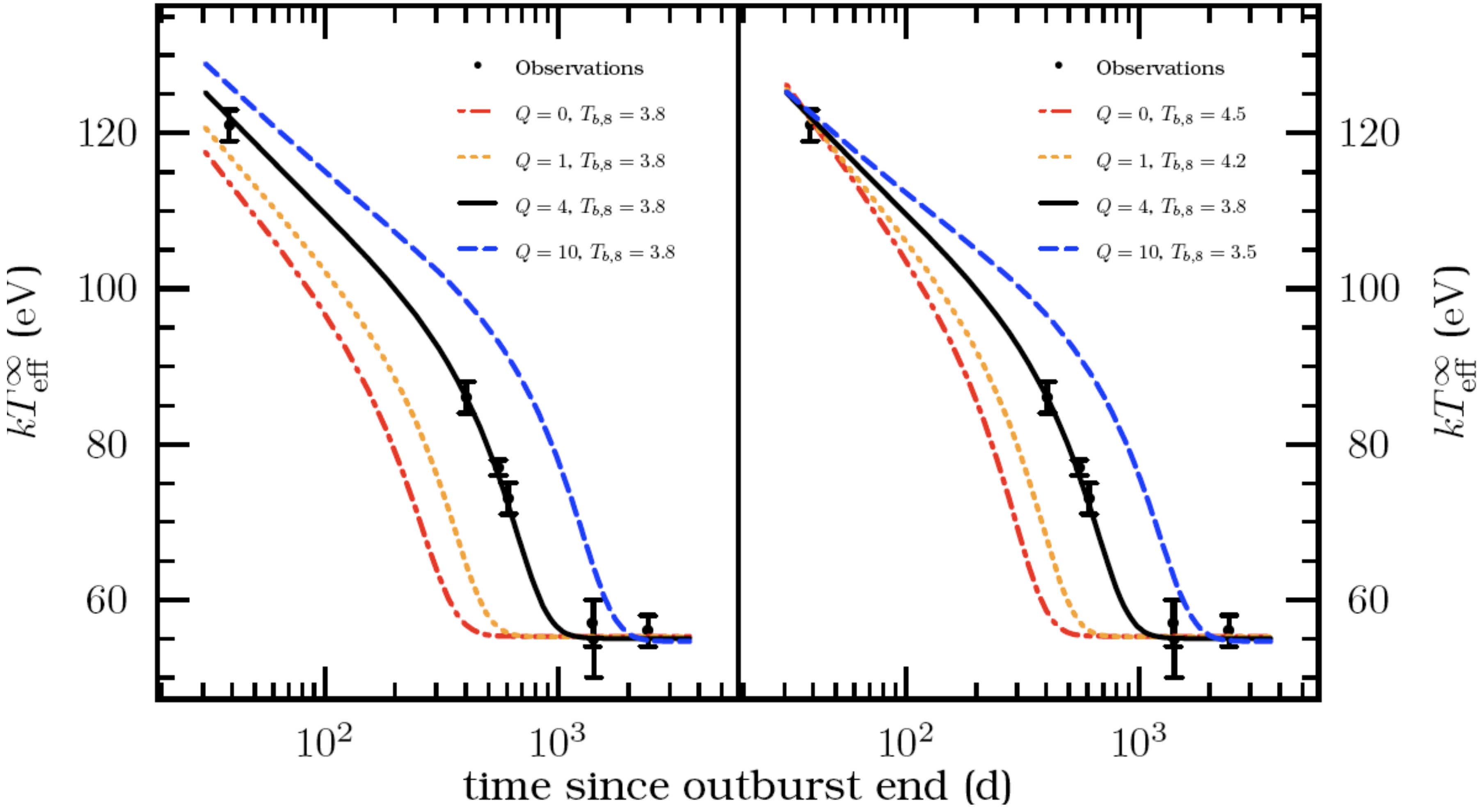
thermal time

$$\tau = \left[\int_0^z \left(\frac{\rho C_P}{4K} \right)^{1/2} dz \right]^2$$



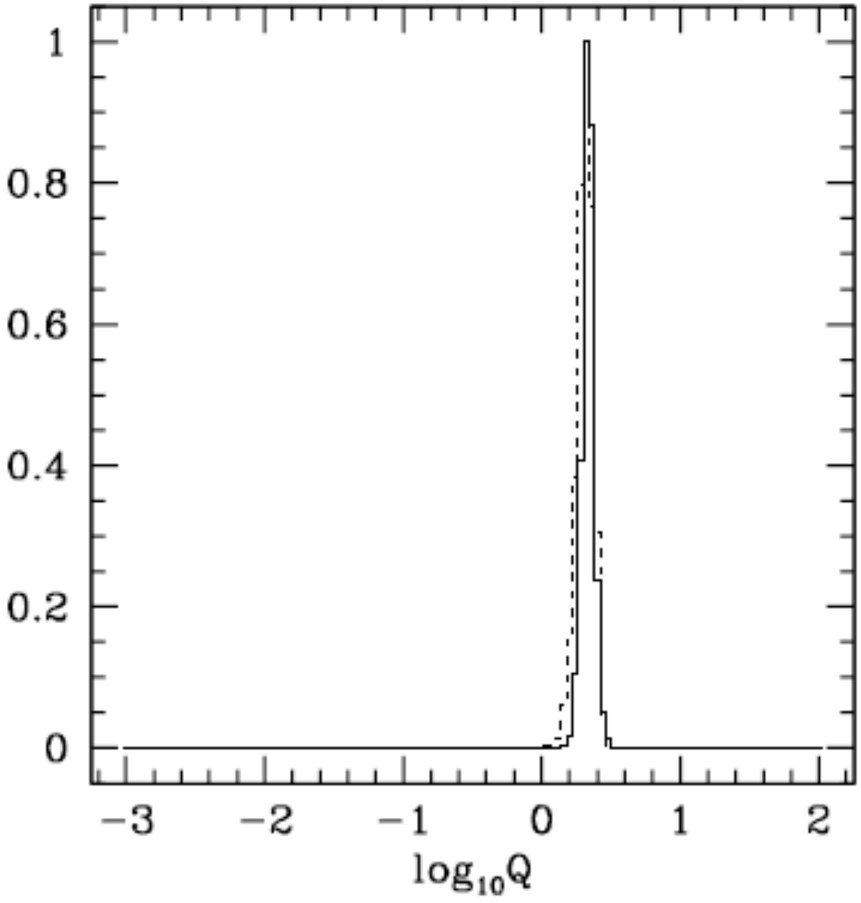
Outer crust | Inner crust

Constraints on Q for MXB 1659-29



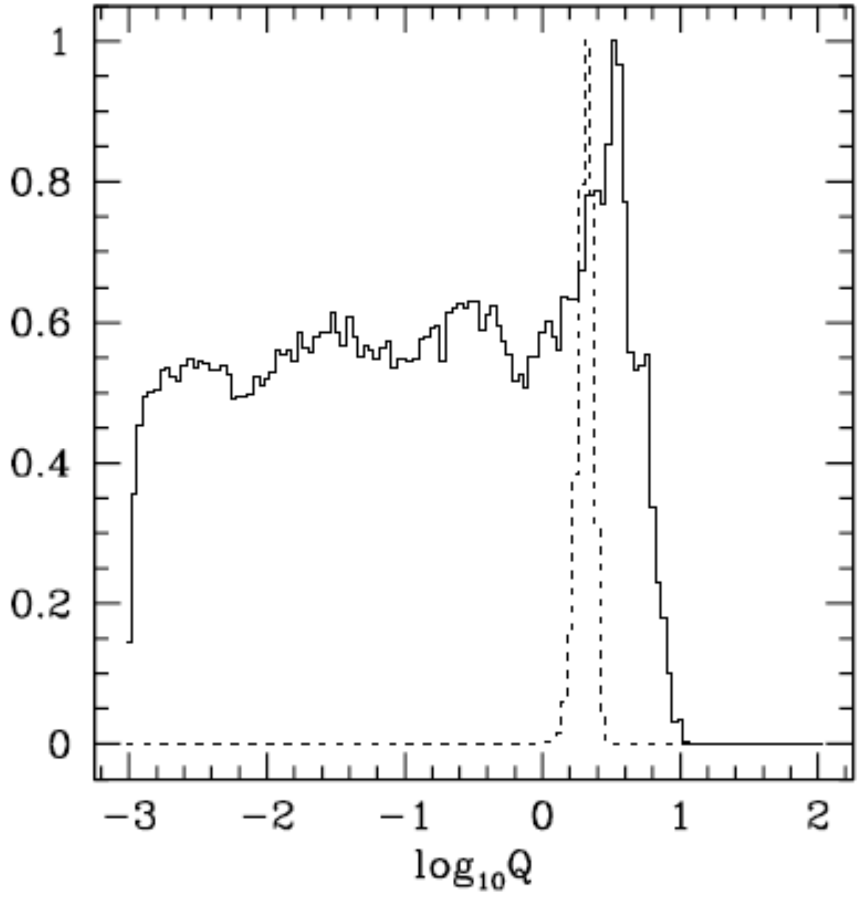
Constraints on Q for MXB 1659-29

Q larger than 10 ruled out
in agreement with Shternin et al. (2007)



specific choice of M,R

M=1.4 M_{sun} R=11.2km

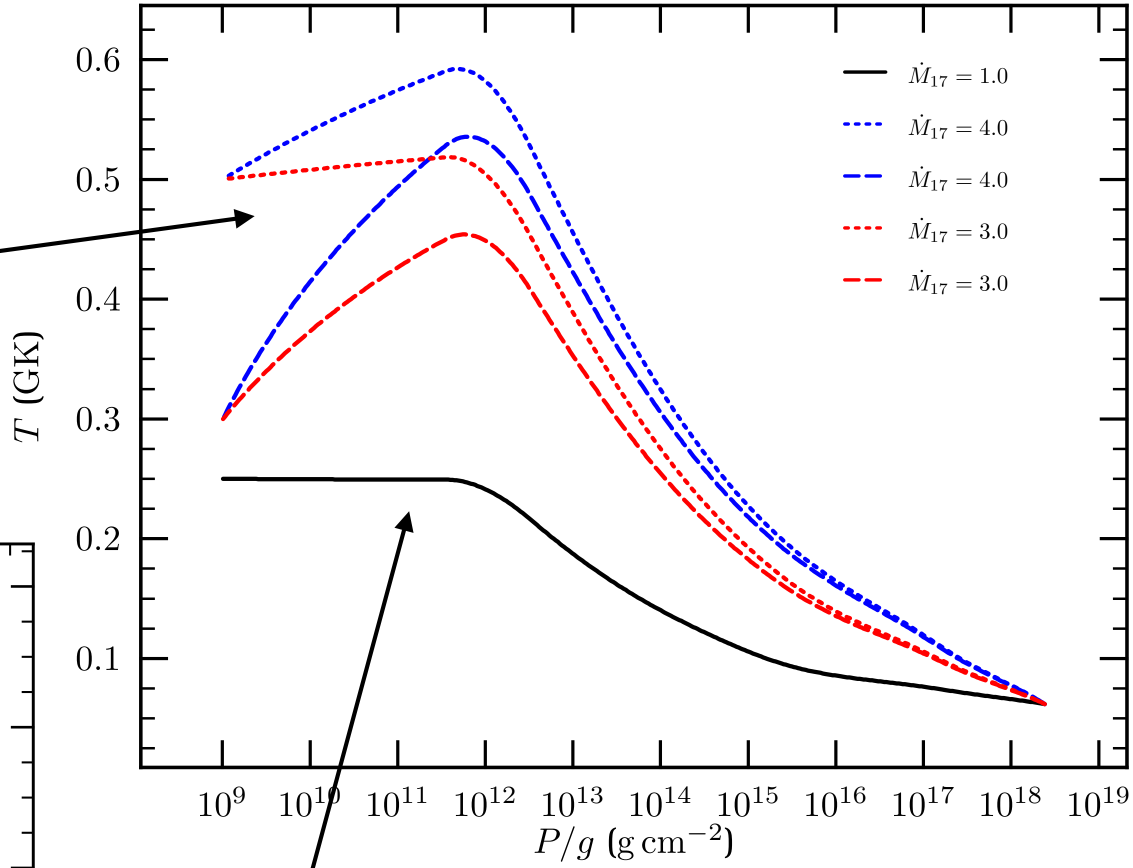


with M,R allowed to vary

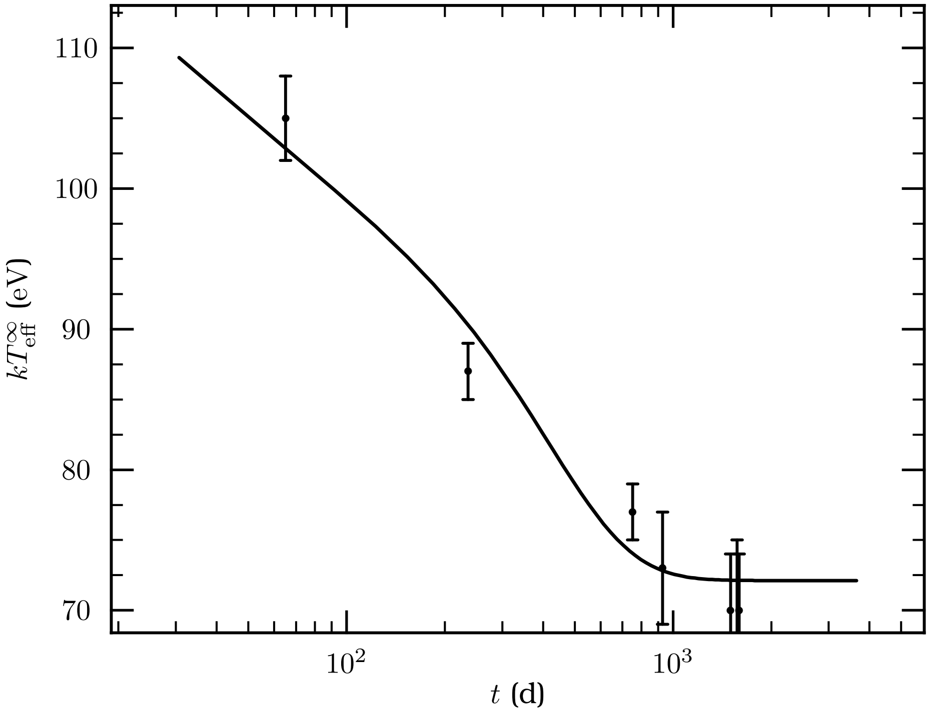
A consistent scenario for KS 1731

add extra heating 0.5 MeV/nucleon
at column depth 10^{12} g/cm^2

temperature profile at the time of the superburst - gets into the (5-6)x10^8K range needed to ignite carbon



temperature profile at the end of the outburst - fits the observed cooling curve



Conclusions

- Long Type I X-ray bursts probe the heat flux coming from the crust while accretion is ongoing
- The lightcurve of a cooling transients maps out the temperature profile of the crust at the end of the outburst
- Both of these point to extra heating at shallow depths in the crust/ocean

What is the heating ?
- pynonuclear reaction in the outer crust? Horowitz et al. 2008
- associated with the liquid/solid boundary? Horowitz et al. 2007

Why is the conductivity high?
The ashes from H/He burning have Q ~ 100. Horowitz et al. 2008 find that the solid has Q ~ 20. How to make Q=2?

For the most constraining lightcurve, important to get observations quickly after the outburst ends (<days)