Thermal evolution of neutron stars and constraints on their internal properties

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What is a neutron star (NS) ?

Origin

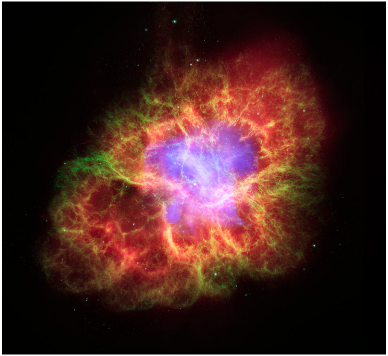
Remnant from the gravitational collapse of a $\sim$ 10 $M_\odot$ star during a Type II, Ib, Ic supernova event.

Properties

- mass $M \sim 1.4\ M_\odot$,
- radius $R \sim 10$ km,
- compactness $\frac{GM}{Rc^2} \sim 0.2$,
- average density $\bar{\rho} \sim 10^{15}$ g cm^{-3},
- magnetic field $B \sim 10^8 - 10^{15}$ G.

$\Rightarrow$ **relativistic objects sustained by the strong interaction.**

Crab Nebula hosting a pulsar



Credits : NASA/ESA.

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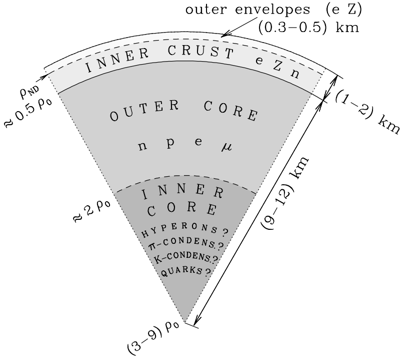
Observations

$\gtrsim$ 2000 NSs from radio to γ-rays :

- a majority as radio pulsars,
- $\sim$ 100 binary systems,
- $\sim$ 10 in double NSs binaries.

Structure



From Haensel et al. book (2007).

$\rho_{\rm ND} = 4 \times 10^{11}$ g cm^{-3}, $\rho_0 = 2.8 \times 10^{14}$ g cm^{-3}.

Envelope

- Plasma,
- Determines the spectrum and properties of the NS emission.

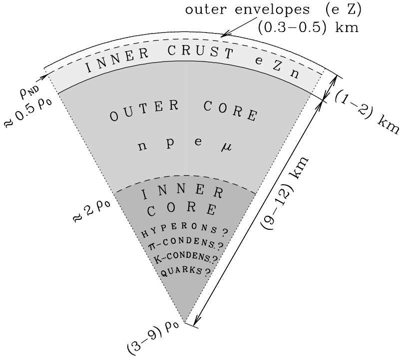
Outer crust

- Gas of electrons,
- lattice of ions.

Inner crust

- Electrons,
- free neutrons $\rightarrow$ superfluid,
- a lattice of very neutron-rich atomic nuclei.

Structure



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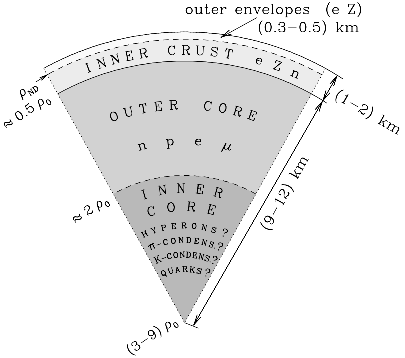
Outer core

- Free neutrons $\rightarrow$ superfluid,
- free protons $\rightarrow$ superfluid,
- electrons,
- muons.

Inner core

- ?

Structure



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Key point

NSs are astrophysical laboratories for microphysics in particular for $\rho \gtrsim 10^{14}$ g cm^{-3} at low T, not reachable in terrestrial laboratories.

Cooling of isolated NSs

$t = 0$

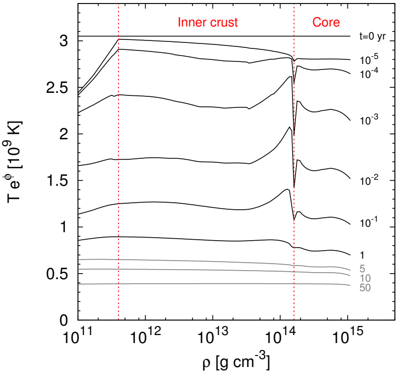
- $T \sim 10^9 - 10^{10}$ K.

$t \sim 1$ year

- the core cools by ν-emission,
- the crust by heat diffusion.

$\rightarrow$ crust properties.

Evolution of the temperature profile



Non-superfluid 1.4 $M_\odot$ NS model.

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$t \lesssim 10^5$ years

- thermal balance between the core and the crust,
- cooling by ν-emission;

$\rightarrow$ core properties.

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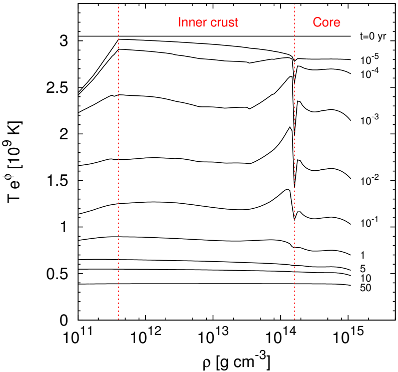
- cooling via emission of photons from the surface.

Evolution of the temperature profile



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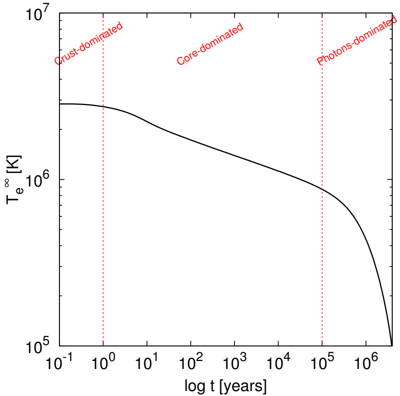
Evolution of the surface temperature



Non-superfluid 1.4 $M_\odot$ NS model.

Observations of isolated NSs

X-ray telescopes eg. XMM-Newton, Chandra, AstroH, NuStar, Athena, . . .

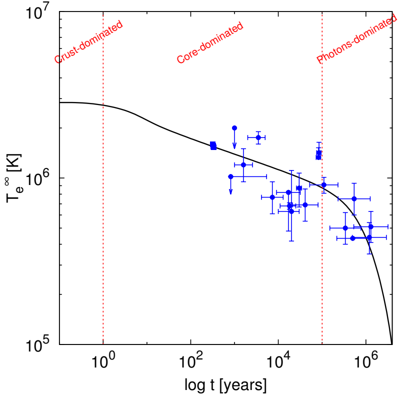
Biases

- small objects: detection of NSs with $T \sim 10^5 - 10^7$ K within few kpc.
- contamination from the supernova and the magnetospheric activity: middle-aged NSs.

Age and temperature determination

- age: uncertain unless the supernova as been observed in the past (cf. Crab pulsar): estimation from spin-down or modelling the expansion of the supernova.
- temperature: composition of the envelope unknown: H, He, Fe ?

Observational data



Observations vs a non-superfluid 1.4 $M_\odot$ NS model.

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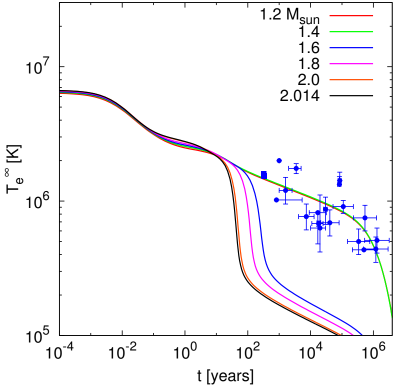

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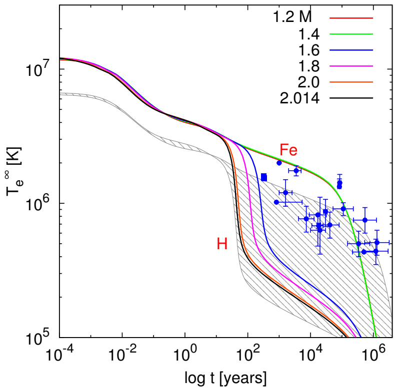

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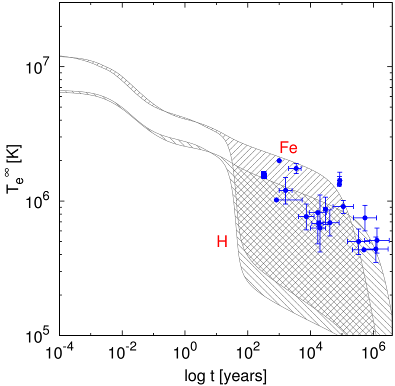

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Constraints?

Too many uncertainties:

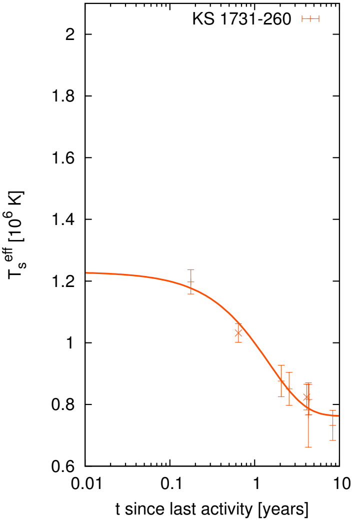
- the mass
- the atmosphere composition
- the age
- the distance
- the composition of the interior
- . . .

to have constraints :-(

Cas A NS

- age known since supernova observed ~ 330 yr;
- first direct observation of a temperature decline during ~ 10 yr (Heinke & Ho, ApJL 2010);
- modeling $\rightarrow$ constraints on the proton and neutron superfluidities in the core of NSs (Shternin et al., MNRAS & Page et al. PRL 2011);
- BUT reanalysis of data: NO temperature decline at all (Posselt et al., ApJ 2013) :-(

Quasi-Persistent X-Ray Transients (QPXRTs)



Observations : Cackett et al., ApJ (2010)

Two phases

- accretion during $\sim$ years to decades ($L \sim 10^{36-39}$ erg s^{-1}),
- quiescence when accretion stops ($L \lesssim 10^{34}$ erg s^{-1}).

Deep crustal heating scenario (Brown et al., ApJ 1998)

While the accreted matter sinks into the crust, it undergoes a series of reactions that heats the crust.

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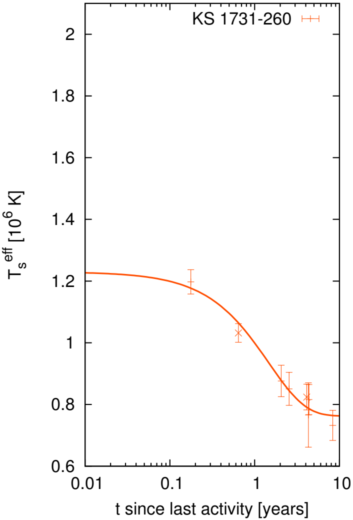

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KS 1731-26

Shternin et al., MNRAS (2007) :

- exclude a very efficient ν-process (DURCA) in the core,
- crystalline crust with superfluid neutrons.

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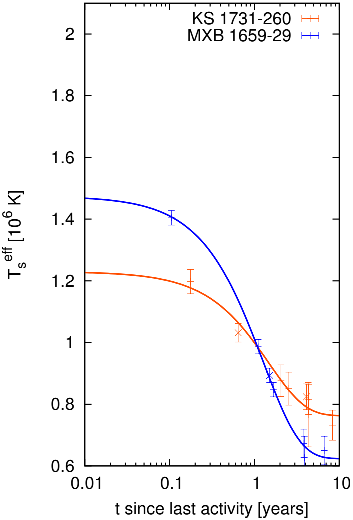

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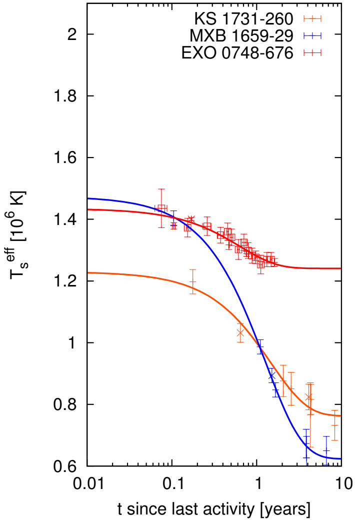
MXB 1659-29

Brown & Cumming, ApJ (2009) :

- $Q_{\rm imp} \sim 1$.

QPXRTs



Observations : Degenaar et al., MNRAS (2011)

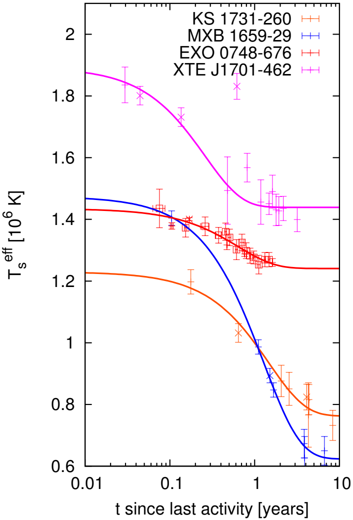
Cooling time scales

	τ (d)
KS	540 ± 125
MXB	465 ± 35
EXO	230 ± 60

Modeling of the thermal relaxation

Faster cooling : very hard to model.

QPXRTs



Observations : Fridriksson et al., ApJ (2011)

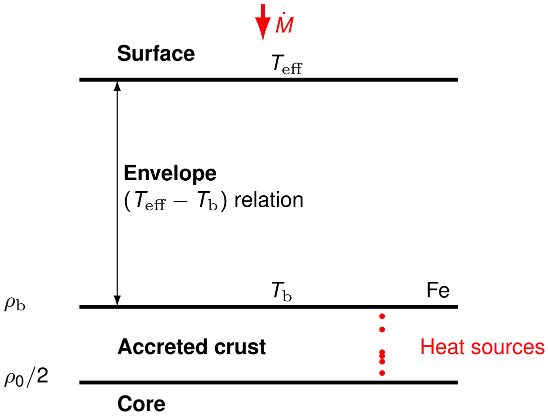
Cooling time scales

	τ (d)
KS	540 ± 125
MXB	465 ± 35
EXO	230 ± 60
XTE	95 ± 15

Modeling of the thermal relaxation

- Too fast to be modeled $\rightarrow$ heat sources at low densities ?
- Burst with a high power-law component $\rightarrow$ residual accretion ?

Model so far :

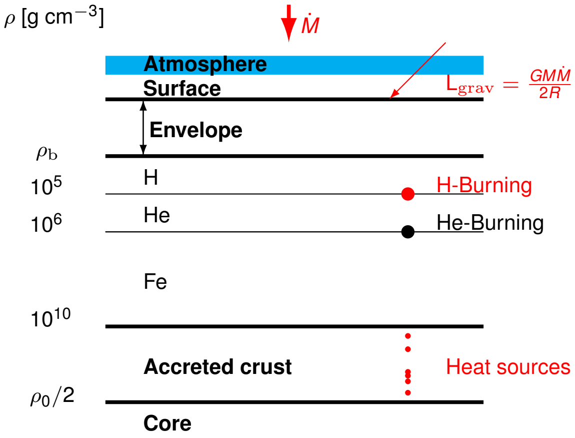


Inputs

- Envelope model at $\rho_{\rm b} = 10^{10}$ g cm^{-3},
- Accreted crust and heat sources
  eg. Haensel & Zdunik, A&A (2008) .

Can not include sources below $\rho = 10^{10}$ g cm^{-3} ...

Model in progress (M.F., J. L. Zdunik & P. Haensel) :



Inputs

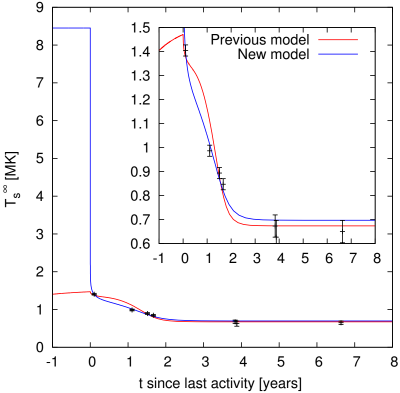
- Envelope model at $\rho_{\rm b} = 10^4$ g cm^{-3},
- H-burning : $Q_{\rm H} \simeq 5$ MeV/acc. nucl.,
- He-burning : only burst : $Q_{\rm He} = 0$,
- Gravitational energy at the surface.

Successful modeling of the thermal relaxation of the 4 QPXRTs.

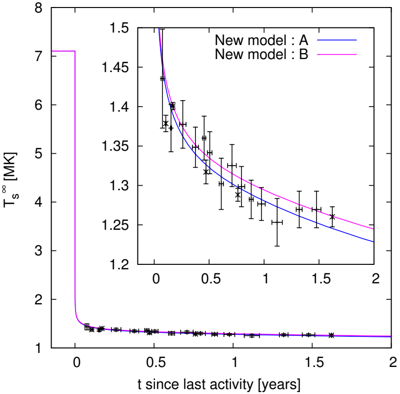
Results : 1.4 $M_\odot$ NS

Fortin et al. (2011)

MXB 1659−29



EXO 0748−676



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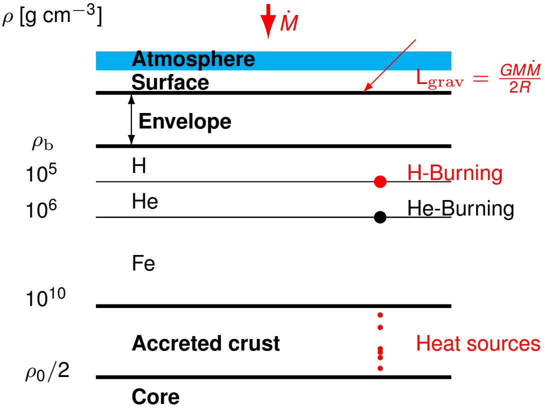
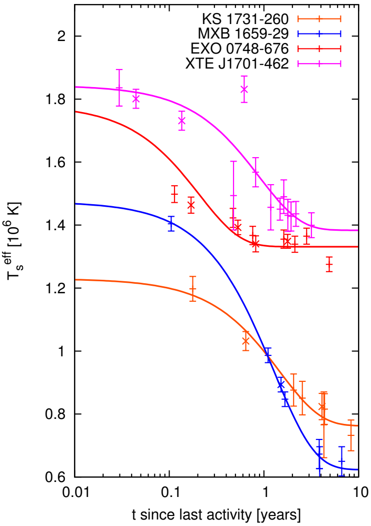


Refinements

- Realistic model of atmosphere : collaboration with A. Różańska (CAMK) $\rightarrow T_{\rm eff}$ + spectra in the accreting phase,
- Realistic model of H-burning : (T, ρ) dependence.

$\Rightarrow$ **Thermal evolution** during both the **accreting** and **quiescent** phases.

New observations



EXO 0748-676

Degenaar et al., ApJ (2014)

	τ (d)
KS	540 ± 125
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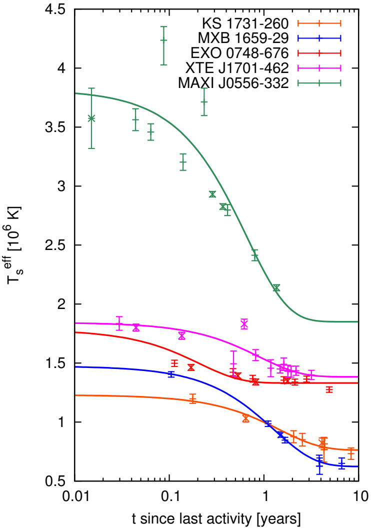
EXO	165 ± 60
XTE	95 ± 15

$\rightarrow$ even faster cooling.

New observations



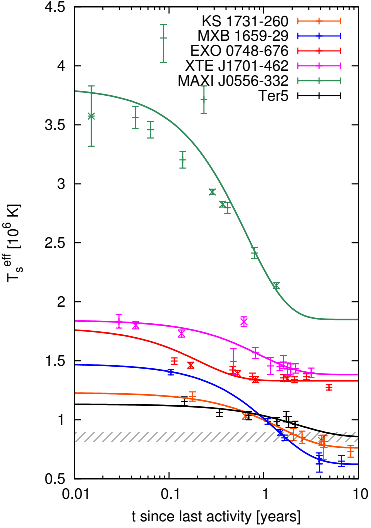
New source: MAXI J0556-332

Homan et al., arxiv 1408.3276

	τ (d)
KS	540 ± 125
MXB	465 ± 35
EXO	165 ± 60
XTE	95 ± 15
MAXI	240 ± 60

τ "normal" but extremely large T
$\rightarrow$ additional heating of the crust: residual accretion?

New observations



New type of source: normal transient

IGR J17480-2446 in Terzan 5 (Degenaar et al., ApJ 2013):
accreted during ∼ 10 weeks only.

	τ (d)
KS	540 ± 125
MXB	465 ± 35
EXO	165 ± 60
XTE	95 ± 15
MAXI	240 ± 60
Ter 5	100 ± 10

New window on the properties of accreting NSs.

Conclusion

Modeling the thermal evolution of isolated and accreting neutron stars enables to put constraint on their interior, eg. on

- the neutrino processes,
- the composition,
- ...

Isolated NSs $\rightarrow$ core properties;
Accreting NSs $\rightarrow$ crust properties.

Observers : please find more of these accreting sources!