Darmstadt Lecture 11 – Neutron Star Cooling

James Lattimer

Department of Physics & Astronomy
449 ESS Bldg.
Stony Brook University

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`James.Lattimer@Stonybrook.edu`

The Urca Processes

Gamow & Schönberg proposed the direct Urca process dominates neutron star cooling. Nucleons at the top of the Fermi sea $\beta-$decay at finite T.

$n \to p + e^- + \nu_e$,
$p \to n + e^+ + \bar{\nu}_e$

Energy conservation guaranteed by $\beta-$equilibrium

$\mu_n - \mu_p = \mu_e$

Momentum conservation requires $|k_{Fn}| \leq |k_{Fp}| + |k_{Fe}|$.

Charge neutrality requires $k_{Fp} = k_{Fe}$, therefore $|k_{Fp}| \geq 2|k_{Fn}|$.

Degeneracy implies $n_i \propto k_{Fi}^3$, thus $x \geq x_{DU} = 1/9$ is required.

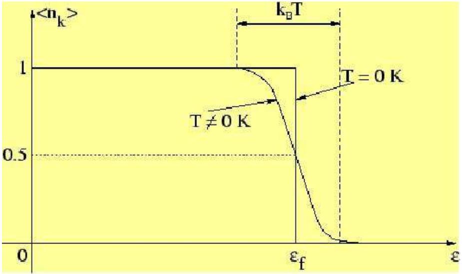
With muons $(n > 2n_s)$
$x_{DU} = [1 + (1 + 2^{-1/3})^3]^{-1} \simeq 0.148$

If $x < x_{DU}$, bystander nucleons needed: modified Urca process.
$(n,p) + n \to (n,p) + p + e^- + \nu_e$,
$(n,p) + p \to (n,p) + n + e^+ + \bar{\nu}_e$

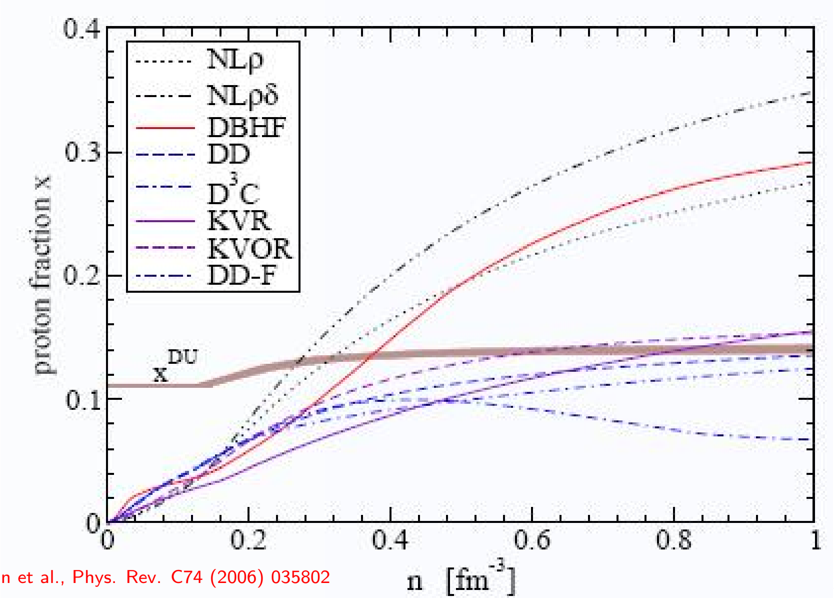
Neutrino emissivities:
$\dot{\epsilon}_{MU} \simeq (T/\mu_n)^2 \, \dot{\epsilon}_{DU} \sim 10^{-6} \dot{\epsilon}_{DU}$.

$\beta-$equilibrium composition:

$$x_\beta \simeq (3\pi^2 n)^{-1} (4E_{sym}/\hbar c)^3 \simeq 0.04\,(n/n_s)^{0.5-2} \; .$$

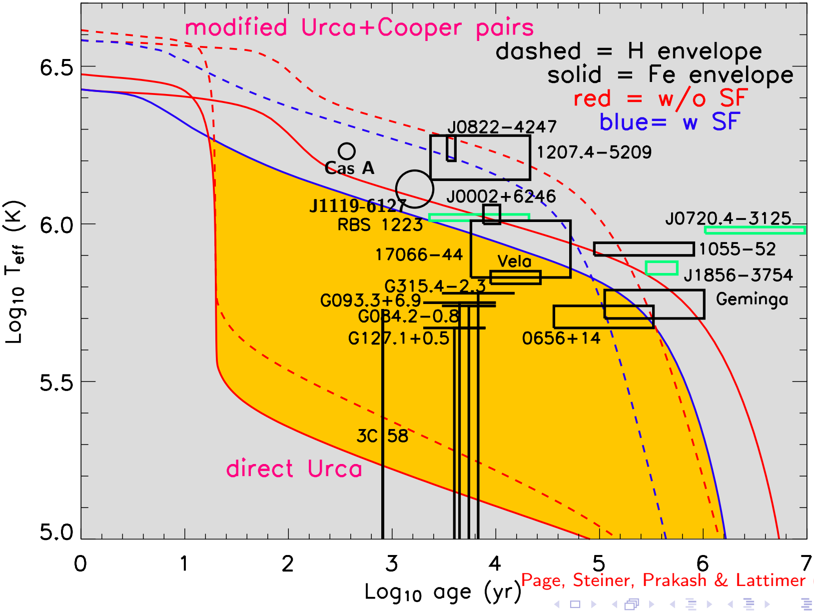


Direct Urca Threshold



Klähn et al., Phys. Rev. C74 (2006) 035802

Neutron Star Cooling



Page, Steiner, Prakash & Lattimer (2004)

Minimal Cooling Paradigm

Minimal Cooling Paradigm: Neutron star cooling including effects of superfluidity, such as Cooper-Pair breaking and formation, but no "rapid" neutrino cooling processes such as direct Urca involving nucleons or exotica.

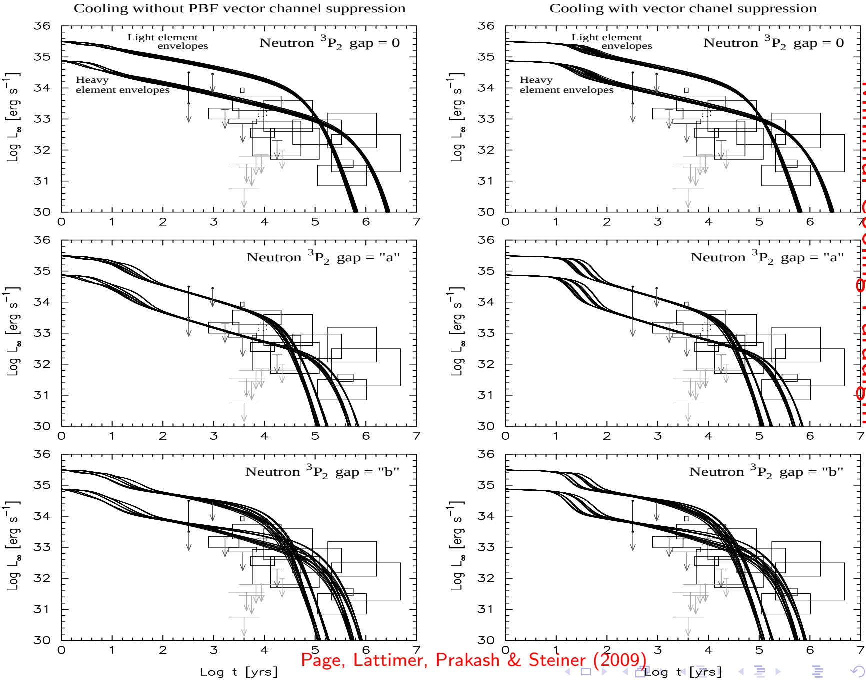
If some observations are inconsistent with the MCP, then according to Sherlock Holmes, rapid cooling must occur for these exceptions.

All sources are consistent with the MCP only IF

- tight conditions are placed on the magnitude and density dependence of the neutron ${}^3\mathrm{P}_2$ gap, AND
- some neutron stars have heavy Z envelopes and others have light Z envelopes, AND
- ALL core-collapse supernova remnants with no observable thermal emission contain black holes.

Highly suggestive that rapid cooling occurs in some neutron stars (of higher masses?)

A possible constraint on $E_{sym}(n)$ or $n_{central}$.



Minimal Cooling Paradigm

Page, Lattimer, Prakash & Steiner (2009)

Transitory Rapid Cooling

MU emissivity: $\dot{\varepsilon}_{MU} \propto T^8$

PBF emissivity ($f \sim 10$):
$\dot{\varepsilon}_{PBF} \propto F(T)\ T^7 \propto T^8 \simeq f\dot{\varepsilon}_{MU}$

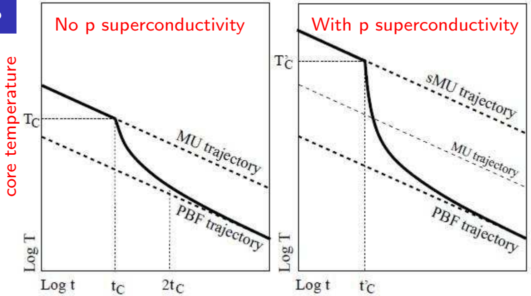
Specific heat: $C_V \propto T$

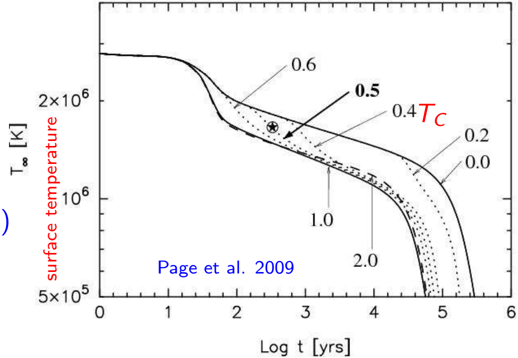
Neutrino dominated cooling:
$C_V dT/dt = -L_\nu$

$\implies T \propto (t/\tau)^{-1/6}$
$\tau_{PBF} = \tau_{MU}/f$

$(d\ln T/d\ln t)_{transitory}$
$\simeq (1-10)(d\ln T/d\ln t)_{MU}$
$\simeq (1-25)(d\ln T/d\ln t)_{MU}$ (p SC)

Very sensitive to n $^1S_0$ critical temperature (T_C) and existence of proton superconductivity





Page et al. 2009

Cas A

Remnant of Type IIb (gravitational collapse, no H envelope) SN in 1680 (Flamsteed).

3.4 kpc distance

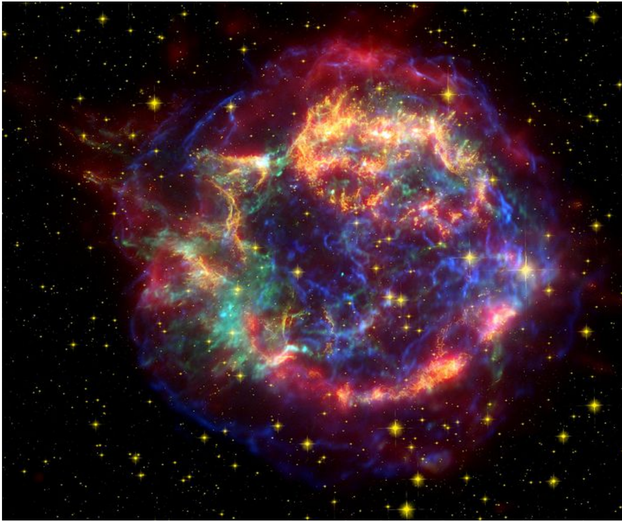
3.1 pc diameter

Strongest radio source outside solar system, discovered in 1947.

X-ray source detected (Aerobee flight, 1965)

X-ray point source detected (Chandra, 1999)

1 of 2 known CO-rich SNR (massive progenitor and neutron star?)



Spitzer, Hubble, Chandra

Cas A Superfluidity

X-ray spectrum indicates thin C atmosphere, $T_e \sim 1.7 \times 10^8$ K (Ho & Heinke 2009)

10 years of X-ray data show cooling at the rate $\frac{d\ln T_e}{d\ln t} = -1.23 \pm 0.14$ (Heinke & Ho 2010)

Modified Urca: $\left(\frac{d\ln T_e}{d\ln t}\right)_{MU} \simeq -0.08$

We infer that

$T_C \simeq 5 \pm 1 \times 10^8$ K

$T_C \propto (t_C L/C_V)^{-1/6}$