New Horizons in Time-Domain Astronomy
Proceedings IAU Symposium No. 285, 2011
R.E.M. Griffin, R.J. Hanisch & R. Seaman, eds.

doi:10.1017/S1743921312000981

Hottest Superfluid and Superconductor in the Universe: Lessons from the Cooling of the Cassiopeia A Neutron Star

Wynn C. G. Ho[1,6], Craig O. Heinke[2], Daniel J. Patnaude[3], Peter S. Shternin[4,5,7], and Dmitry G. Yakovlev[4,5]

[1]School of Mathematics, University of Southampton, Southampton SO17 1BJ, UK
[2]Department of Physics, University of Alberta, Edmonton, AB T6G 2G7, Canada
[3]Smithsonian Astrophysical Observatory, Cambridge, MA 02138, USA
[4]Ioffe Physical Technical Institute, Politekhnicheskaya 26, 194021 St. Petersburg, Russia
[5]St. Petersburg State Polytechnical Univ., Politekhnicheskaya 29, 195251 St. Petersburg, Russia
[6]email: wynnho@slac.stanford.edu [7]email: pshternin@gmail.com

Abstract. The cooling rate of young neutron stars gives direct insight into their internal makeup. Using CHANDRA observations of the 330-year-old Cassiopeia A supernova remnant, we find that the temperature of the youngest-known neutron star in the Galaxy has declined by 4% over the last 10 years. The decline is explained naturally by superconductivity and superfluidity of the protons and neutrons in the stellar core. The protons became superconducting early in the life of the star and suppressed the early cooling rate; the neutron star thus remained hot before the (recent) onset of neutron superfluidity. Once the neutrons became superfluid, the Cooper pair-formation process produced a splash of neutrino emission which accelerated the cooling and resulted in the observed rapid temperature decline. This is the first time a young neutron star has been seen to cool in real time, and is the first direct evidence, from cooling observations, of superfluidity and superconductivity in the core of neutron stars.

Keywords. dense matter, equation of state, neutrinos, stars: evolution, stars: interiors, stars: neutron, supernovae: individual (Cassiopeia A), X-rays: stars

---

Neutron stars are created in the collapse and supernova explosion of massive stars. They begin their lives very hot ($T > 10^{11}$ K) but cool rapidly through the emission of neutrinos. Neutrino emission depends on uncertain physics at the supra-nuclear densities ($\rho \gtrsim 2.8 \times 10^{14}$ g cm^{-3}) of the neutron star core (Tsuruta 1998; Yakovlev & Pethick 2004; Page *et al.* 2006; Yakovlev *et al.* 2011). Current theories indicate that the star may contain exotica such as hyperons and deconfined quarks, and matter may be in a superfluid/superconducting state (Migdal 1959; Lattimer & Prakash 2004; Haensel *et al.* 2007). Observing cooling neutron stars and comparing their temperatures to theoretical models allow one to constrain the (uncertain) physics that governs the stellar interior.

The compact object at the centre of the Cassiopeia A supernova remnant was discovered in CHANDRA first-light observations (Tananbaum 1999) and subsequently identified as a neutron star (Ho & Heinke 2009). The supernova explosion is estimated to have occurred in 1681 ± 19 (Fesen *et al.* 2006); that makes the Cassiopeia A neutron star the youngest-known neutron star: its age is $\sim$330 yr. Heinke & Ho (2010) analyzed CHANDRA ACIS observations taken during the last 10 years and found a steady temperature decline of 4%. If the rapid decline is due to passive cooling, then that is evidence for superfluidity and superconductivity in the core of a neutron star.

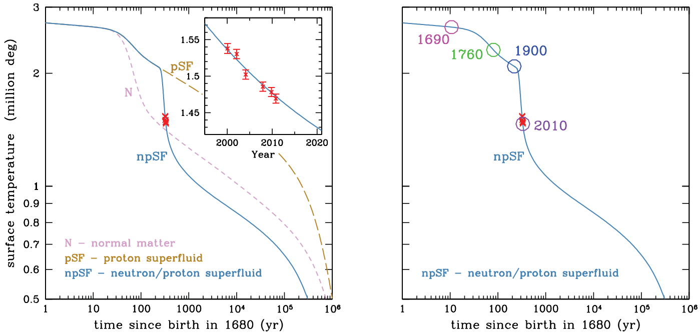

Figure 1. Theoretical models of neutron-star cooling with superfluid neutrons and protons (npSF – solid), normal neutrons and superfluid protons (pSF – long-dashed), and normal neutrons and protons (N – short-dashed). Left: Data (inset) are from CHANDRA observations of the Cassiopeia A neutron star (crosses). Right: Calculated temperatures at particular ages (circles; denoted by the year) corresponding to the four sets of panels in Fig. 2

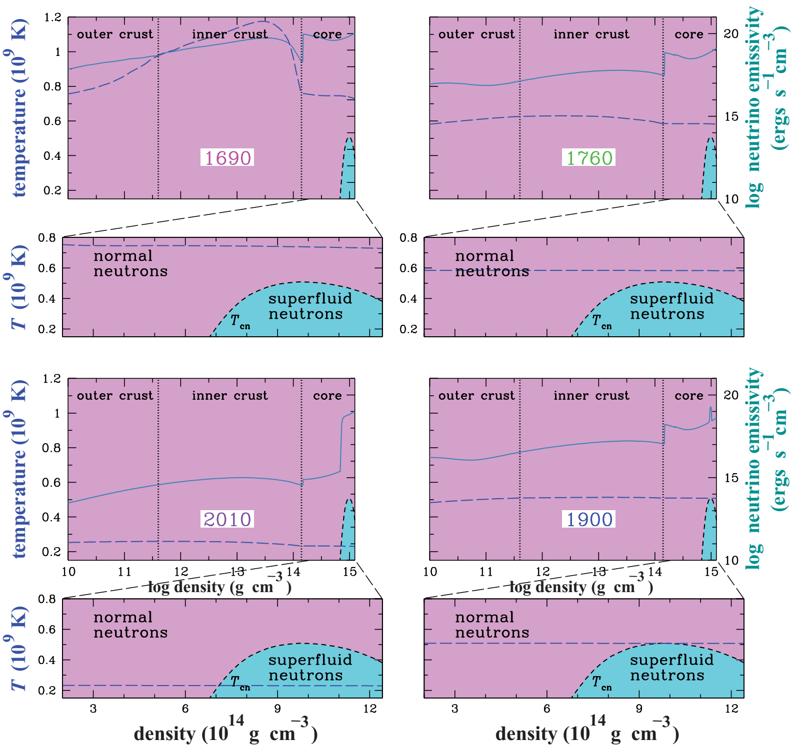

Figure 2. Profiles of neutron-star interior temperature (long-dashed) and neutrino emissivity (solid) as a function of density. The short-dashed lines indicate the critical temperature $T_{\rm cn}$ for superfluid formation: neutrons become superfluid at densities where $T < T_{\rm cn}$. Each set of (upper and lower) panels is at a particular age/year (see also right panel of Fig. 1), starting with the top left (in year 1690) and continuing clockwise until the bottom left (in year 2010). Upper set: outer parts of the star are at lower densities and labelled outer/inner crust, and inner parts at supra-nuclear densities are labelled core; the core has a radius of ∼10 km, while the crust thickness is ∼1 km. Lower set: close-up of the core and neutron superfluid transition region.

https://doi.org/10.1017/S1743921312000981 Published online by Cambridge University Press

The left panel of Fig. 1 shows surface temperatures for three theoretical models of neutron star cooling: "N − normal matter" corresponds to neutron star matter that does not contain any sort of superfluid, "pSF−proton superfluid" is for a proton superfluid in the core, and "npSF−neutron/proton superfluid" is for superfluid protons and neutrons in the core. The inset shows CHANDRA surface temperature measurements of the Cassiopeia A neutron star from 1999 to 2010 (Heinke & Ho 2010; Shternin *et al.* 2011). Note the clear difference between the cooling behaviour of models with normal matter (N) and matter containing superfluids (pSF or npSF) after time ∼40 yr. A proton superconductor forms soon after neutron star formation, and that suppresses neutrino emission so the cooling rate is weaker than for normal matter. The neutron star is thus able to stay relatively warm, but precipitating a rapid temperature drop once neutrons become superfluid (Gusakov *et al.* 2004; Page *et al.* 2004). The model with superfluid neutrons and protons (npSF) fits the data at an age of a few hundred years. The right panel of Fig. 1 shows the npSF model of neutron star cooling; the four circles trace the cooling curve predicted by that model from about 10 years after the supernova explosion (SN in ∼1680) to near the present date.

The four sets of panels of Fig. 2 show the interior temperature and neutrino emissivity at the four ages/dates corresponding to the circles in Fig. 1. At early ages (top left), the neutron-star core cools so rapidly by neutrino emission that the crust does not have time to react. The crust was thus hotter than the core in 1690 (age ∼10 yr; protons were superconducting by that time), and the surface temperature declined very slowly. The surface temperature eventually reacted to the "cooling wave" that swept through the crust and started to drop more quickly. After 1760 (top right) the temperature became almost constant throughout the star. Then in ∼1900 (bottom right) the interior temperature dropped below the critical value for a neutron superfluid to form, and a spike in neutrino emission occurred in the core as neutron Cooper pairs formed. Energy was lost as the neutrinos were emitted, causing the core to cool off and another cooling wave to travel outwards. As neutrons in large regions of the core became superfluid the surface temperature dropped quickly, beginning in ∼1930 and continuing to the present date (bottom left). Further details can be found in Shternin *et al.* (2011).

Very similar results and conclusions were obtained independently by Page *et al.* (2011). Continued monitoring will allow tests of our model, and will also reveal important fundamental physics that cannot be accessed in laboratories on Earth.

References

Fesen, R. A., *et al.* 2006, *ApJ*, 645, 283
Gusakov, M. E., Kaminker, A. D., Yakovlev, D. G., & Gnedin, O. Y. 2004, *A&A*, 423, 1063
Haensel, P., Potekhin, A. Y., & Yakovlev, D. G. 2007, *Neutron Stars 1. Equation of State and Structure* (New York: Springer)
Heinke, C. O. & Ho, W. C. G.. 2010, *ApJ*, 719, L167
Ho, W. C. G. & Heinke, C. O. 2009, *Nature*, 462, 71
Lattimer, J. L. & Prakash, M. 2004, *Science*, 304, 536
Migdal, A. B. 1959, *Nucl. Phys.*, 13, 655
Page, D., Geppert, U., & Weber, F. 2006, *Nucl. Phys. A*, 777, 497
Page, D., Lattimer, J. M., Prakash, M., & Steiner, A. W. 2004, *ApJS*, 155, 623
Page, D., Prakash, M., Lattimer, J. M., & Steiner, A. W. 2011, *Phys. Rev. Lett.*, 106, 081101
Shternin, P. S., *et al.* 2011, *MNRAS* (Lett.), 412, L108
Tananbaum, H. 1999, *IAU Circ.* 7246
Tsuruta, S. 1998, *Phys. Rep.*, 292, 1
Yakovlev, D. G. & Pethick, C. J. 2004, *ARAA*, 42, 169
Yakovlev, D. G., *et al.* 2011, *MNRAS*, 411, 1977