NEUTRON STAR COOLING

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THE X-RAY MYSTERIES OF NEUTRON STARS AND WHITE DWARFS

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MANIFESTATIONS
A NEUTRON STAR: SURFACE and INTERIOR

- CREDIT: DANY PAGE, UNAM
“STANDARD” COOLING

Yakovlev+04

Page+04: Effects of envelope
COLLECTED MEASUREMENTS

• ABOUT 13 CENTRAL COMPACT OBJECTS, ‘TINS’; AGES, DISTANCES, LUMINOSITIES CONSTRAINED

• ABOUT 25 PULSARS; AGE, DISTANCE, LUMINOSITY LESS WELL KNOWN

• 7 NEARBY ‘XINSS’=X-RAY ISOLATED NEUTRON STARS

Potekhin+20, selection
COOLING MECHANISMS

• NEUTRINO PROCESSES:
  • DIRECT URCA (P → N + E^+ + NEUTRINO, N → P + E + ANTI-NEUTRINO)
  • URCA-LIKE (PIONS, HYPERONS, QUARKS)
  • MODIFIED URCA
  • NEUTRON BREMSSTRAHLUNG

• EFFECTS OF SUPERFLUID NUCLEONS:
  • PAIRING SUPPRESSES ALL URCA
  • REDUCE HEAT CAPACITY
  • PAIR BREAKING & FORMATION (PBF)
DIRECT URCA: FAST COOLING

$T = 3 \times 10^8$ K

$\log Q$ (erg cm$^{-3}$ s$^{-1}$) vs $\log \rho$ (g cm$^{-3}$)

$\log T_\infty$ (K) vs $\log t$ (yrs)

Yakovlev+2004
URCA-LIKE PROCESSES

Yakovlev+04
COOLING MECHANISMS

- **NEUTRINO PROCESSES:**
- DIRECT URCA (P -> N + E⁺ + NEUTRINO, N -> P + E + ANTI-NEUTRINO)
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- **EFFECTS OF SUPERFLUID NUCLEONS:**
- PAIRING SUPPRESSES ALL URCA
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SUPERFLUID EFFECTS

With pairing (no PBF)

Without pairing

With pairing (and PBF)
CAS A: RAPID COOLING

Shternin+ 2011
IS CAS A COOLING?

Elshamouty+2013

Posselt+2013
Posselt+2022, subarray data; T decline by 1.5-2.3% per decade

Posselt+22, Ho+21 graded data; T decline by 2-3% per decade
HEATING BY ACCRETION

Degenaar & Suleimanov 2018
CRUST HEATING, COOLING

\[ \dot{M}(t) = \frac{0.000 \dot{M}_{\text{Edd}}}{0.000 \dot{M}_{\text{Edd}}} \]

N. Degenaar
CRUST PHYSICS CONSTRAINED

Merritt+2016
KS 1731-260 cooling

Core temp
7-11e8 K

Impurity
1-10

Shallow heating
0.6-3.5 MeV/nucl.

Pasta ρ,
6-10e13

Pasta impurity,
2-40

See also V. Allard poster
SHALLOW HEATING

Terzan 5

Swift J174805.3-244637 (T5 X-3)
EXO 1745-248 (T5 X-1)
IGR J17480-2446 (T5 X-2)

See also N. Chamel poster!

Degenaar+15

Degenaar+11

Neutron star temperature (eV)

Time since end of accretion phase (days)

2011 February

2011 April

Quiescent base level 2003/2009

No shallow heat source

Qextra = 0.5 MeV/nucleon

Qextra = 1.0 MeV/nucleon
DIFFERENT BEHAVIORS

Wijnands 2017
LOW-MASS X-RAY BINARIES

Heinke+10; tracks from Yakovlev+04
BROADENING URCA TRANSITION

Beznogov & Yakovlev 2015
CONCLUSIONS

- Young neutron stars cool by neutrinos; superfluid PBF important.

- Is Cas a cooling? Different datasets coming to agree; yes.

- Measuring crust cooling constrains physics of crust; relatively pure crust, pasta layer, unknown shallow heating.

- Some old NSS are very cold, require enhanced neutrino emission (e.g. direct URCA) in massive neutron stars.
EXTRA SLIDES
THEORY

- AS CORE TEMP DROPS, COOLING IN STAGES; SLOW, BURST PBF, SLOWER; FASTER AT END.

- NS MASS AFFECTS PEAK NS DENSITY, ACCESS TO FAST COOLING

Shternin+11; tracks for different NS masses, assuming strong n SF.
DATA VS. THEORY

- CAN EXPLAIN YOUNG NSS WITH RANGE OF ENVELOPES PLUS SUPERFLUIDITY;
  OR ADD DIRECT URCA (BROADENED THRESHOLD)

Beznogov+15; broadened direct Urca transition

Page+04: minimal cooling (heavy vs. light envelopes, SF gap).
LIMITS ON YOUNG NS

- KAPLAN+04 SEARCHED 4 YOUNG SNRS, FOUND NO NS.
- IF NS, COLD; REQUIRE DIRECT URCA?

Page+04, plotting Kaplan+04 limits
ATMOSPHERES

- FREE-FREE ABSORPTION MAKES NS SPECTRA HARDER THAN BLACKBODY
- SUBTLE DIFFERENCES IN SPECTRAL SHAPE OF BLACKBODY, H, HE ATMOSPHERES
- LARGE DIFFERENCES WITH FE, O ATMOSPHERES
- INFERRRED TEMPERATURE, RADIUS VARY; C ATM GIVES 3-4X LARGER RADIUS THAN H

Ho & Heinke 2009
UNCERTAINTIES

• TEMP, LUMINOSITY EACH SUFFER UNCERTAINTIES

• LUMINOSITY DIRECTLY PREDICTED BY THEORY. BUT DISTANCE RARELY WELL-KNOWN.

• TEMPERATURE CAN BE FIT BY SPECTRA. HOWEVER, OFTEN NOT TEMP OF FULL SURFACE. ATMOSPHERE COMPOSITION OFTEN NOT KNOWN—SO REAL KT NOT CLEAR.

Potekhin+20