COOLING NEUTRON STARS: THE PRESENT AND THE FUTURE

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CONTENT

I. INTRODUCTION

Early 1933: Oppenheimer/Volkof – Isolated Neutron star (INS) structure (*1)

Early 1960s: Tsuruta and Cameron – INS cooling (*2)

Early 1780s: Einstein Observatory – First upper limits to INS temperature (*3)

Early 1990s: ROSAT – First possible four detections of INS temperature (*4)

Current: Better INS temperature data from Chandra and XMM/Neutron (*5)

- **Standard Cooling**: **modified URCA** neutrino emissivity, etc. (*5)

- **Non-standard Cooling**: faster cooling, with **`exotic'** processes such as **direct URCA** processes involving **nucleons, pions, hyperons, kaons, quarks**, etc. (*5)

- **Note: All non-standard cooling - too fast to be consistent with the observational detection data, without superfluid suppression (*5).**

- **Superfluid Suppression** (*5):

- Fast cooling suppressed in the presence of superfluid particles

When particles are in a superfluid state, neutrino emisivity involving these particles are suppressed as:

- Exp ($-$ a T_{crit}/T),
- when T << T_{crit},.

- where T_{crit} is superfluid critical temperature, which depends on superfluid energy gap, and T is the internal temperature of the star. a is a constant.

- **Cooper Pair Cooling** (*6)

- It affects neutrino emissivity involving superfluid neutrons in a very complicated way – for a certain choice of the energy gap it can be significantly enhanced- bringing the cooling curve down.

- Proton superfluidity (superconductivity) can affect cooling also.

- But effects of Cooper pair cooling on hyperon and pion cooling cases are minor.

II. BASIC EQUATIONS AND PHYSICAL INPUT, in our most recent work

Basic Equations:

General relativistic equations of hydrostatic equilibrium(*1) and thermodynamics (energy balance and energy transport)(*5)

Physicsl Input:

Equation of State(EOS):

(i) Hyperon matter, for $\rho > \rho_{crit} = 4\,\rho_{N.}$ (*7a)(*8a)

(a) TNI3U(stiff)

(b) TNI6U(medium)

(c) TNI2U(soft)

(ii) Pion Condensates, for $\rho > \rho_{crit} = 2\,\rho_{N.}$ (*7b)(*8b)

TNI3P(stiff)

(where ρ_N is nuclear density = 2.8 x 10^{14} gm/cm^{3}).

Neutron matter with density (*9)

$\rho < \rho_{crit}$ (critical transition density)

EOS:

(a)TNI3(stiff)

(b) TNI6(medium)

(c) TNI2(soft)

Below ~ nuclear density, regular crusts and atmospheres -

EOS - same as in Tsuruta 1998 (T98)(*5)

Neutrino Emissivity:

Standard Cooling: **Modified URCA** (both nucleons in the core and heavy ions in the crust), **Cooper Pair,** nucleon bremsstrahlung, plasmon neutrino, photo neutrino, pair neutrino emissivity, etc.(*5)

Non Standard Cooling:

(i) **Λ and Σ Hyperon direct URCA** emissivity, including Cooper pair emissivity (*7a)(*8a)

(ii) Pion direct URCA emissivity, including Cooper pair emissivity (*7b)(*8b)

Heating: **Vortex creep heating(*10)(*11)**

Superfluidity:(depends on density and temperature)

Neutron superfluidity:

OPEG-B(*9)

Hyperon superfluidity: ND-Soft (*7a)(*8a)

Pion superfluidity:

Modified Tamagaki (*7b)(*8b)

Proton superfluidity: CCY(*5)

Opacity/Conductivity: Standard, as adoptred in Ref: (*5)

Atmosphere: Blackbody ~ Fe atmosphere (*5)

III. RESULTS AND COMPARISON WITH OBSERVATION

A Our Results -- See Figures 1 to 3

(i) Hyperon Stars

Fig. 1a: Stiff (TNI3U)
Fig. 1b: Medium (TNI6U)
Fig. 1c: Soft (TNI2U)

Effects of EOS

For smaller mass stars (#1): standard cooling of neutron stars:

since central density $\rho < \rho_{\mathbf{crit}}$

(#1) $M_g \sim 1.3 M_\odot$ for stiff and medium models, $M_g \sim 1.2 M_\odot$ for soft model

Both neutrons and protons in **superfluid states**

Note: For hot pulsar PSR 1055, small mass neutron star (no hyperons) o.k. if heating included!

More massive stars (#2):

Hyperon (non-standard) cooling, with superfluid suppression, since $\rho_c > \rho_{crit.}$

(#2) $M_g \sim 1.6\ M_\odot$ for stiff, $M_g \sim 1.5 M_\odot$ for medium, $M_g \sim 1.3 M_\odot$ for soft EOS.

O.K. with cooler stars (e.g., Vela, Geminga, 3C58, etc.)

Most massive stars (#3)

(#3) $M_g > \sim 1.6 M_\odot$ for stiff, $M_g > \sim 1.5 M_\odot$ for medium, $M_g > \sim 1.3 M_\odot$ for soft EOS.

Too cold for Vela, but O.K. for other upper limits, and cold candidates (#4)

Note: Larger mass required for stiffer EOS!

(#4) Note that most recently Kaplan et al. (*12) suggested that if the compact objects in several supernova remnents (SNR) are neutron stars, they should be very cold. The data points not shown in our figures because these authors gave only the upper limits for X-ray luminosity, while our theoretical curves refer to the bolometric (total stellar) luminosity. Even taking that into account, these upper lmits are far below the Vela detection data, and hence require more massive cold stars.

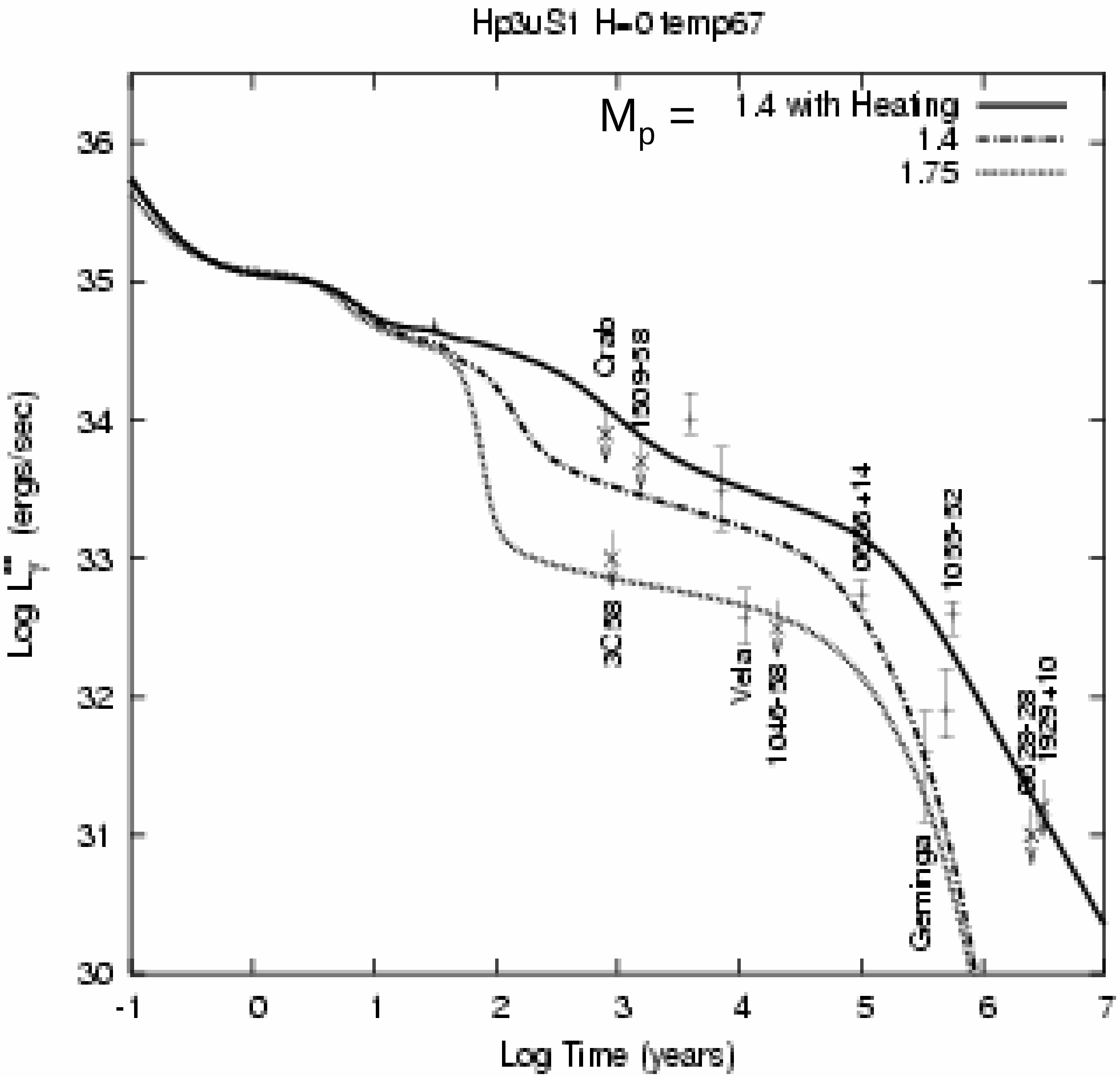

Fig. 1a

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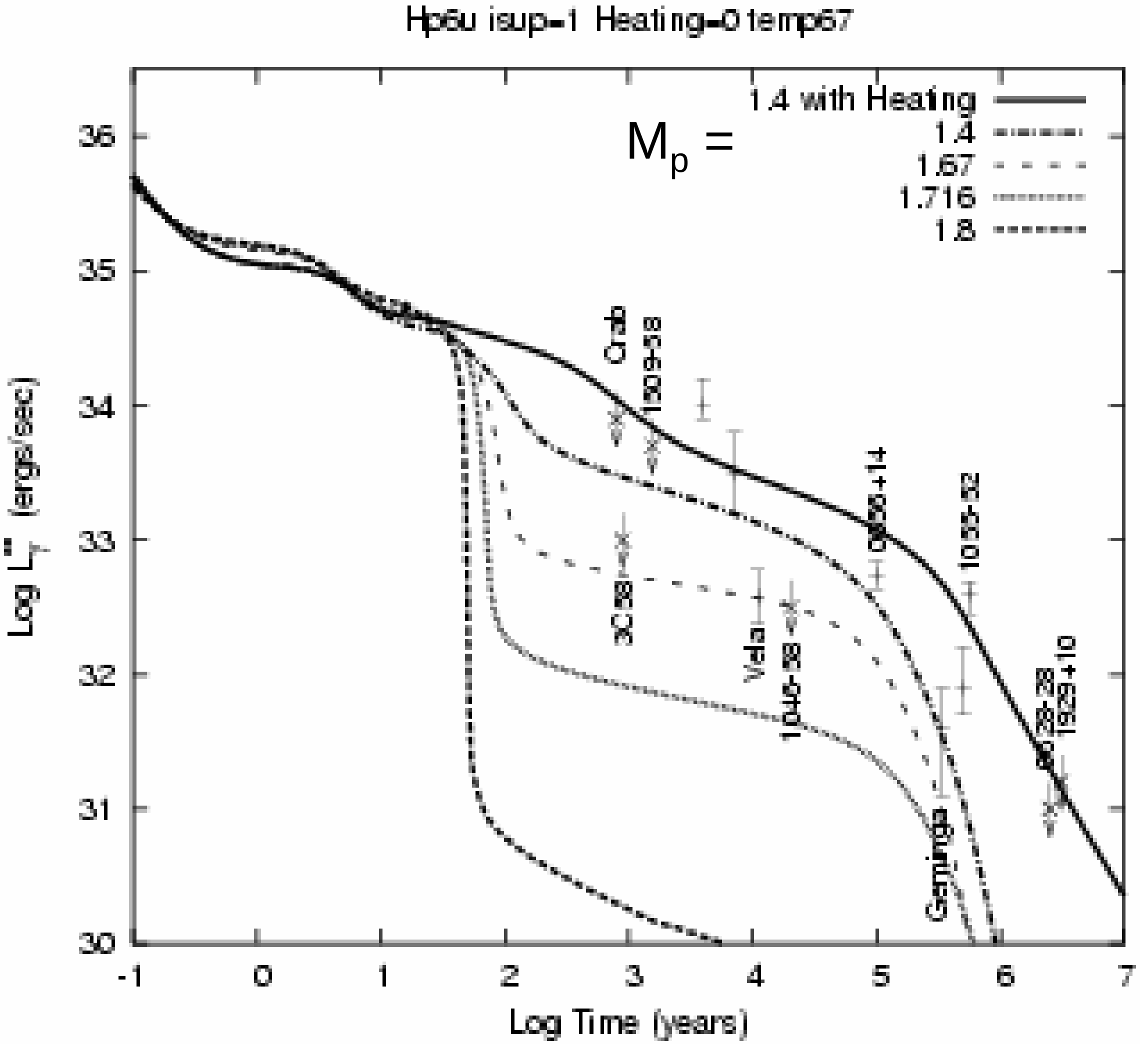

Fig. 1b

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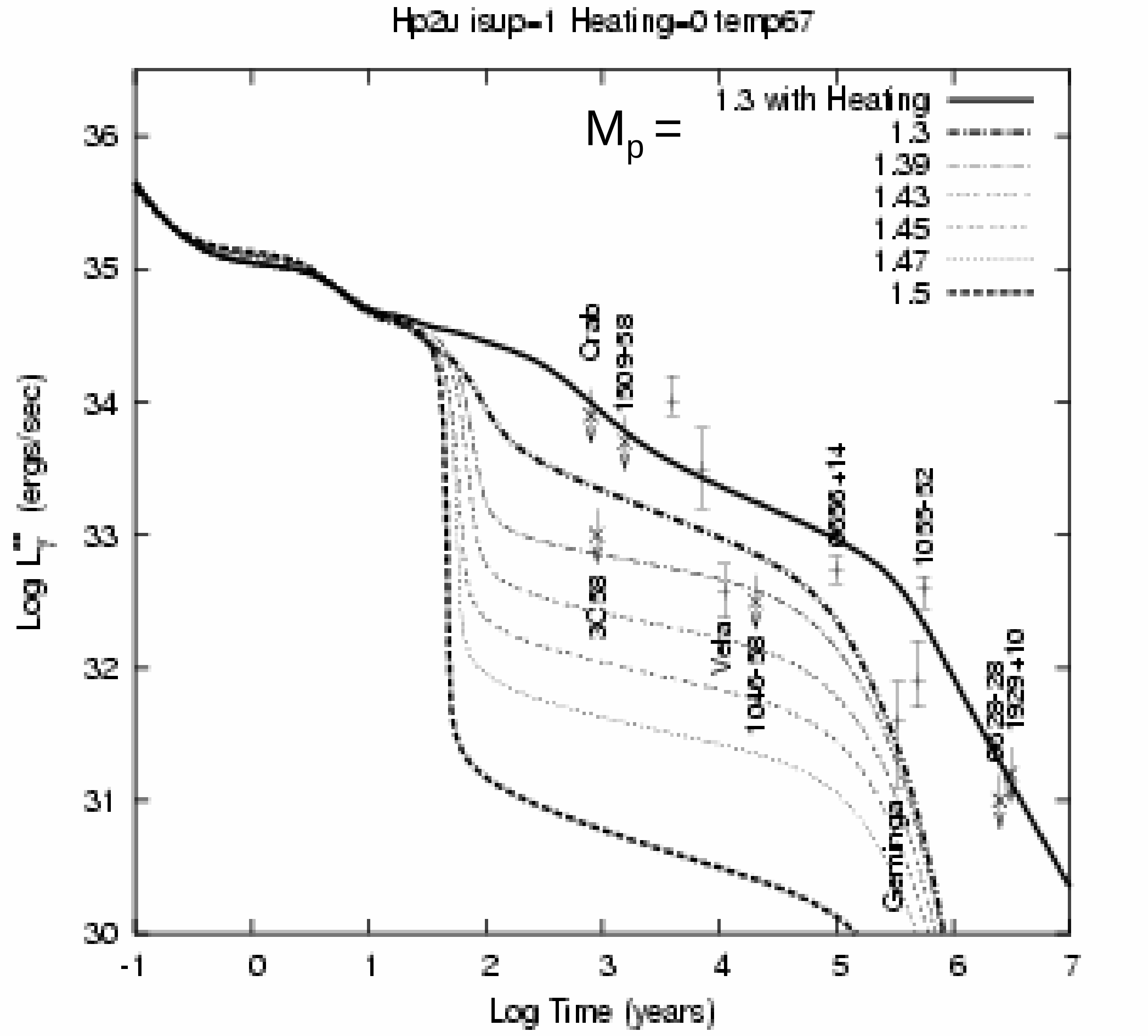
Hp2u isup=1 Heating=0 temp67
M_p =
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1.5
Crab
1509-58
3C58
Vela
1046-58
0656+14
1055-52
Geminga
0538-28
1929+10
Log L_γ^∞ (ergs/sec)
Log Time (years)
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Fig. 1c

Effects of Heating:

Medium EOS (TNI6U) adopted as a typical case

(i) Medium heating: Figure 2a

Pulsar 1055 o.k. if uncertainly in age very large

Other conclusions (e.g., vela with $M_g \sim 1.5M_\odot$) same as without heating.

(ii) Strongest heating: Figure 2b

Pulsar 1055 o.k.

Slightly larger mass (but not much, $M_g \sim 1.52M_\odot$) required for Vela, etc. (instead of $M_g \sim 1.5M_\odot$)

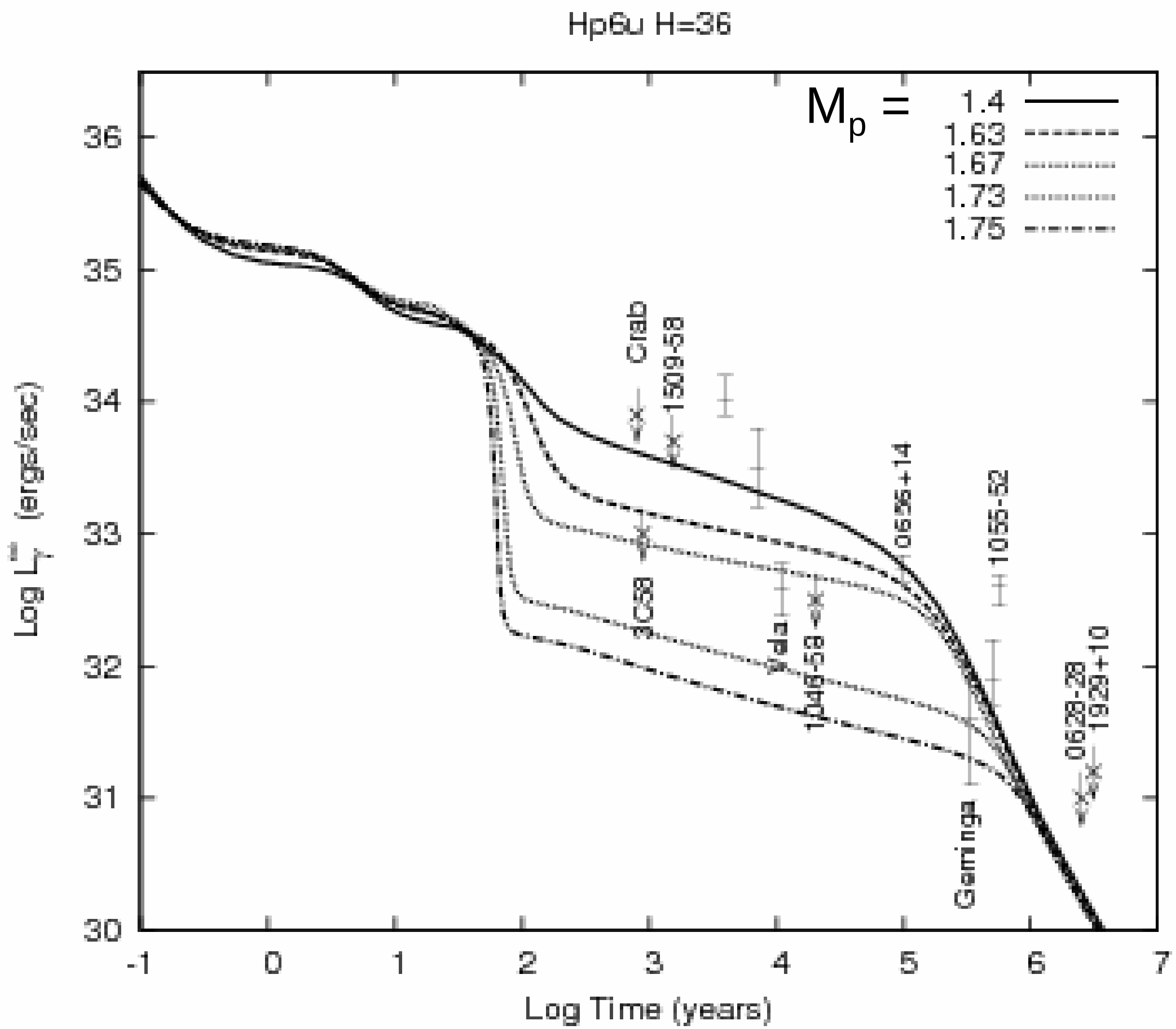

Fig. 2a

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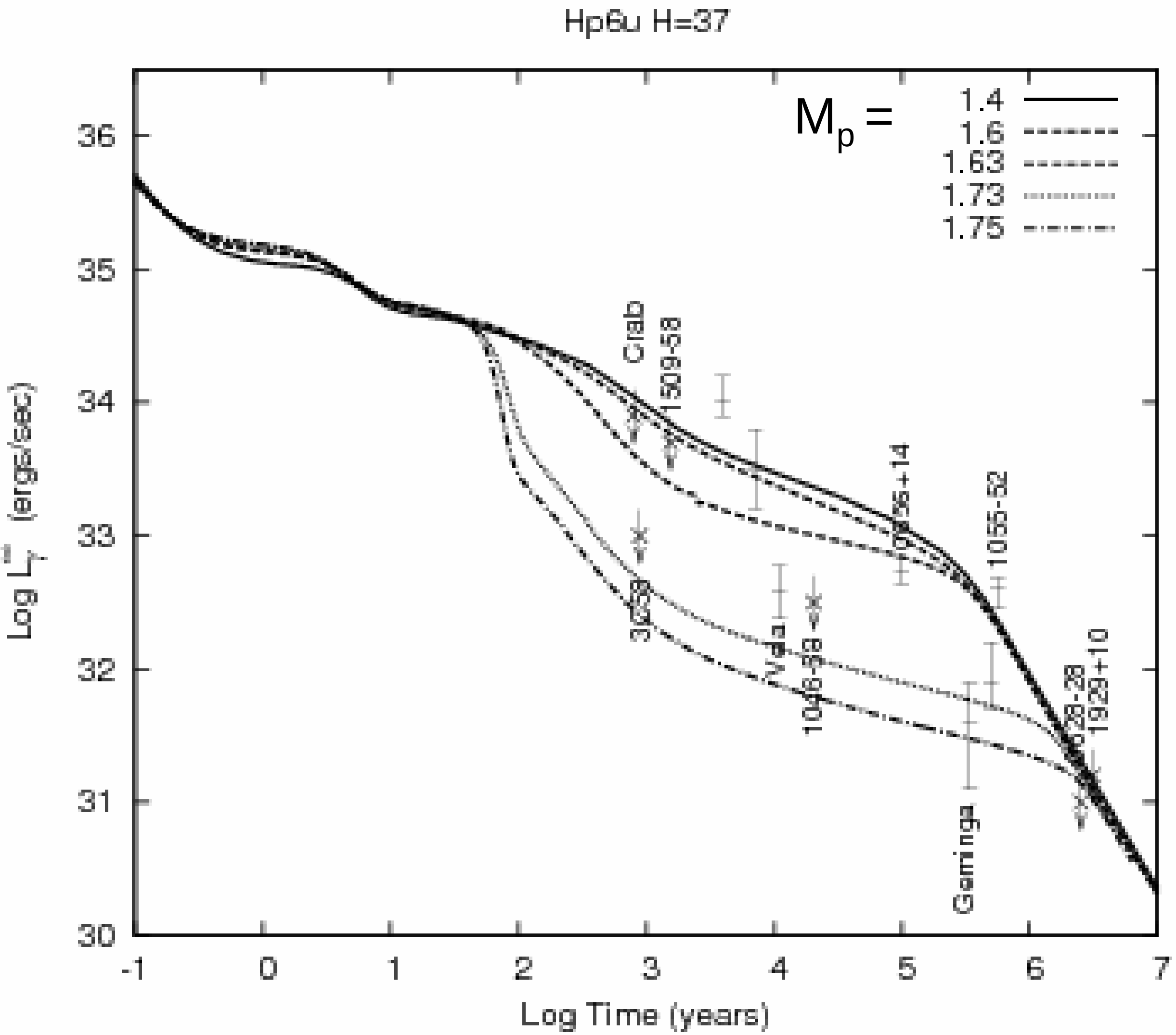

Fig. 2b

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(ii) Pion Stars (*7b)(*8b)

TNI3P(stiff) Model chosen

Low mass $M_g \sim 1.3M_{\odot}$ **stars:**

(…..) **with strong heating**

(__) No heating

For hot pulsar PSR 1055, $M_g \sim 1.3M_{\odot}$ star o.k., if heating included!

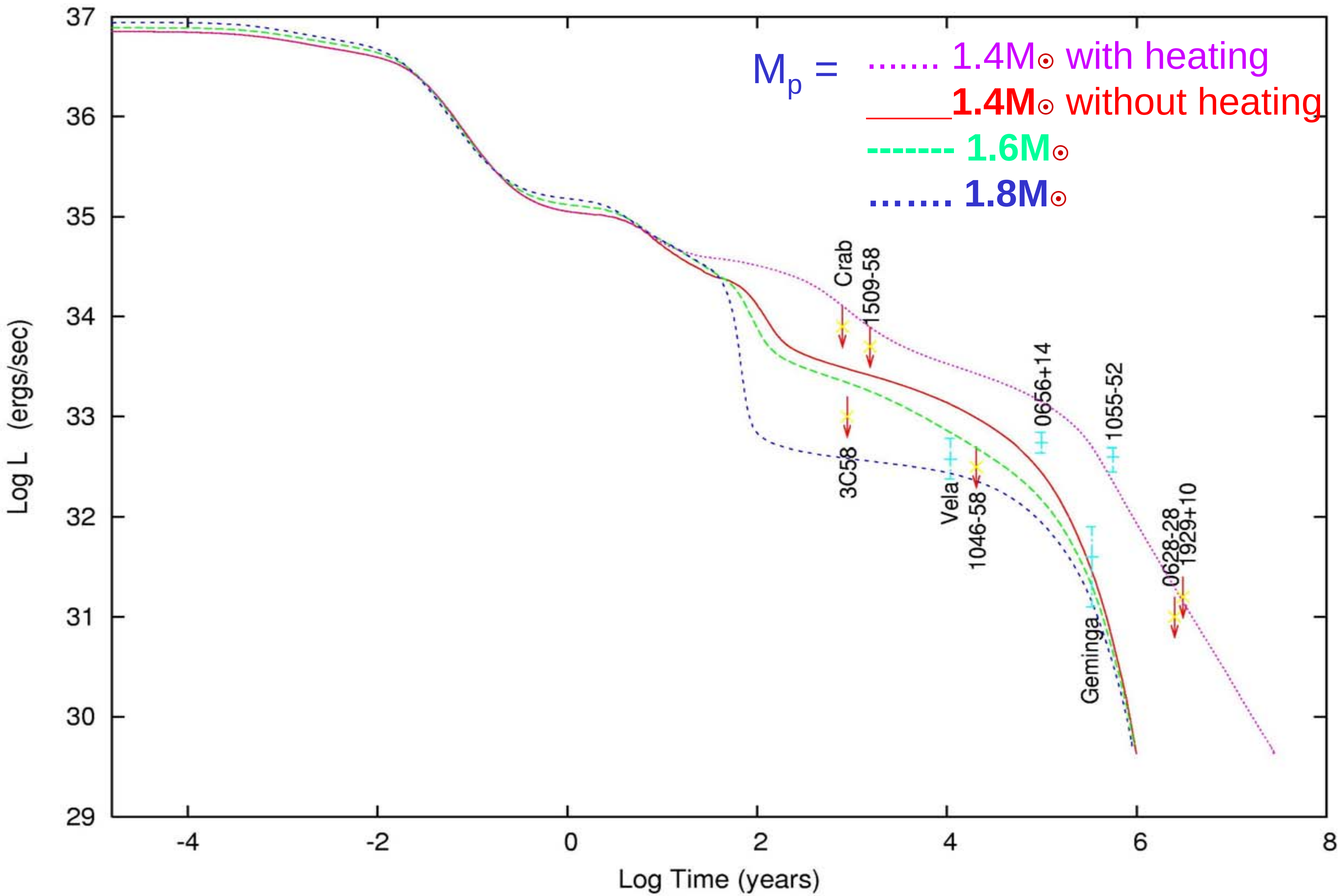
More massive stars:

Pion (non-standard) cooling, with superfluid suppression,

$M_g \sim 1.5\text{-}\ 1.6M_{\odot}$ O.K. with cool stars (e.g., Vela, Geminga, 3C58, etc.)

Most massive stars ($M_g > 1.6M_{\odot}$)

Too cold for Vela, but O.K. for other upper limits, and cold candidates (#4)



Pion Stars

Fig. 3

COMMENTS:

(i) For hot pulsar PSR 1055 data, **both protons and neutrons can be in the superfluid state if heating is included** for standard scenario – **consistent with both current nuclear physics theory and observational evidence (e.g. glitches).**

(ii) Hyperons and pions must be in a superfluid state if cool pulsar data (e.g. Vela, 3C58) are **detections.**

(iii) Larger mass ($M_g \sim 1.5 – 1.8M_{\odot}$) reported by Nice et al. (*13) from observation. If the mass range larger (e.g., $M_g \sim 1 - 2M_{\odot}$), then softer EOS (e.g., TNI2U) should be excluded, but medium to stiff EOS (e.g., TNI6U, TNI3U) still o.k.

(iv) Kyoto-Gifu experimental group reports(*14) that their experiment suggests that **Hyperon attractive force may be much weaker than considered earlier – then, Hyperon superfluid critical temperature may be too low. If confirmed, Hyperon cooling for cooler data will be out** if the cooler data are <u>detections</u>. Then, **Pion cooling is more likely**.

(v) By changing mass, all data are consistent with theoretical thermal evolution (cooling + heating) theories (*15)

B. Comparison with Other Major Work:

by Yakovlev Group: Y2004 (*16)

Mostly similar to our work, BUT

Major differences are:

(i) Reached different conclusion that: “To be consistent with PSR 1055 data, **protons must be in the superfluid (superconductor) state, but**

NOT neutrons.

(ii) Adopted **NUCLEON DIRECT URCA** for non-standard cooling.

(iii) They say: Since nucleon (neutron and proton) direct URCA is o.k.,

No `exotic’ particles are needed!

- **Major Reasons for Differences and Implication**:

(i) Y2004 says: Protons must be, but neutrons must not be superfluids,

BUT they **did not include heating**:

Note: Our results show that **with heating, standard cooling with both neutron and proton superfluids agrees with PSR 1055 data.**

Comment 1: *Protons being superfluid while NOT neutrons - not theoretically acceptable*(*15)

Comment 2: ***`No neutron superfluid'*** *may contradict with other observational evidence* (*15).

(ii) Y2004 **adopted NUCLEON direct URCA** for non-standard cooling: But if Vela and 3C58 data are indeed detections, **NUCLEON direct URCA will be too cold for these data.**

Reason: At the temperatures of these pulsars, **nucleons (both neutrons and protons) are NOT in the superfluid state(*17) → no superfluid suppression → too cold!**

Note: For NUCLEON direct URCA to work, *proton fraction must be much larger than ordinary neutron star matter*.

Implication – *significant reduction of superfluid critical temperature* T_{crit} *(energy gap)*

(Note:*Same applies to Kaon cooling(*18))*

(iii) Then, we **DO need `exotic' particles**!

IV. CONCLUSION

- **By changing stellar mass, both hotter and cooler pulsar data are consistent with current thermal evolution theories when heating is taken into account.**

- **Constituent 'exotic' particles**

  (pions, hyperons, etc.) for non-standard cooling must be in the superfluid state, if cooler data are <u>detections.</u>

- **Heating needed for PSR 1055 data.**

- **If cooler data (e.g., Vela, 3C58) are detections, both NUCLEON and KAON direct URCA cooling are NOT consistent with observation**

  →too cold!

Then, we DO need `exotic' core particles, such as pions and hyperons.

- **In that case, if Kyoto-Gifu experimental results are confirmed, that Λ hyperon superfluid gap is too small, then hyperon cooling also will be out. Then only pion or quark cooling will remain as the viable model.**

- If stellar mass should be very close to 1.4M , then softer EOS, such as TNI2U, should be favored. In this case, pion EOS may be too stiff.

- If the stellar mass should extend to wider ranges, such as ~ 1 to 2M (e.g., see (*13)) then more stiffer EOS, such as TNI6U (hyperon model), and TNI3U (pion model), should be favored.

- **OBSERVATIONAL IMPLICATION:**

  Current and future very long observations of important sources, such as Vela and 3C58, by Chandra, XMM/Newton and future missions, would be critical, to obtain more definitive conclusion – for testing thermal evolution theories with observation – e.g., whether `exotic' particles are needed, and if so, which one.

- (*1) Oppenheimer and Volkoff 1939
- (*2) Tsuruta and Cameron 1966
- (*3) Nomoto and Tsuruta 1987
- (*4) Becker 1995
- (*5) e.g., Tsuruta 1998, Tsuruta et al. 2002
- (*6) Flowers et al. 1976; Yakovlev et al. 1999
- (*7a) Tsuruta et al. 2006a
- (*7b) Tsuruta et al. 2006b
- (*8a Takatsuka et al. 2006
- (*8b) Tamagaki and Takatsuka 2006
- (*9) Tamagaki et al. 2004
- (*10) e.g., Alper t al. 1988
- (*11) Umeda, Tsuruta, Nomoto 1995
- (*12) Kaplan et al. 2004
- (*13) Nice et al. 2004
- (*14) Takahashi et al. 2001
- (*15) Tsuruta 2004
- (*16) Yakovlev et al. 2004
- (*17) Takatsuka and Tamagaki 1997
- (*18) Takatsuka and Tamagaki 1995