Neutron Star Interiors and Pulsar Manifestations

Shuhua Yang, Xiaoping Zheng
（杨书华、郑小平）

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Outline

1、 Introduction

2、Surface temperature observations of NSs and the cooling theory

3、NS cooling with the heating due to r-mode damping

4、The rapid cooling of Cassiopeia A NS and its explanations

5、Summary

1、Introduction

Pulsar observations **Physics in NS interiors**

1) Mass → Equation of state

2) Rotation frequency → Viscosity of cold dense matter

3) Surface temperature → Thermal physics

Heat capacity

Neutrino emission rates

Heating mechanisms:

(rotochemical heating,

Joule heating,

heating due to r-mode damping, etc.)

2、Surface temperature observations of NSs and the cooling theory

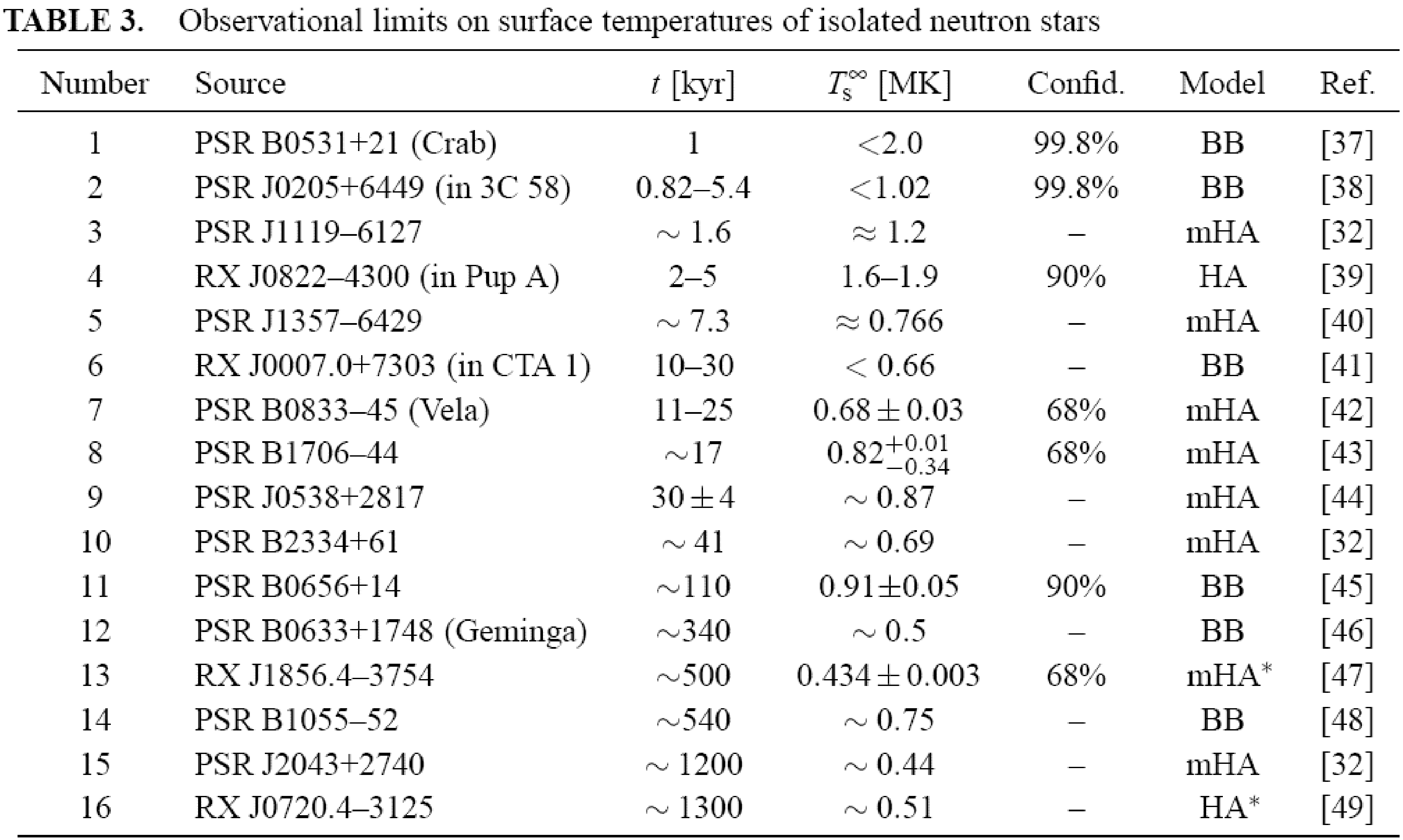


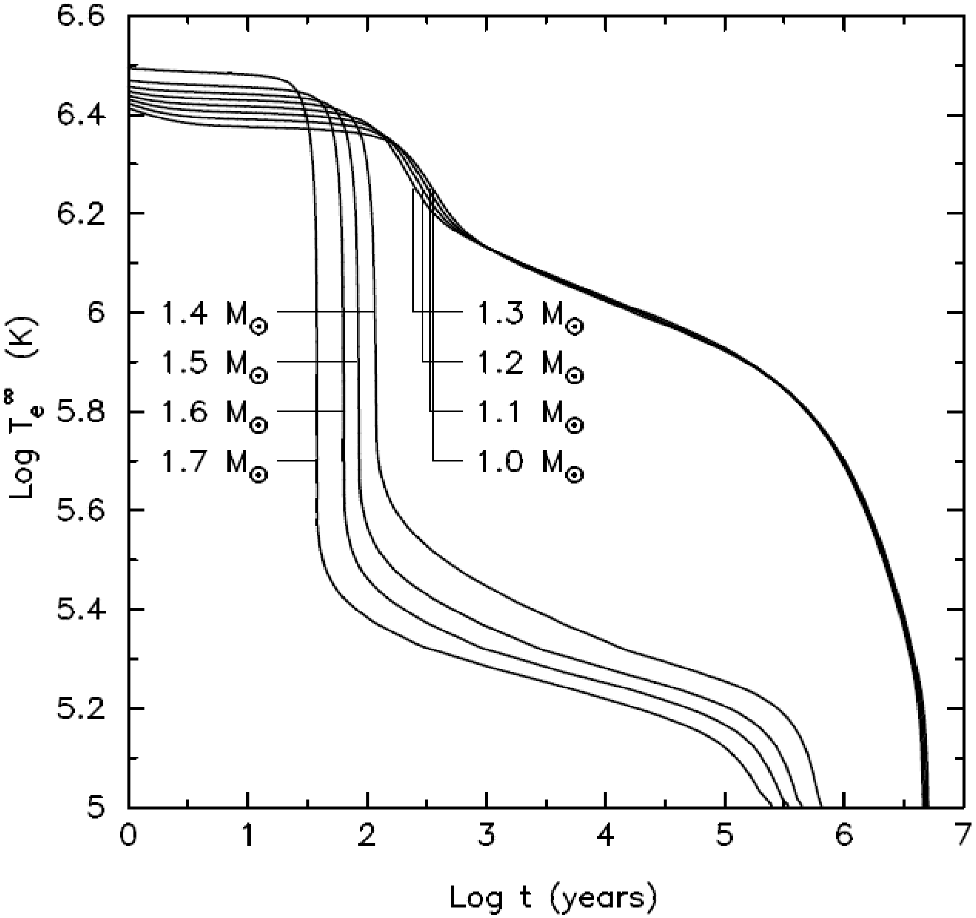
TABLE 3. Observational limits on surface temperatures of isolated neutron stars

Number	Source	t [kyr]	T_s^∞ [MK]	Confid.	Model	Ref.
1	PSR B0531+21 (Crab)	1	<2.0	99.8%	BB	[37]
2	PSR J0205+6449 (in 3C 58)	0.82–5.4	<1.02	99.8%	BB	[38]
3	PSR J1119–6127	~ 1.6	≈ 1.2	–	mHA	[32]
4	RX J0822–4300 (in Pup A)	2–5	1.6–1.9	90%	HA	[39]
5	PSR J1357–6429	~ 7.3	≈ 0.766	–	mHA	[40]
6	RX J0007.0+7303 (in CTA 1)	10–30	< 0.66	–	BB	[41]
7	PSR B0833–45 (Vela)	11–25	0.68 ± 0.03	68%	mHA	[42]
8	PSR B1706–44	~ 17	$0.82^{+0.01}_{-0.34}$	68%	mHA	[43]
9	PSR J0538+2817	30 ± 4	~ 0.87	–	mHA	[44]
10	PSR B2334+61	~ 41	~ 0.69	–	mHA	[32]
11	PSR B0656+14	~ 110	0.91 ± 0.05	90%	BB	[45]
12	PSR B0633+1748 (Geminga)	~ 340	~ 0.5	–	BB	[46]
13	RX J1856.4–3754	~ 500	0.434 ± 0.003	68%	mHA*	[47]
14	PSR B1055–52	~ 540	~ 0.75	–	BB	[48]
15	PSR J2043+2740	~ 1200	~ 0.44	–	mHA	[32]
16	RX J0720.4–3125	~ 1300	~ 0.51	–	HA*	[49]

Yakovlev et al. (2008) , AIPC,983,379

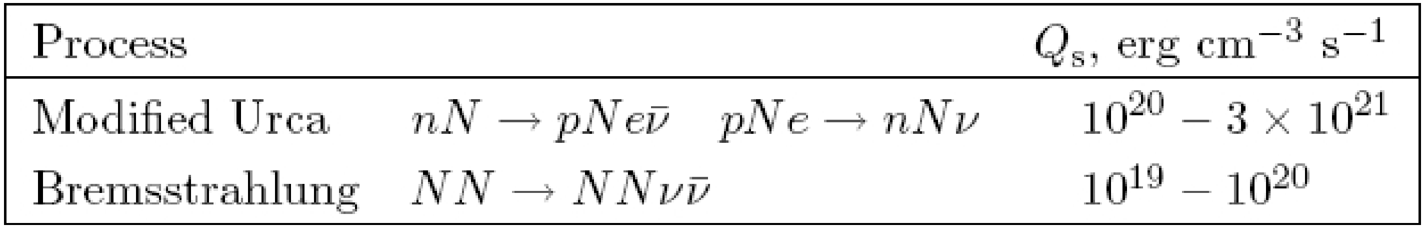
The thermal evolution equation with the approximation of isothermal interior

$$C_V \frac{dT}{dt} = -L_\nu - L_\gamma + H$$

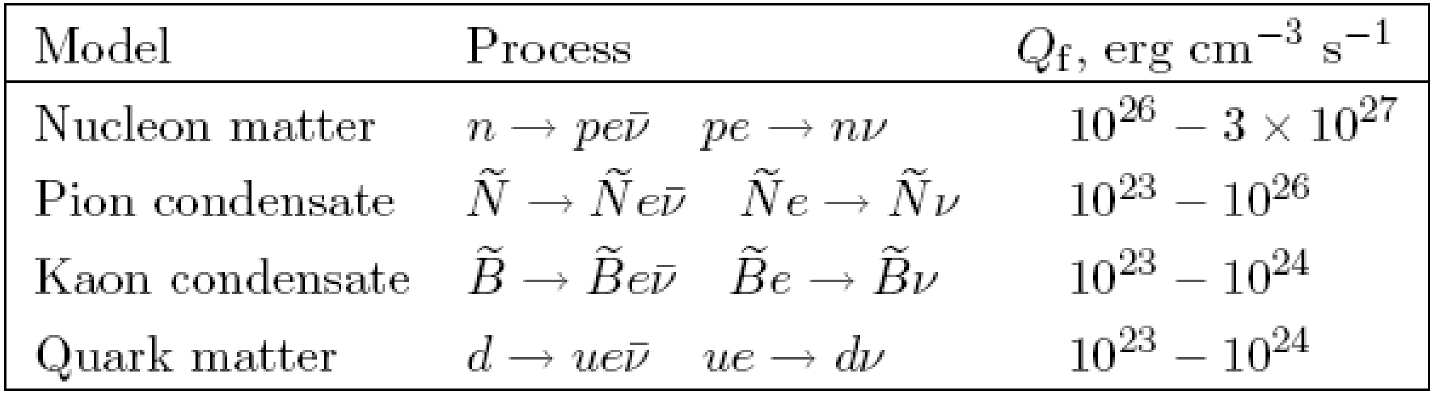


Page and Applegate (1992) , ApJL,394,17

Slow and fast neutrino emission processes

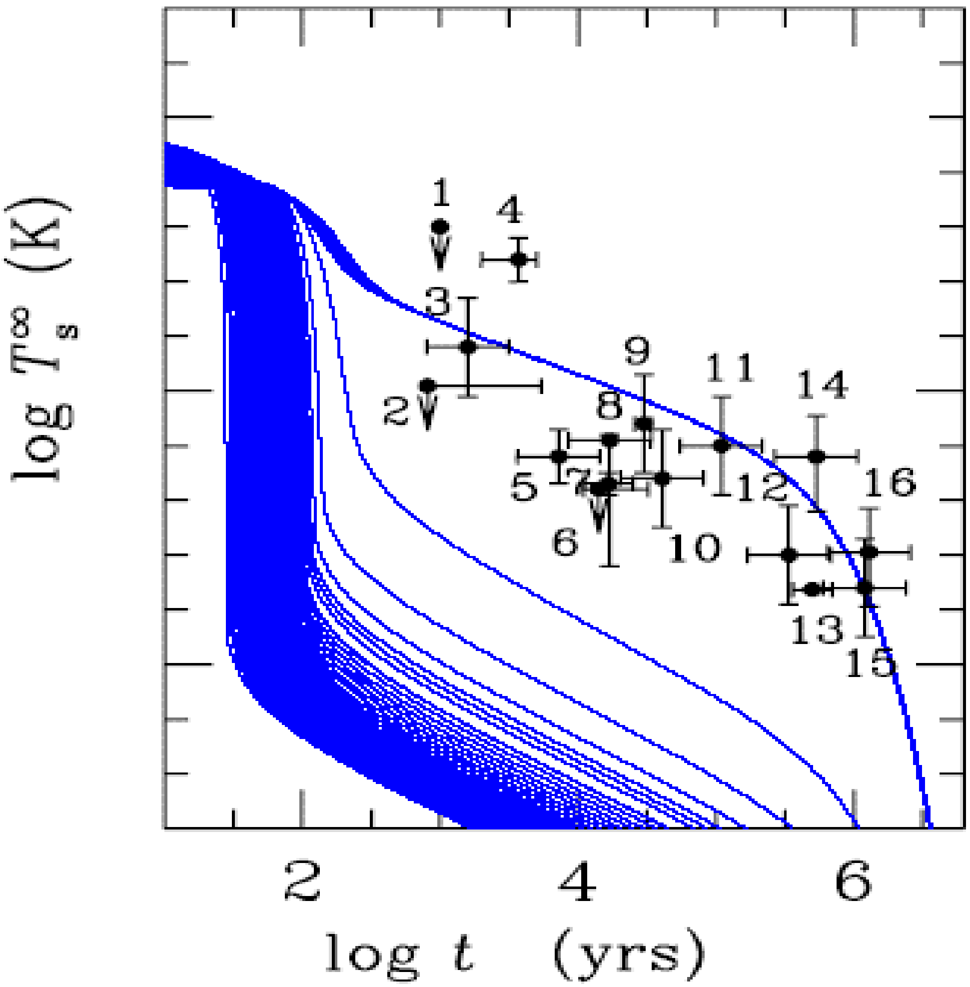


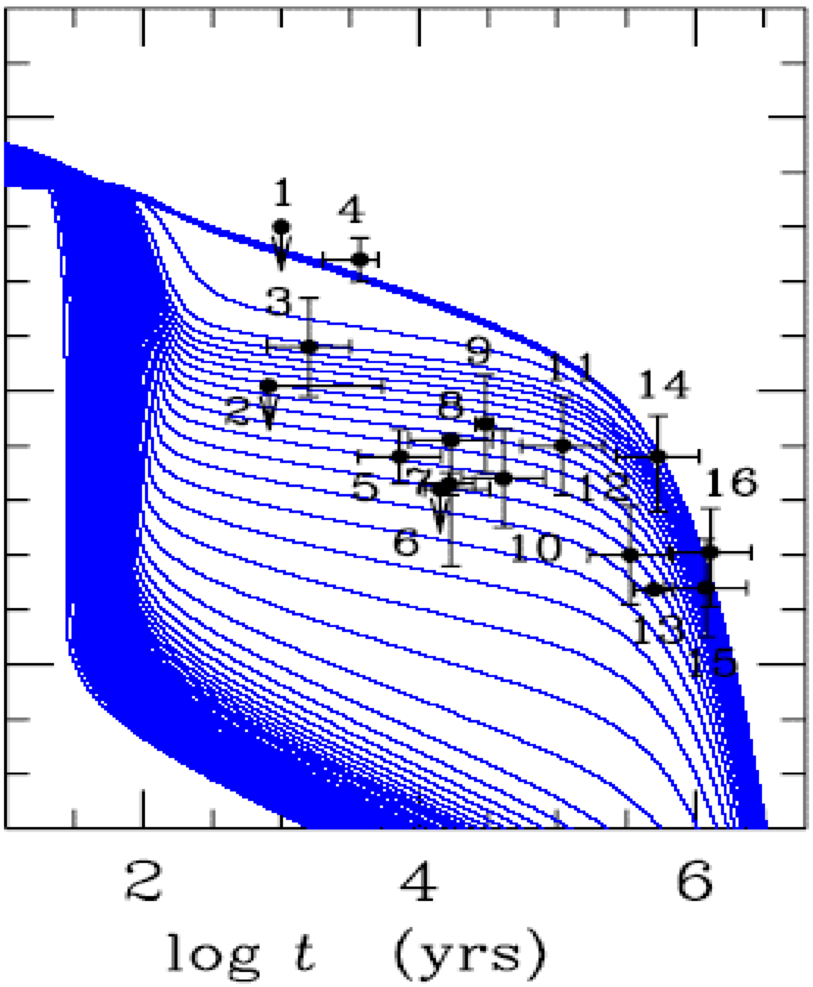
Process			Q_s, erg cm^{-3} s^{-1}
Modified Urca	$nN \to pNe\bar{\nu}$	$pNe \to nN\nu$	$10^{20} - 3\times10^{21}$
Bremsstrahlung	$NN \to NN\nu\bar{\nu}$		$10^{19} - 10^{20}$



Model	Process		Q_f, erg cm^{-3} s^{-1}
Nucleon matter	$n \to pe\bar{\nu}$	$pe \to n\nu$	$10^{26} - 3\times10^{27}$
Pion condensate	$\widetilde{N} \to \widetilde{N}e\bar{\nu}$	$\widetilde{N}e \to \widetilde{N}\nu$	$10^{23} - 10^{26}$
Kaon condensate	$\widetilde{B} \to \widetilde{B}e\bar{\nu}$	$\widetilde{B}e \to \widetilde{B}\nu$	$10^{23} - 10^{24}$
Quark matter	$d \to ue\bar{\nu}$	$ue \to d\nu$	$10^{23} - 10^{24}$

$$Q_\mathrm{slow} = Q_\mathrm{s}T_9^8, \qquad Q_\mathrm{fast} = Q_\mathrm{f}T_9^6.$$





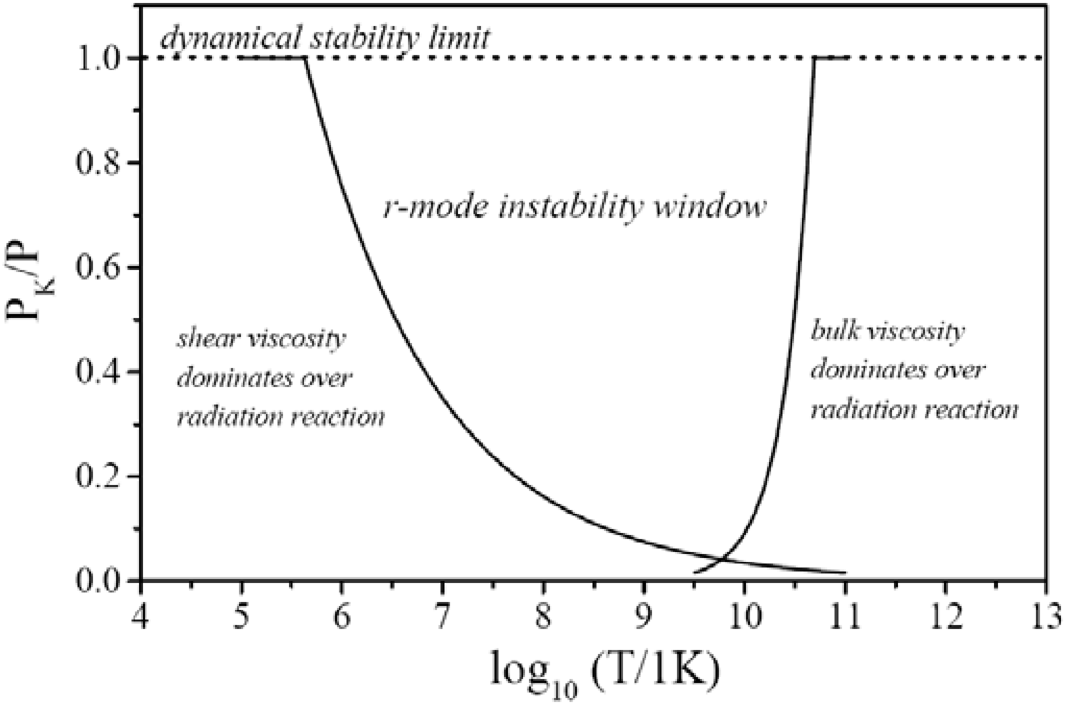
No superfluidity

Proton superfluidity $T_{cp}^{max} = 6.8 \times 10^9 \, K$

Yakovlev et al. (2008) , AIPC,983,379

3、NS cooling with the heating due to the r-mode damping

- R-mode in a perfect fluid star with arbitrary rotation due to the action of the Coriolis force with positive feed back, succumbing to CFS instability.
- In contrast, the growth of the modes can be suppressed by the viscosity of the stellar matter.



$$\frac{1}{2E}\frac{dE}{dt} = \frac{1}{t_{\rm gw}} + \sum \frac{1}{t_{\rm diss}} = 0$$

$$\frac{1}{t_{\rm diss}} = \frac{1}{t_{\rm sv}} + \frac{1}{t_{\rm bv}}$$

$$+ \text{ other dissipation terms}$$

Andersson et al (2001)

R-mode evolution in neutron stars

The r-modes of rotating barotropic Newtonian stars are solutions of the perturbed fluid equations having velocity perturbations

$$\delta \boldsymbol{v} = \alpha R \Omega \left(\frac{r}{R}\right)^{l} \boldsymbol{Y}^{B}_{l\,m} e^{i\omega t}$$

where $\Omega|$ is angular velocity of the unperturbed the star,

α is the dimensionless amplitude of the perturbation,

$\boldsymbol{Y}^{B}_{l\,m}$ is the magnetic-type vector spherical harmonic:

$$\boldsymbol{Y}^{B}_{l\,m} = [l(l+1)]^{-1/2} r \nabla \times (r \nabla Y_{l\,m})$$

- First-order r-modes (Owen et al. 1998)

In spherical coordinates, solving the linear fluid equations at the first order of the r-mode amplitude (α), we can get the r-mode solutions:

$$\delta^{(1)} v^r = 0, \tag{1a}$$

$$\delta^{(1)} v^\theta = \alpha \Omega C_l l \left(\frac{r}{R}\right)^{l-1} \sin^{l-1}\theta \sin(l\phi + \omega t), \tag{1b}$$

$$\delta^{(1)} v^\phi = \alpha \Omega C_l l \left(\frac{r}{R}\right)^{l-1} \sin^{l-2}\theta \cos\theta \cos(l\phi + \omega t), \tag{1c}$$

◆ Second-order r-modes

At the second order of the r-mode amplitude (Sa 2004)

$$\delta^{(2)} v^r = 0, \tag{10a}$$

$$\delta^{(2)} v^\theta = 0, \tag{10b}$$

$$\begin{aligned}\delta^{(2)} v^\phi &= \frac{1}{2}\alpha^2 \Omega C_l^2 l^2 (l^2 - 1)\left(\frac{r}{R}\right)^{2l-2} \sin^{2l-4}\theta \\ &+ \alpha^2 \Omega A r^{N-1} \sin^{N-1}\theta,\end{aligned} \tag{10c}$$

A and N are two constants determined by the initial condition.

- This second-order solution gives a differential rotation, producing large scale drifts of fluid elements along stellar latitudes.

- Sa & Tome (2005) suggested N = 2l -1 and redefined A by introducing a new free parameter K as

$$A = \tfrac{1}{2} K C_l^2 l^2 (l+1) R^{2-2l}$$

The physical angular momentum of the l=2 r-mode calculated up to the second order is **(Sa & Tome 2005)**

$$J_r = J^{(1)} + J^{(2)} = \frac{(4K+5)}{2}\alpha^2 \tilde{J} M R^2 \Omega,$$

For $K = -2$， $J^{(2)} = 0$， J_r return to the first order case.

$$\frac{dJ_r}{dt} = \frac{2J_r}{\tau_{\rm g}} - \frac{2J_r}{\tau_{\rm v}}$$

$$\tau_{\rm v} = (\tau_{\rm sv}^{-1} + \tau_{\rm bv}^{-1})^{-1}$$

$$\frac{dJ}{dt} = -\frac{3\alpha^2 \tilde{J} M R^2 \Omega}{\tau_{\rm g}} - \frac{I\Omega}{\tau_{\rm m}}$$

$J = I\Omega + J_r$ is the total angular momentum of the star,

$\tau_{\rm m}$ is the magnetic braking timescale.

R-mode evolution

$$\frac{d\alpha}{dt} = \left[1+\frac{4}{3}(K+2)Q\alpha^2\right]\frac{\alpha}{\tau_{\mathrm{g}}} - \left[1+\frac{1}{3}(4K+5)Q\alpha^2\right]\frac{\alpha}{\tau_{\mathrm{v}}} + \frac{\alpha}{2\tau_{\mathrm{m}}}$$

Spin evolution of NSs

$$\frac{d\Omega}{dt} = -\frac{8}{3}(K+2)Q\alpha^2\frac{\Omega}{\tau_{\mathrm{g}}} + \frac{2}{3}(4K+5)Q\alpha^2\frac{\Omega}{\tau_{\mathrm{v}}} - \frac{\Omega}{\tau_{\mathrm{m}}}$$

Thermal evolution of NSs

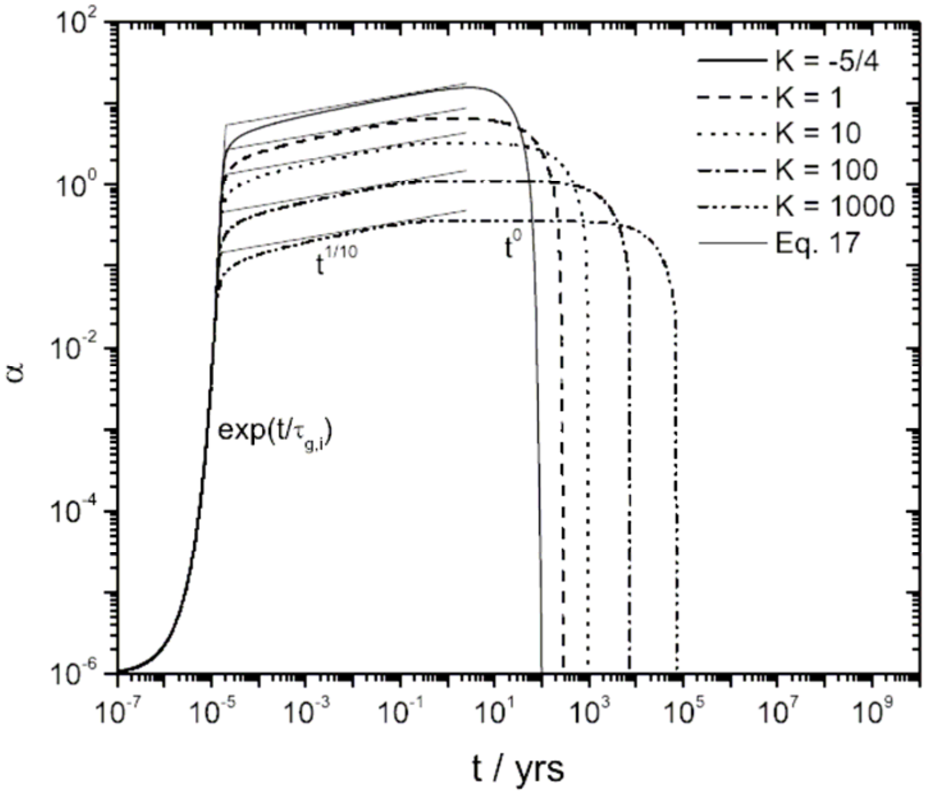
$$C_V\frac{dT}{dt} = -L_\nu - L_\gamma + H_\nu$$

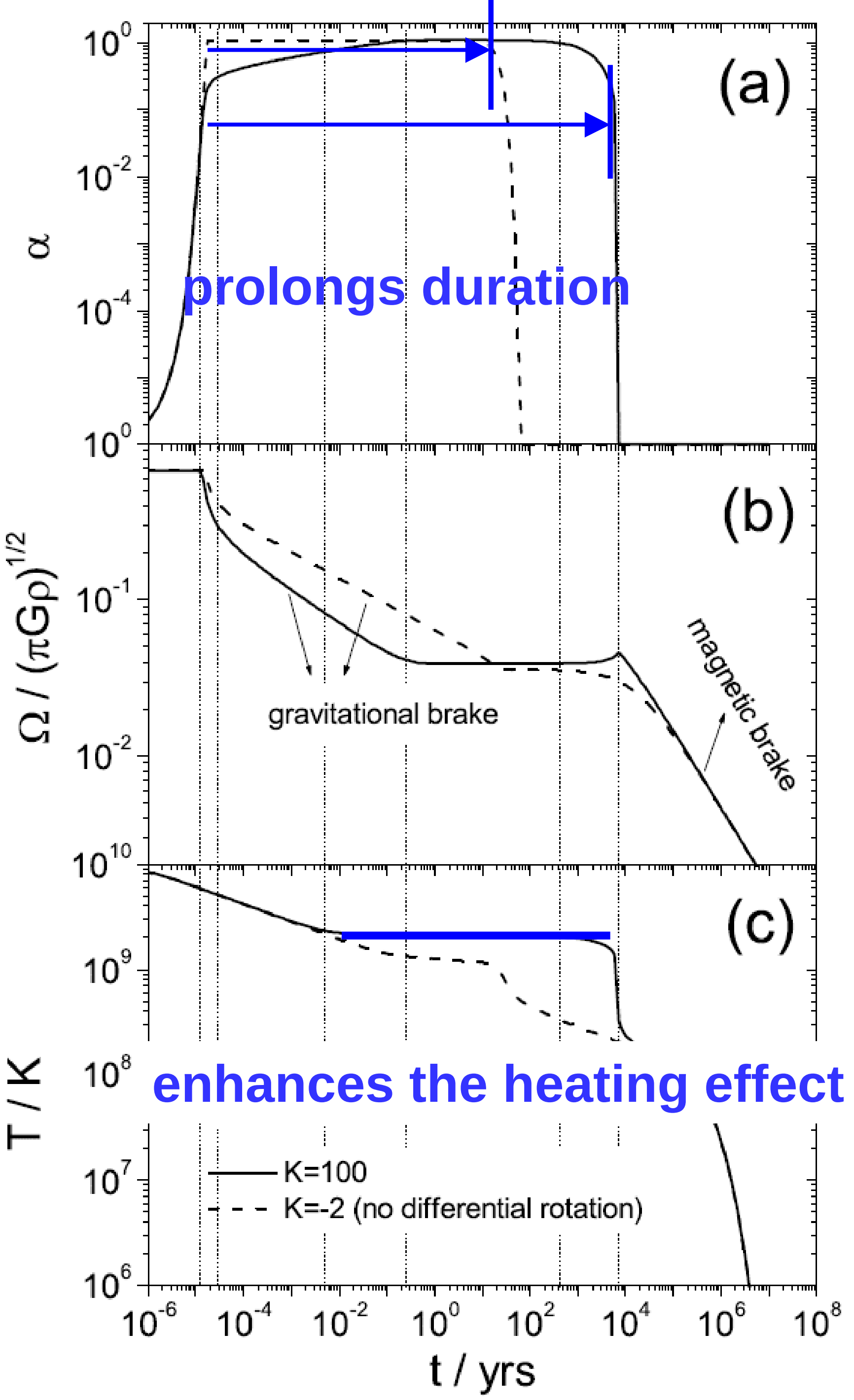
$$H_\nu = 2E_r\left(\frac{1}{\tau_{s\nu}} + \frac{1}{\tau_{b\nu}}\right)$$

Long-term evolution of isolated NSs

Research in Astron. Astrophys. **2009 Vol. 9 No. 9**, 1024–1034

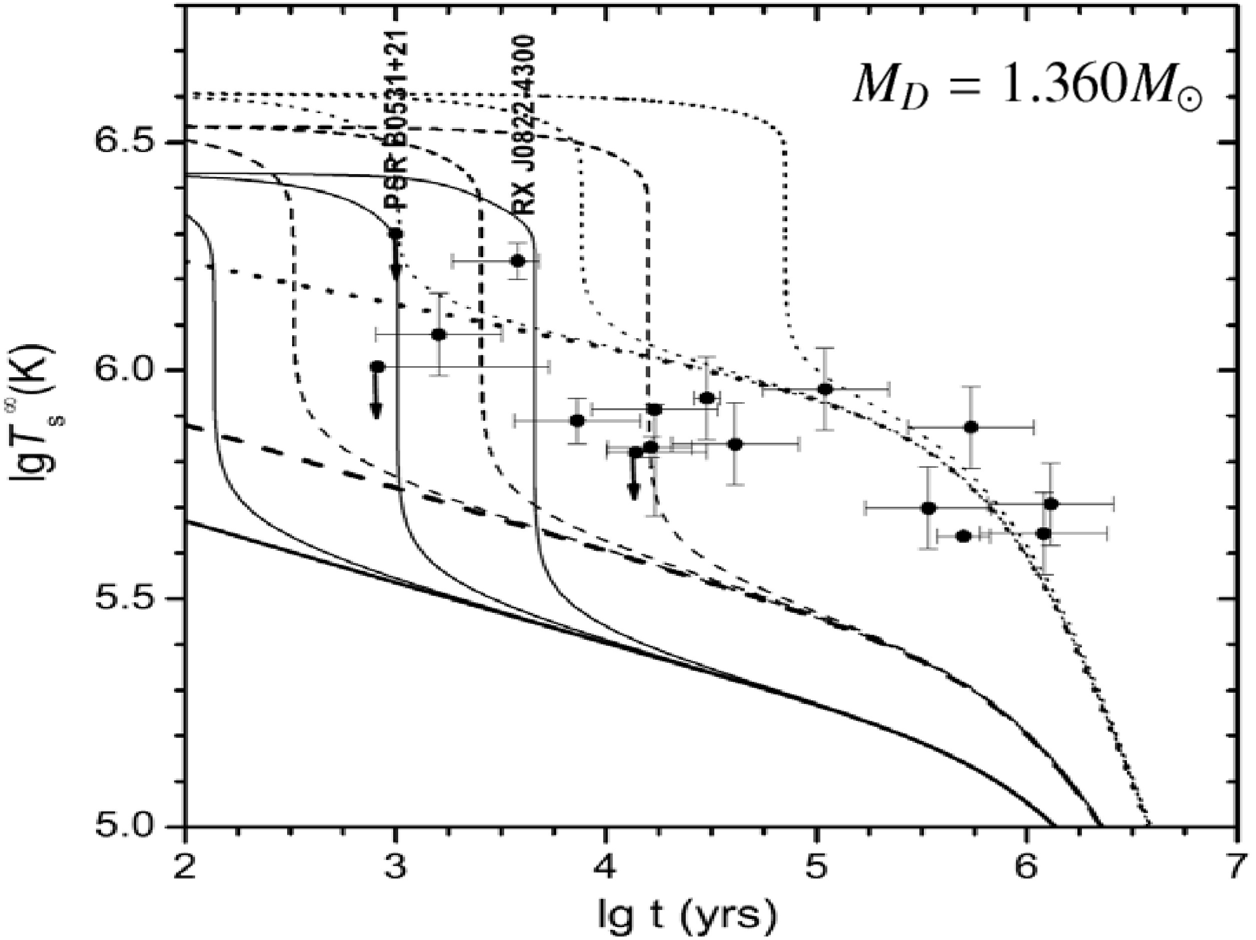
Yun-Wei Yu, Xiao-Feng Cao and Xiao-Ping Zheng





prolongs duration

enhances the heating effect



The dot, dashed and solid curves correspond to $M = 1.3M_\odot$, $M = 1.365M_\odot$ and $M = 1.4M_\odot$, respectively. The thick lines are calculated without the r-mode dissipation effect, and the thin lines refer to $K = 10, 100, 1000$ form left to right.

S H Yang et al , MNRAS, 2010

Conclusions:

(1)The NS is heated due to shear viscous damping of r-modes, and it can keep a high temperature for several thousand years, even tens of thousands of years.

This enables us to explain two young and hot pulsar data (PSR B0531+21 and RX J0822-4300) with NS model composed of only npe matter, without superfluidity or exotic particles.

(2)If consider a wider value range of NS mass and K, our light curves may probably cover all of the young and middle-aged thermal emission data, and the artificially strong p superfluidity invoked in Kaminker et al. (2001) is no longer needed .

4、The rapid cooling of Cassiopeia A NS and its explanations

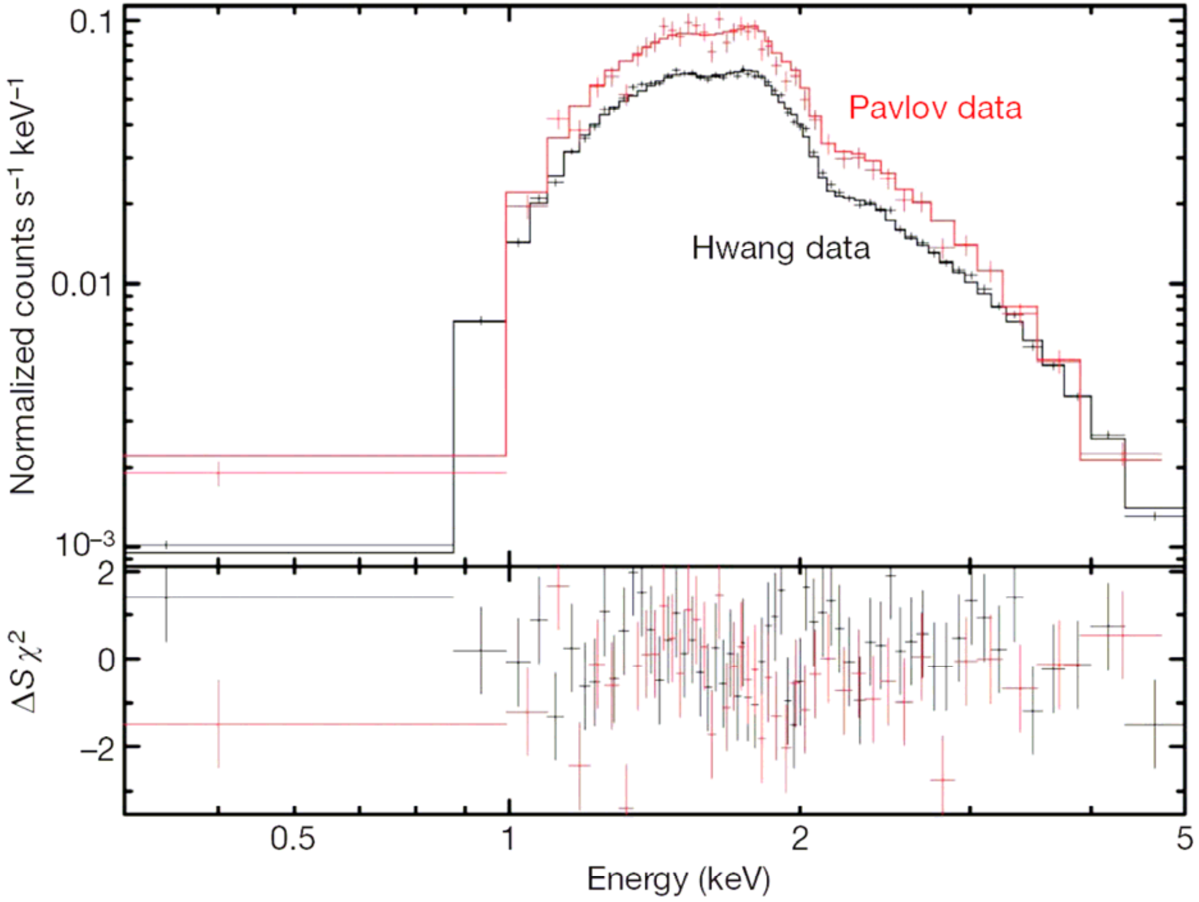


Figure 1 | Chandra X-ray spectra of Cas A. Spectra from the Hwang (black) and Pavlov (red) observations and fits with our C spectral model. Error bars

Heinke and Ho, Nature, 2009

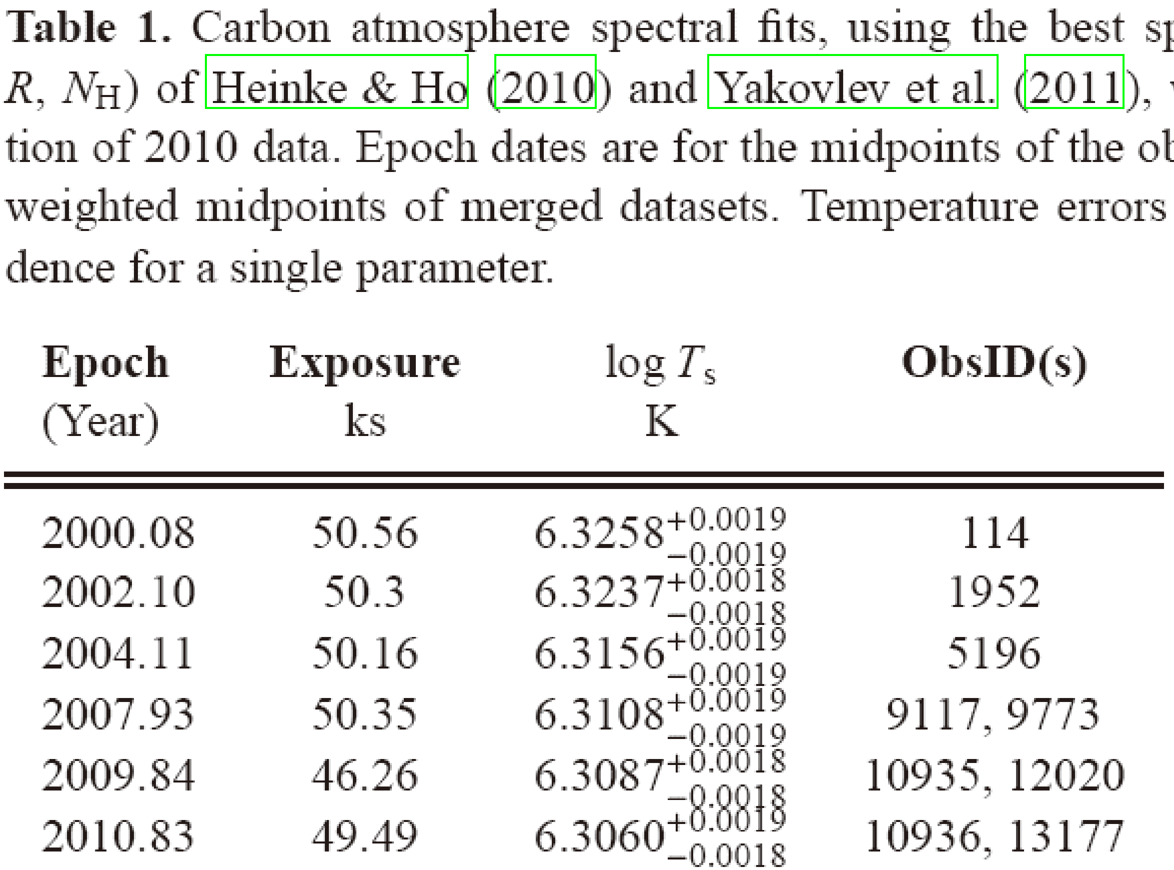


Table 1. Carbon atmosphere spectral fits, using the best spectral fit (M, R, $N_{\rm H}$) of Heinke & Ho (2010) and Yakovlev et al. (2011), with the addition of 2010 data. Epoch dates are for the midpoints of the observations, or weighted midpoints of merged datasets. Temperature errors are 1σ confidence for a single parameter.

Epoch (Year)	**Exposure** ks	$\log T_{\rm s}$ K	**ObsID(s)**
2000.08	50.56	$6.3258^{+0.0019}_{-0.0019}$	114
2002.10	50.3	$6.3237^{+0.0018}_{-0.0018}$	1952
2004.11	50.16	$6.3156^{+0.0019}_{-0.0019}$	5196
2007.93	50.35	$6.3108^{+0.0019}_{-0.0019}$	9117, 9773
2009.84	46.26	$6.3087^{+0.0018}_{-0.0018}$	10935, 12020
2010.83	49.49	$6.3060^{+0.0019}_{-0.0018}$	10936, 13177

Age of Cas A:

$t \approx 330 \pm 20$ yr

Rapid cooling of about 4% in 10 years!

Shternin et al. MNRAS, 412 (2011) L108

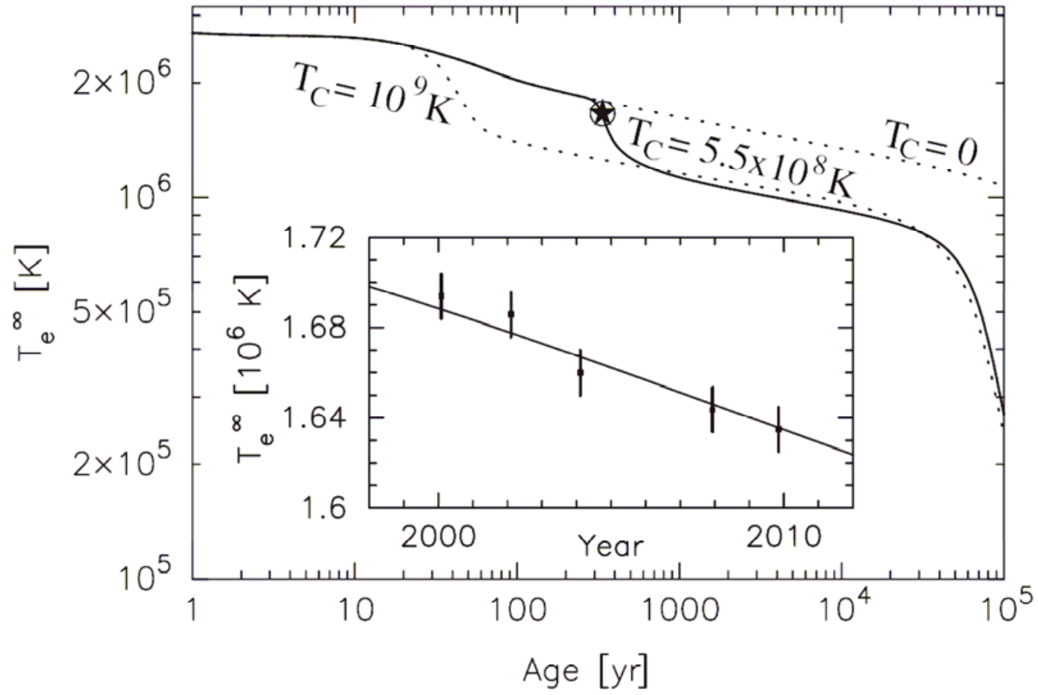


FIG. 3. A typical good fit to Cas A's rapid cooling for a $1.4 M_\odot$ star, built from the EOS of APR [25] with an envelope mass $\Delta M_{\rm light} = 5 \times 10^{-13} M_\odot$. The two dotted curves, with indicated values of T_C, are to guide the eye. The three models have a proton ${}^1S_0$ gap from [26] (the model "CCDK" in [14]) which results in the entire core being superconducting. The insert shows a comparison of our results with the five data points of [7] along with their 1σ errors.

Superfluid Model

Rapid cooling of Cas A NS is triggered by "breaking and formation of Cooper pairs(PBF)" Neutrino-emission process.

Page et al. Phys.Rev.Lett, 106, 081101 (2011)

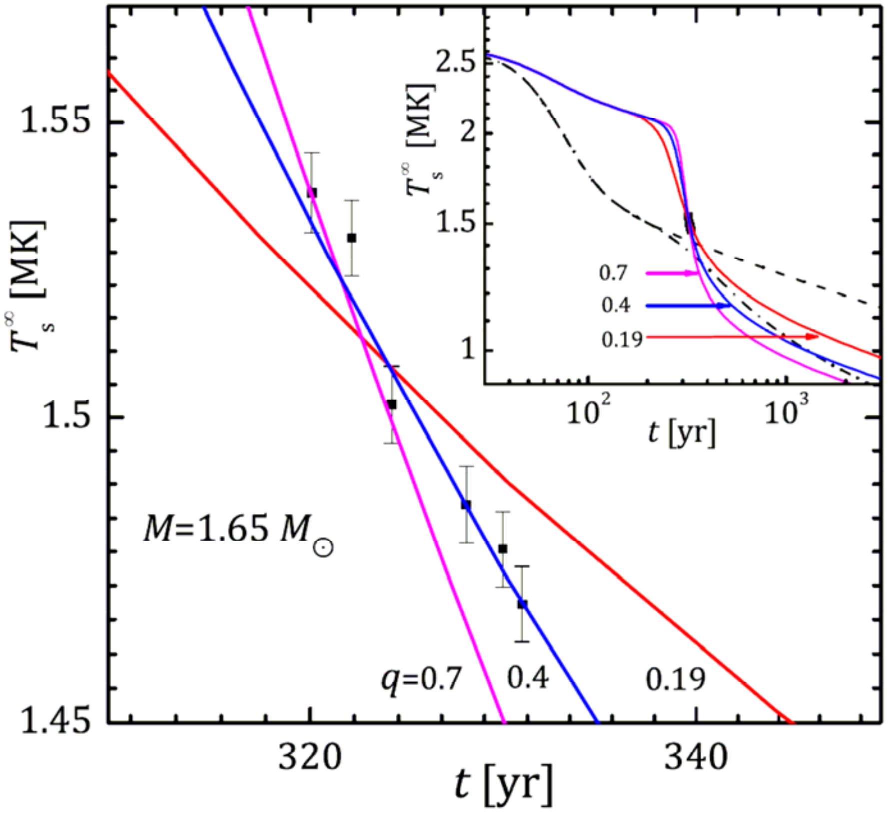


Figure 3. (Color on line) Same as on the right panel of Fig. 1 but for constant $T_{\rm cn}$ over the core at three values $q = 0.19$ ($T_{\rm cn} = 7.55 \times 10^8$ K), 0.4 (7.2×10^8 K) and 0.7 (7×10^8 K). The inset shows the same cooling curves but over larger range of ages, together with the dashed curve for non-superfluid star and the dash-and-dot curve for the star without proton superfluidity but with neutron superfluidity at $T_{\rm cn} = 4.3 \times 10^8$ K.

Superfluid Model

Shternin et al. MNRAS, 412 (2011) L108

- [Science News] 2011.2.4

Supernova to superfluid

- [New Scientist] 2011.2.4

Neutron star seen forming exotic new state of matter

- [NASA press release] 2011.2.23

NASA'S Chandra Finds Superfluid in Neutron star's core

- [Nature news] 2011.4.1

Superfluid state for Galaxy's youngest neutron star?

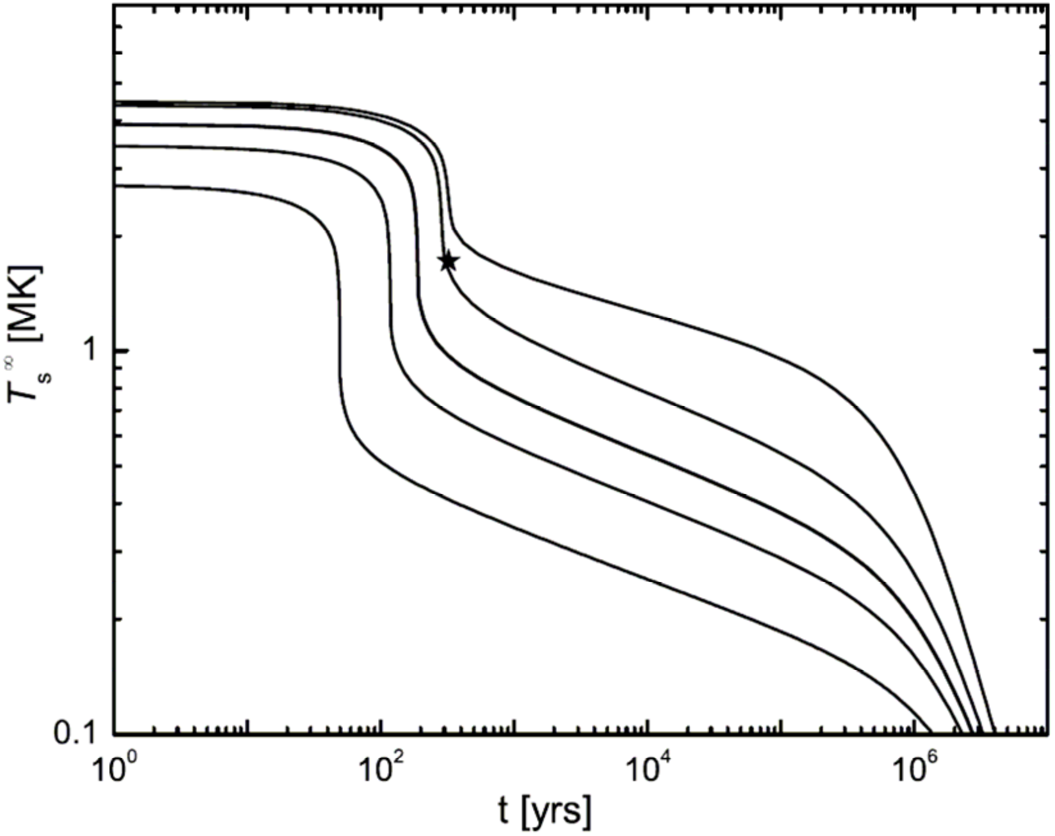


Fig. 1.— Cooling curves of neutron stars with $K = 2$. The curves correspond to the NS mass $1.360M_\odot$, $1.361M_\odot$, $1.362M_\odot$, $1.365M_\odot$ and $1.4M_\odot$, respectively. The pentagram presents the location of the observed cooling data of Cas A NS.

The rapid cooling of Cas A NS suggested that the star is experiencing the recovery period following the r-mode heating process.

S H Yang, C M Pi, X P Zheng, arXiv:1103.1092

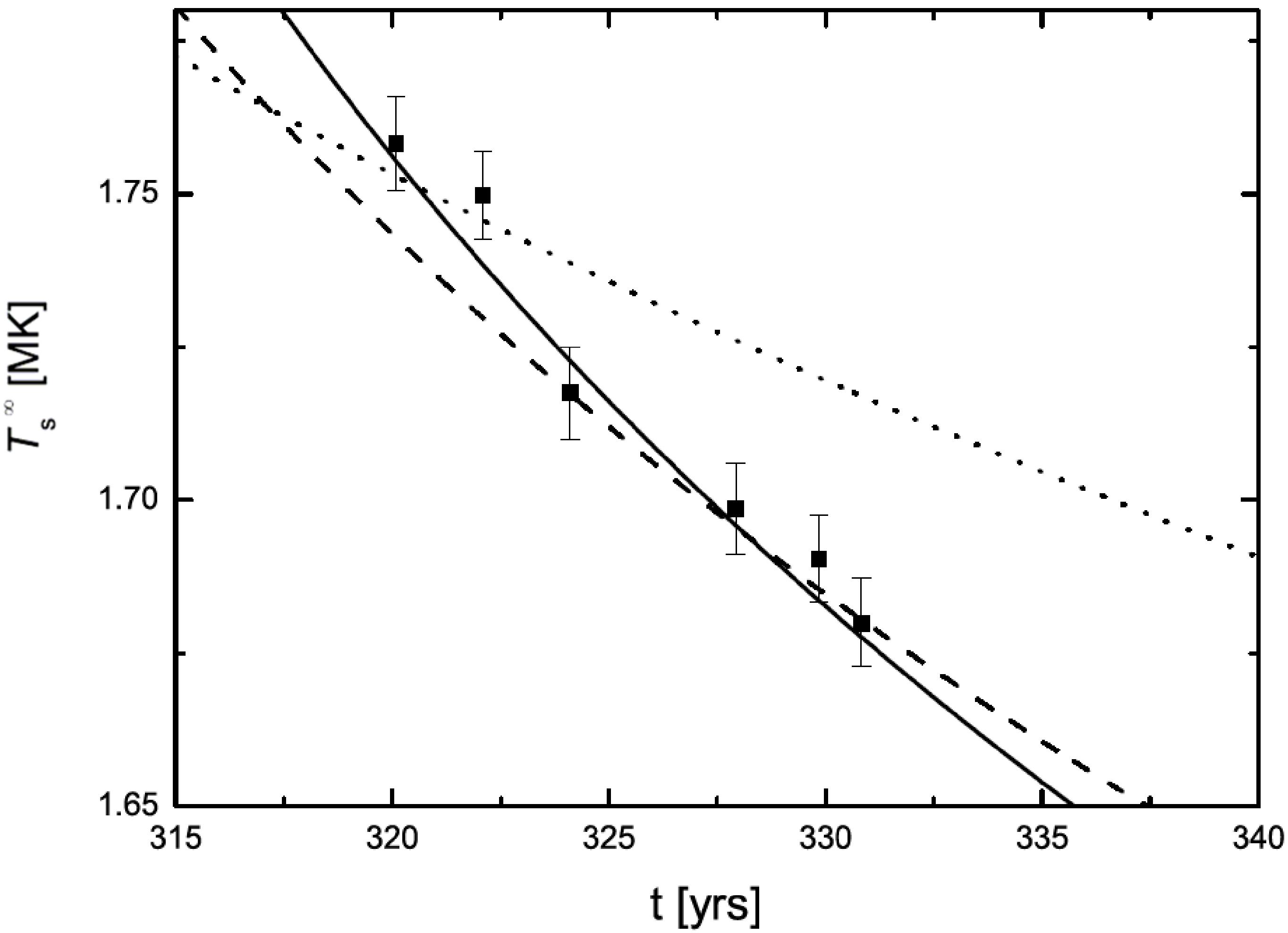


Fig. 2.— Cooling curves of the $1.361 M_\odot$ neutron star. The dot, dashed and solid curves correspond to $K = 1.5$, $K = 2.1$ and $K = 2.3$, respectively.

S H Yang, C M Pi, X P Zheng, arXiv:1103.1092

Comparison between Two Models

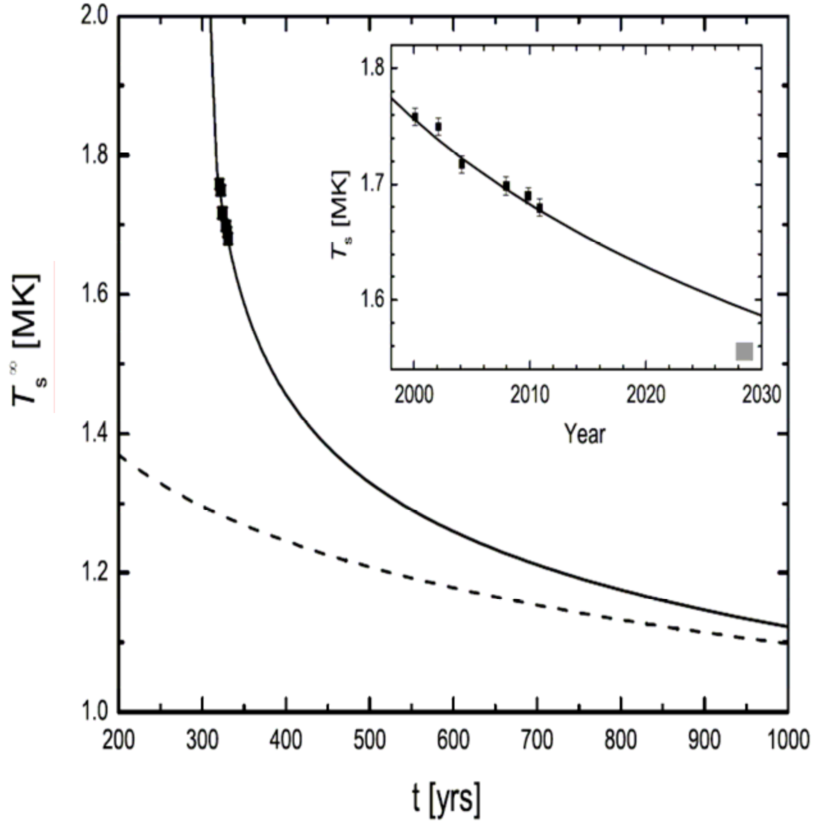


Fig. 3.— Cooling curves of the 1.361$M_\odot$ neutron star with $K = 2.3$ (solid line). For comparison, the dashed line is calculated without the r-mode heating effect. The insert shows the temperature evolution in the following twenty years and the grey rectangle indicates the possible temperature scope predicted by the neutron-superfluidity-triggering model.

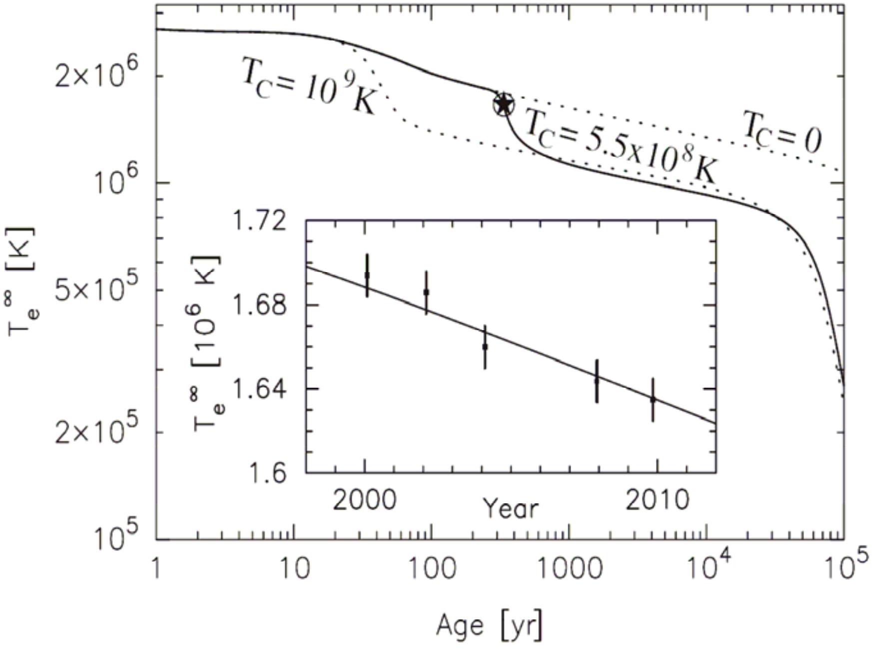


FIG. 3. A typical good fit to Cas A's rapid cooling for a 1.4$M_\odot$ star, built from the EOS of APR [25] with an envelope mass $\Delta M_{\mathrm{light}} = 5 \times 10^{-13} M_\odot$. The two dotted curves, with indicated values of T_C, are to guide the eye. The three models have a proton $^1S_0$ gap from [26] (the model "CCDK" in [14]) which results in the entire core being superconducting. The insert shows a comparison of our results with the five data points of [7] along with their 1σ errors.

Page et al. Phys.Rev.Lett, 106, 081101 (20

5、Summary

- The heating due to r-mode damping enables us to explain the surface temperature data with NS model composed of only npe matter, without the including of superfluidity or exotic particles.
- The heating due to r-mode damping enables us to explain the rapid cooling of Cas A NS without the triggering by “breaking and formation of Cooper pairs(PBF)” Neutrino-emission process.
- Thermal emission is closely related to compositions and internal physics of neutron stars, which is believed to become future probe into NSs.

Thank you!