RAPID COOLING OF THE NEUTRON STAR IN CASSIOPEIA A AND \( r \)-MODE DAMPING IN THE CORE

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Received 2011 March 4; accepted 2011 June 2; published 2011 June 16

ABSTRACT

We proposed an alternative explanation to the rapid cooling of neutron star in Cas A. It is suggested that the star experiences the recovery period following the \( r \)-mode heating process assuming the star is differentially rotating. Like the neutron-superfluidity-triggering model, our model predicts that the rapid cooling will continue for several decades. However, the behavior of the two models has slight differences, and they might be distinguished by observations in the near future.

Key words: stars: evolution – stars: neutron – supernovae: individual (Cassiopeia A)

1. INTRODUCTION

The neutron star (NS) in Cassiopeia A (Cas A) is one of the most important isolated NSs in testing the thermal evolution theory of NSs because both its age and surface temperature are reliably estimated: \( t \approx 330 \pm 20 \) yr (Fesen et al. 2006) and \( T_s \sim 2 \times 10^6 \) K (Ho & Heinke 2009). The importance of Cas A NS was greatly enhanced recently, as Heinke & Ho (2010) found a steady decline in \( T_s \) by about 4\% by analyzing the 10 year Chandra observations; the new observational data reported by Shkernin et al. (2011) confirm and extend this cooling trend (see Table 1 in Shkernin et al. 2011).

Page et al. (2011) and Shkernin et al. (2011) suggested that the observed decrease in the surface temperature of Cas A NS is difficult to explain by the cooling theory despite considering the triplet-state neutron superfluidity, the cooling rate of which is much larger than that expected from the standard modified Urca process; and it is not likely due to the crust–core relaxation, which is supposed to last for typically \( \leq 100 \) yr (e.g., Lattimer et al. 1994; Yakovlev et al. 2010). They also found that if this rapid cooling is triggered by the “breaking and formation of Cooper pairs (PBF)” neutrino-emission process, the cooling data may constrain the critical temperature of the triplet-state neutron superfluidity to several times of \( 10^8 \) K.

In this Letter, we present an alternative explanation to the rapid cooling of Cas A NS, which suggests that the star experiences the recovery period when the \( r \)-mode heating process is over. In the next section, we discuss the \( r \)-mode heating mechanism during the thermal evolution of NSs. After that, our explanation of the cooling data of Cas A NS is given. In the last section the conclusions and discussions are presented.

2. \( r \)-MODE HEATING IN NEUTRON STARS

Ever since 1998, the \( r \)-mode instability has been extensively studied in compact stars as the most important gravitational-radiation-driven Chandrasekhar–Friedman–Schutz instability (Andersson 1998; Friedman & Morsink 1998), and it is believed that it determines the spin limit of compact stars and the gravitational wave emitted during the unstable process of the star can be detected by the new generation of gravitational-wave detectors (Andersson & Kokkotas 2001). However, the role of the \( r \)-mode dissipation for the thermal evolution of compact stars has long been ignored because the heating effect due to the \( r \)-mode dissipation is supposed to exist only in the first several decades of the newly born NSs (Watts & Andersson 2002). Nevertheless, Zheng et al. (2006) found that for strange stars made of strange quark matter (SQM), the \( r \)-mode heating effect can last for even \( 10^7 \) years.

In fact, there exists a saturated amplitude for \( r \)-modes in compact stars during the unstable process. Since the saturated amplitude is determined by the nonlinear effects, it is usually put into the model artificially (Owen et al. 1998; Ho & Lai 2000). Many efforts have been made in studying the nonlinear effects to naturally demonstrate a saturated \( r \)-mode amplitude (e.g., Schenk et al. 2002; Arras et al. 2003; Brink et al. 2004, 2005). As an important nonlinear effect, the differential rotation induced by \( r \)-modes was studied extensively (Rezzolla et al. 2000, 2001a, 2001b; Stergioulas & Font 2001; Lindblom et al. 2001; Sá 2004). Among them Sá (2004) and Sá & Tomé (2005, 2006) solved the fluid equations within nonlinear theory up to the second order in the mode amplitude and described the differential rotation analytically. By doing so, they obtained a saturated amplitude of \( r \)-modes self-consistently, which depends upon the parameter that describes the initial condition of the differential rotation.

Using the model developed by Sá (2004) and Sá & Tomé (2005, 2006), Yu et al. (2009) investigated the long-term spin and thermal evolution of isolated NSs under the influence of the differential rotation, and pointed out that the stars can maintain a nearly constant temperature for over one thousand years since the differential rotation significantly prolongs the duration of \( r \)-modes. The detailed study by Yang et al. (2010) found that the heating effect of the prolonged \( r \)-modes enables us to explain the two young and hot pulsar’s (PSR B0531+21 and RX J0822–4300) temperature data with an NS model composed of simple npe matter, without the inclusion of superfluidity or exotic particles.

In the thermal evolution curves of Figure 2 in Yu et al. (2009) and Figure 1 in Yang et al. (2010), it can easily be found that a rapid cooling period emerges immediately after the \( r \)-mode heating process is switched off. Therefore, we try to explain the observed rapid cooling of Cas A NS following Yang et al. (2010) in the next section.

3. RESULTS

In order to simulate the thermal evolution, the thermal evolution equation of an NS must be solved numerically coupled with the equations of the \( r \)-mode evolution and the spin evolution
of the star (see Equations (13)–(15) of Yang et al. 2010). We take the initial temperature $T_0 = 10^{10}$ K, the initial $r$-mode amplitude $\alpha_0 = 10^{-6}$, and the initial angular velocity $\Omega_0 = \frac{5}{2}\sqrt{\pi GR_\odot}$.

In our simulation, we considered the magnetic field as $B = 5 \times 10^{10}$ G since the X-ray spectral fits of Cas A NS suggest $B < 10^{11}$ G (Ho & Heinke 2009), and the NS is believed to be one of the several so-called central compact objects (CCOs) which has $B \sim 10^{10}$–$10^{11}$ G (Halpern & Gotthelf 2010; Ho 2011).

Following Yang et al. (2010), a moderately stiff equation of state (EOS) proposed by Prakash et al. (1988) is employed (model I). The maximum mass of this model is $M = 1.977\,M_\odot$, and the direct Urca process is forbidden in the $M < M_D = 1.36\,M_\odot$ case. The relation between $T_s$ and the internal NS temperature $T$ is taken from the study of Potekhin et al. (1997), which assumes that the outer heat-blanketing NS envelope is made up of ions and that the effects of surface magnetic fields can be neglected.

The cooling data of Cas A NS are taken from Table 1 of Shaterin et al. (2011). Note that the effective surface temperature detected by a distant observer is $T_s^\infty = T_s\sqrt{1 - R_e/R}$, where $R_e$ is the gravitational stellar radius. Because we mainly focus on the $M = 1.36\,M_\odot$ NS model (the corresponding radius is $12.93$ km), the value $T_s^\infty \approx 0.83 T_s$ is taken.

Figure 1 shows the cooling curves of NSs with different masses and fixed $K = 2$ ($K$ is a free parameter describing the initial condition of the differential rotation). The plateaus of the curves indicate the heating effect due to $r$-mode dissipation, and the duration of the high temperature depends on the parameter $K$ of the selected NS mass (see Figure 3 of Yang et al. 2010). Since the direct Urca process begins to happen in the $M = 1.36\,M_\odot$ NS model (which can greatly enhance the neutrino emission rate compared with the modified Urca process), the cooling curves sensitively depend on the mass in its vicinity (see the curves of $M = 1.361\,M_\odot$, $1.362\,M_\odot$, and $1.365\,M_\odot$), and only the $M = 1.361\,M_\odot$ curve passes through the region where the observed data are located. Comparing to Figure 2 of Yu et al. (2009), one can easily find that the rapid cooling that can be used to explain the Cas A NS data occurs just after the complete shutoff of the $r$-mode heating process.

Figure 2 displays the cooling curves of the $1.361\,M_\odot$ NS with different values of $K$ and the curves are compared with the Cas A NS data. In comparison with the observations, the differential rotation parameter $K$ can take the values around $2.0$. In Figure 3, we plot our best-fitted cooling curve ($K = 2.3$) in a larger span of ages and the curve without the $r$-mode heating effect is also displayed for comparison. An inset is also displayed to show the possible temperature drop in the following 20 years and the gray rectangle indicates the possible temperature scope predicted by the neutron-superfluidity-triggering model. It can be seen that the rapid cooling near the Cas A NS data will continue for several decades, and it will take a few hundred years to recover to the normal cooling rate, which does not consider the $r$-mode heating effect. Although the behavior of the rapid cooling process of our model seems similar to the neutron-superfluidity-triggering model (Page et al. 2011; Shatenin et al. 2011), there are differences in the details. The part of the curve that best fits the observational data in both of their studies (see Figure 3 of Page et al. 2011 and Shaterin et al. 2011) is closer to a straight line than that of our curve. As a result, our best-fitted
The Astrophysical Journal Letters, 735:L29 (3pp), 2011 July 10

Figure 4. Evolution of the amplitude of $r$-modes of the 1.361 $M_\odot$ neutron star with $K = 2.3$.

curve predicts about 2\% higher temperature in two decades (see the inset). Perhaps, this difference is distinguishable in future observations.

In Figure 4, we plot the evolution of the amplitude of $r$-modes with the same parameters as shown in Figure 3. Abadie et al. (2010) analyzed the data of Cas A NS in a 12 day interval taken by LIGO and no gravitational-wave signal is found. But they gave the upper limits on the $r$-mode amplitude, which is 0.005–0.14. As far as our model is concerned, one can easily see from Figure 4 that the amplitude of $r$-modes dropped to 0.005 about 24 years ago (that is, in the year 1987). We also do not expect that the gravitational wave due to $r$-modes can be observed even by the advanced LIGO and Virgo interferometers, since the amplitude of $r$-modes declined to its initial value ($\alpha = 10^{-6}$) in 1997.

4. CONCLUSIONS AND DISCUSSIONS

Based on our former work about the $r$-mode heating effect of an NS, we explained the rapid cooling of the Cas A NS. When the $r$-mode heating process is switched off, the NS cools down rapidly, and it needs a few hundred years to recover to the normal cooling rate (which refers to the case that does not consider the $r$-mode heating effect). The rapid cooling as the Cas A NS occurs in the beginning of this recovery period and will last for several decades. We also found that the behavior of our model and the neutron-superfluidity-triggering model has slight differences, and they might be distinguished by observations in the near future.

The essential element of our interpretation of the rapid cooling of Cas A NS is that the $r$-mode instability period of the star can last for about 300 years. Although many models addressing the nonlinear evolution of $r$-modes in NSs did not expect such a long duration of the $r$-mode instability (e.g., Rezzolla et al. 2001a, 2001b; Bondaresu et al. 2009), some models did incorporate it (e.g., Arras et al. 2003).

In our calculation, we assumed that the outer heat-blanketing NS envelope is made up of ions. However, the Cas A NS is believed to have a carbon atmosphere (Ho & Heinke 2009).

Theoretically, light elements make the envelope more heat transparent and the surface temperature of a same-mass NS can be increased (Potekhin et al. 1997), and one has to explain the observations of the Cas A NS with an NS model of a slightly larger mass than 1.361 $M_\odot$.

What is more, we only considered a constant magnetic field in our simulation. Nevertheless, Rezzolla et al. (2001a, 2001b) showed that the differential rotation induced by $\alpha$-mode will generate a strong toroidal magnetic field, this could affect the $r$-mode evolution and should be taken into account in further work.

We acknowledge Y. W. Yu for useful discussion. We are especially indebted to the anonymous referee for his/her useful comments that helped us to improve the Letter. This work is supported by the National Natural Science Foundation of China (grant 11073008).

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